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THE IMPACT OF POWER LIMITATIONS AND ADJACENT RESIDENCE INTERFERENCE ON THE PERFORMANCE OF WLANS FOR HOME NETWORKING APPLICATIONS

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ABSTRACT

This paper considers the application of 5GHz Wireless LAN technology to home networking applications. An assessment of physical layer performance is presented for both the IEEE 802.11a and HIPERLAN/2 standards in the form of achievable data rate as a function of received signal to noise ratio. The transmit power limitations imposed by the relevant regulatory bodies are presented and the implications of transmit power amplifier limitations considered. Based on this information, a state of the art propagation modelling tool is used to evaluate the performance of the 802.11a and HIPERLAN/2 systems in an example residential environment. The achievable data rate and coverage is evaluated for a variety of scenarios and the implications of potential co-residence interference are evaluated. It is found that data rates greater than 20Mbits/s can be achieved with 100% coverage if the Access Point is well located and the transmit power is high. Even in the case where transmit power is severely limited, data rates in excess of 10Mbits/s can be achieved throughout much of the example environment. Adjacent residence interference is found to have a severe debilitating effect and is thus identified as topic of crucial importance.

I. INTRODUCTION

Together, the IEEE 802.11a (North America), ETSI HIPERLAN/2 (Europe) and ARIB HISWAN (Japan) standards provide a worldwide definition for broadband Wireless Local Area Network (WLAN) technology operating in the 5GHz band [1,2,3]. Since these three standards all specify near-common physical layers [4] and have similar frequency band allocations, a very real possibility exists for a single broadband WLAN product to be produced that is capable of operation anywhere in the world. The ongoing attempts by the relevant standards organisations to unify their standards further strengthens this possibility.

All three standards are capable of achieving data rates up to 54Mbits/s and are thus suitable for broadband multimedia applications. One application of this new technology is to facilitate the Wireless Home Network (WHN), allowing in-home distribution of high definition audio and video without the need for wired links. The WHN application represents a huge potential market for new consumer electronics products.

In this paper, a state of the art propagation modelling tool is used to determine the performance achieved by WLAN technology in an example residential environment. To facilitate this analysis, a number of transmit power scenarios are discussed in section II. These scenarios are based on both the transmit power limitations imposed by the relevant regulatory bodies and on consideration of the available transmit power amplifier technology. Also, system throughput results for both the IEEE 802.11a and HIPERLAN/2 standards are presented in section III. The example residential environment and the WHN operating scenarios are presented in section IV. The propagation modelling tool is introduced in section V. In section VI, this tool is applied to the example residential environment to evaluate the path loss between the WLAN access point (AP) and mobile terminal (MT) for a variety of scenarios. By combining the path loss calculations, transmit power limit information and system throughput results, the performance of the WLANs can be evaluated in terms of the achievable data rate as a function of AP/MT locations. Results are analysed in section VII and conclusions are drawn.

II. TRANSMIT POWER SCENARIOS

Two factors need to be considered in the development of transmit power scenarios for 5GHz WLANs: limitations imposed by the relevant regulatory bodies and limitations imposed by transmit power amplifier technology.

The transmit power limitations imposed by the regulatory bodies for 5GHz WLANs in America, Europe and Japan are summarised in table 1.

Region	Band Allocation	Limit (EIRP)
North America	5.15-5.25 GHz	23dBm
	5.25-5.35 GHz	30dBm
Europe	5.15-5.35 GHz	23dBm
	5.47-5.73 GHz	30dBm
Japan	5.15-5.25 GHz	23dBm

Table 1. Regional Regulatory Limits on Transmit Power

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Due to the non-linear signal envelope resulting from the COFDM modulation scheme employed [5], both the IEEE 802.11a and HIPERLAN/2 WLAN standards place significant demands upon transmit power amplifier technology. It is typically necessary to employ non-linear amplifiers and back-off significantly from the amplifier's maximum output power. As a result power efficiency is reduced considerably.

Based on regulatory and technological limitations, three scenarios are defined here to represent different WHN products:

1. 1W EIRP. Achievable by mains powered devices operating only within the higher power bands available in Europe and America. Due to the low efficiency of the power amplifier, 1W output power will probably only be achieved by mains powered devices.

2. 200mW EIRP. Achievable by PC Card devices in any band and by mains powered devices in the lower power bands (available worldwide). 200mW is likely to be the upper limit on transmit power that can be achieved by Laptop PCs.

3. 1mW EIRP. Achievable by handheld devices in all bands. 1mW output power facilitates the use of low cost PA technology with low input power requirements. Small, hand held, battery powered devices are represented by this scenario.

III. SYSTEM THROUGHPUT

An analysis of the throughput performance of both the IEEE 802.11a and HIPERLAN/2 standards has been undertaken previously and presented in [4,6]. This analysis takes account of overheads in both the PHY and MAC layers of these two standards to determine maximum achievable throughput for a given SNR. Figure 1 presents the achievable data rate versus SNR for the eight transmission modes in the 802.11a link adaptation scheme (a 1500 byte packet size is assumed). Figure 2 presents similar information for the seven transmission modes of the HIPERLAN/2 link adaptation scheme (packet size is fixed at 54bytes, 5 Mobile Terminals assumed).

