Williamson, M. R., Athanasiadou, G. E., & Nix, A. R. (1997). Investigating the effects of antenna directivity on wireless indoor communication at 60 GHz. 635 - 639. 10.1109/PIMRC.1997.631109

Investigating the Effects of Antenna Directivity on Wireless Indoor Communication at 60GHz

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ABSTRACT

This paper investigates the nature of the indoor radio channel at 60GHz, with regard to its use for future high bit-rate broadband wireless networks. It is proposed that, for operation in the millimetre-wave indoor channel, directional antennas can be used to mitigate multi-path effects, thus reducing the need for complex equalisation or multi-carrier techniques. An image based, ray-tracing prediction model is used to study the channel characteristics and to analyse the variation in received power, RMS delay spread and k-factor within a typical operating environment. The performances of different antenna combinations are investigated and narrowbeam, suitably aligned antennas are shown to reduce received delay spread for both LOS and non-LOS locations. The effects of non-optimal antenna alignment are observed, and system outage is determined for certain system design criteria. The results suggest that it will feasible to combat multi-path effects using switched-beam directional antennas.

INTRODUCTION

The demand for wireless network facilities is expected to grow considerably in forthcoming years, with users desiring fast and easy access to information and the communication infrastructure. There is thus a requirement for flexible indoor systems providing convenient networking facilities to portable and hand-held terminals. In wired applications, developments in fibre optics and asynchronous transfer mode (ATM) operation are enabling broadband voice, video and data transmission between terminals at very high data rates. Consequently there is much interest in the design of indoor wireless LANs to support ATM operation at up to 155Mbps [1].

The conventional frequency bands used for mobile communications are not suitable for broadband applications due to the lack of available bandwidth. In this respect the millimetre-wave frequency bands above 20GHz are considered most suitable [2][3]. The US Federal Communications Commission (FCC) has recently allocated spectrum in the 59-64 GHz millimetre-wave band, intended for general purpose unlicensed operations, and there is significant interest in this band as a result. At these frequencies signals suffer attenuation due to atmospheric oxygen (~15dB/km) [4]. They are also heavily attenuated by transmission through walls and other objects, and this means that frequency re-use between neighbouring rooms is viable.

For high-speed indoor applications, delay distortion due to multi-path propagation causes severe impairment of system performance. For the purposes of current wireless LAN systems, adaptive equalisation and multi-carrier techniques are regarded as the most suitable means of combating multi-path effects [5]. However, in the millimetre-wave region, directive antennas of relatively compact size can be realised, allowing gains in excess of 20dB to be implemented, potentially for hand-held portable terminals. It may therefore be feasible to employ electronic switched-beam antennas to track the LOS or significant signal components, and eliminate many unwanted multi-path components.

MODELLING THE INDOOR CHANNEL

It is essential to characterise the nature of the indoor propagation channel before designing a suitable system architecture. In recent years ray-tracing has been shown to be a viable technique for producing deterministic channel models [6]. For this paper a three-dimensional, image based ray-tracing algorithm is used to model propagation in a single-floor indoor environment. The model considers each ray separately, with reflections and transmissions computed using vector mathematics, and each object characterised by its permittivity, conductivity and thickness. At 60GHz specular reflections from surfaces are the principle mode of electromagnetic propagation. Neither diffraction nor diffuse reflection (scattering) contribute significantly to the received power, and are thus not taken into account in the model.

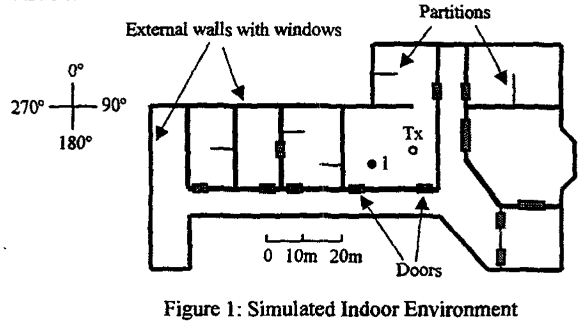

Figure 1: Simulated Indoor Environment

Figure 1 shows the simulated environment used for this study. It consists of various rooms and corridors (with 30cm-thick concrete walls), containing windows, doors and partitions. The ceiling height is 4.5m and the transmitter height is 3m. The transmitter output power is 32mW (15dBm) and the channel impulse response is analysed over a 2m resolution grid of receiver locations at a height of 1m.

