

EUROPEAN COOPERATION
IN THE FIELD OF SCIENTIFIC
AND TECHNICAL RESEARCH



EURO-COST

Source: COST IC1004
Date: 26/April/2016

COST IC1004 White Paper on Channel Measurements and Modeling for 5G Networks in the Frequency Bands above 6 GHz

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Executive summary

This white paper states the views of the researchers of the European COST Action IC1004 on Channel Measurements and Modelling for 5G Networks in the Frequency Bands above 6 GHz.

The growth in demand for data has generated interest in identifying contiguous sections of the spectrum in the higher frequency bands as a possible solution. This has led to numerous efforts worldwide into channel measurements and channel modelling in the frequency bands above 6 GHz. In particular the millimetre wave band has been identified as a strong candidate with the World Radio Communications Conference held in November 2015 (WRC15) identifying several bands between 24-86 GHz as possible frequency allocations. To coordinate the international effort in this area, Study Groups (SG) SG3 and SG5, of the International Telecommunications Union (ITU) are holding various meetings and setting up Correspondence Groups for measurement techniques and channel characterisations targeting future 5G systems and propagation models to update current ITU recommendations. Other standardisation bodies include 3GPP and ETSI.

In this white paper we present the views of the COST IC1004 Action on channel measurements and modelling for 5G systems operating in the higher frequency bands for both fixed links and mobile links in indoor and outdoor environments. State of the art radio channel capability with channel measurements and channel models developed thus far are presented with future planned measurements in the identified WRC15 frequency bands.

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2 Abstract

Future wireless networks are expected to operate with high data rates 5000 fold higher than current networks. In the currently allocated frequency bands below 6 GHz, there is room for increase in system spectral efficiency through techniques such as Coordinated Multi-Point (CoMP), Massive MIMO, interference management and cancellation techniques. While these techniques are especially useful for bands below 10 GHz the availability of large contiguous blocks of spectrum in the higher frequency bands could be exploited enabling the possibility of very significant (~1 GHz or more) increase in bandwidth. This has been recognized by the World Radiocommunications Conference WRC15 which identified a number of frequency bands ranging between 24 GHz to 86 GHz for possible future allocation with significant bandwidths up to 10 GHz in the 66-76 GHz band. Having access to such large blocks of spectrum makes it possible in early deployments to trade off spectral efficiency for bandwidth, where high data rates are achieved even with low-order modulation schemes requiring lower powers, lower complexity, and lower cost.

In these higher frequency bands, the wavelength, and consequently antenna elements, are smaller, which facilitates the implementation of large antenna arrays for beam forming to compensate for propagation losses, and to achieve significant system capacity and throughput gains.

Exploitation of mm-wave frequencies for the next generation of mobile communication standards (5G) has started to gain considerable traction within the wireless industry, such as EU's Horizon 2020, 5G PPP initiative, regulators, and the International Telecommunications Union (ITU). Study Group 5 of the ITU is working on the potential of IMT at higher frequencies, and Study Group 3 is working on propagation measurements and channel modeling in the higher frequency bands with the formation of two Correspondence Groups within Working Party 3K.

Technologies operating in the 60 GHz unlicensed frequency band for indoor usage are already commercially available, based on the IEEE 802.11ad standard. On the other hand, mm-wave technologies for ultrahigh capacity mobile communication are currently at a very early stage. Although initial results and trials look promising, a number of important challenges need to be overcome before the technology moves towards inclusion in 5G standards and, ultimately commercial deployment by roughly 2020.

One of the basic, yet highly important, challenges in the development of mm-wave technologies for 5G is appropriate channel measurements and models for typical scenarios such as indoor, outdoor, and outdoor to indoor environments in vehicles, trains, aircraft, etc... While information relating to gaseous and rain attenuation are available from ITU-R recommendations ITU-R P676-10 [1] and ITU-R P 530-16 [2], there are no channel parameters relating to path loss coefficients apart from a very brief statement, and a few wideband channel parameters such as rms delay spread in ITU-R 1411-8 [3] and ITU-R 1238-8 [4], which respectively deal with propagation data and prediction methods for the planning of outdoor short-range radio-communication systems and radio local area networks in the frequency range 300 MHz to 100 GHz. Such models are of great importance in order to: (i) develop and test the required physical and higher layer components, (ii) perform link and system level feasibility studies, and (iii) investigate spectrum engineering regulatory issues such as interference risks and co-existence in the mm-wave bands.

The aim of this white paper, therefore, is to provide an overview of the COST IC1004 action approach to mm-wave propagation measurements, characterization, and modeling, from the perspective of future 5G systems and applications.

The paper is organized as follows:

1. Use scenarios of the mm-wave band.
2. An overview of propagation characteristics based on available ITU-R recommendations and recent studies.
3. State of the art channel sounding techniques for mm-wave measurements for the different use scenarios.
4. Channel measurement and ray tracing results.
5. Propagation models.
6. Standardization prospects.
7. Recommendations for further studies.

3 Use Scenarios of the Mm-wave Band

To significantly enhance network throughput, future cellular networks are expected to comprise of dense small cells with a radius of a few hundred meters. Urban micro (UMi) cells with mm-wave communication technologies are promising as a typical radius of a mm-wave cell around 200-300 m. An example of UMi mm-wave deployment with radius 200 m is shown in Figure 1.



Figure 1. UMi Deployment Scenario of mm-wave

Two specific UMi scenarios known as the street canyon scenario and the open square scenario attract many researchers' attention, as a massive number of terminals can be served by the mm-wave network without suffering from large penetration loss through buildings. An UMi street canyon scenario and UMi open square scenario are depicted in Figure 2, (a) and (b) respectively. In both scenarios, the access points are usually located below rooftops with a height of 3 to 20 m. At the receiver side, a typical terminal antenna height is 1.5 m.

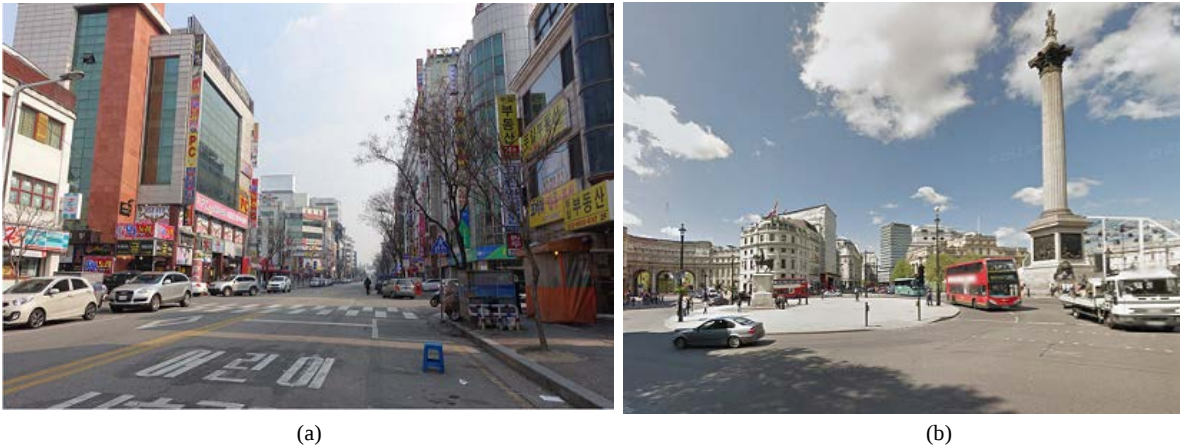


Figure 2. Umi Scenarios (a) Street Canyon, (b) Open Square

In addition, indoor offices and indoor shopping malls (shown in Figure 3) will be important mm-wave scenarios. The inner surfaces of offices and shopping malls may be built with various materials, which will have a great impact on the channel environment. Access points are mounted on ceilings with a typical height of 3 m while terminal antenna height is 1.5 m.



Figure 3. Indoor Shopping Mall Scenario

A number of indoor and outdoor scenarios have been identified by the IEEE 802.11 TGay Next Generation 60 GHz ISM band (NG60) Study Group which include point to point and point to multi-point communication. Environments include indoor wireless local area networks (WLAN), train, airplane, bus, exhibition center, conference room, classroom, factory, virtual reality, and ultra-short range applications such as device to device. Outdoor environments include short range access points (AP) with even shorter ranges of 50 m for lamp post to user, backhaul, and front haul. Other mm-wave scenarios are on body networks and on-body to off-body, as illustrated in Figure 4.

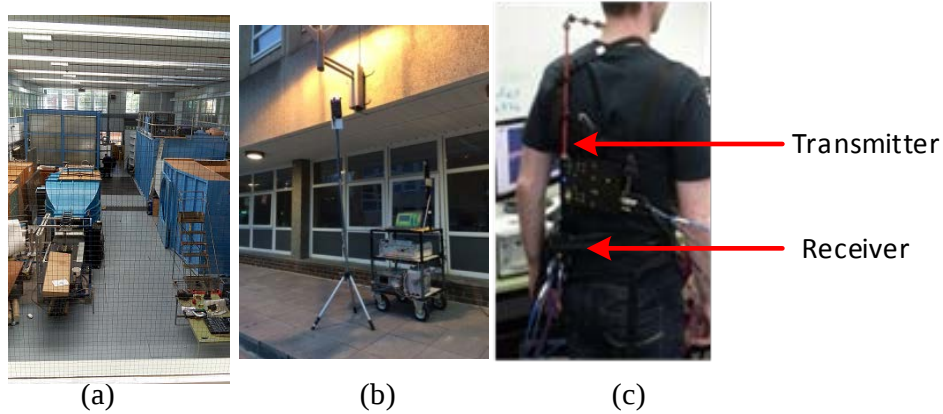


Figure 4. Possible Scenarios for Future Mm-wave Applications: (a) Indoor Factory Environment, (b) Outdoor Lamp Post to User, (c) On-Body Networks

Taking the train application as an example, to realize the objective of “Smart, green and integrated transport” supported by Horizon 2020 [5], it is required to realize a seamless high-data rate wireless connectivity in railways, such as on-board and wayside high definition (HD) video surveillance that is critical for security concerns, on-board real-time HD video for business video conferencing, entertainment, train operation information, real-time train dispatching HD video, and journey information. Scenarios are illustrated in Figure 5.

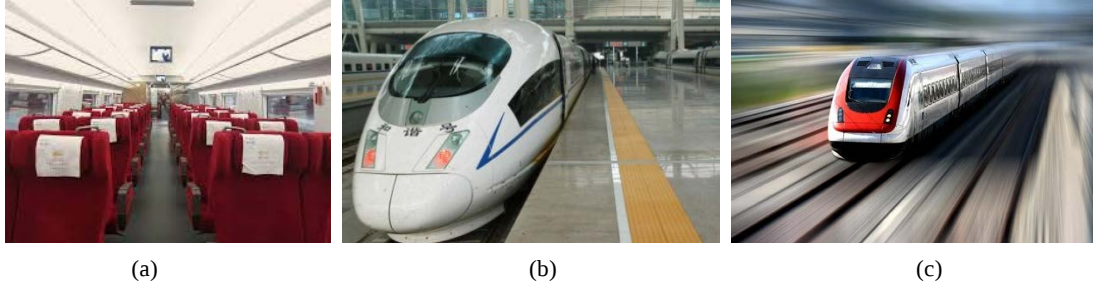


Figure 5. Train Scenarios: (a) Inside Train Communications, (b) Train Station, (c) Train to Infrastructure

The five communication scenarios for the frequency bands above 6 GHz in future railways described in [6] include:

Train-to-infrastructure: Bidirectional streams with high data rates and low latencies, as well as robust communication links with latencies lower than 100 ms together with availability of 98–99 percent, while moving at speeds up to 350 km/h or above.

Inter-car: This scenario requires high data rate and low latency because the APs are arranged in each car such that each AP serves as a client station for the AP in the previous car, while also serving as an AP for all the stations within its car.

Intra-car: The links provide connectivity between the APs in the car and the passengers or sensors of equipment inside the car. In this scenario, real-time HD videos need to be accessed with low latencies.

Inside the station: The links provide wireless access between the APs and the user equipment in railway stations. The stations provide a fixed/wireless communication infrastructure to support general commercial (e.g., cash desks) as well as operational services (e.g., automatic doors, surveillance, and fire protection).