For the purposes of this paper a link adaptation strategy based only on received SNR is assumed. Furthermore, the link adaptation is assumed ideal within this constraint, i.e. that the mode offering the highest data throughput is always used for a given received SNR. Thus, the link adaptation algorithm does not take into account issues such as packet error rate and delay. Delays in the successful reception of data will have significant impact on time bounded applications such as video transmission. For a discussion of link adaptation strategies and their impact on video applications the reader is referred to [7,8].
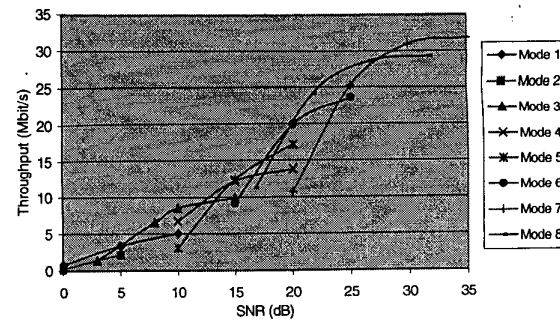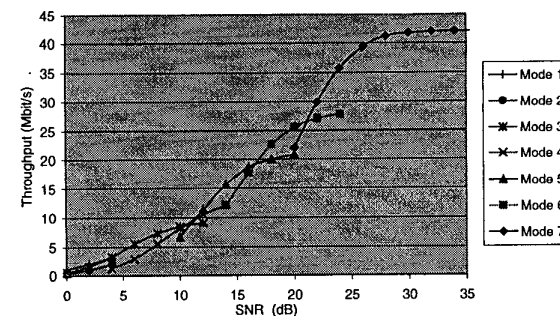

Figure 1. IEEE 802.11a Link Throughput

Figure 2. HIPERLAN/2 Link Throughput

It can be seen that HIPERLAN/2 is capable of achieving a superior throughput to IEEE 802.11a for a given SNR. This is primarily due to differences in the MAC protocol and a smaller packet size. For a more detailed discussion of the relative performance of these two standards, the reader is referred to [6].

IV. THE EXAMPLE RESIDENTIAL ENVIRONMENT AND WIRELESS HOME NETWORKING SCENARIOS

The example residential environment considered in this paper consists of two similar, adjacent residences. Each is a four bedroom house and consists of two storeys, each with 3m high ceilings. Construction is primarily of brick with concrete floors. The walls are 15cm thick and the floors 25cm thick. Overall dimensions are 16x11x6m. Plan and side views of this environment are shown in Figure 3a and Figure 3b respectively. The central vertical wall in the plan view is the dividing wall between the two residences.

Three distinct scenarios for the WHN analysis are defined by the location of the access point.

1. Set Top Box (STB). The AP for the WHN is integrated into an STB (a digital television receiver, for example). The AP is thus placed in the corner of one of the main rooms of the ground floor at a height of 20cm. This scenario represents a case where an existing consumer electronics device is upgraded to provide WHN capabilities.

2. Loft Mounted Box (LMB). The AP is mounted in the loft to provide easy access to exterior (roof mounted) antennas and wireless distribution within the home. The AP antenna is fed through the first floor ceiling and suspended 10cm below it. This scenario represents a case where a new consumer electronic product is introduced to the residential market.

3. Interfering STB (ISTB). A similar scenario to 1, but the STB is placed in the adjacent residence. This scenario will be used to assess the effect of adjacent residence interference.
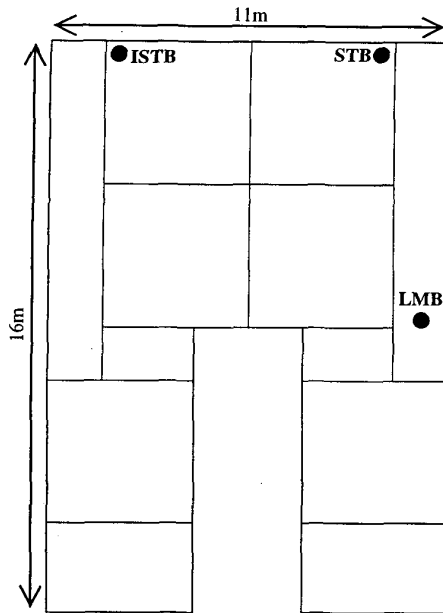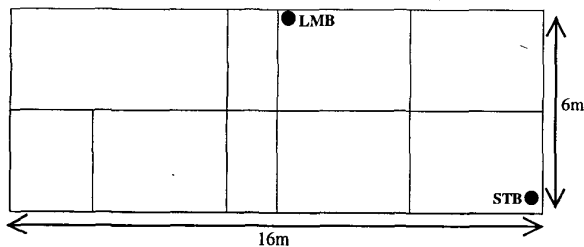

Figure 3a. Residential Environment – Plan View

Figure 3b. Residential Environment – Side View

V. THE PROPAGATION MODELLING TOOL

The propagation modelling tool is based on a sophisticated ray launching technique. The tool simulates the launch of multiple 'test rays' at discrete angles from the transmitter. The interaction of these test rays with the subject environment is simulated until the ray's power falls below a given threshold – at which time the ray is terminated. For

a more detailed description of the model, the reader is referred to [9].

