Characterisation of propagation in 60 GHz radio channels (invited)

Citation for published version (APA):
Smulders, P. F. M., & Correia, L. M. (1997). Characterisation of propagation in 60 GHz radio channels (invited). *Electronics and Communication Engineering Journal*, *9*(2), 73-80. https://doi.org/10.1049/ecej:19970204

DOI:
10.1049/ecej:19970204

Document status and date:
Published: 01/01/1997

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Characterisation of propagation in 60 GHz radio channels

by P. F. M. Smulders and L. M. Correia

Narrowband as well as wideband measurements have been performed in various indoor and outdoor environments in order to enable the development of reliable prediction models for 60 GHz radio channels. In addition, results of deterministic modelling on the basis of geometric ray-tracing have been compared with measurement results, showing that simple ray-tracing can be used to estimate both the narrowband and wideband characteristics of a 60 GHz radio channel. This paper reviews the measurement and modelling activities performed by various research institutes.

1 Introduction

Developments in broadband radio networking are being spurred by the need for high-bit-rate services at mobile terminals. Many probable uses of broadband wireless systems can be found in environments such as shipyards, airbases, in- and outdoor factory sites, railway stations, hospitals, shopping centres, vehicle guidance/traffic control and in security and surveillance with video cameras linked to control centres. In the medical field, video communication between ambulances and medical specialists in a hospital might contribute to efficient emergency handling.

The UHF bands normally used for mobile communication systems are not suitable for mobile broadband applications since broadband systems with an aggregate network capacity of hundreds of megabits per second will require hundreds of megahertz of spectral space. Uncongested bandwidths of this order are only available at radio frequencies above about 25 GHz. In the case of indoor applications, high traffic density can be achieved by using frequency bands above approximately 40 GHz. This is because frequencies can be reused between neighbouring rooms owing to the severe attenuation of electromagnetic waves at these frequencies by most inner walls. For frequency reuse in outdoor cells, the band around 60 GHz is especially advantageous because of the specific attenuation characteristic of about 15 dB/km due to atmospheric oxygen.[1] The 60 GHz band is also of special interest for indoor systems since radio waves are still able to pass through windows and thus have the potential to interfere with neighbouring outdoor cells and with other indoor systems operating in neighbouring buildings.

In order to exploit these new frequency bands for high-bit-rate systems it is essential to estimate the channel dispersion in addition to, for example, path loss and received power. This is because significant performance degradation due to channel dispersion occurs if the bandwidth of the transmitted (one carrier) signal is not low in comparison to the coherence bandwidth of the channel. The coherence bandwidth $(\Delta f)_c$ of the channel can be loosely defined as the maximum frequency difference for which two sinusoids are still strongly correlated. If a *wideband* signal is transmitted through the channel, i.e. if $W >> (\Delta f)_c$, where W is the bandwidth of the transmitted signal, the signal is severely distorted by the channel. On the other hand, if a *narrowband* signal is transmitted through the channel, i.e. if $W << (\Delta f)_c$, all of the frequency components in the transmitted signal undergo the same attenuation and phase shift so that no channel distortion occurs.

Principal abbreviations

DI	=	delay interval
DOA	=	direction of arrival
DW	=	delay window
LOS	=	line of sight
MD	=	mean delay
NRP	=	normalised received power
OBS	=	obstructed
RDS	=	RMS delay spread
SDW	=	sliding delay window