Infrastructure-to-infrastructure: HD video and other information is transmitted in real time among multiple HDTV IP/HD-SDI cameras, and the APs deployed on trains, on station platforms, and the wayside along rail tracks, as a high data rate wireless backhaul or the Internet of Things. Infrastructures are real-time connected and interactive, supported by bidirectional data streams with very high data rate and low latencies.

4 Propagation Characteristics Based on Available ITU-R Recommendations and Recent Studies

4.1 Rain and Atmospheric Effects

Attenuation of mm-waves by atmospheric gases, fog, rain, and sandstorm is documented in several ITU-R recommendations. It is generally considered that due to the short range of future cellular networks (200–300 m) in the mm-wave band, that the additional attenuation due to gases can be considered negligible. However, for back haul applications which can extend up to 1–2 km the additional attenuation needs to be taken into account.

ITU-R recommendations relating to absorption: Most absorption by atmospheric gases is due to oxygen and water vapor molecules [7]. ITU-R P. 676-10 recommendation provides two models for prediction of the gaseous attenuation in dry air and water vapor [1]. The first model, considered accurate for 1–1000 GHz, is computationally complex, as it requires the summation of the individual oxygen and water vapor resonance lines together with small additional factors that take into account the non-resonant Debye spectrum of oxygen, the pressure induced nitrogen attenuation, and the excess water vapor absorption [1]. The second model represents a simplified approximation of the specific attenuation of dry air and water vapor in the frequency range 1–350 GHz and is applicable to an altitude from sea level up to 10 km. Both models in [1] require input parameters, which describe the local atmospheric conditions, such as temperature, ambient pressure, and water vapor density. In the absence of local atmospheric data, recommendations in ITU-R P.836-5 [8] and ITU-R P.1510 [9] can be used to estimate the respective water vapor density and the mean annual surface temperature for the location in question. These two recommendations make use of years of collected data to define a location based average.

Figure 6 shows the total specific attenuation due to atmospheric gases as well as the individual oxygen and water vapor attenuation computed using the simplified model with assumed atmospheric condition values of temperature of 20° C, pressure 760 mm Hg, and water vapor density of 7.5 gm/m³. Despite the increase in the attenuation profile with frequency, absorption peaks corresponding to the resonance frequencies of the oxygen or water vapor molecules can be seen with attenuation levels of 0.2 dB/km at around 22 GHz, 15 dB/km at 60 GHz, and 2 dB/km at 120 GHz. Though high attenuation may limit the coverage range, it also presents an opportunity in terms of frequency reuse.

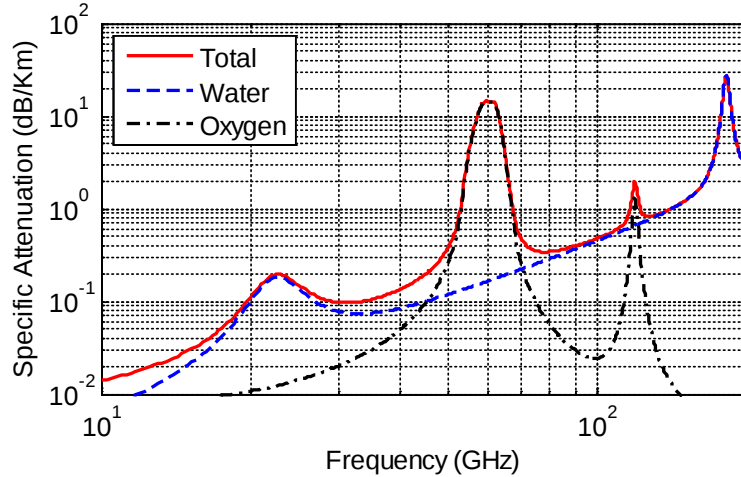


Figure 6. Specific Attenuation of Oxygen and Water Vapor

Fog consists of condensed water droplets, of sizes generally less than 0.1 mm, suspended in air. The liquid water content in fog varies and in rare cases it can become as high as 1 g/m³ [10]. ITU-R P.840-6 [11] provides the procedure for the estimation of the attenuation due to fog and cloud for frequencies up to 200 GHz. The specific attenuation by fog in frequencies below 100 GHz is less than 5 dB/km as shown in Figure 7.

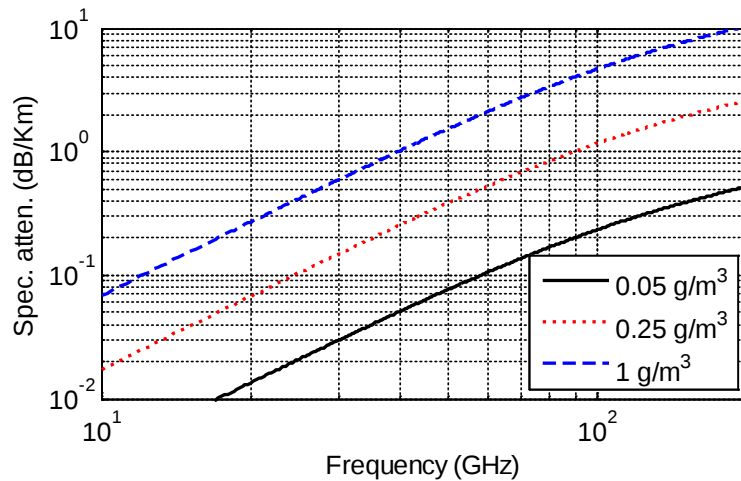


Figure 7. Specific Attenuation of Fog

Attenuation by rain occurs as a result of scattering and/or absorption of electromagnetic waves by raindrops. The raindrops shape and size vary in practice both in time and space. This makes it difficult to create a theoretical rain attenuation model, as its accuracy will mostly depend on the assumed raindrop size distribution [7]. Consequently, a model may give a good prediction of attenuation in a particular part or region of the world while proving inaccurate for another region.

ITU-R P.838-3 [12] provides a simple model for the estimation of the specific attenuation due to rain in the frequency range 1–1000 GHz. The model uses the rainfall rate as the only climatic related parameter and provides a set of tabulated constants which are frequency and polarization dependent. Results from the model in [12], shown in Figure 8, indicate a monotonic increase in the specific attenuation for frequencies less than 100 GHz which level off or even taper slightly after that. Moreover, differences in the specific attenuation as a result of polarization are less than 5dB/km for rainfall rates less than 150 mm/hr. Practically the rainfall rate measured at a point along or near the link is either assumed constant throughout the path or an average value is estimated from it and used in the computation of rain attenuation.

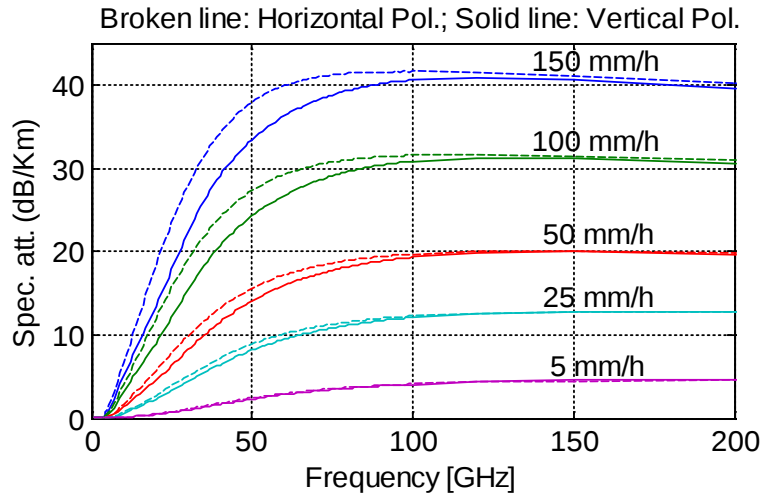


Figure 8. Specific Attenuation of Rain

In recommendation ITU-R P.452-16 [13] the point measured rainfall rate is assumed constant within a certain circular cross-section area, termed rain cell, and outside this cell the rain intensity decays as a function of distance. A link with a length smaller than the cell diameter suffers the full rain attenuation. Whereas if part of the link is outside the rain cell then the decay factor is taken into account. The cell diameter is inversely proportional with rain rate, as seen in Figure 9.

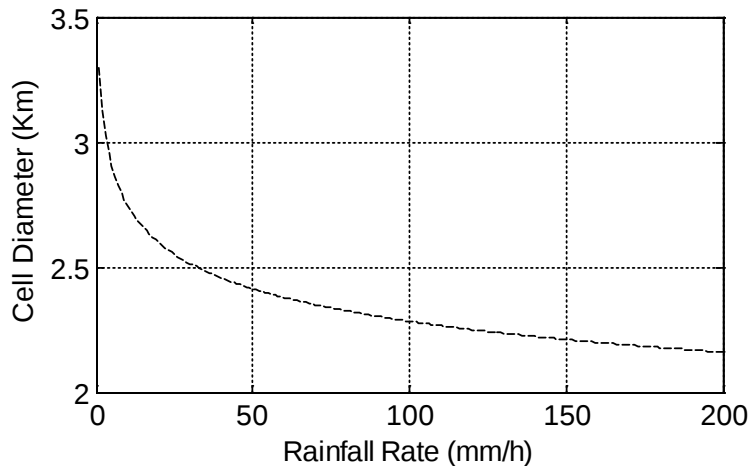


Figure 9. Rain Cell Distance vs. Point Rainfall Rate

In recommendation ITU-R P.1410-5 [14] the concept of area average rainfall rate is introduced for the estimation of cellular coverage reduction due to rain attenuation. For a particular point rainfall rate the equivalent area average rainfall rate decreases with the increase of cell radius, as depicted in Figure 10.

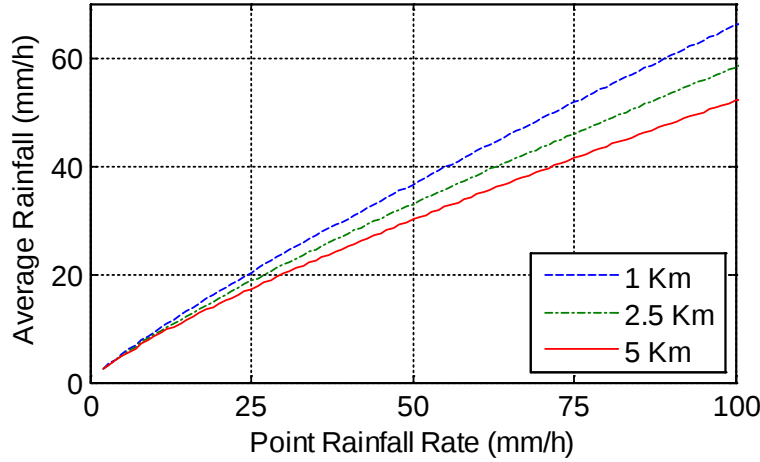


Figure 10. Area Averaged Rainfall Rate vs. Point Rain Fall

In the computation of the rain attenuation, the model presented in recommendation ITU-R P.530-16 [2] assumes the point rainfall rate as a constant and adjustment is made on the path length through a path scaling factor (given in eq. 32 [2]), with a recommended maximum value of 2.5. This is supposed to compensate for any variability of rain along the path. Figure 11 shows the path scaling factor curves as a function of the link distance for 100 mm/h and 5 mm/h rainfall rates at frequencies of 30 GHz and 85 GHz. However, for short distance links, the rapid increase of the scaling factor may render the attenuation model unsuitable.