A point to point analysis such as that illustrated in Figure 4 can be employed to generate comprehensive information on the radio channel perceived by a transmitter and receiver at distinct points in the environment. Signal power, delay spread, K-factor and angle of arrival/departure may all be determined. Furthermore, a point to multipoint analysis may be employed to evaluate the same information at multiple locations within the subject environment.

For the purposes of this paper, the propagation modelling tool has been employed to provide a point to multipoint (i.e. single AP location to multiple MT location) analysis of the path loss within the example residential environment. Both ground and first floor are analysed for each scenario presented in section IV, with the path loss calculated at 0.2m intervals at a height of 1m above the floor.

Once the path loss has been calculated for a given AP scenario, a received signal power can be calculated for each transmit power scenario.

Subsequently, the system throughput results presented in section III can be used to translate received signal power into achievable data rate for both 802.11a and HIPERLAN/2 WLANs.
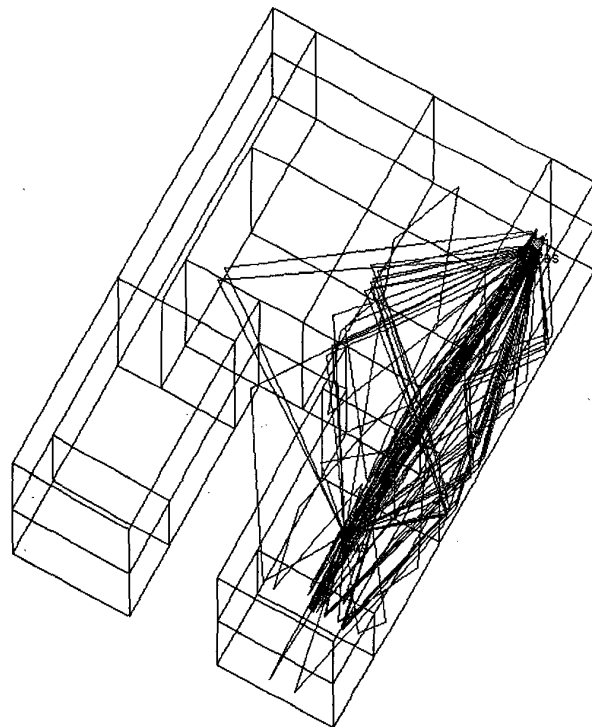

Figure 4. A Point-to-Point Ray Launching Analysis

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VI. RESULTS

Path loss results were generated for both floors for all AP scenarios. Dipole Antennas were assumed in all cases. The effects of doors and windows (decreased path loss) and furniture and other 'clutter' (increased path loss) in the environment were not modelled. Examples of these path loss results are shown in Figures 5a, 5b and 5c. Figure 5a presents path loss results for the ground floor and the STB scenario. Figure 5b presents results for the first floor and the LMB scenario. Figure 5c presents results for the first floor and the STB scenario.
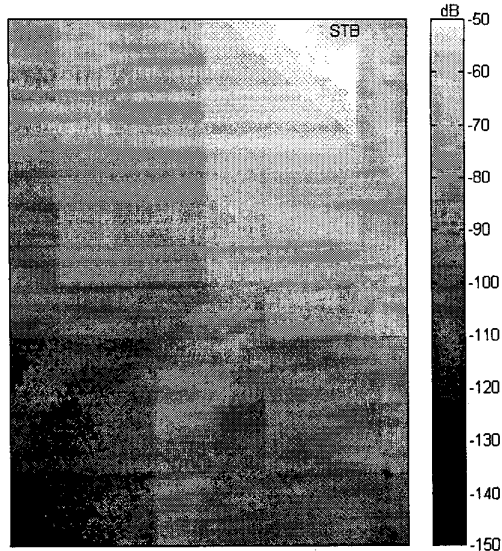

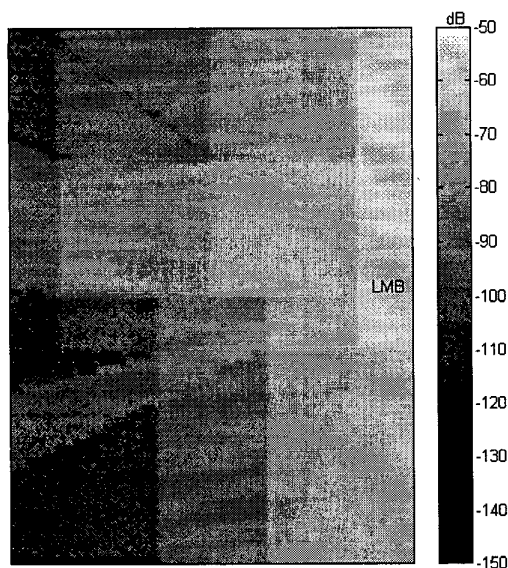*Figure 5a. Ground Floor Path Loss for STB Scenario*