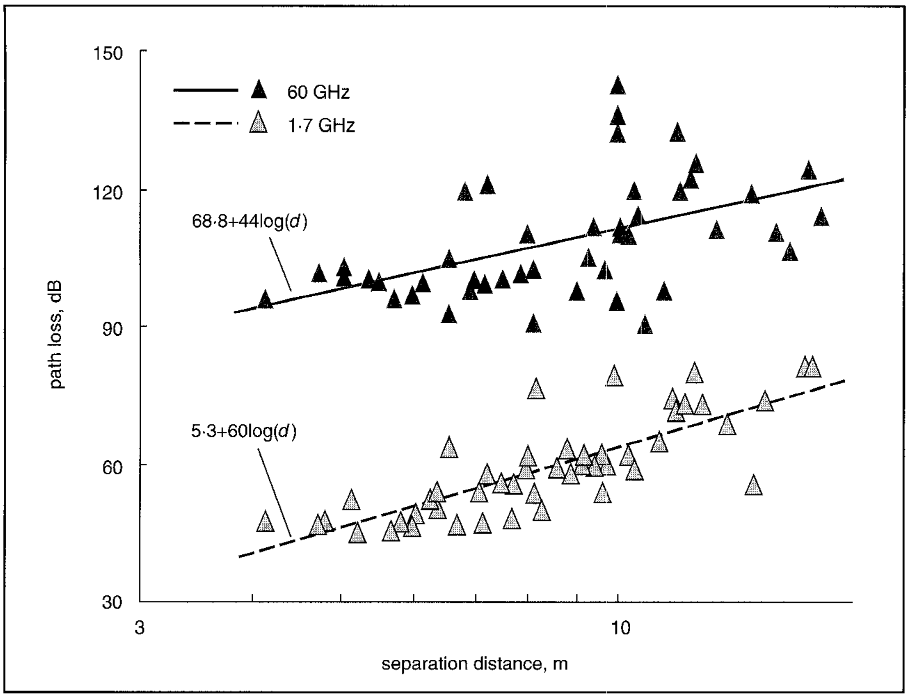

Fig. 1 Path loss against distance at 1·7 and 60 GHz

In general, a propagation prediction model, i.e. an idealised mathematical representation of the characteristics of the channel, can be a useful tool for the prediction of transmission performance and thus for system design and network deployment. In principle, a channel model can be a *statistical* representation as well as a *deterministic* representation. A statistical channel model represents the statistical properties of the channel by describing its parameters in terms of probability distribution functions and/or their statistical moments. These are derived from measurement results. A deterministic model is a set of algorithms to calculate the channel properties from a predefined environment. Deterministic modelling can be based on geometrical optics and possibly on diffraction and scattering theory. The two modelling methods, statistical modelling and deterministic modelling, have their own merits and complement each other; statistical modelling provides a compact summary of the overall characteristics for an environment or class of environment types whereas deterministic modelling can provide more site-specific detail.

Considerable work has been carried out to develop reliable prediction models for the millimetre-wave (mm-wave) frequency bands between 57 and 66 GHz. In what follows, we will review the results obtained for indoor and outdoor environments, respectively.

2 Indoor radio channel

For the characterisation of indoor propagation, narrowband as well as wideband measurements have been performed in various indoor environments. Narrowband measurements are not able to resolve the individual multipath components in the time domain. Hence, narrowband characterisation is limited to modelling the path loss and direction of arrival. Wideband characterisation may also concern the modelling of channel impulse response parameters.

Path loss

Narrowband path-loss measurements against separation distance at 60 GHz have been performed with a CW source and spectrum analyser.[2] The radiation pattern of the measurement antennas was narrow (3 dB beamwidth 5°) in the vertical plane and broad (90°) in the horizontal plane.

The results obtained at 47 positions in an office building are shown in Fig. 1. Results obtained in the same environment at 1·7 GHz have been included to highlight the differences between the two frequency bands. All the measurements were performed with the transmitter and receiver on the same floor. The direct path was typically blocked by furniture or a light internal wall. A clear line-of-sight (LOS) path was present only in a few of the measurements.

In Fig. 1 it can be seen that the path loss is considerably higher at 60 GHz. Even at higher separation distances (15 m), where the excess attenuation is small, the difference between the two frequencies is rather high: 45 dB. The difference (31 dB) in free-space loss partly explains this result. The rest of the difference, 14 dB, is due to the higher penetration loss of materials as well as higher reflection and diffraction loss at 60 GHz. It can also be seen that the variance of path-loss values is proportional to frequency. This is due to more severe shadowing effects at 60 GHz.

Direction-of-arrival

Direction-of-arrival (DOA) data can be used to investigate individual signal paths and to assess the advantage that can be achieved by using steered high-gain antennas. If the DOA pattern shows distinctive peaks it is clear that the path loss can be reduced by steering a high-gain antenna towards the maximum peak.

DOA measurements at 60 GHz have been performed using the same type of measurement system as for the path-loss measurements, but with a different antenna at the receiver;[3] this antenna had a narrow beamwidth (5°) in both vertical and horizontal planes. The antenna was rotated through 360° while path loss between the transmit and receive antennas was measured. The level of link improvement achievable by using antenna steering in the azimuth plane can be estimated by calculating the DOA pattern gain. The gain is calculated by dividing the maximum peak of the pattern by the average received power. According to 27 DOA patterns measured in a laboratory the gain is better than 8·4 dB with 90% probability.

In another measurement campaign[4,5] a vector network analyser was used in combination with a high-precision positioning system to study the spatial variations of impulse responses as well as spatial Doppler spectra. DOA patterns can be derived from the Doppler spectra by applying a simple transformation. The DOA results of References 3–5 confirm the conjecture that the dominant contributions to the received power come from specular reflections.

Received power

Wideband measurements of normalised received power (NRP), i.e. the ratio of received to transmitted power, have been performed in a 2 GHz bandwidth centred around 58 GHz.[6,7] The measurement system was built up around a vector network analyser. Two identical biconical horn antennas were used, based on a design described in Reference 8. These antennas exhibit an omnidirectional radiation pattern in the azimuth plane and a torroidal beam in the elevation plane. The elevation beamwidth was 9°.

The measurements were carried out in eight indoor environments. In each of these environments at least one series of 20 measurements was conducted at randomly chosen positions of the remote transmitter throughout the room. The biconical horn antenna on the transmitter was located 1·4 m above the floor. The biconical horn at the receiving end was elevated to 3 m and placed in the centre of the room. Both antennas were levelled horizontally at every measurement position.

Owing to the radiation pattern of the biconical horn antennas the path loss is partially compensated by the antenna radiation pattern in elevation. Hence, the received power does not depend significantly on the horizontal position of the remote antenna. In order to examine this interesting effect we should consider the NRP, which includes antenna effects rather than path loss.

Fig. 2 shows scatter plots of the NRP against separation distance on a log scale for both line-of-sight as well as obstructed (OBS) situations. The values for OBS situations have been derived from the measurement data obtained under LOS conditions by mathematical removal of the direct ray. This method is justified by the observation that blockage of the direct ray by a person or cabinet caused a total drop of the LOS ray.

High values of NRP were found for environments with highly reflective (metal) objects and metal walls, whereas relatively low values were found in rooms with only poorly reflective materials like wood.

The decay slope exponents of the linear fits were typically much smaller (<0·5) than those reported for indoor UHF radio channels due to the path-loss compensation effect mentioned earlier.