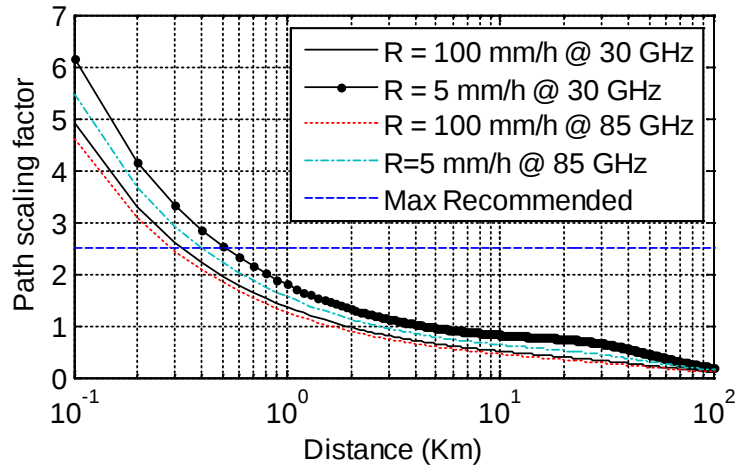


Figure 11. Path Scaling Factor

As the characteristics of the rainfall vary with time, season, and location, the statistics, either yearly or monthly, are of great importance to estimate the reliability of radio links. Particularly, one can estimate from long term collected meteorological data distributions the percentage of time during which the rainfall rate exceeded a certain value. The rain attenuation model in [2] is only appropriate when the rainfall rate is exceeded 0.01% of the time. Attenuation at other exceeding percentages of the time in the range of 0.001% to 1% is obtained through a power-law interpolation function (eq. 34 in [2]). In [2] the statistics of rainfall rate with 1 minute integration time are used. In the absence of local measured long term rainfall rate the procedure in recommendation ITU-R P.837-6 [15] can be used to derive the rainfall rate for any given percentage and geographical location based on the meteorological data available from the ITU Study Group-3 database.

Attenuation models due to sandstorms are of interest especially in desert or semi desert areas where this phenomenon occurs most often. A prediction model of the specific attenuation by sandstorm or dust particles in the frequency range of 1-100 GHz has been proposed and experimentally validated in [16], [17]. Currently no model is available within the ITU-R recommendations for attenuation due to sandstorms.

4.2 Outdoor Channel Propagation in the Built Environment

Recommendation ITU-R 1411-8 [3] is concerned with outdoor radio propagation and provides wideband channel parameters and path loss coefficients. So far the recommendation has limited statistics of path loss coefficient and of wideband channel parameters in the mm-wave band. A limited number of scenarios are reported with values of rms delay spread and line of sight outdoor path loss coefficients are given on the order of 1.9-2.1, which is close to free space propagation. Further measurements are needed for the path loss coefficient, shadowing, number of paths, angular spread, fading statistics, and cross polarization in typical outdoor environments. These include urban, residential, and rural environments in scenarios such as over rooftop, street level, vegetation at street level, and open areas such as car park below rooftop level.

Another standardized channel model is called “3GPP 3D” [18]. It has been designed for LTE / LTE-Advanced (4G / 4.5G systems), and the main improvement in that model is user distance and height dependent elevation of departure for elevation beam forming. The 3GPP 3D model belongs to the family of Geometry-based Stochastic Channel Models (GSCMs), which was first standardized by namely 3GPP/3GPP2 as Spatial Channel Model (SCM) [19], and further developed by WINNER II [20], IMT-Advanced [21], WINNER+ [22], and the stochastic model part of METIS [23]. The ITU report [21] defines channel models for 4G system evaluations, and the model was adopted by 4G proponents such as 3GPP and WiMAX Forum.

In all of the GSCMs the channel parameters are determined stochastically, based on statistical distributions of large scale and small scale parameters extracted from channel measurements. The parameters are randomly drawn according to the statistical distributions for each “drop” of users. The models are antenna independent, i.e. different antenna patterns can be embedded to the same propagation model. Each drop has a different realization of large scale and small scale parameters, which means that the channel is discontinuous when moving from one drop to another. Different propagation scenarios are modeled by using the same approach, but different parameters.

4.3 Indoor WLAN Channel Models and Propagation Characteristics

In addition to the GSCM family, there are some other standardized indoor WLAN MIMO channel models. IEEE 802.11 Task Group n (TGn) defined correlation matrix based channel models [24], and TGac extended the TGn channel models to support wider bandwidth, higher order MIMO and MU-MIMO [25]. More recently, IEEE has been working on mm-wave channel models in TGad [26]. Indoor scenarios include factory, corridor, hallway, office, computer room, classroom, office to office, floor to floor, and corridor to office.

The TGad channel model is a MIMO model based on a mixture of ray-tracing and measurement-based statistical modeling. It is a double-directional cluster-based channel model that supports several different environments. Another double-directional GSCM was developed in [27] for the 60 GHz conference room environment. Both of these models are parameterized by inter-cluster parameters, describing the delays and angles of the clusters, and intra-cluster parameters, that describe the delays and angles of the rays in each cluster. The inter-cluster angles and delays can be modeled either based on ray-tracing or stochastically using probability distributions. The intra-cluster angles are typically modeled using a Laplacian or Gaussian distribution, and the delays are modeled using exponential inter-arrival rates.

The indoor mm-wave channel is typically characterized by a limited number of strong specular reflections. Each cluster is therefore typically modeled using a strong main component with a K-factor that describes the power-ratio between the main component and the remaining rays in the cluster. These K-factors are typically about 8-14 dB for indoor environments [26], [27]. Similar to the classical Saleh-Valenzuela model, the power of each component is modeled by exponential cluster and ray decay factors, which depend heavily on the room size. The performance of mm-wave channel models is quite sensitive to these parameters, making it necessary to consider the limitation due to noise when estimating these factors [27].

4.4 Human Body Shadowing in mm-wave Channels

Due to the short wavelength at mm-wave frequencies, the attenuation due to shadowing or obstruction by objects or humans is much more severe compared to lower frequencies. For this reason, it is necessary to characterize and model the shadowing appropriately. A lot of research has focused on the shadowing due to human bodies in the 60 GHz band. The shadowing has been shown to cause severe losses that can be as high as 30-60 dB in the deepest shadowing region for persons obstructing the line-of-sight [29], [30], [31]. To overcome this large attenuation, beam forming techniques need to be utilized in many mm-wave systems. The severity and duration of the shadowing of course depends on the number of persons and their activity. Therefore, the blockage needs to be modeled stochastically, either by a simple blockage probability function, or by simulating the human movement in the environment. A stochastic human blockage model has been developed for the IEEE802.11ad model in [29]. For the outdoor mm-wave channel, very little work has been performed when it comes to characterizing and modeling the dynamic effect of shadowing by humans and other dynamic objects such as cars.

Characteristics in the frequency bands above 6 GHz are not studied intensively for railway environments, such as subway tunnels and rail through urban areas. In the recent IEEE 802.15 meetings, two documents “IEEE 802.15-15-0666-02-hrrc” [32] and “IEEE 802.15-15-0837-00-hrrc” [33] present characterization of the radio channel in the 30 GHz band for a train moving at a speed of 100 m/s in tunnels and Beijing Central business district (CBD), respectively. The channel characteristics imply that the usage of the directive antennas on both the transmitting and receiving sides is critical for providing sufficient coverage range and suppressing the metrics resulting from multipath propagation, such as Doppler spread, delay spread, etc. However, such antenna setup increases the spatial correlation of the received signal power. Thus, a larger MIMO inter-element separation is required in order to get the diversity gain against deep fading [32]. For the beam forming strategy, the results in [33] show that the fixed beam forming on the transmitting and receiving sides is sufficient to provide a channel as good (meaning high received power, low Doppler spread or delay spread) as the adaptive beam forming in urban areas when the line-of-sight (LOS) path is in the main lobe of both antennas. However, when the receiver is very close to the transmitter, the channel dramatically deteriorates due to the LOS being out of the main lobes. Hence, advanced handover strategies should be designed in this region, or adaptive beam forming should be considered even though it is very complex to realize for fast-moving vehicles.

5 State of the Art Channel Sounding Techniques for Mm-wave Measurements

Radio channel sounding in the mm-wave bands is challenging due to the wide available bandwidths, and the number of possible frequency bands identified by the WRC15 in the frequency ranges from 24 GHz to 86 GHz. In addition to the requirement of covering multiple bands, the mm-wave channel sounder needs to provide high time delay resolution on the order of cm's and cover high Doppler shifts for outdoor applications. These two requirements imply the use of waveforms with a large transmission bandwidth and a high repetition rate.

In channel sounding, measurement of the complex transmission properties of the radio channel, are of interest. In theory, an infinite bandwidth Dirac pulse would be transmitted periodically over the radio channel to measure the time variant channel impulse response, $h(\tau, t)$, at the receive side of the radio channel. However, in a real environment:

- The radio channel is band limited; however, the bandwidth needs to be flexible.
- There is unknown multipath propagation, i.e. there is a need to detect signal echoes with the maximum possible time resolution and dynamic range.
- There is frequency dependent path loss and the propagation range is limited by the sensitivity of the receiver and the given transmit power. Thus, best possible system sensitivities are required for all considered frequency ranges and bandwidths.
- Transmitter and receiver of the channel sounder setup can be difficult to time synchronize sufficiently in outdoor campaigns, i.e. an error consideration is of interest for that case in particular.

A number of channel sounding solutions are available and these can be classified as commercial off the shelf (COTS) equipment based on vector network analyzers (VNA), arbitrary waveform generators for signal generation at the transmitter, spectrum analyzers as receivers, and custom designed channel sounders. Two waveforms commonly used in channel sounding are the pseudo random binary sequence (PRBS) and the frequency modulated continuous waveform (FMCW). State of the art channel sounders based on these two techniques have been recently developed and reported in the COST IC1004. Both offer a flexible and multi-band architecture and enable dual polarization measurements.

5.1 Equipment Based Channel Sounding

1. Frequency domain measurement of the complex frequency response with sweeping CW signals

This method uses a vector network analyzer (VNA) where the channel impulse response is measured indirectly as the inverse Fourier transform of the measured complex frequency response, $H(f, t)$, measured with sweeping CW signals across the desired bandwidth. However, this method requires cable connections between the transmitter and receiver, which at mm-wave frequencies suffer from high losses. It is also limited to time invariant channels due to the limited speed of the required CW sweeping process. Nevertheless, this method is almost not limited with respect to the channel bandwidth.

2. Time-domain measurement of the channel impulse response with pulse compression methods

This measurement technique uses a wideband signal generator, e.g. an arbitrary waveform generator and a receiver with correlator. It is based on the transmission of dedicated “sounding signals” with outstanding autocorrelation properties, such as m-sequences, Frank-Zadoff-Chu sequences or FMCW signals (chirps). The receiver then correlates the incoming signal with the known sounding sequence, which directly yields the channel impulse response. However, the available hardware might limit the maximum bandwidth and synchronization between the transmitter and the receiver. Figure 12 depicts the proposed most compact and easiest possible channel sounder setup in the time domain, using standard R&S T&M instruments. The sounding signal, with a scalable bandwidth and the desired carrier frequency, is generated with a single instrument, the R&S®SMW200A. Thus, the sounding signal that excites the radio channel of interest benefits from the outstanding signal purity (e.g. minimum phase noise) and flexibility only a high quality signal generator can provide, including long-term stability and repeatability. Another single instrument, such as the R&S®FSW spectrum analyzer, covers all receiver functions including down-conversion and baseband sampling. The sampled IQ baseband data captured by the instrument is post-processed by a software correlator R&S®TS-5GCS to calculate the complex channel impulse response. Again, the receiver benefits from the great quality properties of such high-end instruments, e.g. low noise figure and linearity. Finally, the robustness, the traceability, and the simple operation of standard T&M instruments saves a lot of time regarding the realization of sounding campaigns. For on the air synchronization of the receiver and transmitter instruments, external references are required, e.g. GPS disciplined references or pre-aligned and stabilized high quality oscillators with minimum jitter (e.g. Rubidium). Of course, all required interfaces for synchronization purposes like frequency reference and trigger inputs/outputs are provided by such T&M instruments, but would also need cable connection.

