Maximizing Signal Strength for OFDM Inside Buildings

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***Abstract*—Propagation inside buildings suffer from large shadowing and high multipath effects. This is a serious problem for wireless local area network (WLAN) systems. This paper shows that shadowing and path loss can be minimized by exploiting the multipath tolerance of orthogonal frequency-division multiplexing (OFDM). This can be achieved by using multiple transmission antennas spread over the area of a WLAN cell. These antennas act as repeaters, transmitting and receiving the same signal at the same time. This decreases the average path loss, but increases the multipath delay spread. Using OFDM allows the advantage of reduced path loss to be utilized without detrimental effects of inter-symbol interference caused by the increased delay spread. The reduced path loss allows an increased system capacity, quality of service, or a decrease in intercellular interference in a cellular WLAN.**

***Index Terms*—Access point repeater, broad-band communications, indoor radio communication, multipath channels, orthogonal frequency-division multiplexing, wireless LAN.**

I. Introduction

WIRELESS networking is an emerging technology allowing users the freedom of movement. The aim of wireless local area network (WLAN) systems is to provide users with a data rate comparable with wired networks within a limited geographic area. Currently most WLAN products use direct-sequence spread-spectrum (DSSS) techniques, based on the IEEE 802.11b Standard, providing a data rate of 11 Mb/s in the 2.4-GHz industrial–scientific–medical (ISM) band [1]. The next generation of WLAN systems will be based on two similar WLAN standards known as: Hiperlan/2 (Europe) and IEEE802.11a (U.S.) [2]. These support a physical layer transmission rate of up to 54 Mb/s and use orthogonal frequency-division multiplexing (OFDM) for the physical layer implementation.

OFDM is a multicarrier modulation scheme, which has a high immunity to multipath effects and allows a wide range of carrier modulation schemes to be used. Hiperlan/2 adaptively changes the forward error correcting coding rate and the carrier modulation scheme (BPSK, QPSK, 16 quadrature amplitude modulation (QAM), 64 QAM) allowing the data rate to be maximized based on the current radio channel characteristics. Using a higher spectral efficiency modulation scheme, such as 64 QAM, allows the data rate to be increased, but requires a higher SNR for a fixed error rate. Thus, minimizing the path loss, allows the SNR and corresponding data rate to be maximized.

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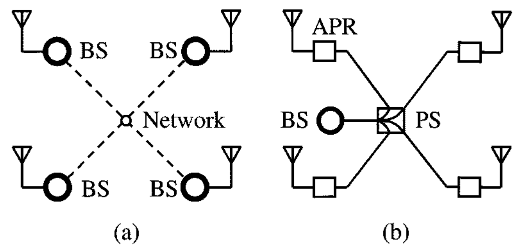

Fig. 1. Methods for obtaining spatial diversity. Access point repeater (APR). Base station (BS). Power splitter/combiner (PS). (a) Cellular system with four cells controlled by four BSs, connected with a wired network for hand off between cells. (b) Single multiple transmission cell using APRs.

Shadowing can result in numerous regions of the building having an inadequate coverage, resulting in a poor quality of service (QOS). This is a significant problem as the QOS of WLAN systems is very important if they are to replace wired networking. Shadowing also increases the average path loss compared with free space, requiring more transmission power in order to maintain communications.

High-quality coverage of a building can be obtained by using a cellular system, as shown in Fig. 1(a). Each base station (BS) forms a cell covering a small area of the building. These cells operate at different frequencies to prevent interference between them. The path loss is minimized, as the distance from the mobile station to the closest BS is minimized. Additionally, if the transmission path to the closest BS is blocked, the mobile can connect to another cell. However, this type of implementation can be expensive, due to the requirement of a number of BSs. Additionally, it requires multiple frequency bands for cellular implementation and hand offs between cells, increasing the system complexity. This paper presents a simpler and cheaper method for obtaining reliable coverage in an environment that suffers from shadowing.

II. Spatial Diversity by Multiple Repeat Transmissions

A form of spatial diversity can also be achieved by splitting the signal from a single central BS and transmitting the same signal from multiple locations around the building to be covered. This is shown in Fig. 1(b). Shadowing is reduced because there are multiple opportunities to receive the signal. Even if several paths are blocked by walls or buildings, others may have a reasonable transmission path. Using multiple transmitters effectively reduces the transmission distance, as the closest transmitter dominates the signal power.