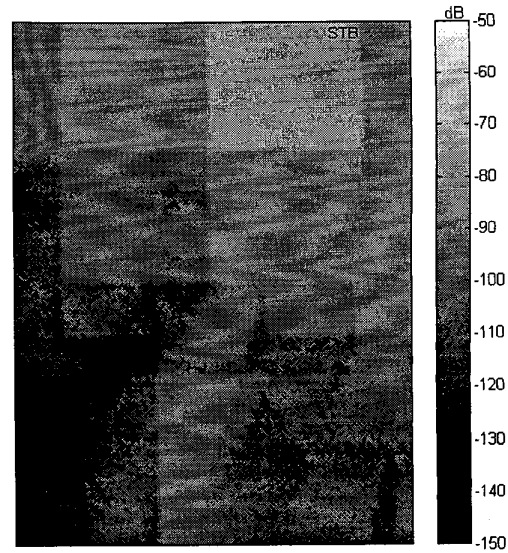*Figure 5b. First Floor Path Loss for LMB Scenario*

Figure 5c. First Floor Path Loss for STB Scenario

It can be seen that for the STB scenario, path loss varies considerably (50-110dB loss) within the ground floor of the subject residence. A further loss of up to 20dB occurs, but only within the adjacent residence.

For the LMB scenario, path loss on the first floor is typically lower and less variant: 56-71dB within the subject residence, rising to a maximum of 115dB in the adjacent residence. This can be attributed to the more central placement of the LMB within the environment when compared with the STB.

Not surprisingly, path loss increases considerably when the transmitter and receiver are on different floors. 80-115dB of path loss can be seen within the subject residence for the first floor-STB combination, with losses in excess of 140dB perceived in the adjacent residence.

VI.1 Comparing IEEE 802.11a and HIPERLAN/2

In order to compare the performance of the 802.11a and HIPERLAN/2 WLANs, the system throughput of each has been calculated for the ground floor and the case of 23dB transmit power for both STB and LMB scenarios. The results are shown in Figures 6a, 6b, 7a and 7b.

It is clear from these results that HIPERLAN/2 is capable of achieving a higher data rate than IEEE 802.11a in those areas where the path loss is low. From Figures 6a and 6b it can be seen that a HIPERLAN/2 STB achieves a data rate of over 40Mbits/s per second for much of the ground floor. 802.11a achieves a data rate of approximately 30Mbits/s in similar areas. This difference in the upper limit of the data rate achieved is due to the superior throughput capabilities of HIPERLAN/2 as discussed in section III. It should be noted however, that both systems are capable of achieving data rates in excess of 30Mbits/s over more than two thirds of the ground floor. This data rate is sufficient to support

very demanding applications such as transmission of DV, DVD and multiple MPEG-2 streams.
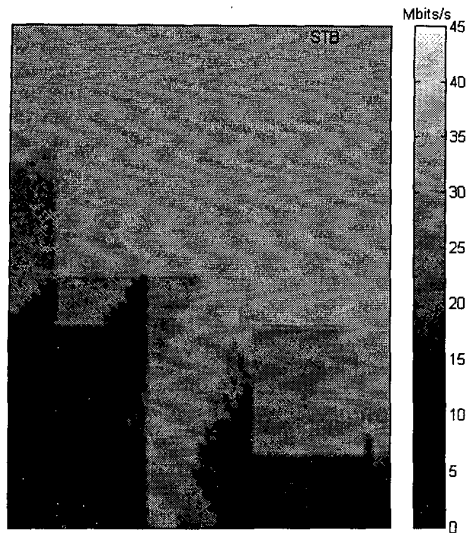

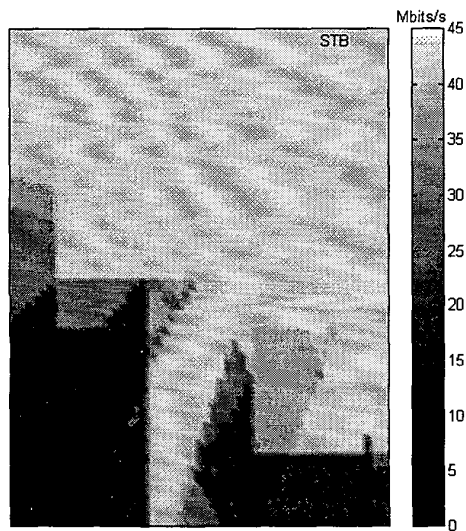*Figure 6a. Ground Floor Data Rate Supported by 802.11a STB at 23dBm*