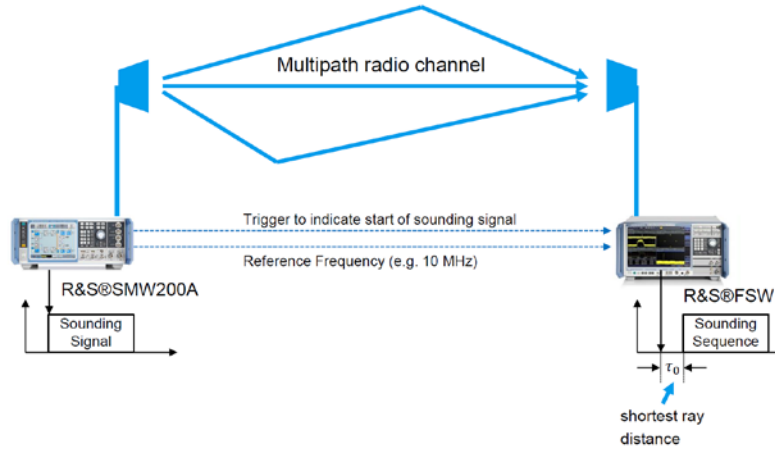


Figure 12. Time Domain Sounding Setup Using T&M Instruments

5.2 Custom Designed Sounders

A number of channel sounders have been developed for mm-wave propagation studies, but these are primarily based on either the pseudo random binary sequence (PRBS) waveform or frequency swept method (FMCW). Such sounders are the dual-polarized ultra-wideband PRBS multi-channel sounder (DP-UMCS) developed at TU Ilmenau, [34], the direct sequence

spread spectrum sounder developed at TU Brno [35], and the 2 by 2 MIMO FMCW sounder developed at Durham University [36].

The sounder at TU Ilmenau has a modular architecture, consisting of ultra-wideband (UWB) units and up-down converters [37] (see (a) of Figure 13). The sounder uses a PRBS signal, generated by a 12-bit digital shift register clocked at 6.75GHz, which results in a maximum delay window of 606 ns (~ 182 m). The data are acquired at a sub sampling factor of 512, allowing a measurement rate of about 1600 channel impulse responses (CIRs) per second. The measurements are subsequently coherently averaged to 200 CIR per second, to cope with the high amount of data and to enhance the signal-to-noise ratio (SNR). This gives a dynamic range of approximately 70 dB, which enables the identification of weak multipath components. The CIR rate enables measurements of a maximum velocity of 1 m s⁻¹ at 30 GHz. To accommodate higher velocities, UWB units featuring a CIR rate of 10 kHz are under development.

Currently, frequency converters with bandwidth from 28GHz–38GHz, 57GHz–67GHz, and 71GHz–78GHz are available. The modular concept allows different measurement stages at distributed locations for measurements of multi-link scenarios [38]. The converter unit has one transmitting channel with an automatic switch for two transmit antennas.

The UWB units shown in (b) of Figure 13 contain the signal generator and acquisition part of the sounder and are based on a radar chip set [38], [39]. Each unit has 2 receiving channels allowing the possibility of dual polarized measurements or simultaneous measurements of 2 frequency bands (dual-band measurements). The units feature a size of 100 × 100 × 210 mm and a weight of approximately 2kg. Due to the lightweight and compact construction, mounting of the UWB units in conjunction with up-down converters on positioning devices for directional scanned measurements is also possible.

The 30GHz and 60GHz down-converter modules feature step attenuators and the 70GHz up-converter features a level set attenuator, enabling power adjustment to avoid saturation of the low noise amplifier (LNA) in the down-conversion modules. For spatial channel resolution at both link ends, commonly stated as double-directional measurements, synthetic aperture measurements are conducted by utilizing 3D positioning devices in conjunction with directional antennas.

In order to avoid time misalignment by clock drifts and ensuring coherent measurements, a single clock signal is distributed to all sounding units. The clock is generated centrally and is distributed via optical cables. Currently, a maximum link-to-link distance of 200m is possible. Furthermore, rotation joints are used at the positioning devices to avoid clock signal variations due to movement. Table 1 gives a summary of the features of the sounder.

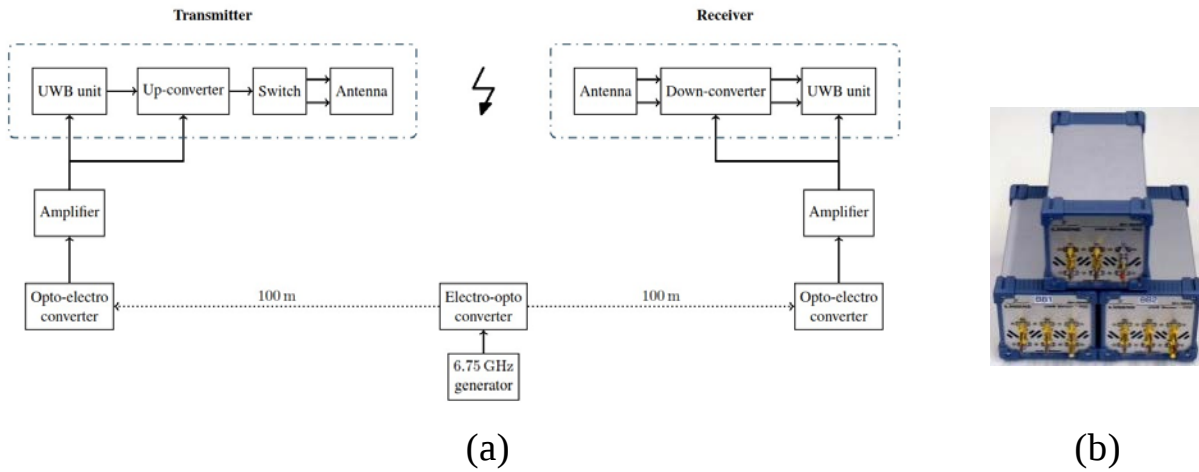


Figure 13. (a) Block Diagram of Ilmenau Sounder (b) UWB Units

Table 1. Summary of Features and Parameters of the TU Ilmenau Sounder

Frequency band	30 GHz	60 GHz	70 GHz
Stimulus signal Bandwidth	PRBS, 6.75 GHz		
CIR length	606 ns		
CIR rate	200 Hz		
Dynamic range	70 dB		
Polarimetric MIMO sub-channels	1 Transmitter and 2 Receivers		
Transmit power	25 dBm	20 dBm	30 dBm
Center frequency	33.75 GHz	59.3 GHz	75.4 GHz
Antenna HPBW	25°	40°	15°
Antenna Gain	18 dBi	14 dBi	20 dBi
Antenna XPI	20 dB	25 dB	20 dB

The sounder at Durham University uses the FMCW waveform and consists of three basic modules as in Figure 14. The sounder uses a rubidium standard at each end of the link with a clock distribution for all the oscillators and the data acquisition. The second module contains a programmable direct digital frequency synthesizer (DDFS) which is capable of generating frequencies up to 1 GHz and a first stage up-converter. The third module has a two stage up-converter that provides the IF for the mm-wave up-converters. Thus, it provides simultaneous outputs at several frequency bands including: 250 MHz-1 GHz, 2.2-2.95 GHz, with 750 MHz bandwidth and 4.4-5.9 GHz, and 12.5-18 GHz with a maximum bandwidth of 1.5 GHz. This output is then fed to the mm-wave RF heads. In the E and V bands the RF heads have dual channel frequency multipliers at the transmitters for dual polarized and dual antenna measurements, while at the receiver, a dual channel receiver is available. In the K band, the RF heads consist of 8 transmit and 8 receive channels thus allowing the capability of measuring the angular information in azimuth using custom designed antennas with 45° beam width. Current available frequency multipliers provide outputs at several frequency ranges. Table 2 gives an overview of the available frequencies, antennas, and their relationship to the WRC15 frequency bands. Table 3 gives a summary of the capability of the sounder.

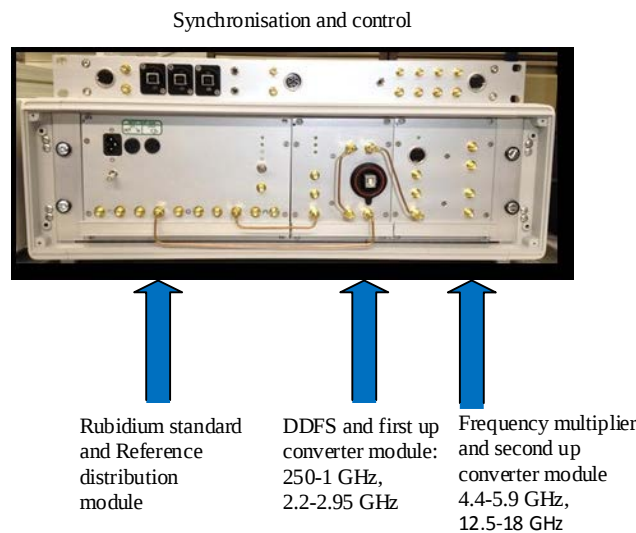


Figure 14. Basic Sounder Modules up to IF for Mm-wave RF Heads

Table 2. WRC15 Identified Frequency Ranges for 5G and Sounder Multiplier in RF Heads with Available Antenna Specifications for Measurements

WRC15 Band (GHz)	Designation	Sounder Multiplier Unit	Specification of Available Antennas			
			Antenna Type	Freq. Range (GHz)	Beam-width (degrees)	Gain (dB)
24.25-27.5	I	x2	Dual Polar.	18-40	50	15
31.8-33.4	II	N/A	N/A	N/A	N/A	N/A
37-43.5	III	N/A	N/A	N/A	N/A	N/A
45.5-50.2	IV	N/A	N/A	N/A	N/A	N/A
50.4-52.6	V	x4	horn	50-75	15	18
66-76	VI	x4	horn	60-90	55	10
			horn	50-75	55	10
81-86	VII	x6	horn	60-90	18	20

Table 3. Summary of the Durham Sounder Capability

frequency band (GHz)	0.25-1	2.2-2.95	4.4-5.9	12.5-18	25-31	50-75	60-90
Maximum Bandwidth (GHz)	0.75		1.5		3	6	9
Stimulus signal	FMCW with programmable bandwidth						
Waveform duration	Programmable from ~204.8 μs						
Waveform repetition rate	Programmable and inversely proportional to waveform duration, maximum of 4.88 kHz						
Data acquisition	14 bit cards with two channels with 400 MHz sampling rate per channel 14 bit card with eight channels with 100 MHz sampling rate per channel						
MIMO sub-channels	2 co-located transmitters and 2 co-located receivers for frequency bands 50-90 GHz and two single receivers for multi-point reception, and 8 co-located transmitters and 8 co-located receivers for the 25-31 GHz band						
Transmit power at the output of the RF heads in the mm wave band	16 dBm at 25-31 GHz 10 dBm at 50-75 GHz 6 dBm at 60-90 GHz						

6 Channel Measurements and Ray Tracing Results

Measurements were conducted in different indoor and outdoor environments to study MIMO capacity, angle of arrival (AOA) and angle of Departure (AOD) of the multipath components in azimuth and at different frequencies at TU Ilmenau and at Durham University.

The measurements at TU Ilmenau were conducted in two environments representing an access point scenario. In the entrance hall, measurements were conducted at 60GHz and 70GHz whereas in the small office the measurements were at 70GHz [40], [41], (see Figure 15).



Figure 15. (a) Entrance Hall of The Zuse Building - Rx Position 1, (b) Small Office Environment – Rx Position 4

Similarly, measurements were performed indoor and outdoor at Durham University with horn antennas for the estimation of MIMO capacity and with a lens antenna to measure the AOA in azimuth with dual polarization. Two of the measured environments are shown in Figure 16. Other measured environments include a factory like environment, vegetation, road side, and car park.

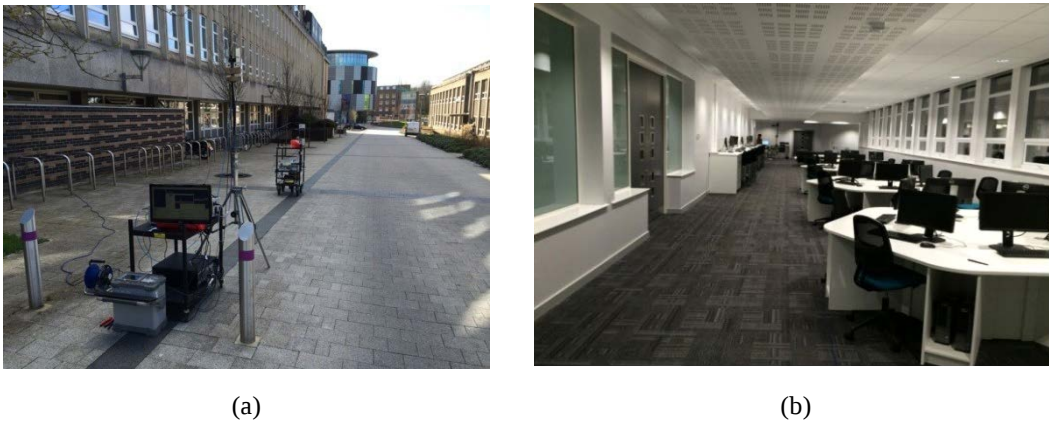


Figure 16. Measured Environments in Durham University: (a) Outdoor, (b) Indoor

6.1 Spatial Channel Resolution

Spatial resolution measurements at both ends of the link are important for testing beam forming algorithms and for the derivation of spatial channel models. Figure 17 displays the power spectra in the azimuth plane for the (AoA) and (AoD) for the entrance hall and small office. Rich scattering is seen in the entrance hall, due to the metallic surfaces such

as window frames, handrails and plant pots. In addition, the measurement indicates the occurrence of single and double-bounce reflections, as explained in Table 4, indicating a very reflective environment at mm-wave frequencies. On the other hand, only one strong scatterer is present in the small office, due to the wooden furniture and concrete walls. Thus beam forming at both link ends is necessary in this environment to capture this single scatterer.