An example of how spatial diversity maximizes power efficiency is lighting of a building. If you were trying to illuminate a typical large building with a single light bulb, the high opacity of the walls would result in many deep shadowed regions. The amount of power that would be required, for all parts of the building to be reasonably bright, would be extremely high, as shadowed regions would be lit solely from reflections and gaps in obstructing walls, such as doorways. However, by using one light per room, the illumination will be much more even, with minimal shadowing and a reduced total lighting power. The same is also true for radio signals; thus, by using multiple transmitters spread over the area of a building, we can reduce the average path loss.

Most communication systems need two-way communications using a forward and reverse link. Due to the reciprocal nature of radio propagation, the properties of the reverse link will be the same as the forward link. Thus, the path loss for the reverse link can also be minimized by using multiple receive antennas connected to a single central BS. The receive and transmit antennas can be combined into one unit, referred to here as an access point repeater (APR). The use of APR can provide a significant improvement with minimal expense.

The problem with using APRs is that the mobile receiver will see signals from all APR transmitters. The propagation delay from each transmitter will be different and, thus, will arrive at the receiver with a different delay. This is equivalent to receiving the signal distorted by a strong multipath. This causes frequency-selective fading and an increase in the delay spread of the transmission, which can result in inter-symbol interference (ISI). This is particularly a problem for modulation schemes such as frequency shift keying (FSK), as the maximum symbol rate is limited by ISI caused by delay spread.

DSSS systems have a high multipath tolerance due to use of a RAKE receiver [3]. A RAKE receiver uses correlation to resolve delayed copies of the signal caused by multipath propagation. These are then aligned in time and combined. This allows the signals from each of the transmitters to be resolved and combined. The maximum delay spread that can be tolerated by an IEEE802.11b DSSS WLAN system, using a 16-tap RAKE receiver, is 125 ns at 11 Mb/s and 250 ns at 5.5 Mb/s [4]. This level of multipath tolerance should allow APRs to be spaced out with a maximum diameter of about 20–35 m, although problems might arise due to the increased delay spread. This small antenna spacing means that there would be little advantage in using multiple APRs with an IEEE802.11b system, as sufficient coverage can easily be obtained over 20–35 m with a single transmitter.

OFDM has a higher multipath tolerance than DSSS and can transmit using a higher spectral efficiency. Minimizing the path loss allows the SNR to be increased, provided inter-cellular interference is low. This improved SNR can be utilized by adaptively setting the modulation scheme based on the SNR, allowing the throughput of the system to be increased.

The high multipath tolerance of OFDM is due to the low symbol rate used and the use of a guard period between symbols. The guard period is a cyclic extension of each OFDM symbol, giving protection against ISI, provided it is longer than the delay spread of the radio channel. Typically, the guard period is made to be a small fraction of the OFDM symbol time and, thus, by using a large number of narrow bandwidth carriers, the delay spread tolerance can be varied to suit the radio conditions.

Multipath causes frequency selective fading, which can result in carriers of the OFDM signal being lost in nulls in the spectrum. These nulls are typically handled by including forward error correction to compensate for the lost data. Adding multiple transmitters will result in an increased delay spread, resulting in a decrease in the correlation bandwidth of the channel. This will not cause any detrimental effects on the OFDM transmission, provided that enough carriers are used.

Indoor propagation normally suffers from a combination of Rician and Rayleigh fading [5]. Using multiple APRs will increase the multipath energy, resulting in more areas in the building suffering from Rayleigh fading. However, this increase in fading should be more than compensated for by the decreased path loss due to the multiple APRs. More research is needed to establish the extent of the additional multipath when using APRs.

The use of multiple transmitters to obtain improved coverage was first introduced in the digital audio broadcasting (DAB) system [6]. DAB uses OFDM with a low symbol rate and a long guard period. With DAB, it is possible for all transmitters to use the same frequency and transmit copies of the same signal, referred to as a single-frequency network (SFN). For VHF band transmissions, DAB uses 1536 carriers with a the symbol time of 1 ms and a guard period of 246 μs, allowing transmitters to be up 96 km apart in an SFN before the delay spread is too large.

Hiperlan/2 has a guard period of 800 ns, which would provide an effective delay spread protection of up to 250 ns. This would allow APRs within each cell to be placed with a maximum diameter of 40–60 m, which is sufficient for coverage of most buildings. Additional research is needed to verify this.