Figure 6b. Ground Floor Data Rate Supported by HIPERLAN/2 STB at 23dBm

Figures 6a and 6b give insight into the relative performance of the two WLAN technologies. For ease of comparison, Figure 8 presents the coverage achieved versus data rate for each of the scenarios considered in this section. As stated, when the path loss is low, HIPERLAN/2 is clearly superior. Although both systems achieve their maximum data rate in approximately 70% of locations, HIPERLAN/2 offers 10Mbits/s more data rate in these locations. However, in those parts of the residential environment where the path loss is higher, the relative performance of the two systems is quite similar. There is only 1% coverage difference between the two systems for

a data rate of 10Mbits/s (sufficient to support MPEG-2 and DVD video). A data rate greater than 9Mbits/s is achieved by both systems with 99% coverage. For the WHN to be a success, the ability to support data rates in the region of 10Mbits/s in the more demanding areas is perhaps more important than the ability to achieve very high data rates in the less demanding areas. Hence, the difference in performance between HIPERLAN/2 and 802.11a is not as great as might have been anticipated from the results in section III.
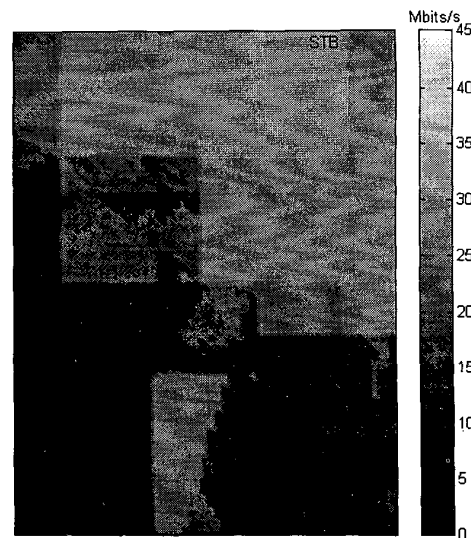

Figure 7a. First Floor Data Rate Supported by 802.11a STB at 23dBm
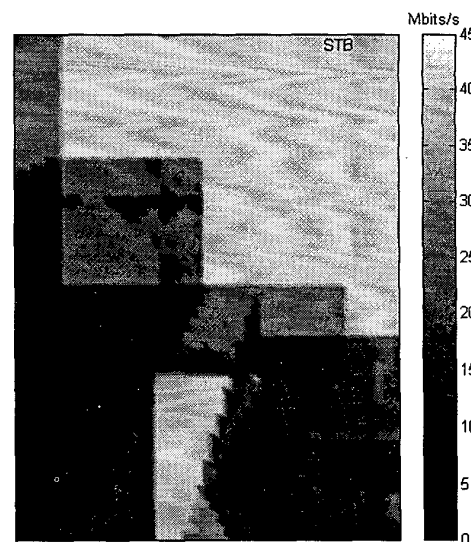

Figure 7b. First Floor Data Rate Supported by HIPERLAN/2 STB 23dBm

The results presented in Figures 7a and 7b consider the data rates achieved across two storeys. This is expected to be more challenging for the WHN since the path loss

across multiple storeys tends to be higher. From Figure 8, it can again be seen that both HIPERLAN/2 and 802.11a STBs achieve their maximum data rate in approximately 55% of first floor locations, in comparison to 70% of ground floor locations. For data rates in the range of 10-15Mbits/s, HIPERLAN/2 exhibits around 8% superior coverage. However, for data rates less than 8Mbits/s the difference is again minimal.
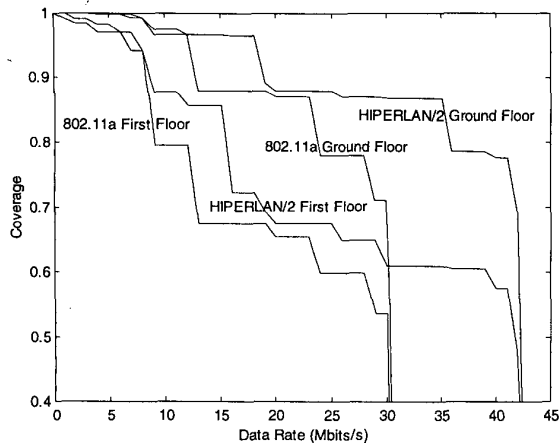

Figure 8. Coverage Comparison of 802.11a and HIPERLAN/2 STBs at 23dBm

VI.2 Comparing the STB and LMB

Figures 6a and 7a present the data rate achieved by an 802.11a STB with 23dBm transmit power for the ground and first floor respectively.

For comparison purposes, Figures 9a and 9b present equivalent results for the LMB AP scenario. Figure 10 presents coverage statistics for these four scenarios. The STB achieved superior coverage on the ground floor than on the first floor. Unsurprisingly, the LMB achieves superior coverage on the first floor than on the ground floor. Furthermore, it can be seen that the LMB achieves maximum data rate throughout the first floor. This is superior to the ground floor coverage achieved by the STB, which achieves its maximum data rate in only 70% of ground floor locations. Similarly, the LMB achieves 100% ground floor coverage for data rates up to 13Mbits/s. The STB does not achieve 100% first floor coverage for data rates greater than 1Mbit/s. The superior performance of the LMB can be attributed to its more central position within the environment.