60GHZ PROPAGATION

In the 60GHz band, signals are heavily attenuated by standard building materials such as brick and concrete. This means that operation is likely to be restricted to locations where there is either a LOS path between transmitting and receiving terminals, or a reflecting path which does not undergo wall transmission [7]. This limits the area of coverage mainly to single rooms, but reduces problems due to co-channel interference and thus allows higher capacity due to increased spectrum re-use. Figure 2 shows the variation in average received power in the study environment for transmission at 5.1GHz, the frequency used for current wireless LAN standards such as HIPERLAN. Figure 3 shows the corresponding variation in received power at 60GHz.

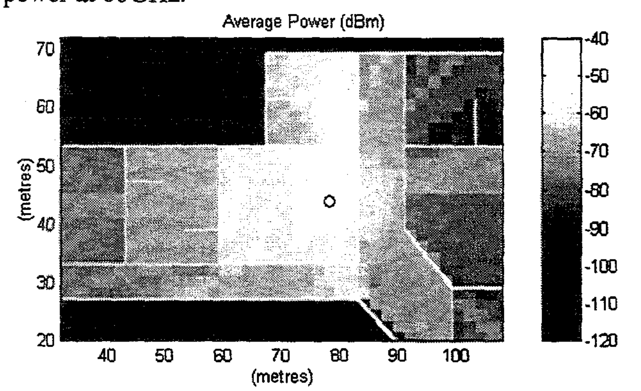

Figure 2: Variation in Received Power at 5.1GHz (32mW transmit power)

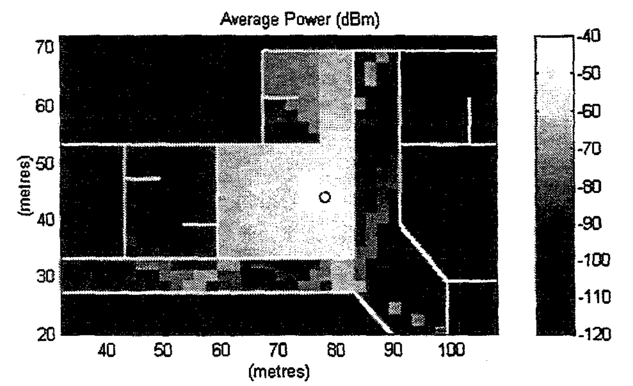

Figure 3: Variation in Received Power at 60GHz (32mW transmit power)

Comparing Figures 2 and 3 we see a significant difference in the coverage provided at the two frequencies. For 5GHz systems, operation can be supported when transmitter and receiver are located in adjacent rooms, and a number of wall boundaries are required before frequency re-use is viable. At 60GHz, the coverage cell is well defined by the perimeter of the room. However, some significant power levels are observed in the adjacent corridors, due to signals escaping through the doors in the corners of the room.

EFFECTS OF ANTENNA DIRECTIVITY

In order to investigate the nature of the 60GHz indoor radio channel and to demonstrate the effects of antenna directivity, the variations in received power, RMS delay spread and k-factor have been studied throughout the simulated environment. Analysis of RMS delay spread is of benefit since channels with suitably low delay spreads do not suffer problems due to inter-symbol interference (ISI) at high bit-rates. The k-factor of the channel impulse response is taken as the ratio of the power in the LOS or dominant signal component to the sum of that in the random multi-path components. The k-factor has a direct impact on the quality of the eye-diagram at the receiver, and consequently high-bit rate operation can only be supported when suitably high k-factors are achieved.

