Gigabit/s Indoor Wireless Systems with Directional Antennas

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***Abstract*—The consequences of designing indoor wireless systems with directional antennas at one or both ends of a line-of-sight (LOS) link are investigated. We determine how narrow the beamwidth must be so that the maximum data rate is not limited by multipath effects. For such beamwidths, simple unequalized two-level frequency shift keying (FSK) or phase shift keying (PSK) modems can be used in place of the more costly and complex "anti-multipath" modems, and data rates above 1 Gb/s may be achieved.**

The channel impulse response in an empty room is estimated using geometrical optics, observing that with directional antennas, multipath rays must arrive from the same direction as the LOS ray. The link outage probability is then estimated as a function of antenna beamwidth, and guidelines are established for the selection of frequency band and antenna placement. Experiments using a 19-GHz 622-Mb/s binary phase shift keying (BPSK) link and 15° beamwidth horn antennas in an office building with plaster walls and large metallized windows have demonstrated error-free performance on both LOS and non-LOS (NLOS) links.

I. Introduction

THE design of a high speed (>150 Mb/s) wireless local-area network (WLAN) requires that many factors be considered, including technical, economic, and regulatory. A major technical factor is the channel response behavior (multipath) in the indoor environment as a function of frequency band, building type and radio system architecture.

To achieve the desired high speeds, the design approach can be focused on either:

1) accepting the presence of multipath (with delays of the order of the room size) and mitigating it with multitone or equalization techniques, or
2) using line of sight (LOS) links with narrow beam antennas to eliminate virtually all multipath and thus use simple unequalized [frequency shift keying (FSK), phase shift keying (PSK)] modulation schemes.

In the first case, the design effort will emphasize communications/modulation techniques, whereas in the second case, the work concentrates on antenna/beamsteering techniques. These techniques must be used because multipath delays in the typical indoor environment are on the order of the target bit time (10 s of nanoseconds), and would cause intersymbol interference. The delays are related to the room dimensions independent of carrier frequency [1], [4], [5].

In this paper, we explore the consequences of the second approach. Thus we assume that at high speeds, a simple two- or four-level FSK or PSK system is used, because equalization, diversity or multitone techniques are deemed to be impractical or too expensive. For such a simple system to work reliably, the channel impulse response should not contain significant multipath components, so that the data rate is not limited by multipath effects. We also make the initial assumption that high speed and high capacity WLAN's can use a femtocellular architecture [3], with a single cell for each room, and multiple cells for a large open area office. The consequences of using non-LOS (NLOS) links are considered also. Indoor propagation measurements [4], [5] show that multipath can be reduced with directive antennas.

For this "LOS with directive antennas" approach, the amount of multipath will depend on the number of ray paths between base station or network port (transmitter T) and remote station or portable (receiver R), which in turn will depend on the directivity (beamwidth) of the antennas at T and R, as well as details of the environment. If omnidirectional antennas are used at both T and R, then there will be many possible ray paths, whereas if highly directional antennas are used, then there may be only a single LOS path. The beamwidth which may be achieved with an antenna of practical size (and thus the amount of multipath) depends on the radio frequency (RF) carrier frequency. If the frequency is too low, then the beamwidth will be large, thus admitting many ray paths. Thus, a frequency is selected for which the beamwidth is sufficiently narrow that there is no significant multipath, but the frequency should not be so high that the technology is impractical or the cost is prohibitive.

To explore the consequences of this "LOS with directive antennas" approach, we estimate the channel impulse response using geometrical optics with practical values for antenna beamwidth, reflection coefficients and surface roughness. The image method is used to find ray paths. We search for T and R locations in which multipath can occur, i.e., where multipath rays arrive at R from the same direction as the LOS ray.

This paper is organized as follows: In Section II, we consider multipath in the idealized environment of an empty office with dielectric walls. The results yield some useful insights which may be applied to more realistic (more complex) environments. First the ray paths which arise in an empty office are reviewed. Then the number of ray paths that are "captured" within the beamwidth of the antenna,

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along with the resulting multipath components, are determined. Methods of how to define what is "significant" multipath which would cause performance degradation are reviewed. Even for very narrow beamwidth antennas, there are ray paths which can create multipath on a narrowbeam LOS link. Thus, certain critical locations are found within the office where multipath components may be observed even for a narrow beamwidth, and the ray paths which cause this multipath are identified. For slightly larger beamwidths, these points expand into "critical regions." The placement of the base antenna T, which minimizes the size of the "critical regions" for a given beamwidth, is determined for rooms of different shapes. With certain assumptions, the outage probability may be related to the ratio of the size (volume) of the critical region to that of the room. This "fractional outage ratio" is determined as a function of the antenna beamwidth. Guidelines for antenna placement are given to further reduce the fractional outage ratio. The effect of using an omni antenna at one end of the link is also considered.

In Section III, we consider the consequence of using NLOS links to the nth adjacent office, and find that the size of the critical regions increases as n^2. In Section IV, we present experimental results using a 19-GHz 622-Mb/s binary phase shift keying (BPSK) link and 15° beamwidth horn antennas in an office building with plaster walls and large metallized windows. Here, we demonstrate error-free performance on both LOS and NLOS links. The results of this study are summarized in Section V.