Although the positions of STB and LMB considered here are fairly arbitrary and the analysis overly simplistic, it is likely the LMB will offer superior performance, since its location will not be constrained by the need for proximity to the television set or its wired signal input. However, there will be more effort involved in the installation of the LMB and its ceiling mounted antenna and it will be very difficult to move once installed. In comparison, the STB could be deployed 'straight out of the box.'
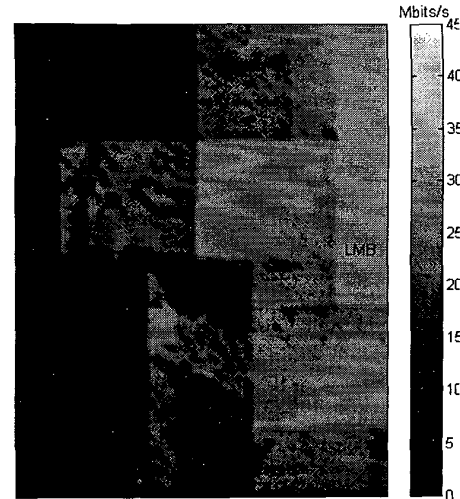

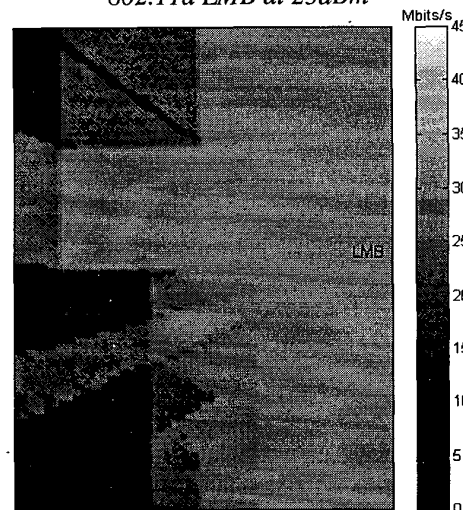*Figure 9a. Ground Floor Data Rate Supported by an 802.11a LMB at 23dBm*

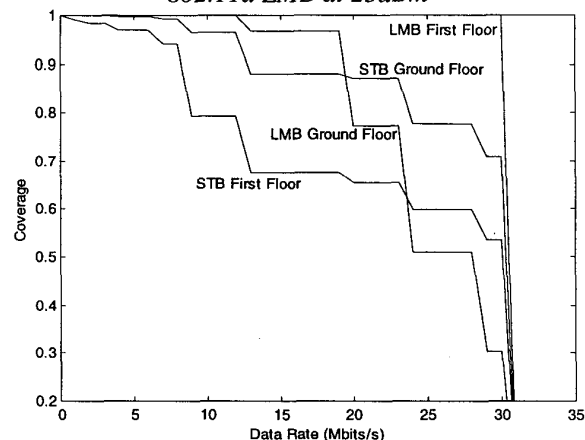*Figure 9b. First Floor Data Rate Supported by an 802.11a LMB at 23dBm*

Figure 10. Coverage Comparison of 802.11a STB and LMB at 23dBm

VI.3 The Effect of Transmit Power Limits

In order to assess the impact of transmit power limitations, the data rate achieved by an 802.11a LMB is considered. Figures 11a and 11b present coverage statistics for the 0dBm, 23dBm and 30dB transmit power scenarios for the ground and first floor respectively.

For the ground floor, an increase in transmit power from 23dBm to 30dBm achieves significant increases in data rate and coverage. In the range of 23-28Mbits/s coverage is improved by 25-35%. The lowest data rate achieved with 100% coverage is increased from 12Mbits/s to 23Mbits/s. Data rates this high facilitate the support of a very broad range of services: distribution of MPEG statistical multiplexes, multiple DVD transmissions, or simultaneous provision of high rate video services and broadband data access. The capability of the WHN to provide this level of service throughout the entire residential environment is extremely desirable.

For the first floor, the same increase in transmit power has no impact since the 802.11a LMB is already capable of supporting its maximum data rate of over 30Mbits/s with 100% coverage with 23dBm transmit power.

Predictably, coverage is reduced for the 0dBm transmit power scenario. A reliable signal cannot be achieved for around 40% of the ground floor. For the remainder of the environment, data rates are significantly lower than for the higher transmit power scenarios. On the ground floor, the data rates required to support MPEG-2 and DVD transmission are achieved with just 12% coverage. The highest achievable data rate is 19Mbits/s. On the first floor, performance is more impressive. 100% and 85% coverage are achieved for the data rate requirements of MPEG-2 and DVD respectively and the maximum data rate of 802.11a is achieved with around 20% coverage. When considering the impact of the different transmit power scenarios it is important to remember the applications that they are intended to represent. The 30dB case in intended to represent mains powered devices. It is highly likely that the AP will be mains powered. Thus, the high performance that is achieved with this transmit power will be achieved on the downlink, whatever the nature of the MT. This is very important since many applications (internet access and video transmission, for example) are highly asymmetric in terms of data rate requirements. Similarly, the 0dBm case is intended to represent highly portable, low power, battery powered devices. It is clear from the results above that these devices will not be able to achieve high data rates on the uplink to the AP. However, they will still be able to enjoy the benefits of the higher power AP downlink transmissions. Thus, the low rates achieved by such devices in much of the environment is not a major concern. Provided a reliable uplink exists, asymmetric data transfer will still be possible. However, in those cases where a reliable uplink cannot be established, the device will not be able to participate in the WHN. Thus, whilst these low power devices may perform