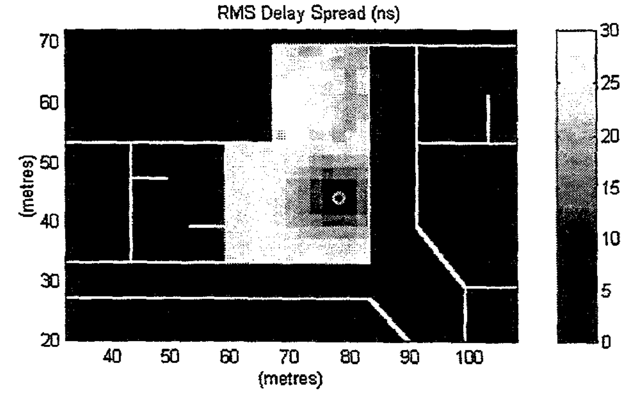

Figure 4: Variation in RMS Delay Spread (omni:omni)

Figure 4 shows the spatial variation in received delay spread in the room where the transmitter is located, using omni-directional antennas for both transmitter and receiver. The half-wave dipole radiation pattern is assumed for both antennas. The average delay spread in the room is 22.7ns. Figure 5 shows the variation in delay spread using directional antennas for both transmitter and receiver. Both antennas have ideal Gaussian main-beams with a 3-dB beamwidth of 60°, a constant sidelobe level of -30dB, and a gain of 12dBi in the maximum direction. For each grid location the peak of the radiation pattern of each antenna is pointed directly towards the angle of arrival or angle of departure of the most significant ray. Comparing Figures 4 and 5 we see that the use of directional antennas greatly reduces the received RMS delay spread for both LOS and non-LOS locations, giving an average delay spread value of 8.2ns.

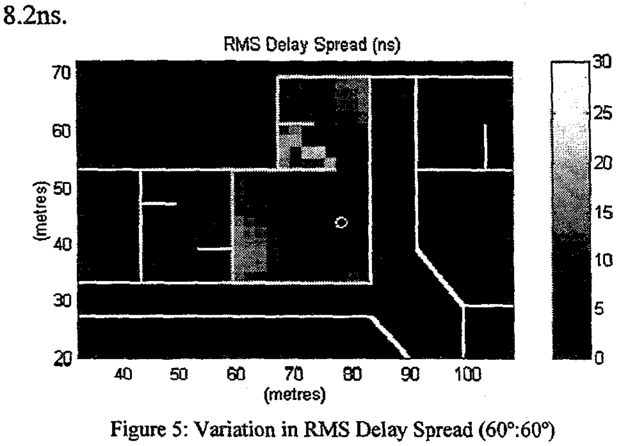

Figure 5: Variation in RMS Delay Spread (60°:60°)

For the omni-directional antennas, an average k-factor of 4.5dB is observed and using the directional antennas this value is increased to 15.4dB. For all locations the received RMS delay spread and k-factor are improved by the use of directional antennas. However, for many non-LOS locations the benefit is less significant, since no individual ray is particularly dominant.

Figure 6 shows the impulse response experienced at a typical LOS receiver location, position 1 (Figure 1), using omni-directional transmitter and receiver. In order to illustrate the degree of multi-path suppression provided by using 60° directional antennas, Figure 7 compares the spatial impulse responses received for the two antenna configurations.

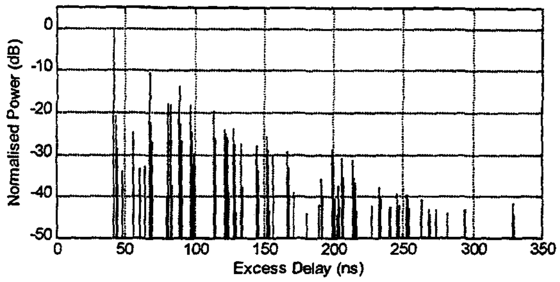

Figure 6: Temporal Impulse Response
(Position 1, omni:omni)

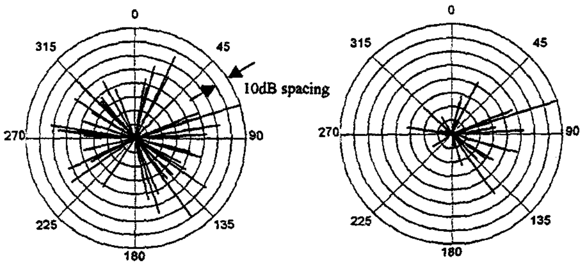

Figure 7: Comparing Spatial Impulse Responses
(Position 1, omni:omni and 60°:60°)

For the omni:omni configuration, although the LOS path is clearly dominant, first-order reflected rays of relatively high amplitude (10-20dB below LOS) arrive from various directions in the azimuth plane, giving an RMS delay spread of 24.8ns and k-factor of 5.6dB. Using 60° directional antennas provides suppression of most major rays outside of the gain beamwidth, giving an RMS delay spread of 12.1ns and k-factor of 18.3dB.