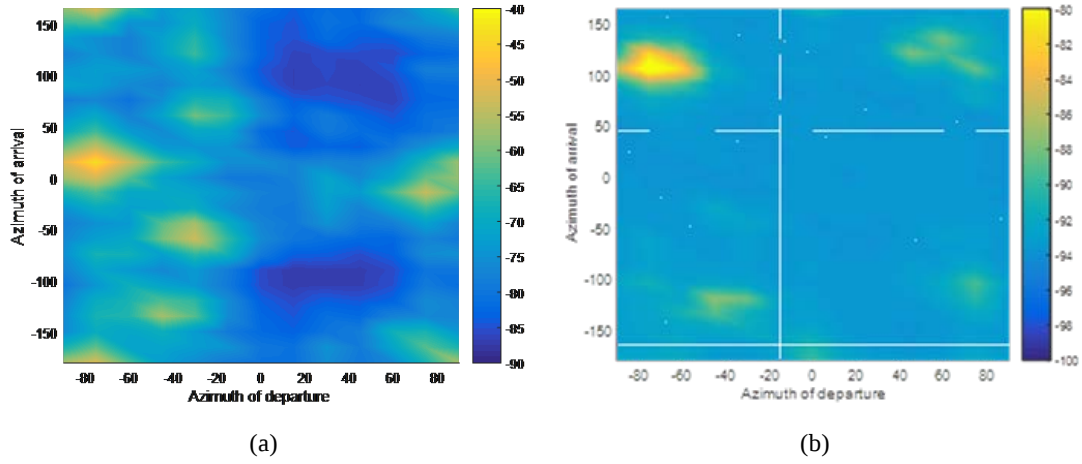


Figure 17. Azimuth Power AoA vs. AoD: (a) Hall Environment, (b) Small Office

Table 4. Angle of Arrival and Angle of Departure

	AOD	AOA
Line of sight	-90°	0°
Single bounce	90°	0°
Single bounce	-90°	-180°
Double bounce	90°	-180°

The measurements at Durham University were also analyzed for AOA using the lens antenna and an example is shown in Figure 18.

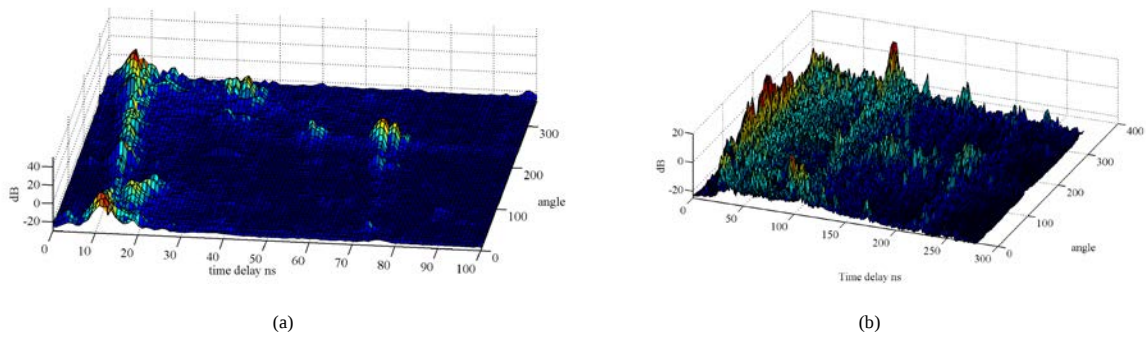


Figure 18. AoA Measurements in the Environments Shown in Figure 16: (a) Outdoor, (b) Indoor

The figure shows the dense multipath structure in the indoor environment in comparison to the outdoor environment. Figure 18 (a) shows the tunneling effect resulting from the transmitter being placed between two buildings and the likely outage that might result when the user is not facing the transmitter. The data were analyzed with 0.9 ns time delay resolution for rms angular spread and the results for 90% of the locations were 37.5 ns and 24.5 ns for the indoor and outdoor environments, respectively.

6.2 Polarimetric Channel Resolution

The polarimetric characteristics of the radio channel at 70GHz were investigated using polarimetric omni-directional power, averaged over all directions in the azimuthal plane, estimated using (1).

$$PDP(\tau, \gamma_{TX}, \gamma_{RX}) = \sum_{\varphi_{TX}} \sum_{\varphi_{RX}} \|h(\tau, \gamma_{TX}, \gamma_{RX}, \varphi_{TX}, \varphi_{RX})\|^2 \quad (1)$$

with $\varphi_{TX}, \varphi_{RX}$ the antenna azimuth angle at the transmitter and receiver, and γ_{TX}, γ_{RX} the polarization at the transmitter and receiver, which can be either H or V. The variable $h(\tau, \gamma_{TX}, \gamma_{RX}, \varphi_{TX}, \varphi_{RX})$ denotes a measured CIR, depending on the previously mentioned parameters and the delay.

The power delay profiles (PDPs) for each polarization are shown in Figure 19 for the entrance hall and small office, where the first letter indicates the polarization at the transmitter and the second letter indicates the polarization at the receiver. Figure 19 (a) indicates that the PDPs from the entrance hall are not entirely reduced to the noise floor, indicating that a CIR length of 606 ns is inappropriate to measure this environment. Therefore, longer sounding sequences are required. To meet this requirement new UWB units are being developed at TU Ilmenau, featuring a 15-bit binary pseudo-noise M- sequence, which enables a CIR length of 4.8 μ s at an RF-clock of 6.75 GHz.

The PDP's indicate the presence of a large number of path components with large excess delays which is likely to lead to long guard intervals or cyclic prefixes for OFDM transmissions. The CIR in the small office is limited to 100 ns duration with only a few components. Investigating the polarization characteristics for the entrance hall as well as the small office it is seen that strong cross-polarization components are present. This indicates that just considering single polarized antennas at one link end, will reduce the receiver SNR and therefore decrease system capacity. Hence, dual- polarized antennas in conjunction with polarization adjustment by e.g. beam forming will be important for front-ends at mm-wave frequencies.

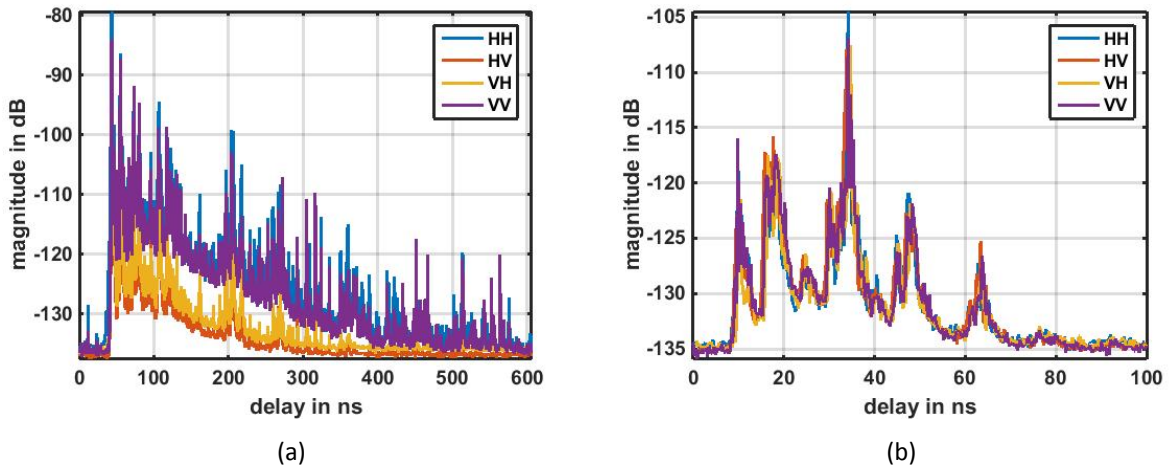


Figure 19. Power Delay Profiles for Dual Polarized Transmission: (a) Hallway Environment, (b) Small Office

Channel measurements using dual polarized antennas at 30 GHz in the outdoor and indoor environments of Figure 16 were conducted at Durham University. Figure 20 shows an example of the dual polarized measurements performed in the outdoor environment with the cross-polar antennas having more delay spread than the co-polarized antennas.

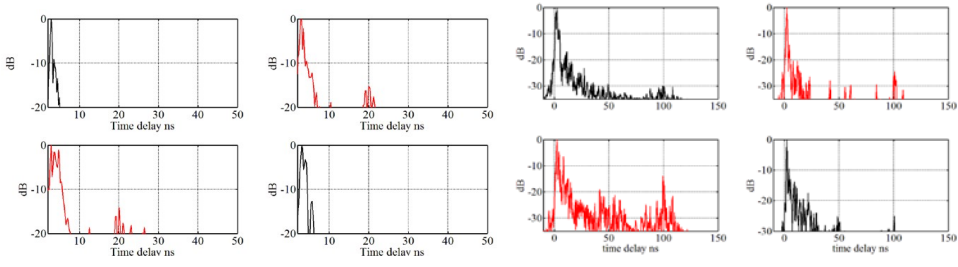


Figure 20. Power Delay Profiles for Dual Polarized Measurements at 30 GHz: (a) Outdoor, (b) Indoor, black: co-polarised, red: cross polarised

6.3 Comparison of Different Frequency Bands

Comparison of measurements derived in the same environment but at different frequency bands is quite important for the development of channel models. Here, measurements in the entrance hall at the frequency bands of 60GHz and 70 GHz are compared according to their omni-directional PDPs shown in Figure 21. The PDPs are the summed power over all polarimetric omni-directional PDPs estimated from (2).

$$PDP(\tau) = \sum_{Y_{TX}} \sum_{Y_{RX}} PDP(\tau, Y_{TX}, Y_{RX}) \quad (2)$$

The figure shows that similar paths occur at the same delay, indicating that scatterers are reflective at both frequency bands which give a measure of consistency between the different frequency bands. Modeling this inter-frequency-band consistency becomes important, if simulation based comparisons of different frequency bands is of interest for e.g. communication system validation.

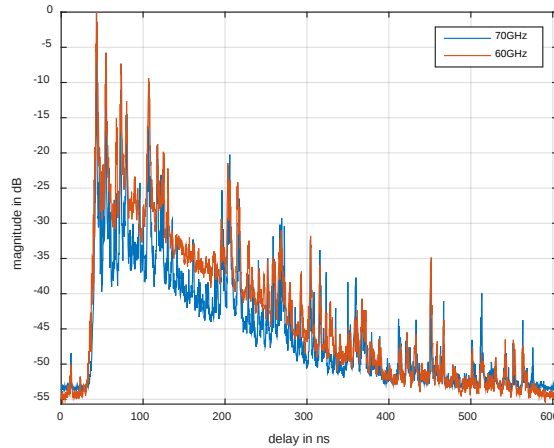


Figure 21. Omni-Directional Power Delay Profile at 60 GHz and 70 GHz for Hallway Environment Shown in Figure 15 (a)

Another measured environment is the intra-vehicle environment. In [42] wideband radio channel measurements were carried out with transmitter and receiver locations within the passenger compartment of a vehicle as illustrated in Figure 22.