extremely well for the majority of applications in much of the environment, some outage must be expected.
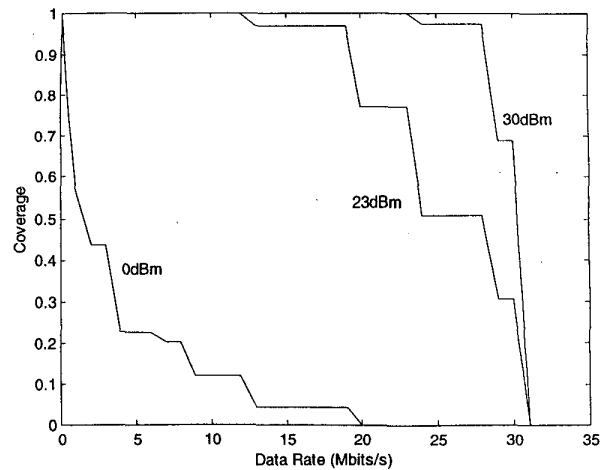

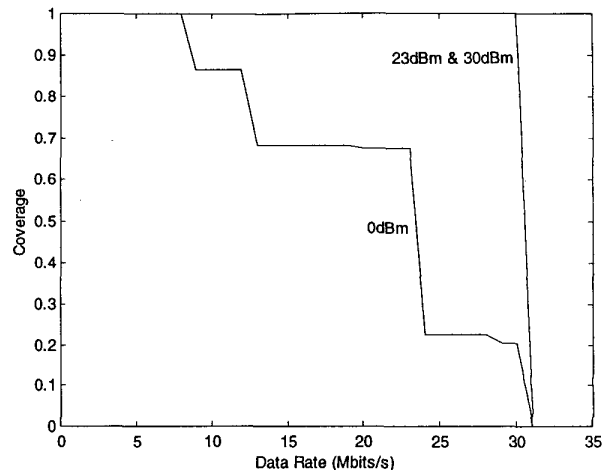*Figure 11a. Coverage Comparison of 802.11a LMB for the Ground Floor*

Figure 11b. Coverage Comparison of 802.11a LMB for the First Floor

VI.4 The Impact of Adjacent Residence Interference

In order to investigate the impact of adjacent residence interference on a HIPERLAN/2 system, ground floor coverage has been evaluated for both STB and LMB scenarios in the presence of an STB in the neighbouring residence (ISTB). It is assumed that both the subject and interfering APs have a transmit power of 23dBm. Figures 12a and 12b present the achieved data rates under these conditions. Coverage statistics are presented in Figure 13.

It can be seen that the interfering AP has a huge impact on the coverage achieved by the subject AP. For all data rates, the coverage under interference conditions is reduced to one half or less of its value without interference. The required data rates for video distribution can no longer be achieved with any degree of reliability and the maximum data rate of HIPERLAN/2 is no longer obtained anywhere

within the subject residence. Similar results were observed for cases when the transmit power of both subject and adjacent APs was 0dBm and 30dBm.

It should be noted that this is a relatively simplistic analysis, due to the following:

- Both APs are assumed to be using the same channel.

- The position of both APs are entirely arbitrary.

- The adjacent AP is assumed to be transmitting all the time and at full power. However, as has been seen from earlier results this will often be necessary in order to achieve high data rates.

- Interference is assumed to come only from the adjacent STB and not from MTs associated with it. In reality, neighbouring MTs will be the source of some of the adjacent residence interference. The amount of interference from these MTs will vary from that from the AP (which is used in these results) depending on the MTs position. However, this is as likely to result in more interference as it is in less.

- The analysis presented here is specific to one example environment. The example environment used in this paper has quite thick walls and floors. It is to expected that many residential environments will have internal walls and floors which attenuate the radio signal significantly less than in the case considered here.

However, it is clear from these results that the impact of adjacent residence interference on the HIPERLAN/2 WHN is disastrous and must be avoided at all costs. Hence, successful interference avoidance strategies are crucial.

The effects of adjacent residence interference on an 802.11a WHN will be different to those on the HIPERLAN/2 WHN. This is due to the 'listen before talk' approach employed by the 802.11 MAC. This should result in adjacent 802.11a systems avoiding interference by simple time sharing of the channel. This will still result in a reduction in throughput but will be much less catastrophic. It thus seems likely that the 802.11 MAC may be better suited the WHN applications in terms of its ability to avoid the severe problems suffered by HIPERLAN/2 under adjacent residence interference conditions. This issue warrants further investigation.

It should, of course, be noted that there will be little or no interference between adjacent APs, provided that they operate in different channels. Although co-channel operation is very much a worst case scenario, it serves to illustrate the point that adjacent APs must operate in separate channels if the best performance is to be achieved. Thus, the methods by which a WHN is assigned a channel (or chooses a channel for itself) are crucial. Dynamic Frequency Assignment (DFS) has been proposed