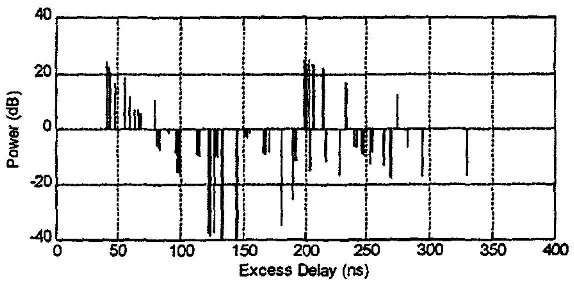

Figure 8: Impulse Response Difference Plot
(Position 1, 60°:60° - omni:omni)

Figure 8 shows the difference between impulse responses for the two antenna combinations. Using directional antennas the power in the LOS path is increased due to the additional gain whilst the majority of random components are suppressed. The other components that show an increase in power correspond to signal paths that undergo various orders of reflection and arrive at the receiver within the 60° gain beamwidth. The delayed components which exhibit a power increase for the 60°:60° configuration can be seen to have gained around 24dB; this corresponds to twice the maximum gain of the 60° antenna.

COMPARING ANTENNA COMBINATIONS

For the design of future 60GHz wireless systems, it is necessary to compare the performance of a number of antenna combinations. This will enable decisions to be made as to whether directional antennas should be used for the central, ceiling-mounted terminal, for the portable terminals, or for both. In addition suitable antenna beamwidths must be chosen. This is dependent on the cost, complexity and availability of suitable antenna technology and will also determine the number of sectors required if a switched-beam configuration is to be employed. In theory, at 60GHz very small beamwidths are possible due to the wavelengths involved, and these are realised in practice using either dielectric lens antennas or arrays of patches.

For the purposes of this investigation the performances of omni:omni, 60°:omni, 30°:omni, 60°:60°, and 30°:30° antenna configurations are compared. Figure 9 shows the cumulative distribution of RMS delay spread for LOS and non-LOS locations in the room where the transmitter is located. Figure 10 shows the corresponding distribution of k-factor values. In each case the directional antennas are optimally aligned.

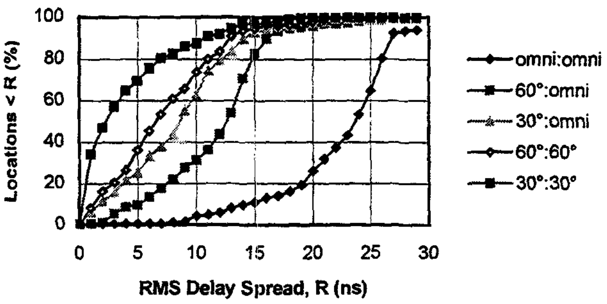

Figure 9: CDF of RMS Delay Spread

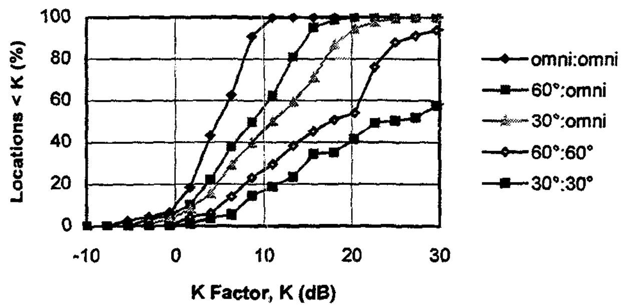

Figure 10: CDF of K-Factor

It can be seen that the 30°:30° configuration gives rise to the lowest delay spreads and highest k-factors. For 90% of the locations studied the received impulse response has a delay spread of less than 10ns, or k-factor of more than 7dB. This is a considerable improvement over the omni:omni configuration, for which 50% of the locations have a delay spread greater than 23ns, or k-factor of less than 5dB.