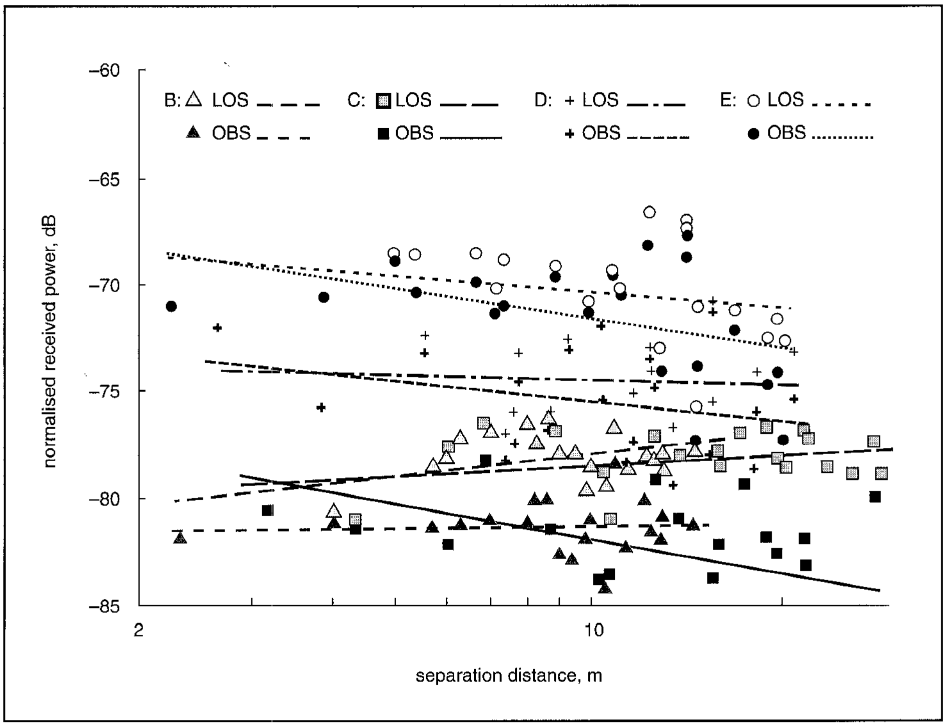

Fig. 2 Normalised received power against distance in large rooms (B, D), a hall (C) and a corridor (E)

Channel dispersion

An example of an observed (complex equivalent lowpass) impulse response is shown in Fig. 3 (magnitude only). Individual rays could be detected by blocking the associated ray by an absorbing material, leaving other rays not noticeably influenced. The measured channel impulse responses in which individual rays can be resolved due to a measurement resolution of 1 ns show that a mm-wave indoor radio channel is essentially a multipath channel. Hence, mm-waves are sufficiently small to be modelled as rays following discrete paths.

Fig. 4 shows the cumulative distribution functions of RMS delay spread (RDS) values for both LOS and OBS situations. RDS values tend to increase with increasing reflectivity of the walls. Furthermore, it is clear from Fig. 4 that the RDS is fairly independent of the position of the remote station in each environment. Blocking of the direct path does not necessarily imply that RDS has to increase; slightly higher and lower values are observed for OBS-situations in Fig. 4. Typical RDS values range between 15 and 45 ns for small rooms (not included in Fig. 4) and between 30 and 70 ns for large indoor environments. The largest value obtained was 100 ns.

In References 6 and 9 a statistical model is derived from measurements of the impulse response details of the indoor mm-wave radio channel. In Reference 6 the relation between the model parameters and environment properties (dimensions and wall reflectivity figures) are

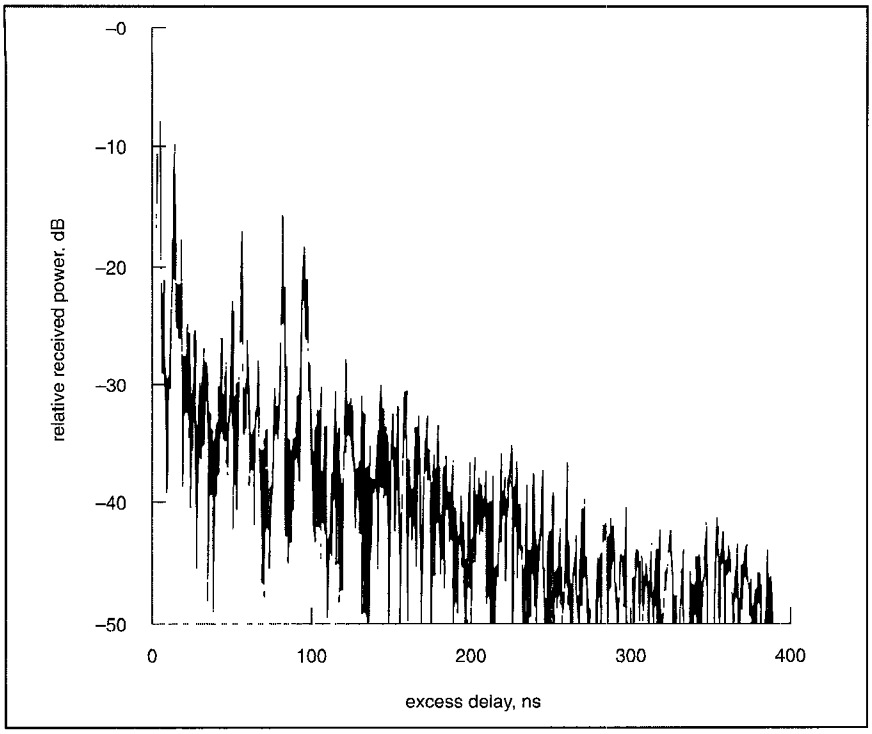

Fig. 3 Example of measured impulse response (magnitude)