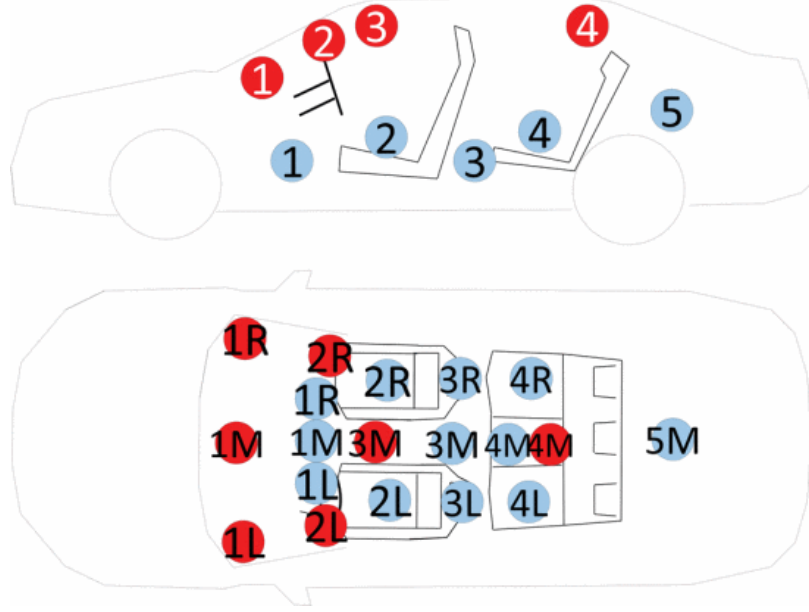


Figure 22. Intra Vehicle Measurement Scenario

Channels in the mm-wave frequency band have been measured in 55-65 GHz using open-ended rectangular waveguides as wide-aperture antennas. The channel exhibits both large and small scale fading. The decomposition is done by a Hodrick-Prescott filter. The small scale fading is parametrized utilizing Maximum-Likelihood Estimates (MLE) for the parameters of a generalized extreme value (GEV) distribution and the MLE are given in Table 5. The large scale fading is modeled by a two-dimensional polynomial fit while the small scale fading model can be simplified to a log-Weibull-distributed random process.

Table 5. Parameters of a Generalized Extreme Value for the Intra Vehicle Measurements [42]

55-65 GHz	Distribution type	Mean ν	Variance η
Shape parameter κ	GEV	-0.902	0.0031
Scale parameter σ	GEV	4.81	0.1004
Location parameter μ	GEV	-2.317	0.0308

A 3D ray-tracing simulation on 5/18/28/38/73 GHz bands is performed in Daejeon, Korea. The 3D geographical data of the city is used as the input to the ray tracer. To provide a better insight of the simulated environment, a 3D view is shown in Figure 23. The transmitter (TX) is located in the rooftop and receivers (RX) are distributed on the road. It is assumed that all buildings are modeled with concrete ($\epsilon = 6.5, \sigma = 0.668$) and the ground is modeled with wet earth ($\epsilon = 15, \sigma = 1.336$).

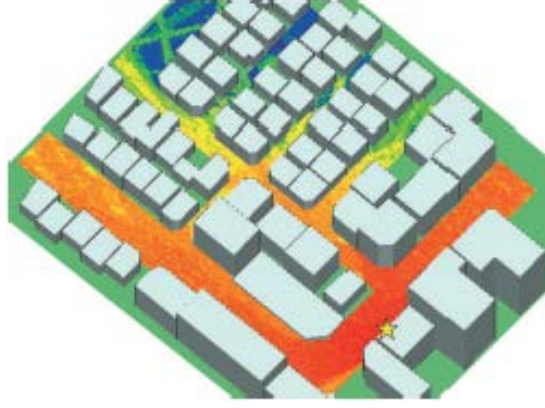


Figure 23. 3D Diagram of the Ray Tracing Environment

During the ray tracing simulation, all paths are modeled by reflection, diffraction, and penetration based on the geometrical optics (GO) and uniform theory of diffraction (UTD). Up to 40 paths are traced, within 250 dB measurable path loss. The outputs of the ray tracing simulator include total power, path power, path delays, path angle information (elevation / azimuth angles at both the transmitter and receiver). More ray tracing simulation parameters can be found in Table 6.

Table 6. Ray Tracing Simulation Parameters

Parameter	Value	Parameter	Value
Simulation Area	920 m x 800 m	Max. number of reflections	12
Observation Area	600 m x 600 m	Max. number of penetrations	2
TX height	16.05m	Max. number of diffractions	1
RX height	1.5m	EIRP	0 dBm
RX Spacing	1m	Number of transmitter sites	1
Polarization	Vertical	Minimum received power	-250 dBm
Ray spacing	0.1 degree	Number of the RX point	12283

In total, 12283 RX are placed with 1m spacing grids. Therefore, there are 12283 CIR samples. Among these samples, 5096 samples are with LOS and 7187 samples are in NLOS locations. Path loss and corresponding linear fits of different frequencies in LOS conditions are illustrated in Figure 24. The path loss is modeled using the close-in model [43], defined by:

$$PL[dB] = FSPL(f, 1m)[dB] + 10n\log_{10}d + X \quad (3)$$

Where X is the shadow fading in dB. Path loss for NLOS with 38 GHz are shown in Figure 25 (other frequencies show similar patterns for 38 GHz). It can be observed that the spread of data points increases as the distance becomes larger, which suggests distance dependencies of shadow fading.

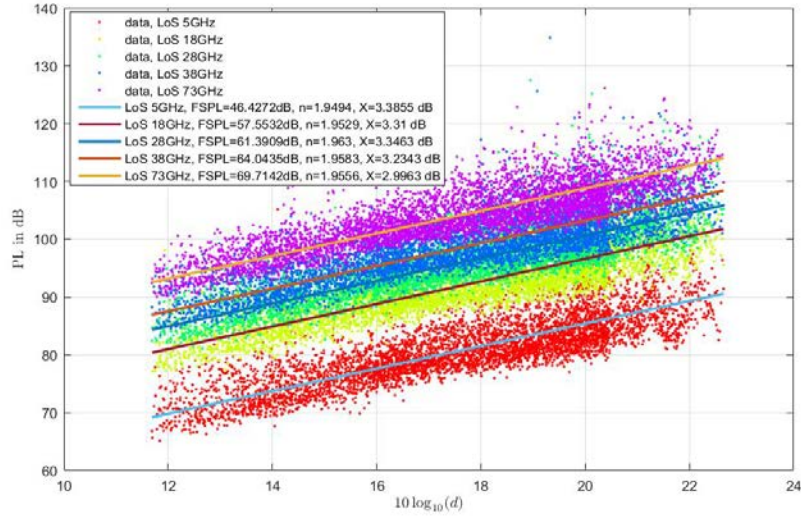


Figure 24. LOS Path Loss with Fit

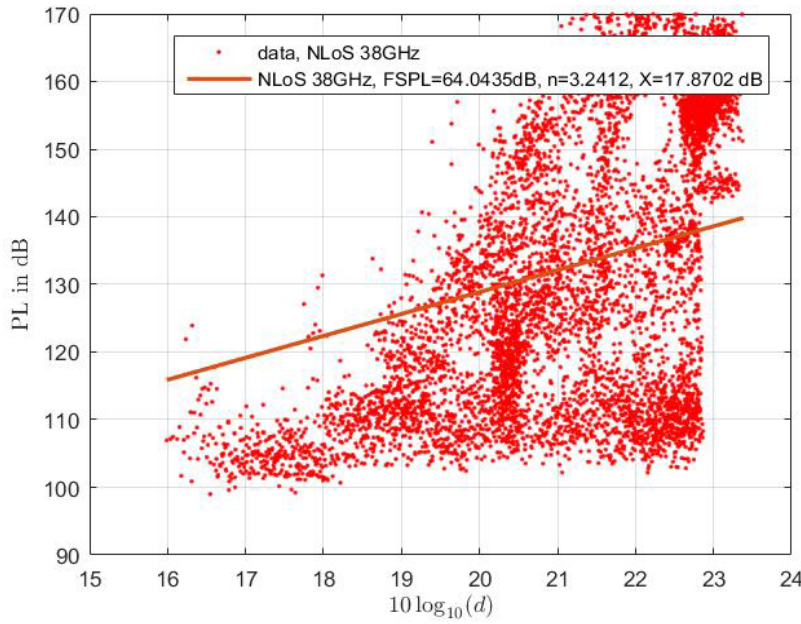


Figure 25. NLOS Path Loss at 38 GHz with Fit

To study distance dependent shadow fading, Figure 26 depicts the standard deviations of shadow fading with respect to distance for different frequencies. The data are linearly fitted by:

$$\text{std}(\text{SF})[\text{dB}] = 10a\log_{10}d + b \quad (4)$$

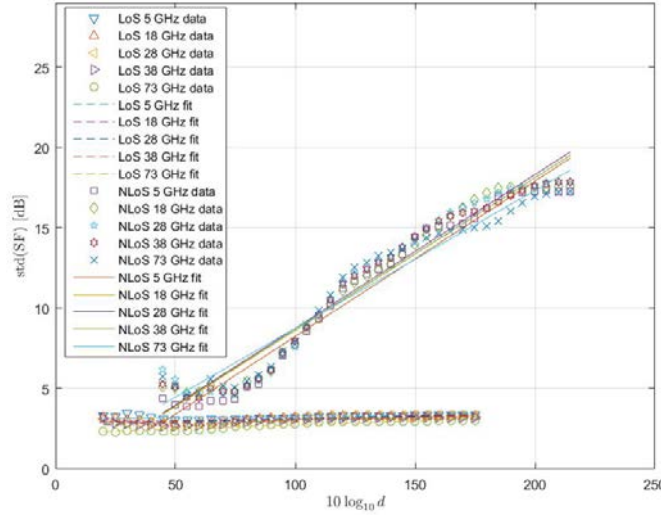


Figure 26. Standard Deviation of Shadow Fading with Distance

Values of a and b for other frequencies can be found in Table 7 where it can be observed that the LOS scenarios do not show significant distance dependent of shadow fading. However, NLOS scenarios show strong distance dependence on shadow fading.

Table 7. Parameters of Linear Fit for Distance Dependent Shadow Fading

f_c (GHz)	a (LoS, NLoS)	b (LoS, NLoS)
5	0.0013, 0.0967	3.1287, -1.415
18	0.0027, 0.0950	2.8743, -0.870
28	0.0040, 0.0956	2.7320, -0.796
38	0.0037, 0.0946	2.6655, -0.799
73	0.0052, 0.0858	2.2219, 0.188

Due to the high loss in the mm-wave band, measurements are usually performed using directional antennas. Figure 27 (a) shows an example of received power using the 2 by 2 channel sounder at Durham University in the 60 GHz band. The measurements were obtained in the indoor environment of Figure 16 (b) using a lens antenna at one receiver and an open waveguide at the other input. At the transmitter dual polarized antennas with 15° beam width were used. The Figure illustrates the effect of polarization and antenna beam width on the received power. The corresponding power delay is shown in Figure 27 (b) where the lens antenna due to its narrow beam width did not have any received power in certain angles while the open waveguide continued to receive power from almost all angles of arrival. These considerations should be taken into account in the design of beam forming.

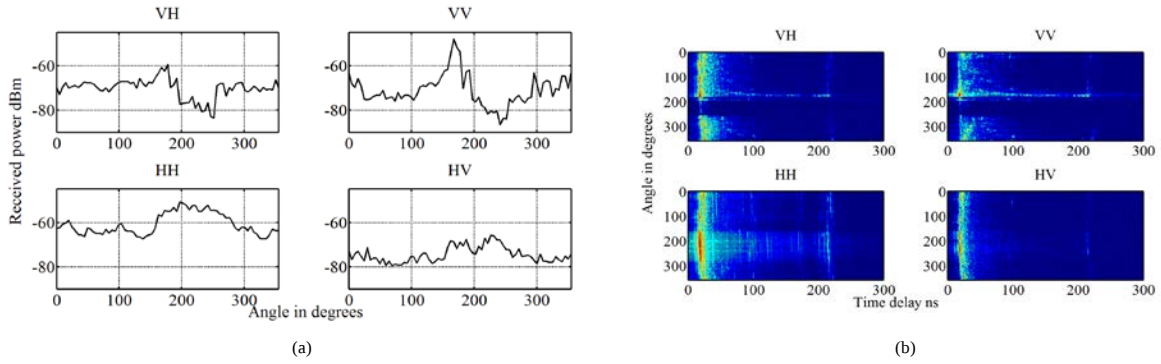


Figure 27. Received Power vs. Angle of Rotation: (a) Estimated Power from PDP, (b) PDP - Top Profiles Obtained with Lens Antenna, Bottom Profiles Obtained with Open Waveguide

In contrast Figure 28 shows measurements performed in an outdoor environment with dual polarized antennas with 15 degrees beam width at both the transmitter and receiver. The figure shows the received power as angle of rotation and the power delay profile. The data were analyzed to estimate the SNR and wideband channel parameters such as rms delay spread and angular spread. Figure 29 displays the rms delay spread as a function of the received power for all power delay profiles with SNR greater than or equal to 15 dB and the corresponding received power. The figure shows that as the received power decreases the rms delay spread increases and that the four channels have different received power for the different angles with different reliability to achieve the 15 dB SNR. The rms delay spread variations versus power can be related to the angle of rotation of the antenna since when the receive antenna is pointing towards the transmitter the received signal is dominated by the LOS component and as the antenna rotates away from the transmitter the received signal is dominated by reflections/scattered components which can arrive from larger distances.