III. Implementation of an APR

All APRs within the same cell transmit and receive the same signal, thus only one BS is needed per cell. For transmission, the signal generated by a BS is split N ways, where N is the number of APRs. Coaxial cable or some other medium, such as optic fiber, is used to deliver the signal to each APR. The signal is then amplified at the APR to compensate for any losses in the coax transmission. For reception, the reverse process is used. Each APR has a low noise amplifier (LNA) to compensate for losses in the coax in order to maintain a low noise figure. The received signals from all APRs are combined, then demodulated at the BS. Phase differences between the APRs have little or no effect as they corrected for in the OFDM demodulation process.

Fig. 2 shows a simple implementation of an APR, which can be used when the loss in the coaxial cable is low ($<$20 dB). The master head amplifier operates at the RF frequency and, thus, no frequency translation is required. A low frequency control signal can be used to select whether to transmit or receive. For a full duplex system, the RF switches can be replaced with diplexers.

In larger systems where the cable losses are too large, the signal can be transmitted on the cable at an IF frequency. A common clock reference must be used by all APR's to ensure

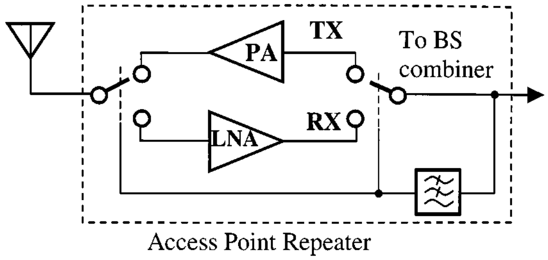

Fig. 2. Possible implementation of an APR.

frequency synchronization, otherwise frequency errors will reduce the orthogonality of the OFDM, causing inter-carrier interference. A suitable out-of-band clock reference must be transmitted from the BS. This common clock can then be frequency multiplied using a phase-locked loop (PLL) to generate the local oscillator (LO) for the IF–RF mixing. For such a design, care must be taken to ensure the phase noise of the clock reference is low and that the clock signal does not interfere with the received signal.

Another method for distributing high-frequency RF signals is to use optic fiber. The RF signals can be converted to optical signals and transmitted over long distances with optic fiber. This type of technology is currently being developed for use in mobile phone applications as a method for producing pico-sized cells [7].

IV. Experimental Setup

An experiment was set up to test the effectiveness of using multiple transmitters (i.e., APRs) to minimize shadowing in an indoor environment. The forward link from the BS to the mobile stations was tested by measuring the effective path loss from fixed transmitters to a mobile receiver. The path loss from a single transmitter (simulating a single access point) was compared with the path loss when using two transmitters (simulating two APRs).

The path loss was measured at 235 locations on the second floor of the Electrical and Computer Engineering (ECE) Building, James Cook University, Townsville, Qld., Australia. The measurement locations and the building layout are shown in Fig. 3. The internal walls are shown as dark lines. The selection of the measurement locations, the position of the transmitters, and the construction of the building can easily influence the overall path-loss probability distribution. However, the results presented will be representative of the improvement that could be expected in a typical building of similar construction to the one the measurements were taken in.

The transmitter set up is shown in Fig. 4. Simple monopole antennas were used and were assumed to have an effective gain of 0 dBi, including matching losses. The uncertainty in the gain of the antennas resulted in an absolute error in the path-loss measurements of approximately 3 dB and a differential error between the single and dual transmitter measurements of 1 dB. The signal strength at each location was measured using a spectrum analyzer on a trolley and converted to path loss by compensating for transmitter power and receiver gain. A slightly different frequency was used for the single and dual transmitters to allow simultaneous measurements of the path loss. The receiver antenna

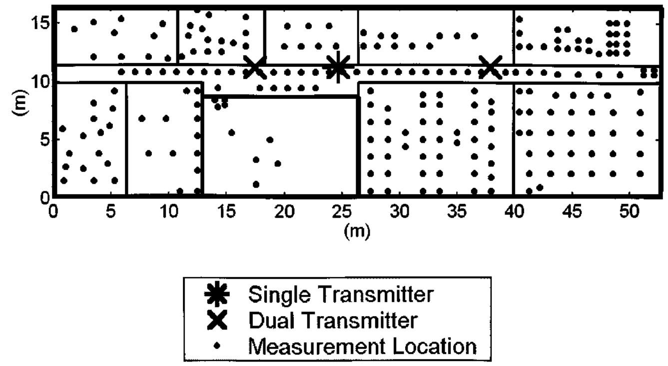

Fig. 3. Path-loss measurement locations in the ECE Building. Lines represent internal walls. The thin lines are plaster board walls and the thick ones are concrete walls.