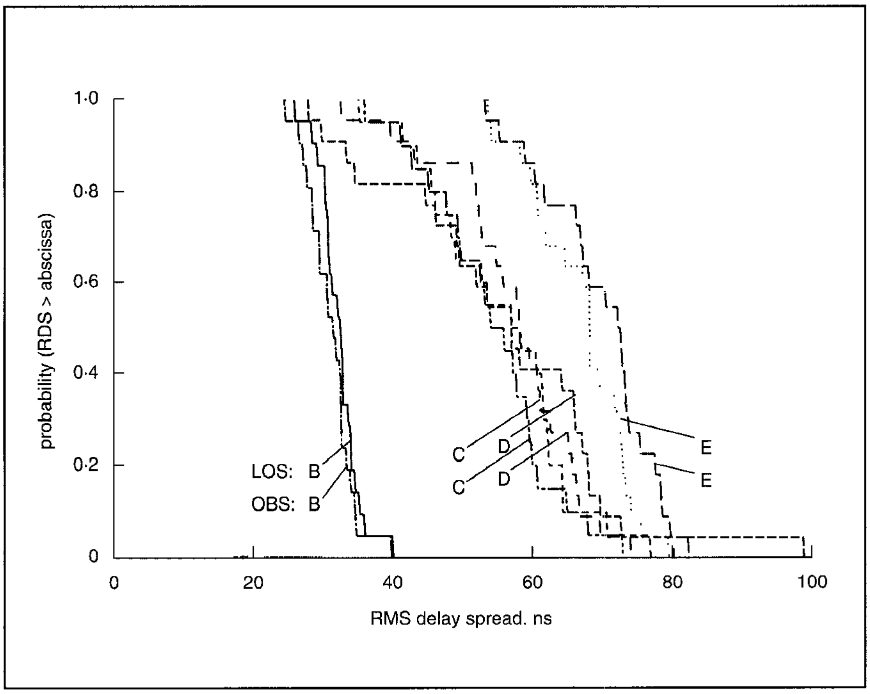

Fig. 4 Cumulative distributions of RMS delay spread (RDS) in large rooms (B, D), a hall (C) and a corridor (E)

related to the specific properties of the particular environment under consideration and the antennas used. The ray interarrival times were modelled as independent random variables that are exponentially distributed (i.e. a Poisson process).

The values of statistical parameters derived from the 57–59 GHz measurement results have been compared with measurement results obtained at 41–43 GHz using a similar measurement con-figuration with scaled biconical-horn antennas. The difference in atmospheric attenuation (0·1 dB/km at 41–43 GHz and 12 dB/km at 57–59 GHz) was not noticeable in our measurement results. This indicates that the statistical model can also be used for other frequencies in the mm-wave band.

Deterministic modelling of mm-wave indoor radio channels has been performed by various researchers.[3,6,10–12] In Reference 6 the significance of diffraction and scatter effects is examined as part of the deterministic modelling. Typically, the diffracted power does not yield a significant contribution to the total received power. The surface roughness of building materials that typically can be found in indoor environments is such that the resulting scattering (diffuse reflection) does not contribute significantly to the total received power either. The dominant contributions are expected to come from specular reflections. These contributions can be calculated on the basis of the electrical characteristics of the material (as well as the material thickness and a factor that accounts for scatter loss).

described by first order approximations. The ray phases were modelled as independent random variables that are uniformly distributed over [− 180°, 180°]. The amplitude values of the LOS rays were not modelled since they can be determined easily on the basis of the radio equation. The amplitude values of reflected rays were modelled as independent random variables that are Rayleigh distributed. The normalisation parameter of this distribution was modelled as a function of excess delay by a constant level part followed by a linear decrease (dB value). The level of the constant-level part as well as the slope parameter of the linearly decreasing part was

In accord with the above considerations a channel model has been proposed based on geometrical optics (GO) and taking into account the polarisation and radiation patterns of both the transmit and receive antennas. The mathematical fundamentals for its implementation are given in Reference 6. The accuracy of the proposed model is examined by comparing simulation results with data obtained from measurements. The indoor environments defined in the simulation software are simplifications of the corresponding real environments in which the measurements took place. Although the model includes only the superstructure (walls, floor and ceiling) and lacks details such as tables and cabinets, the simulation results are in good agreement with the measurement results. This indicates that the results are mainly determined by the superstructure of the indoor environment.

3 Outdoor radio channel

Both narrow- and wideband measurements have been conducted in several outdoor environments in the mm-wave band.

Received power

Initially, narrowband measurements of received power against separation distance were performed[13,14] in different environments: airport field, urban street and city tunnel. In all cases, the results showed an interference pattern typical of those associated with the sum of several rays, suggesting that ray-tracing techniques can be used to model the propagation phenomena. Simple ray-tracing tools have been developed[13, 14] which account only for direct and reflected (up to second order) rays; the simplest scenarios were considered, neglecting any objects (for instance streets are considered as dielectric canyons). Comparisons of measured and simulated results, of which Fig. 5 is a good example, show good agreement, indicating that reflections of third order, or higher, and diffraction can be neglected as far as modelling the variation of power with separation distance is concerned.