Figure 11 shows the variation in received delay spread at position 1 for both 30° and 60° directional antennas as they are rotated through 360°. An omni-directional transmitter is assumed. Figure 12 shows the angular variation in k-factor for the same location. The angle from position 1 to the transmitter is 72°, and both antennas exhibit minimum delay spread (and maximum k-factor) for this orientation, with the 30° degree antenna achieving the lowest value (9ns) due to increased multi-path suppression. However, moving either side of this direct pointing angle gives rise to large values of delay spread up to a maximum of 58ns.

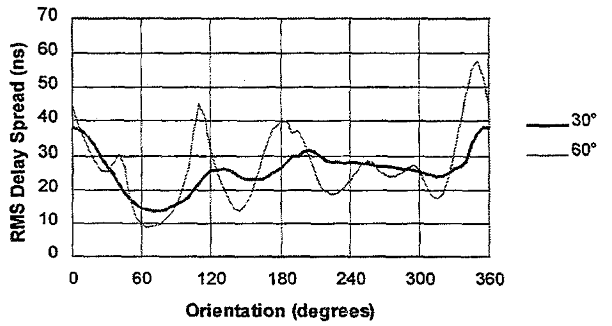

Figure 11: Angular Variation in RMS Delay Spread (Pos. 1)

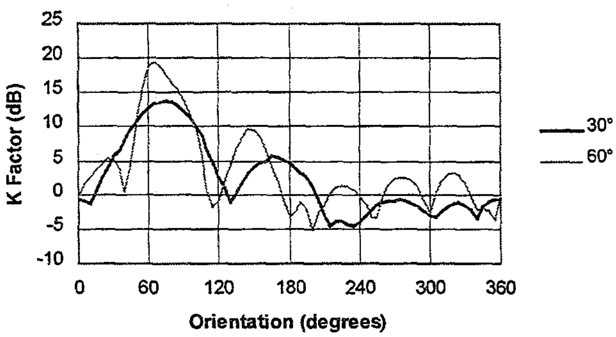

Figure 12: Angular Variation in K-Factor (Pos. 1)

For all LOS receiver locations it has been found that as well as the direct orientation there are other potentially suitable orientations for data transmission between terminals, providing sufficient signal power is available. In this example, low delay spread and high k-factor are also found at an orientation of 144°, when the receiver is pointing in the direction of arrival of the ray which is reflected off the nearest wall. For non-LOS locations the optimum antenna orientations were found to be at angles corresponding to a dominant first or second-order reflecting path rather than the direct (transmission) path between transmitter and receiver. In general it has been found that the use of directional antennas can give rise to 20-30ns reduction in delay spread and an increase of up to 20dB in k-factor for the majority of LOS locations and many obstructed ones. However, incorrectly aligned antennas can give rise to very high delay spreads (>50ns) and low K-factors (<-5dB).

NON-OPTIMAL ANTENNA ALIGNMENT

It is of interest to further investigate the performance statistics for configurations where directional antennas are not optimally aligned. Figure 13 shows the cumulative distribution of RMS delay spread when the transmitter is offset by different angles relative to the optimum alignment. A 30° directional antenna is used for the transmitter with an omni-directional antenna at the receiver. For small angle offsets (<10°) there is no noticeable effect on the delay spread and the same was found to be true for k-factor. This means that some degree of inaccuracy in antenna alignment can be tolerated before operation is affected. However, once the receiver is offset by more than 15°, performance is significantly degraded. In general it was found that offsets of less than 20-30% of the antenna 3dB beamwidth can be tolerated with no significant effect on performance, and typically for an offset angle equal to the antenna beamwidth the RMS delay spread is doubled.

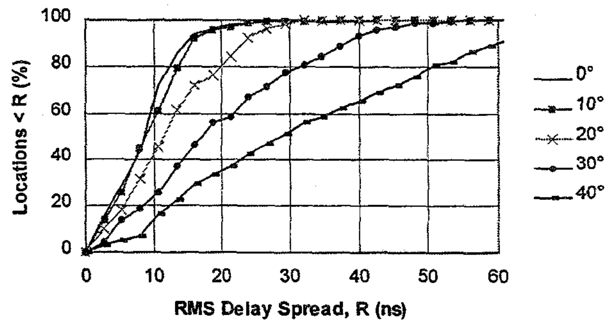

Figure 13: CDF of RMS Delay Spread for Different Angle Offsets

OUTAGE CALCULATIONS

Figure 14 shows the area of operational coverage using omni-directional transmitting and receiving antennas, with the black areas indicating outage. It is assumed that the criteria in Table 1 must be met in order for successful system operation. Here, most outage arises due to high delay spread, and operation is only supported within a radius of about 5m around the transmitter.