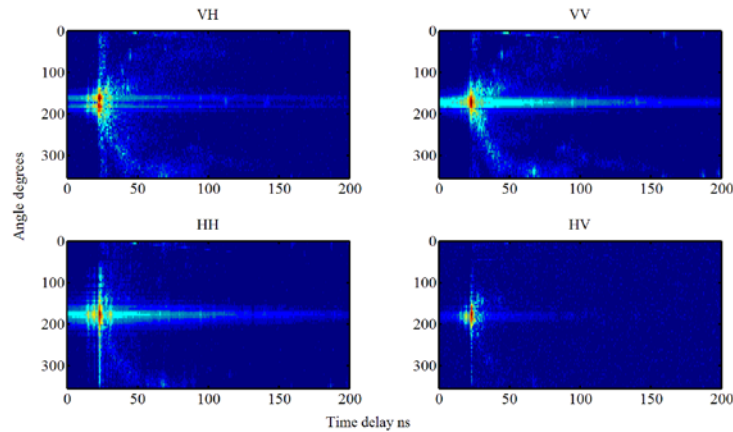


Figure 28. Received power vs. Angle of Rotation

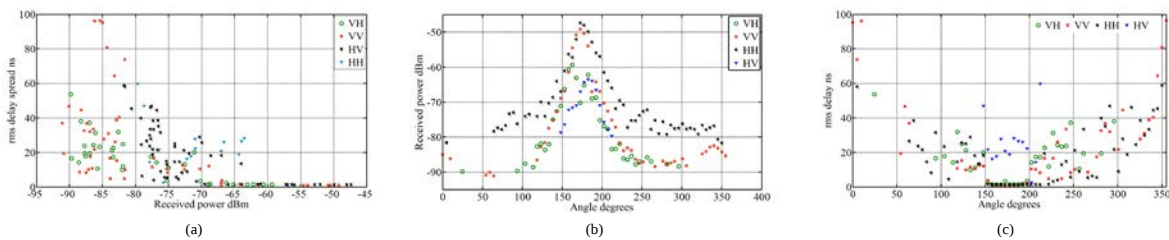


Figure 29. For Location Shown in Figure 28 and 15dB Minimum SNR: (a) RMS Delay Spread vs. Received Power, (b) Received Power vs. Angle of Rotation, (c) RMS Delay Spread vs. Angle of Rotation

To estimate the path loss from these measurements, the data can be analyzed using equation (2) for all receive angles, or by identifying the LOS component which is represented by the strongest received signal in the angular profile when the transmitter and receiver are pointing toward each other, or by filtering out the obstructed line of sight from the power delay profile when the receiver is turned away from the line of sight from the transmitter.

An alternative to the estimation of path loss using a 1m free space path loss as a reference is to use the least square estimator where both the slope and the crossing point are optimized from the fit. This approach is more consistent since it uses the same power coefficient regardless of the distance. The use of free space 1m reference can only be justified when the propagation is predominantly LOS. Figure 30 (a) gives the resulting path loss for the outdoor environment. The data are analyzed by filtering for a 10 dB threshold from the peak where the data below the threshold representing OLOS, and above the threshold representing the power received from the main lobe of the antenna in the LOS. In addition, the maximum received power in the line of sight beam, LOSM and the sum from all the angles to emulate the received power of an omni-directional antenna. The fit shows that the LOSM and the sum fit for the LOS in the main beam and the overall sum are fairly close and the 1m crossing value is close to that of free space at 1 m with a 1.7 coefficient. The crossing point for the OLOS shows higher path loss as would be expected. In this environment shown in Figure 30 (b), the transmitter and receiver were not obstructed by buildings and the environment has a building to one side and a hill to the other side which might have led to a tunneling effect and a lower path loss coefficient. In [36] the path loss coefficient was estimated at 1.9 from the outdoor environment on the campus of Durham University when the transmitter and receiver were pointed toward each other.

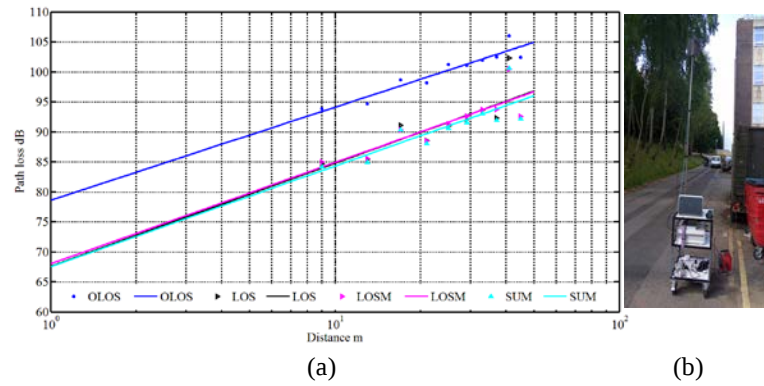


Figure 30. (a) Path Loss Estimation, (b) Measured Environment

7 Propagation Models

Standardized channel models have been extensively and successfully used in the continued development of wireless systems thus far, and undoubtedly this trend will continue. These models, to be useful, must be representative of actual channels with a certain degree of accuracy, as well as be software implementable with reasonable computation complexity. The degree of accuracy required is generally a function of the model's intended use. For example, less accuracy is generally required for the evaluation of wireless systems in the context of algorithms comparisons, feasibility studies, etc. In this case, some form of stochastic modeling has traditionally been used. Although not necessarily accurate for any one specific geographic location, these models are usually parametrically defined for different environments (e.g. urban, rural, indoor, etc.). In contrast, higher accuracy is generally required for the design of a wireless network (network planning) in a specific geographical location. In this case a deterministic approach that takes into account site-specific geographic and morphological information is used. Typically, this approach uses a third-party ray tracing software package that is generally more computationally intensive compared to a stochastic-based approach.

Most of the current standardized stochastic-based channel models were developed for frequencies below 6 GHz. A considerable amount of effort is currently being put into accurately characterizing the mm-wave channel, which has thus far shown to be substantially different from below 6 GHz channels [23]. In addition, mm-wave systems will use much larger bandwidths than the current below 6 GHz systems. Finally, the large antenna arrays used in mm-wave systems allow for a

high degree of beam forming at the user equipment as well as the base station. With this knowledge, it's clear that new channel models are required for the proper analysis of mm-wave based systems.

As mentioned, most of the standardized channel models in use today are stochastic based, and different flavors have been specified over time. One way to classify stochastic modeling techniques is based on whether they are geometry-based or non-geometric [44]. Geometry-based stochastic channel models, GSCM, specify random locations of scatterers in a particular environment and use physical laws to determine various parameters (AoD, AoA, delay, etc.) for each ray. On the other hand, non-geometric stochastic channel models, SCM, determine the various parameters in a stochastic fashion without specifying the locations of scatterers. SCM models can be further classified according to how the generated rays are grouped in time and space. The so-called Saleh and Valenzuela (SV) model introduces the notion of clustering, where a cluster is defined by a group of closely spaced rays that depart/arrive from/at a transmit/receive antenna. Many such clusters make up the entire channel response at any given time. In contrast, the Zwick model [44] generates each ray independently. Two of the most popular standardized channel models in use today are the 3GPP SCM and IEEE 802.11n. Both of these models are of the non-geometric type and both use clustering similar to the SV approach. One approach for specifying a stochastic-based mm-wave channel model in the context of 3GPP would be to extend the current SCM model so that it applies to mm-wave frequencies. This approach will be further elaborated in Section 7.1.

Alternatively, a deterministic channel modeling approach can be used to provide a higher degree of accuracy compared to a stochastic channel model. Although it is unlikely that a vendor specific ray tracing software package would be standardized, an alternative is suggested in [23] that maintains some of the accuracy while reducing the computation complexity compared to a full ray tracing software package. This so called map-based channel modeling technique relies on the ability to create a custom simplified ray tracer in software. At its core this model is fully deterministic, however a hybrid model is also suggested where some aspects can be stochastically generated, thereby reducing the required computation. Another model of this form is suggested in [45], and is referred to as a Quasi-deterministic (QD) channel model. There are various advantages with the map-based approach compared to a purely stochastic approach, however as is usually the case there are trade-offs. From a 3GPP perspective, one of the major (albeit not technical) issues with the adoption of a map-based modeling approach is the amount of legacy with the current stochastic model. Section 7.2 will further elaborate on the map-based channel model as specified in [23].

7.1 Stochastic Channel Model

As a representative example of a stochastic-based channel model, this section will describe the current 3GPP 3D-SCM as specified in [18]. In addition, various model enhancements required to properly account for the propagation characteristics, advanced beam forming techniques, and other mm-wave specific phenomena will be also be described. The 3GPP 3D-SCM is a cluster-based double-directional multi-link model based substantially on work done in the IST-WINNER project [20]. The modeling can be partitioned into three major steps:

1. Scenario Configuration and Large Scale Parameter Generation

A scenario (e.g. Urban Macro-cell, Urban Micro-cell, etc.) is first chosen. Different scenarios correspond to different sets of control parameters (e.g. inter-site distance, base station heights, path loss model parameters, and other low level parameters that control the overall behavior of the model). The next step consists of generating so called large scale parameters (LSP), some of which are used for the generation of small scale parameters. There are seven LSPs that are defined in [18]: shadow fading, Ricean K factor, delay spread, and four angular spreads corresponding to the azimuth and zenith angles of departure and arrival. The generation of these parameters takes into account distance dependent exponentially decaying correlation as well as cross-correlations between the individual parameters. All the parameters are assumed to be log normally distributed with different mean and variances that depend on the scenario and propagation condition. The generation of these so called 'correlated LSPs' is somewhat computationally intensive, while at the same time deriving the correlation parameters from measurement data is non-trivial.

2. Small Scale Parameter Generation

The small scale parameters are generated stochastically and include the per-cluster delays, per-cluster powers, and the azimuth/zenith angles of departure and arrival for all rays. The generation is controlled via the large scale parameters and other control parameters that were previously configured based on the chosen scenario and propagation condition. The propagation condition (i.e. LOS, NLOS) of a specific link is stochastically chosen based on the location of the user (i.e. outdoor, indoor), as well as the link distance and user equipment (UE) height. It's worth noting that the delays are

generated per cluster, which means that the inter-cluster rays are treated as unresolvable in time. With the larger bandwidths being targeted for mm-wave, the inter-cluster ray time delays will likely need to be modeled. Similarly the inter-cluster power distribution, which is currently distributed evenly amongst the inter-cluster rays, may also require more accurate modeling for mm-wave. As a point of reference, [46] suggests the inter-cluster power levels fall off exponentially with the inter-cluster time delays. Another noteworthy observation is that for the 3GPP SCM, a cluster is confined in both time and space. In [46] however, field measurements are said to indicate that this one-to-one relationship between time and space does not hold. The authors suggest that temporal and spatial clusters should be defined independently for mm-wave channels.