According to simulation results, the use of antenna diversity by selectively combining signals from two antennas separated by 1 m (much more than the correlation length for millimetre waves) mitigates fading effects, decreasing the fade depths by several decibels. Selectively combining two or more frequencies (with a separation of the order of 1 GHz) shows that frequency diversity is less effective than at lower frequencies (10 GHz)

In the models used at UHF for the decay of power with separation distance, the slope usually depends on the environment and on break-point distances. These are very simple models based on the interference of a direct and a ground-reflected ray, leading to a simple dependence of the power on distance d of the type $10\alpha\log(d)$, α being the decay slope. It is well known that a two-ray model leads, under conditions that are usually satisfied, to a fourth power law rather than the square law found in free space. One of the conditions to be satisfied is that the path length difference between the direct and reflected rays is less than $\lambda/2$ (λ is the wave length in free space), which defines the break-point distance, $d_{bp} = 4h_t h_r/\lambda$ (h_t and h_r are the transmit and receive antenna heights, respectively), beyond which the fourth power law can be used. Such a model for the millimetre wave band requires evaluation of the break-point distance and an environment classification according to the different values of α. For the frequency range from 60 to 66 GHz (i.e. the band envisaged for mobile broadband services), and $h_r = 1{\cdot}8$ m, $h_t \in [5, 50]$ m, we get $d_{bp} \in [7{\cdot}2,\ 79{\cdot}2]$ km, which is far beyond the expected maximum range for the cell radius (up to 0·5 or 1 km). This means that the fourth power law is not expected to apply at millimetre wave frequencies and that α will be close to the value for free space (α = 2), which is confirmed by measurement results.[13–16]

The value of α does not seem to depend only on the environment, since a value of 2·3 is found in an open space as well as a street. The range in which α varies is not very large (2 to 2·5) and the antenna height seems to influence the value of α. The value of α will, of course, be of greater importance for larger distances, since larger values of α contribute to a faster decay of the power.

The model developed for the 60–66 GHz band[17] includes two additional terms, compared to the UHF band model, besides the usual term related to the slope of the power decay curve with distance: one to account for oxygen absorption and the other for rain attenuation. These terms are negligible in the UHF band but cannot be neglected at higher frequencies. Moreover, oxygen absorption is the main reason for choosing the 60 GHz band. Other factors

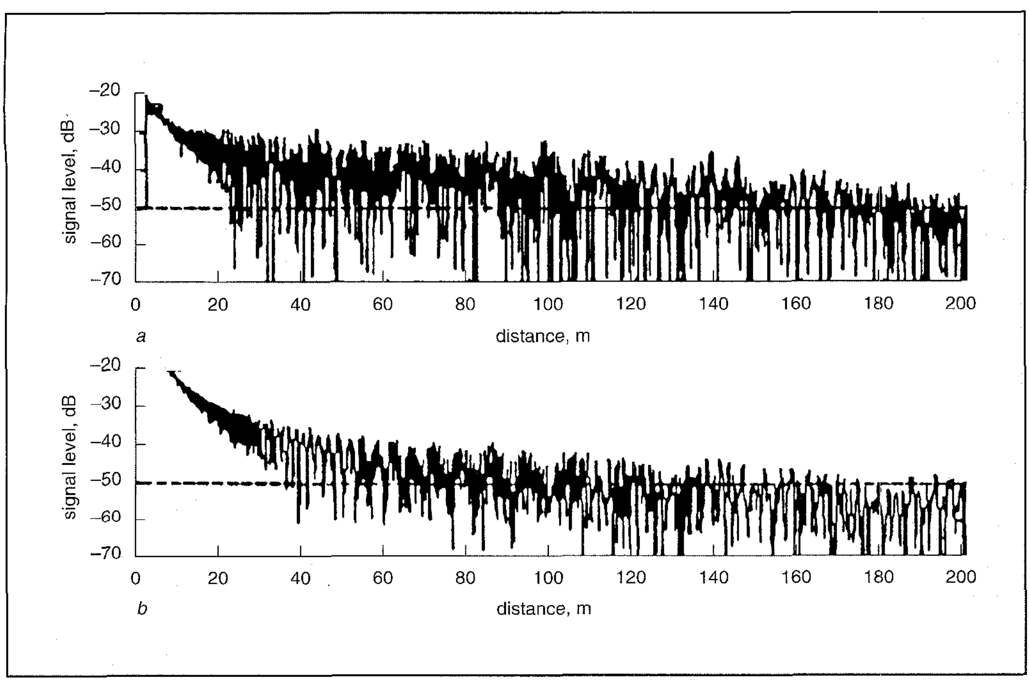

Fig. 5 Comparison between (*a*) measured and (*b*) simulated signal power in a tunnel at 60 GHz

can affect wave propagation, but they are not considered here. Water vapour absorption can be neglected since its attenuation coefficient is of the order of 0·1 dB/km. The influence of fog, hail, snow, sand, etc. can also be neglected, either because the attenuation coefficient is very low or because these environments occur with very low probability. An expression, based on Reference 18, for the specific attenuation due to oxygen absorption has been developed:

$$\lambda_{o[dB/km]}(f_{[GHz]}) = \begin{cases} 15{\cdot}10 - 0{\cdot}104(f-60)^{3{\cdot}26} & (60 \leq f \leq 63) \\ 11{\cdot}35 + (f-63)^{2{\cdot}25} - 5{\cdot}33(f-63)^{1{\cdot}27} & (63 \leq f \leq 66) \end{cases} \quad (1)$$