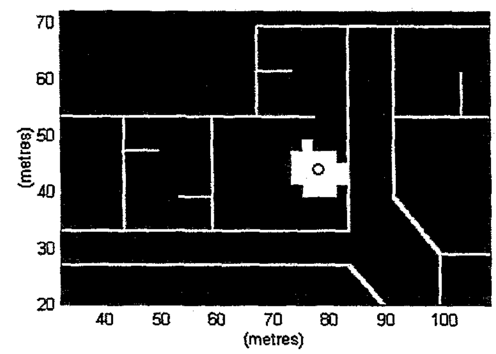

Figure 14: Spatial Outage (omni:omni)

Average Power	> -70 dBm
RMS Delay Spread	< 15 ns
K Factor	> 5 dB

Table 1: Outage Criteria

Figure 15 shows the area of operational coverage for the same criteria, this time using optimally aligned 30° beamwidth directional antennas at both transmitter and receiver.

Here operation is supported in 98.5% of locations within the room where the transmitter is located, as well as some locations in the nearby corridor, due to signals escaping through the doors. Where there is outage in the room it is due to a lack of received power in non-LOS locations, where the dominant ray undergoes two or more orders of reflection. In this particular study environment these problems could be overcome by re-locating the transmitter nearer the edge of the blocking wall.

Figure 15: Spatial Outage (30°:30°)

MULTIPLE-SECTOR ANTENNAS

It is thought likely that future wireless LAN systems will incorporate most of the antenna complexity at the central, ceiling-mounted or wall-mounted terminal, whilst simple omni-directional or wide-beam directional antennas are used at the portable terminal. This will minimise the cost and complexity of the portable equipment and should ensure that the user does not have to consciously re-align the terminal towards the transmitter. To obtain the benefits provided by directivity, multiple antenna sectors can be implemented at the central terminal; alternatively adaptive antenna arrays might be used, but this is likely to be less cost-effective. The probability of a favourable transmission channel can also be increased by using spaced antenna diversity. This can be implemented at the portable terminal, since the spacing required to ensure uncorrelated paths is small at 60GHz.

Figure 16: Spatial Outage (12 sectors of 30°:120°)

Figure 16 shows the spatial outage for the criteria in Table 1, using 12 antenna sectors of 30° beamwidth at the transmitter and a 120° directional antenna (6dBi gain) at the receiver. For each receiver location the best transmit sector is chosen based on minimising the delay spread, providing that a minimum power level of -70dBm is maintained. The coverage is not as good as that obtained using 30° directional antennas at both terminals (Figure 15), but operation is supported in all LOS locations and the majority of non-LOS locations. Again there are non-LOS locations where there is a lack of received power, however most limitations are due to high delay spreads, since the 120° receive antenna gives less effective multi-path suppression.

CONCLUSIONS

In this paper the characteristics of indoor propagation at 60GHz have been investigated using an image-based ray-tracing prediction model. For LOS and non-LOS locations directional antennas have been shown to provide significant suppression of multi-path components giving a reduction in received RMS delay spread, and a corresponding increase in k-factor. In practice this will allow far higher data rates to be supported before problems due to ISI arise. Future 60GHz wireless networks will undoubtedly employ directional antenna technology as a means of combating multi-path effects, since the required antenna size is relatively small due to the wavelengths concerned. It must be decided, however, as to whether this alone can provide sufficient suppression of unwanted components. The results shown in this paper indicate that using directional antennas of, for example, 30° beamwidth for both transmitter and receiver can potentially support high bit-rate transmission in an indoor environment. However, it may be cheaper and less complex to use a switched-beam directional antenna for the central, fixed terminal, and to use wide-beam directional or omni-directional antennas at the portable terminals. Such configurations may need to be used in conjunction with adaptive equalisation.

ACKNOWLEDGEMENTS

The authors would like to thank Hewlett Packard for their funding and support of this project, and Professor J.P.McGeehan for the provision of facilities.

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