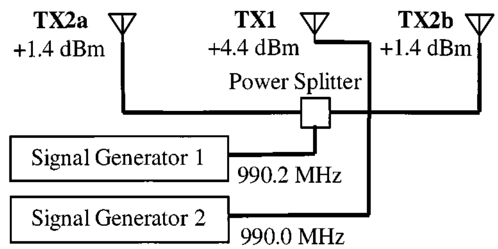

Fig. 4. Transmitter setup simulating APRs. The total transmitter power from $T \times 2a$ and $T \times 2b$ were matched to the $T \times 1$ power.

was placed on a rotating platform that was turned during the received power measurement. Video averaging on the spectrum analyzer was used to average the power over a 0.6 m circular path swept by the antenna. This was done to remove the effects of frequency selective fading and obtain an accurate measure of the path loss. Even though the path loss was measured using a continuous wave transmission, the results are still valid for a wide-bandwidth modulation schemes.

Due to limitations of the equipment available, the measurements were performed at 1 GHz, rather than 5 GHz. This will tend to reduce the effects of shadowing, as the opacity of most materials is lower at lower RF frequencies; thus, we would expect the effectiveness of using APRs to improve at higher RF frequencies.

V. Discussion of Measured Results

Fig. 5 shows the path loss for the single transmitter. The path loss increases rapidly with distance from the transmitter. The path loss in the bottom left-hand corner of Fig. 5 at location 5×5 m has a high path loss of over 100 dB, which is equivalent to 1 km of free-space loss, even though it is less than 20 m from the transmitter. Fig. 6 shows the path loss when two transmitters were used. In this case, the path loss is lower and much more even.

Fig. 7 shows the measured and simulated probability distribution of the path loss. It shows that the measured path loss is more than 7 dB lower when using two transmitters as compared with one. This result is to be expected, as the longest distance to a transmitter was reduced by 1.62 times. The typical path-loss exponent of an obstructed path within a building is 4–6 [8], as compared to a path-loss exponent of 2 for free-space

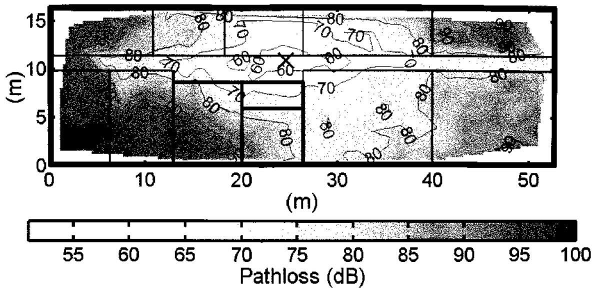

Fig. 5. Measured path loss with one transmitter over the area of the building at 990 MHz. The dark lines are the internal walls. The X shows the location of the transmitters.

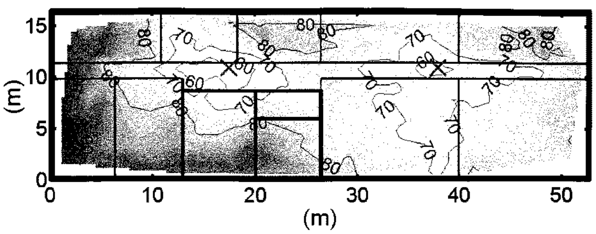

Fig. 6. Measured path loss for two transmitters at 990 MHz. This simulates two APRs. Note the total transmitter power is the same as for the one transmitter measurements. The X shows the location of the transmitters.

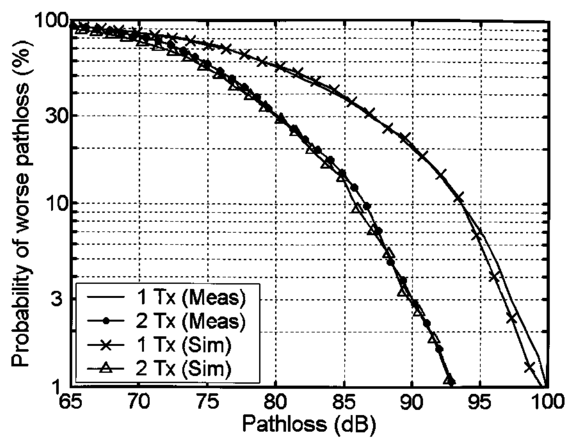

Fig. 7. Path-loss probability distribution within the measured and simulated building.

loss. We would, therefore, expect the path loss to be reduced by 8.4–12.6 dB for a reduction in distance of 1.6 times. Since the transmission power is split over two transmitters, this will reduce the received power by 3 dB, thus resulting in an overall improvement of 5.4–9.6 dB. This compares well with the measured improvement of 7 dB. Even though there are two transmitters, the received signal power tends to be dominated by the closest transmitter due to the rapid fall of power with distance. This is why the improvement in signal power can be estimated with reasonable accuracy by considering the reduction in distance to the transmitter.