II. Multipath with a Directional Antenna

Indoor propagation models assume that the channel may be represented by a low pass complex impulse response $h(\tau)$ which in general may vary with time t, and is written [1], [2]

$$h(\tau;\, t) = \sum_{k=0}^{\infty} \alpha_k(t) e^{-j\theta_k(t)} \delta[\tau - \tau_k(t)] \tag{1}$$

where α_k is a real attenuation factor (with α_0 normalized to 1), θ_k is a linear phase shift due to propagation and τ_k is the time delay of the kth path in the multipath channel.

If both the geometry of the environment and the location vector $\overline{r}$ between transmitter T and receiver R are specified and do not change with time, then the impulse response is written $h(\tau, \overline{r})$ and the parameters $\alpha_k(\overline{r})$, $\theta_k(\overline{r})$, $\tau_k(\overline{r})$ have fixed values depending on $\overline{r}$. General expressions for $h(\tau, \overline{r})$ are obtained in [7] using the method of images for a rectangular room in terms of the room dimensions, wall dielectric constants, T and R locations, direction of arrival at R, antenna patterns, and orientation.

With a directional antenna at R pointed at T, any multipath ray must arrive within the beamwidth of R, i.e., from the same general direction as the direct ray. Thus, a large number of potential multipath components k are attenuated by the R antenna. However, even for a very narrow (infinitesimal) beamwidth at R, there are critical locations where multipath cannot be avoided.

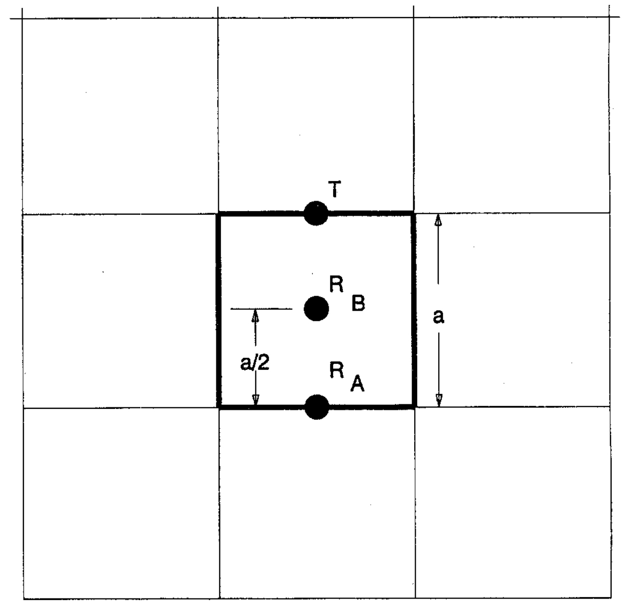

Fig. 1. Empty room.

For example, for T on the ceiling of height a above the floor, and R at location R_A on the floor (Fig. 1) pointing at T

$$h(t) = \sum_{k=0}^{\infty} \frac{\rho_1^k \rho_2^k}{2k+1}\, \delta\left(t - \frac{2ka}{c}\right) \tag{2}$$

where a is the distance from T to R and ρ_i, $i = 1, 2$, are the amplitude reflection coefficients from the two walls, (and $\Gamma_i = |\rho_i^2|$ are the power reflection coefficients). If the reflecting surface i is smooth with relative dielectric constant ϵ_i, for normal incidence

$$|\rho_i| = \frac{\epsilon_i - \sqrt{\epsilon_i}}{\epsilon_i + \sqrt{\epsilon_i}}, \quad i = 1, 2. \tag{3}$$

From (2), the power $|\alpha_k|^2 = \Gamma_1^k \Gamma_2^k/(2k+1)^2$ in a delayed path decreases with increasing k. The same results apply for T against one wall and R on the opposite wall. For R_B in the center of the room at distance $a/2$ from T, the same expression for $|h(t)|^2$ applies with $a/2$ in place of a, except the factors $2k$ are replaced with $4k$.

Thus, the multipath arising from these images will appear at R even for an antenna with extremely narrow beam width. In general, such multipath will arise from double and higher order reflections from two parallel surfaces, which are perpendicular to the LOS path. However, if R is moved away from the critical location, then the images will fall outside the R beam, and the multipath will disappear, as discussed in Section II-A.