3. Channel Coefficient Generation

The final step is to generate the channel coefficients using the small scale parameters from above and to apply path loss and shadowing. The coefficient equation is provided in [18] and generates time domain coefficients for each cluster and for each transmit and receive antenna element pair. Note that in a frequency domain scheduled system (e.g. LTE), a frequency domain representation of the channel is usually preferred to facilitate the scheduling functionality in an overall system level simulation. Furthermore, in practice the channel data is typically pre-generated and loaded into a top level simulation because of the substantial computation time that would be required for channel generation each time a simulation is run. For mm-wave systems, which are envisioned as having large arrays at both the BS and UE, a per antenna element pair channel data file can get prohibitively large, especially for dynamic beam forming simulations.

7.1.1 Mm-wave Channel Model Enhancements

Based on preliminary field measurements [23], in order for the above 3GPP SCM to be applicable to frequencies above 6 GHz, a minimum requirement is to specify new control parameters for the generation of the large and small scale parameters. These new values will undoubtedly be determined based on continued field measurements and analysis, as they were for the current below 6 GHz model. There are, however, other fundamental changes that will be needed in order for the mm-wave channel to be properly characterized. In addition, based on the larger arrays being used at both the UE and BS, some practical considerations may also need to be made in order for the implementation of such a model be practical. Some of the potentially required changes are specified below:

1. Atmospheric and rain attenuation

The attenuation due to the molecular constituency of air and water generally increase with increasing frequency (with more extreme attenuation at certain mm-wave frequencies), and therefore these effects should be incorporated into an above 6 GHz channel model.

2. Static and dynamic blocking

Various objects in the environment (e.g. cars, humans, foliage, etc.) can cause strong attenuation at mm-wave frequencies. This can be partly explained by the decreased wavelengths, which in turn result in a decrease in the first Fresnel zone.

3. Self-blockage

This type of signal blockage is due to the users own body and is a major concern for mm-wave signals, since these frequencies experience much more attenuation from the human body.

4. Temporal and Spatial Cluster Correlation

As mentioned, a cluster is currently defined to be confined in both time and space. Field measurements, [46], indicate that this one-to-one relationship between time and space does not hold for mm-wave channels, possibly due to scattering which is more pronounced because of the smaller wavelength.

5. Large bandwidth support

The larger bandwidth expected to be used for mm-wave communication implies increased temporal resolvability of rays which should be accounted for. In this case, intra-cluster delay spread and power distribution need to be considered.

6. Spatial Consistency

Having a spatially consistent channel model is much more critical for mm-wave communications because of the pencil beam links that will be formed. The current 3GPP SCM generates correlated LSPs, however the small scale parameters are

not spatially correlated. A method for creating spatially correlated small scale parameters, especially AODs and AOAs, should be used for mm-wave channels.

7. Support for 3D dynamic analogue beam forming with large arrays at UE and BS

Analog beam forming is crucial for creating viable mm-wave links, and fortunately large arrays can be supported at the UE and BS because of the small antenna aperture size for mm-wave frequencies. Furthermore, to combat the blockage issue it's likely that a UE will utilize more than one array. Multiple large arrays at the BS and UE greatly increase the memory required when generating per antenna element pair channels. In addition, the beam forming needs to be done dynamically in a top level simulation, which prevents pre-generating channels with fixed beam patterns. An alternative could be to generate a single isotropic channel between each BS and UE that is stored and later loaded into the top level simulation where various antenna structures can be applied and dynamic beam forming can be accomplished. This method simultaneously reduces the required memory and allows for dynamic beam forming, as is required for realistic mm-wave communication systems.

8. Distance or frequency dependent characteristics

Measurements in [47] have reported that certain channel characteristics are distance dependent in mm-wave. The NLOS rms delay spread appears to be a function of distance. Also, due to the wide bandwidth in mm-wave, antenna pattern can be different. Frequency dependent antenna modeling may be needed.

9. Support for Multiple Antenna Array Configurations

Although not directly related to the propagation channel, the antenna patterns at both ends of a link make up the final composite channel seen by the receiver. As mentioned in Section 4.4, mm-wave system will require high beam forming gains in order to establish reliable links. An array of patch antennas is one possible low cost solution, but a single array will have a limited angular field of view. It's likely that multiple arrays per node will be used to improve this field of view [48]. Therefore, any mm-wave channel model should be made to accommodate various multi-array antenna structures so that proper system analysis can be done when these channel models are ultimately used in system level simulations.

10. Greater Support for True Mobility Related System Simulations

Conventional sub 6 GHz channel models, like in [18], are drop-based, modeling virtual translation motion only. The highly directive antennas required for mm-wave systems make these links much more sensitive to true motion. Therefore, any mm-wave channel model should be made to accommodate true motion for proper system analysis. Both translational and rotational motion should be considered. As it turns out, rotational motion can have an even greater impact than translational motion [49], and is also simpler to account for in a drop based stochastic channel model. It's also worth mentioning that a map-based channel model naturally supports both translational and rotational motion.

7.2 Map-Based / Hybrid Channel Model

An alternative to both a stochastic-based channel model and a full ray tracing software based channel model is a so called map-based model [23]. A map-based model, while based on ray tracing, is simplified so as not to require a 3rd party ray tracing software package. Some of the advantages over a stochastic-based channel model are that various carrier frequencies, realistic large scale and small scale parameter correlations, and dynamic modeling are automatically supported due to the physical modeling techniques used. A possible disadvantage is the fact that a specific geographical environment is being modeled. However, if the environment can be made adequately representative of a class of environments, as is the case for the stochastic-based modeling approach, this issue may be alleviated. Furthermore, the model can be extended to incorporate various stochastic components, and is then usually referred to as a hybrid channel model. This approach is applied to the map-based model in [23]. This section briefly describes the map-based model as specified by [23], keeping in mind that the hybrid channel model, which may be an appropriate compromise between the two approaches (stochastic and deterministic modeling), requires relatively minor additions to what is described.

The map-based channel model uses simplified ray tracing principles to construct an accurate representation of the channel. The model accounts for the various propagation mechanisms, such as reflection, scattering, and diffraction, through the use of physical equations. The model also allows for various physical modeling techniques, as well as other simplifying methods, so that computation complexity can be reduced when required. The modeling can be partitioned into four major steps:

1. Environment Creation

This step first creates the geographical and morphological items within the environment (i.e. buildings, cars, interior walls, etc.). Standardized maps are defined [23] (i.e. shopping mall, office space, etc.), however various objects can also be placed stochastically. Note these environments can be pre-computed and saved off-line for importing at the start of the simulation. Another possibility may be to re-compute various stochastic components of the environment (e.g. building heights, distance between buildings, etc.) throughout the simulation in order to more accurately capture the characteristics of the class of environments as opposed to a specific environment, as is the case when using an external ray tracing software package. Finally, this step also specifies the locations of all transmitters and receivers.

2. Ray Pathway Determination

This step is used to determine the various pathways, interaction types, and coordinate points for all rays traveling from each transmitter location to each receiver location. In addition, the path segment lengths, as well as the departure and arrival directions between all interaction points for all rays are computed. Note this step shows the inherent spatial consistency of the map-based approach, which is in contrast to the stochastic-based approach. As mentioned earlier, having a spatially consistent channel model is especially critical when studying advanced beam forming techniques, as is the case for mm-wave communications.

3. Pathway Segment Channel Matrices Determination for all Rays

This step contains the physical modeling for the various interactions for each ray as well as the computation of shadowing loss. The various interaction types; reflection, diffraction, and scattering are all accounted for using physics based equations. Various methods can be used depending on the accuracy desired.

4. Channel Coefficient Generation

The final step, as is the case in the stochastic-based channel model, is to compute the channel coefficients. The coefficient equation used is provided in [23] and again generates time domain coefficients.

Finally, we re-iterate the fact that the above procedure can also be used in conjunction with various parts of the stochastic-based model to create a so-called hybrid channel model. Many different configurations of how these two models are integrated can be envisioned. Regardless of how this integration is performed, it is clear that the hybrid model can not only be used as a compromise between accuracy and computation complexity, but can also be used to take advantage of the strong points from each model (i.e. the better accuracy of the map-based approach and the better applicability to a wider variety of scenarios of the stochastic-based approach).

8 Standardization Prospects

Due to the proliferation of smart devices and a wide range of applications requiring a large amount of data traffic anytime anywhere, providing high quality service at high speed emerges as the new potential use case for the future IMT system. Therefore, a promising communication system will be necessary for maintaining high quality even at high speed which enables successful deployment of applications on user equipment inside a moving platform. Thus, in March 2015, a new interest group named IEEE P802.15 IG HRRC (Interest Group High Rate Rail Communications) was chartered to study the wireless communications providing Gbps data rate with high performance to the user groups inside of fast-moving vehicles. The frequency bands above 6 GHz are main candidates under consideration for backhaul links (outside of the vehicles) and access links (inside of the vehicles). The application scenarios are mainly considered as subway, high-speed train, high-speed bus and normal vehicles. Currently, the IG HRRC is chaired by Electronics and Telecommunication Research Institute (ETRI), and Beijing Jiaotong University is the main contributor providing insight into high frequency channel characteristics by conducting extensive ray-tracing simulations in various scenarios and applications. The main proposed system in IG HRRC is working in the 30 GHz band, named Mobile Hotspot Network (MHN) system which targets supporting Gbps data rate services at speeds over 400 km/h for mobile group vehicles. In the near future, more proposals are expected, because more institutions, such as Bims Laboratories, Wi-SUN Alliance, EthAirNet Associates, etc., are attracted by the IG HRRC.

Recently, 3GPP started a 5G channel model study item [50]. The aim of the study item is to develop a channel model to enable feasibility study and developing framework of using high frequency spectrum from 6 GHz to 100 GHz. The study started as an email discussion between 3GPP RAN delegates. From February 2016, 3GPP RAN WG1 ("RAN1") will develop a channel model for frequencies up to 100 GHz taking into account the 5G requirements defined by 3GPP. The study item of 3GPP will consider the work done outside 3GPP as well as the 3GPP 3D channel model [18] as a starting point. Compatibility

between below 6 GHz and above 6 GHz channel models should be ensured. Therefore, the above 6 GHz channel model may affect to the below 6 GHz channel model [18] as well.

The 3GPP 3D channel model has been designed for LTE / LTE-Advanced (4G / 4.5G systems), but 5G requirements are much more challenging also from channel modeling point of view. The requirements include, e.g., frequency range 0.5 – 100 GHz, bandwidth up to 2 GHz, spatial consistency, large array support, different link types and network topologies, moving base stations, and spectral consistency.

Other efforts towards channel standards are made in the ITU Study Groups 3 and 5 where SG 3 is focusing on radio propagation issues and SG5 is concerned with sharing and co-existence studies as well as developing suitable channel models for system design. Correspondence groups have been set up in SG3 Working Party 3K and a task Group in SG5 to address the system issues with the aim of arriving at suitable recommendations for the next world radio-communications conference WRC19.

9 Recommendations for Further Studies

Since 3GPP is actively discussing 5G channel models, it is timely to propose improvements to the existing channel model frameworks, propose new ideas, and provide measurement results for the frequency range 0.5 – 100 GHz. These ranges would require a great deal of collaboration between institutes in terms of channel measurements and modeling methodologies.

Most of the existing measurements were done for the static radio channel. In 2014, Samsung presented the world's first demonstration for 1.2 Gbps transmission at 28 GHz at 110 km/h cruising speed using dual-beam forming. This shows the strong potential of the frequency bands above 6 GHz for mobile application, but the understanding of the channel dynamics – spatial-temporal Doppler properties – are still absent. The lack of insight into such dynamics inhibits the realization of communication in the frequency bands above 6 GHz in any dynamic environment. Thus, dynamic channel measurements need to be designed and performed with various configurations, such as different moving transceivers and scatterers with variations of speed and motion direction. Similarly, dynamic simulations need to be made by adding the same mobility to the corresponding scenarios. Based on both the measurement and simulation results, the correlations between the mobility and channel dynamics can be estimated. For instance, it is critical to identify how the mobility and the variation of mobility influence the first-order and second-order statistics of the channel dynamic parameters for the frequency bands above 6 GHz.

Another area where research effort is required is interference between fixed links. While it is presumed that directional antennas facilitate point to point link communication, the impact of Rayleigh and Mie scattering from rain and precipitation need to be addressed over multiple links. Such a study is currently being set up at Durham University with a hub with dual polarized antennas and three receive links at multiple frequencies.

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