VI. Reduction in Cellular Interference

At a large distance, multiple APRs appear as a point source and, thus, the received power is the same as when using a single access point, where the total transmitted power is the same. This means that the interference to neighboring systems is approximately the same regardless of the number of APRs used for fixed total transmission power. The near-field path loss can be reduced by 7 dB using two APRs, allowing the total transmitted power to be reduced by up to 7 dB for the same SNR. This will reduce the overall interference to nearby WLAN systems by 7 dB. Further improvements could be made using a higher number of APRs. Using one APR per room could potentially decrease the near field path loss by 20–30 dB, allowing a large reduction in external interference with suitable power control. The reduced interference will allow a better frequency reuse in a cellular system.

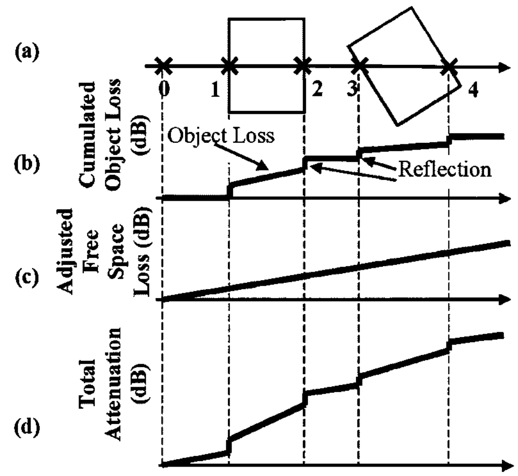

Fig. 8. Attenuation calculations for a ray passing through two objects.

VII. Shadow Modeling

A simplified ray trace path-loss model was developed to allow investigation into the use of multiple APRs. This is similar to the model used in [9]. The two-dimensional (2-D) model calculates the path loss along radial rays, which are converted to a fixed rectangular data grid using interpolation. The rectangular grid allows the signal power from multiple transmitter sources to the added together.

The path loss along each ray is found by calculating its intercept to each object in the environment. The loss through each object is calculated based on the reflection coefficient of the object surface and the distance through the object. Each surface the ray intercepts results in energy being reflected, causing a jump in the accumulated attenuation. As shown in Fig. 8(a), surfaces 1–4 result in jumps in the cumulated object loss shown in Fig. 8(b). In this model, the amount of reflected energy is constant regardless of the angle of the ray. This reflected energy is not calculated as another ray and is ignored to keep the model simple.

In addition to reflected losses, each object absorbs energy as the ray passes through it. This is calculated as a loss proportional, in decibels, to the distance traveled through the object medium. The loss along the ray is accumulated as the ray passes through multiple objects. This loss is then added to the loss calculated by the standard free-space radio path-loss equation to

TABLE I
MATERIAL PROPERTIES OF THE INTERNAL WALLS, SHOWING DIRECT MEASUREMENTS AND WALL LOSS FOUND BY SIMULATION OPTIMIZATION

Wall Type	Thickness (m)	Direct measurement of wall loss (dB)	Wall loss used in simulation (dB)
Plaster Board	0.13	1.5 ± 1	1.4
Concrete	0.2	4 ± 1.5	3.8

obtain the overall attenuation with distance. The radio path-loss equation is

$$P_L = -10\log_{10}\left(\left(\frac{\lambda}{4\pi r}\right)^{\alpha}\right) \quad (1)$$

where P_L is the path loss (in decibels), λ is the wavelength of the radio signal (in meters), r is the distance from the transmitter (in meters), and α is the path-loss exponent. For free-space propagation, $\alpha = 2$. The simulation calculates the path loss due to objects and, thus, ideally, the path-loss exponent used in the simulation should be 2. However due to the simplicity of the model, a path-loss exponent of 2.65 was found to best match the measured results.