where f is the frequency. This specific attenuation can take relatively high values at 60 GHz (around 15 dB/km), but it decreases by an order of magnitude when the frequency is near 66 GHz. This decrease must be taken into account when the frequencies are chosen for the up and down links, especially if the distances are greater than 1 km. Attenuation due to rain can also be of some importance in the mm-wave band, depending on the rainfall rate R (mm/h). The model given by ITU-R[19] is used:

$$\lambda_{r[dB/km]}(f_{[GHz]}, R) = k(f)\, R^{a(f)} \quad (2)$$

where λ_r is the specific attenuation due to rain and $k(f)$ and $a(f)$ are approximated by:

$$k(f) = 10^{1{\cdot}203 \log(f) - 2{\cdot}290} \quad (3)$$
$$a(f) = 1{\cdot}703 - 0{\cdot}493 \log(f) \quad (4)$$

Rain can play an important role in cell coverage reduction, since its attenuation can reach values larger than those for oxygen, depending on the rainfall rate (18 dB/km for 50 mm/h). Oxygen and rain attenuations cannot be neglected if large distances (~1 km) are to be considered, but for calculations within cells (with ranges less than 200 m) they may not be of great importance.

The average received power can be estimated by combining the expressions of almost-free-space received power with the attenuation by oxygen and rain. Thus the received power is given by:

$$P_r = P_t + G_t + G_r - 32{\cdot}4 - 10\alpha \log(d) - 30\alpha - 20\log(f) - \lambda_r d - \lambda_o d \quad (5)$$

where P_t is the transmitted power (dBm), G_t, G_r are the transmit and receive antenna gains (dBi), and d is the separation distance (km). The value for α has to be chosen with some care, depending on the specific application intended for the model. Expression 5 cannot be used for very small distances where the antenna radiation patterns will have a great influence. The model agrees very well with the measurement data from Reference 15, giving a maximum 2 dB error in the estimation of the received power. Comparison with the data from Reference 16 also leads to good results, although the measurements have a maximum range of 200 m.

Channel dispersion

A channel sounder based on correlation has been used for the measurement of channel impulse responses.[20] The RF centre frequency was 59·0 GHz, with a maximum bandwidth of 200 MHz, corresponding to a best resolution of 5 ns.

The parameters of the channel impulse response that were considered were mean delay (MD), RMS delay spread (RDS), delay interval (DI) and delay window (DW). A new delay window parameter, the sliding delay window (SDW), defined as the length of the shortest portion of the impulse response containing a certain percentage of the total energy, was introduced and is believed to be a better measure than DW, e.g. when judging equaliser performance.

The measurement campaign included measurements in city streets, squares, a road tunnel and a parking garage.[21,22] A 90° horn was used as the transmit antenna in all the measurements, whereas the receive antenna was a biconical horn with an elevation beamwidth of 20°. The height of the receive antenna in all measurements was 2·2 m and the transmitter antenna height was generally around 4 m.

It was observed that city streets do not normally represent a severe multipath situation: values of RDS and 90% SDW were typically lower than 20 ns and 50 ns, respectively. The dimensions of a city square, typically being larger than the city streets, result in a much larger dispersion. In this case, the 90% SDW may be 150 ns or more. A road tunnel represents a very homogeneous situation and has many similarities to the city street environment. A parking garage represents a bad multipath situation because of the large dimensions and the relatively smooth surfaces creating strong reflections.

Besides the model for the average received power, a model for the received signal in terms of fading depths and duration and wideband parameters (MD, RDS, etc.) is needed. A ray-tracing tool with the following main features was developed:[23]

- direct and reflected rays (up to the third order) are taken into account
- diffuse reflections and diffractions are neglected
- rays are interrupted by non-reflecting objects such as trees (measurements have shown that diffuse reflection from trees is negligible).

The scenario is described as a dielectric canyon having rough surfaces. Polarisation and radiation patterns of both transmit and receive antennas are taken into consideration. This tool, more complex than the previous ones, is intended to simulate the signal behaviour in outdoor environments, more specifically in urban streets, and to allow the estimation of both narrow- and wideband channel characteristics.

Impulse response results using this tool were checked against measurements.[22] Fig. 6 shows a comparison for a street that has trees both in the middle and on the sidewalks. In general, good agreement was observed, with the exception of the 90% SDW. This is understandable as this parameter is very sensitive to reflected rays with low amplitude, therefore yielding large differences between model and reality.

4 Summary

In order to exploit the 60 GHz frequency band for high-bit-rate systems, it is essential to characterise the channel dispersion in addition to path loss and received power. Various measurement campaigns and modelling activities have been carried out in order to obtain both the narrowband as well as the wideband characteristics of the 60 GHz channel for indoor and outdoor environments.

The results of narrowband indoor path-loss measurements obtained at 60 GHz as well as 1·7 GHz show that shadowing effects are considerably more severe at 60 GHz than at 1·7 GHz. Direction of arrival measurements show that in indoor environments a considerable link improvement can be achieved by applying antenna steering in the azimuth plane (8·4 dB with 90% probability). These measurements also show that dominant contributions to the received power occur from specular reflections.

Results of wideband measurements of normalised received power show that it is possible to achieve a uniform coverage in an indoor environment using biconical horn antennas. Values of RMS delay spread in indoor environments have been found in the range 15–100 ns. A statistical model of the details of impulse responses that occur in indoor environments has been developed. This model includes a relationship between model parameters and environment properties.