and is in fact mandatory for the relevant operating bands in Europe. Originally specified to mitigate fears about interference with the satellite systems that are the primary users of the 5.2GHz band in Europe, the ability of DFS to manage frequency assignments in dense urban environments must be questioned. In such environments the deployment of a new WHN may cause severe 'knock-on' effects as neighbouring systems all reconfigure in response to the presence of the new AP. Equally, if frequency selection is not dynamic, severe problems may occur when a new WHN is deployed – it, and neighbouring systems may suffer severe performance penalties.
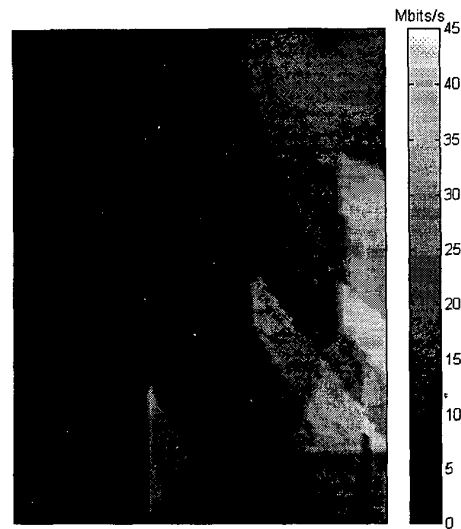

Figure 12a. Coverage of a HIPERLAN/2 STB for the
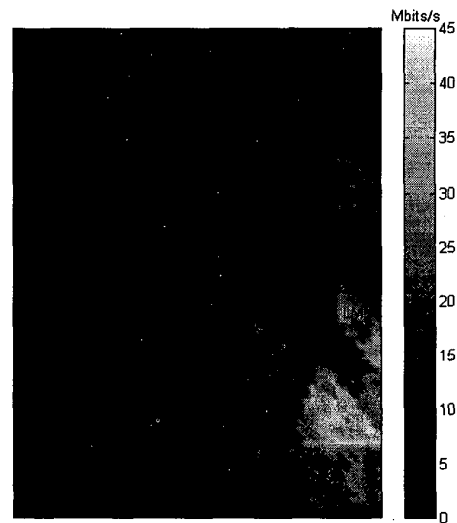Ground Floor Under Interference

Figure 12b. Coverage of HIPERLAN/2 LMB for the
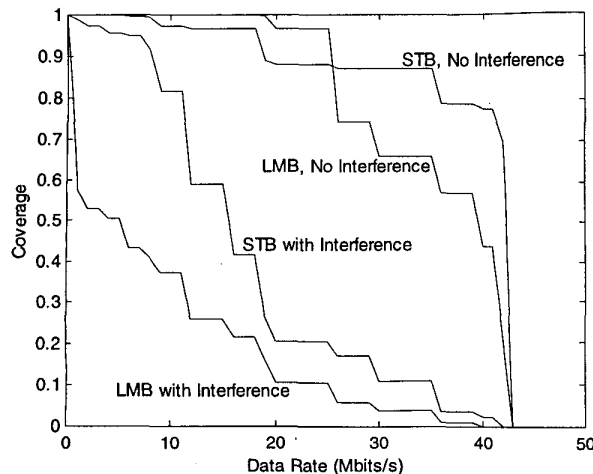Ground Floor Under Interference

*Figure 13.Ground Floor Coverage of a
HIPERLAN/2 System Under Interference Conditions*

VII. CONCLUSIONS

The results presented in this paper evaluate the performance of WLANs for WHN applications for a variety of scenarios. The analysis and the scenarios considered are far from comprehensive. A single example residential environment has been considered in this paper. However, the combination of throughput analysis and propagation modelling employed here provides a flexible analysis tool that can be readily extended to any environment.

The results presented provide valuable insight into the potential performance and the critical factors affecting performance of WHNs and indicate the following:

- HIPERLAN/2 achieves superior performance to IEEE 802.11a (in the absence of adjacent residence interference). The difference is most significant in areas where the received signal is strong and the WLAN is capable of achieving its maximum data rate. In those areas where reception is more challenging, the differences are minor.

- AP location is important. APs integrated into consumer electronics devices such as digital television set top boxes may suffer poor placement due to the requirement to place them near to existing antenna feeds and/or television sets. However, integration of the STB into existing consumer electronic equipment should assist in the uptake of the technology. Alternatively, it may be possible to position dedicated WHN AP devices so as to achieve superior coverage but this may require professional installation.

- The transmit power capabilities of devices in the network are crucial. Fixed and portable devices with access to a mains power supply can operate at the upper limits of transmit power for the allocated band

and thereby achieve superior performance. Hand-held battery powered devices such as PDAs can transmit at more modest rates but (particularly for applications where data rates are asymmetrically biased in favor of the downlink) will still enjoy the benefits of receiving signals from a mains powered AP. However, a reliable uplink cannot always be achieved by low power devices. If the reliable uplink cannot be achieved, the device will not be able to participate in the network.

- Adjacent residence interference has a severe debilitating effect on the WHN. Thus, it must be mitigated if WHNs are to be a successful technology. The 802.11 MAC is likely to be more successful than the HIPERLAN/2 MAC at mitigating adjacent residence interference.

In summary, the technology required to achieve a high performance, reliable WHN exists in the form of HIPERLAN/2 and IEEE 802.11a (and probably other WLAN systems as well). Many challenges are faced by the consumer electronics industry if the WHN is to be a success. Perhaps one of the most important is to develop effective strategies for the selection and re-selection of channels to avoid the severe interference that may otherwise occur in dense urban environments.

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