VIII. MODEL VERIFICATION, TUNING, AND LIMITATIONS

The radio model was compared to the measured results to verify the model accuracy and to adjust the model parameters to give realistic results. The material properties of the walls were measured directly and are shown in Table I. These values compare well with values measured in [9]. The walls were found to be nonhomogeneous, caused by wiring, reinforcing, studs, and nearby objects, making accurate measurements difficult.

In the simulation, the material properties of the walls were optimized to obtain a good match between the simulated and measured building path loss shown in Figs. 5 and 6. The resulting simulation parameters were found to closely match the direct wall-loss measurements, as shown in Table I. Fig. 7 shows the resulting match between the measured and simulated results. This figure shows the percentage area of the building (Y-axis), which has a path loss worse than a specified path loss in the X-axis. For example, 20% of the building has a path loss of greater than 90 dB when using a single transmitter (where it is only 3%) for two transmitters.

There is a good match between the simulated and measured results, despite the simplicity of the model. If the wall loss were considerably higher, then the path loss would have been dominated by diffraction and multiple reflections, resulting in a poor accuracy in the path-loss prediction.

IX. SIMULATED RESULTS

Figs. 9 and 10 show the simulated path loss for a single and double transmitter, respectively, for the same building and transmitter location as measured data shown in Figs. 5 and 6. The probability distribution of the path loss is shown in Fig. 7. The main difference between the simulated and measured results is that the simulated results are smoother, which is the result of the simple environment model.

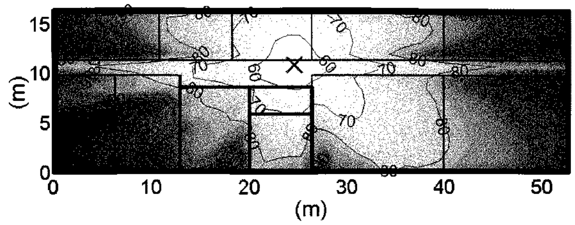

Fig. 9. Simulated path loss for one transmitter at 990 MHz. The X shows the transmitter location.

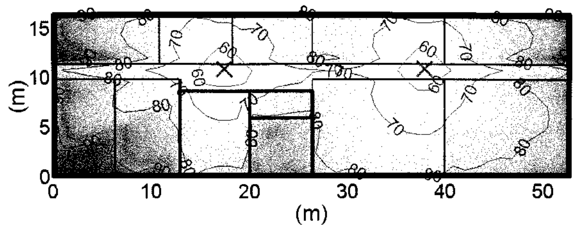

Fig. 10. Simulated path loss for two transmitters. The X shows the location of the transmitters.

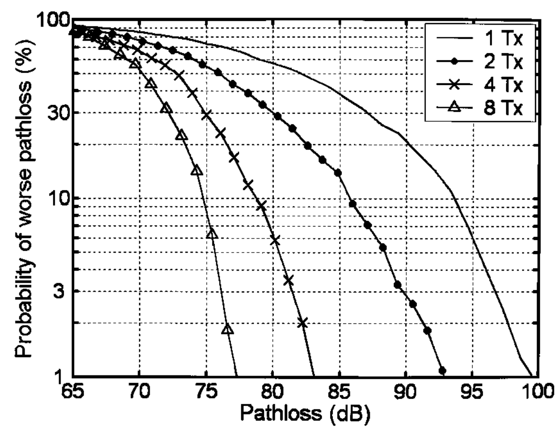

Fig. 11. Cumulative probability distribution for simulated results, showing the result for one, two, four and eight transmitters.

In addition to simulating one and two transmitters, the path loss was simulated with four and eight transmitters. The transmitters were positioned in the simulation to approximately maximize their effectiveness. Fig. 11 shows the path-loss distribution for all the simulated results. The path loss for the worst 2% of the area of the building was improved by 7 dB when using two transmitters, 16 dB for four transmitters, and 22 dB for eight transmitters.

X. CONCLUSION

Using multiple APRs is a low-cost method that can be used to reduce shadowing and near-field path loss within a building. This allows a reduction in intercellular interference with suitable power control. It was shown experimentally to decrease the near-field path loss by 7 dB@1 GHz within an indoor environment using two repeaters, as compared with a single transmitter. Simulated results show that the improvement can be as much as 20 dB for eight transmitters. Using multiple APRs will result in an increase in the received multipath, however OFDM systems, including Hiperlan/2 and IEEE 802.11a, should be able to tolerate this without detrimental effects. This tolerance should allow a maximum spacing of 40–60 m between any two APRs in a Hiperlan/2 cell.

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