For outdoor environments the main conclusion is that city streets do not normally represent a severe multipath situation, values of DS and 90% SDW being typically lower than 20 ns and 50 ns, respectively. The dimensions of a city square, typically larger than those of city streets, result in a much larger dispersion. In this case, the 90% SDW may be 150 ns or more. A road tunnel represents a very homogenous situation and has many similarities to the city street environment. A parking garage represents a bad multipath situation because of the large dimensions and the relatively smooth surfaces, which create strong reflections.

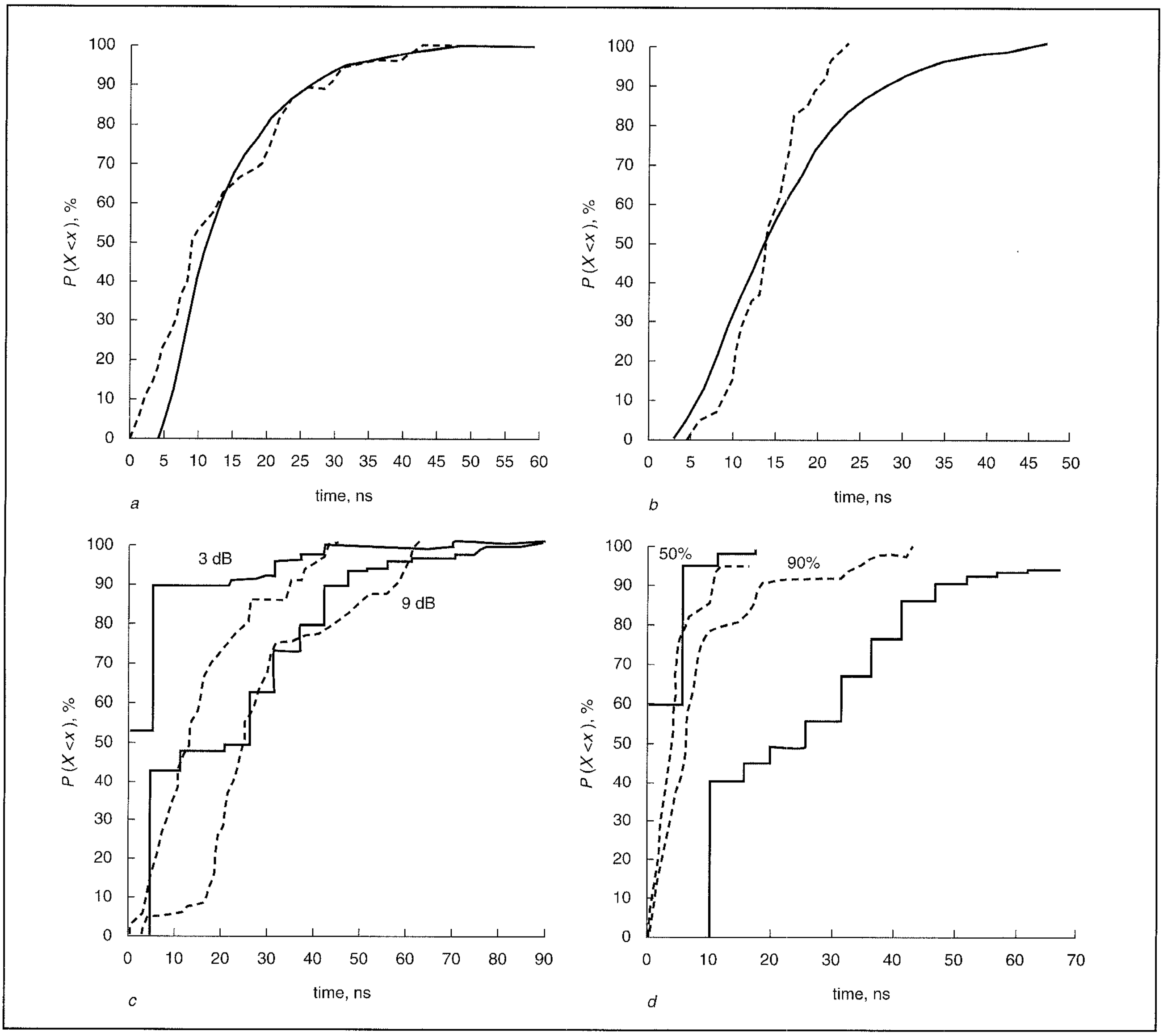

Fig. 6 Comparison between ray-tracing and measurement of statistical parameters: (*a*) mean delay; (*b*) delay spread; (*c*) delay interval; (*d*) sliding delay window (______ measurements; _ _ _ _ simulations)

Peter Smulders graduated from Eindhoven University of Technology in 1985. He joined the Propagation and Electromagnetic Compatibility Department of the Research Neher Laboratories of the Netherlands PTT, where he did research in the field of compromising emanations from civil data-processing equipment. In 1988 he moved to the Eindhoven University of Technology where he has been doing research in the field of mobile communication systems and broadband wireless LANs. This research work has addressed propagation as well as system and implementation aspects. He is currently involved in the ACTS project MEDIAN — wireless broadband CPN/WLAN for professional and residential multimedia applications. He is cofounder and present chairman of the James Clerk Maxwell Foundation.

Address: TU Eindhoven, Vakgroep Telecommunicatie en Electromagnetisme, PO Box 513, 5600 MB Eindhoven, The Netherlands

Luis Correia received the Licenciado, Master and Doctor degrees in Electrical and Computer Engineering from Instituto Superior Técnico (IST — Technical University of Lisbon) in 1981, 1985 and 1991, respectively. since 1982 he has taught telecommunications in the Electrical and Computer Engineering Department of IST, where he is now a professor. He is also a researcher at the Instituto das Telecomunicações. His research interests are in the areas of numerical methods applied to radiation and scattering problems, radiowave propagation modelling and cellular planning for mobile communications. He has participated in the COST 231, RACE MBS and ACTS SAMBA projects.

The main conclusion with respect to deterministic modelling is that simple ray-tracing can be used to estimate channel characteristics, for both narrow- and wideband transmission systems in indoor as well as outdoor environments.

References

1 PRASAD, R., and VAN LIESHOUT, B. C.: 'Cochannel interference probability for micro- and picocellular systems at 60 GHz', *Electron. Lett.*, 1993, **29**, (22), pp.1909–1910

2 LÄHTEENMÄKI, J.: 'Indoor propagation measurements at 60 GHz with high gain antennas'. COST 231 TD(92)100, Helsinki, Finland, 1992

3 LÄHTEENMÄKI, J.: 'Modelling of the indoor short range propagation channel'. 24th European Microwave Conf. Workshop '94, Cannes, France, September 1994

4 DROSTE, H., and KADEL, G.: 'Indoor measurements using a network analyser in combination with a precision positioning system at 17 and 60 GHz'. COST 231 TD(95), Florence, April 1992

5 DROSTE, H., and KADEL, G.: 'Measurement and analysis of wideband indoor propagation charactreristics at 17 GHz and 60 GHz'. Proc. ICAP95, Eindhoven, The Netherlands, pp.288–293

6 SMULDERS, P. F. M.: 'Broadband wireless LANs: a feasibility study'. PhD Thesis, Eindhoven University of Technology, The Netherlands, ISBN 90-386-0100-X, 1995

7 SMULDERS, P. F. M., and WAGEMANS, A. G.: 'Frequency domain measurement of the millimetre wave indoor radio channel', *IEEE Trans. Instrum. Meas.*, 1995, **44**, (6), pp.1017–1022

8 SMULDERS, P. F. M., and WAGEMANS, A. G.: 'Biconical horn antennas for uniform coverage in indoor areas at mm-wave frequencies', *IEEE Trans. Veh. Technol.*, November 1994, **VT-43**, (4), pp.897–901

9 SMULDERS, P. F. M., and WAGEMANS, A. G.: 'A statistical model for the mm-wave indoor radio channel'. 3rd Int Symp. on Personal, Indoor and Mobile Radio Communications, Boston, USA, October 1992, pp.303–307

10 GUÉRIN, S., PRADAL, CH., and KHALFA, P.: 'Propagation measurements and simulations using ray launching programme at 60·5 GHz'. COST 231 TD(95)060, Belfort, France, April 1995

11 FERNANDES, J. J. G., NEVES, J. C., and SMULDERS, P. F. M.: 'Mm-wave indoor radio channel modelling vs. measurements', *Wireless Personal Communications*, 1995, **1**, (3), pp.211–219

12 TAKIMOTO, Y., and IHARA, T.: 'Research activities on millimetre wave indoor communication systems in Japan'. IEEE MTT-S Int. Microwave Symp., Atlanta, USA, June 1993

13 GUNMAR, K: 'Broadband technique for car to car communication at 60 GHz'. COST 231 TD(91)041, Lund, Sweden, June 1991

14 GHEBRETENSAÉ, Z.: 'Simulation of beacon-vehicle communications for drive applications'. COST 231 TD (92) 053, Leeds, UK, April 1992

15 THAREK, A. R., and McGEEHAN, J. P.: 'Outdoor propagation measurements in the millimetre wave band at 60 GHz'. Military Microwaves '88, London, UK, July 1988

16 HAWKINS, N. D., STEELE, R., RICKARD, D. C., and SHEPHERD, C. R.: 'Path loss characteristics of 60 GHz transmissions', *Electron. Lett.*, 24th October 1985, **21**, (22), pp.1054–1055

17 CORREIA, L. M., and FRANCÊS, P. O.: 'A propagation model for the estimation of the average power in an outdoor environment in the millimetre waveband'. IEEE 44th Vehicular Technology Conference, Stockholm, Sweden, June 1994

18 ITU-R Rep. 719-2, Recommendations and Reports of the CCIR, Vol. V, ITU, Geneva, 1986

19 ITU-R Rep. 721-2, Recommendations and Reports of the CCIR, Vol. V, ITU, Geneva, 1986

20 LØVNES, G., PAULSEN, S. E., and RÆKKEN, R. H.: 'A versatile channel sounder for millimetre wave measurements'. 4th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications, Yokohama, Japan, 1993

21 LØVNES, G., REIS, J. J., and RÆKKEN, R. H.: 'Channel sounding measurements at 59 GHz in city streets'. 5th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications, The Hague, The Netherlands, September 1994

22 ANTONSEN, E., LØVNES, G., REISS, J. J., and RÆKKEN, R. H.: '59 GHz wideband propagation measurements'. Telenor R&D Report TF R 36/94, Kjeller, Norway, 1994

23 REIS, J. J., and CORREIA, L. M.: 'A propagation model for outdoor mobile communications at the millimetre waveband in urban scenarios'. COST 231 TD (95) 002, Bern, Switzerland, January 1995

Received 24th June 1996