A. Significant Multipath

Assuming no time variation and constant $\overline{r}$, the values of α_k, θ_k will affect the performance [bit-error rate (BER)] on an unequalized link. The values which produce an unacceptable BER will depend on the modem design [6]. For given ρ_1, ρ_2, if we average over all $\theta_k \in \{0, 2\pi\}$ for each k, then we can in principle establish a threshold value x_0, and

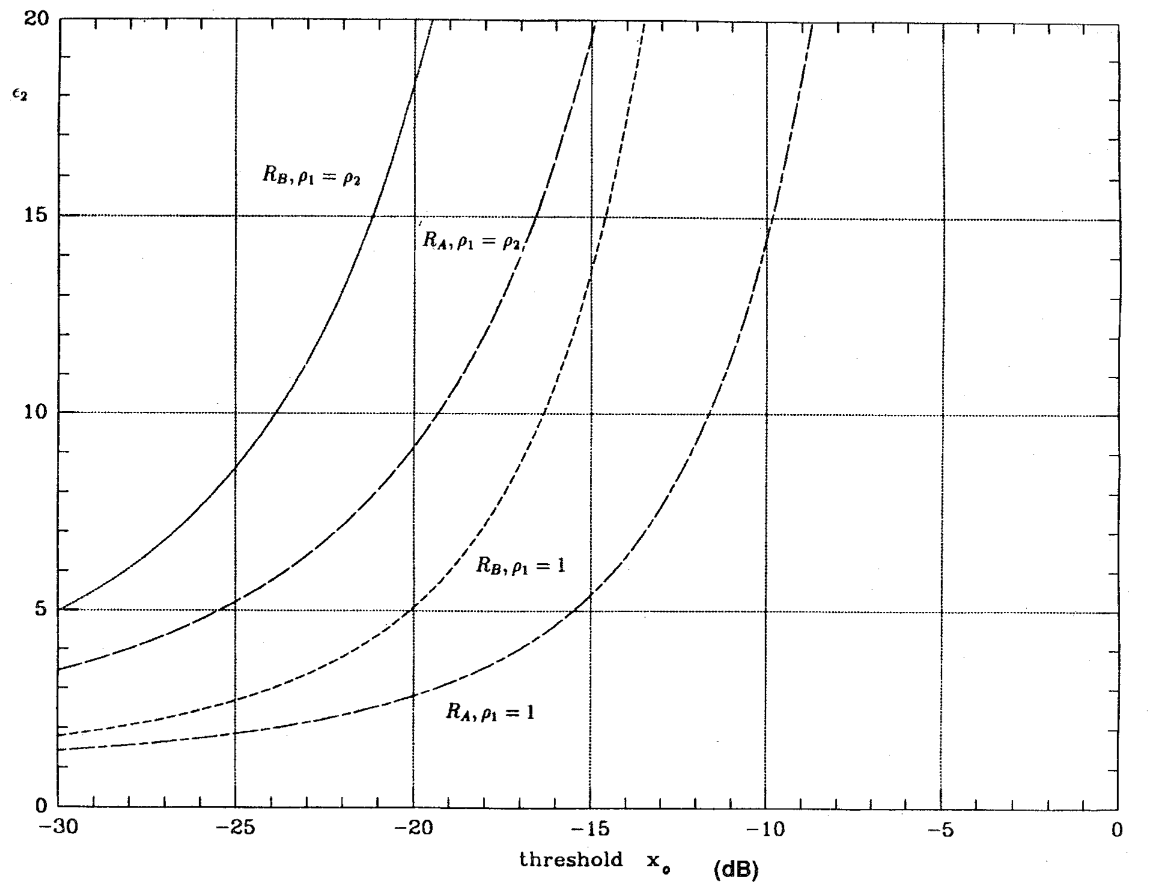

Fig. 2. ϵ_2 versus x. R_A, $\rho_1 = 1$, R_A, $\rho_1 = \rho_2$, R_B, $\rho_1 = 1$, and R_B, $\rho_1 = \rho_2$.

define the presence of "significant multipath" (such that the link BER becomes unacceptable) according to the criterion $\sum_{k=1}^{\infty} |\alpha_k| > x_0$.[1] Typical values of 20 log x_0 are in the range of −20 to −6 dB, depending on the modulation technique, acceptable BER and demodulator design. Since all α_k can be determined from α_1 [as shown from (2)], we need consider only the first multipath component, and thus can use the alternate criterion $|\alpha_1| > x_1$, where $x_1 < x_0$.[2]

Fig. 2 shows the minimum values of ϵ_2 needed to create significant multipath as a function of the threshold 20 log x_0 according to the criterion $\sum_{k=1}^{\infty} |\alpha_k| > x_0$. Results are shown for each location of R (R_A or R_B) for $\rho_1 = 1$ (one conducting wall) and $\rho_1 = \rho_2$ (both walls nonconducting).[3] If $x_0 = 0.1$, the multipath may be significant if at least one of the two parallel surfaces is conducting, since the minimum ϵ_2 may be exceeded by typical building materials (e.g., for limestone $\epsilon_2 \simeq 7.5$, and for brick $\epsilon_2 \simeq 4.5$ [10]). However, if both surfaces are dielectric, then the multipath is not significant (unless the building materials are such that ϵ_2 is unusually high). Surface roughness greater than about $\lambda/4$ may reduce the multipath below threshold. The second multipath amplitude α_2 (four times reflection) is generally insignificant, unless both surfaces are conducting.

The conductors need not be very large if they are located at the point of reflection; a size D such that the distance r_{TS} from T to the reflector S $r_{TS} \ll 2D^2/\lambda$ (near field) is sufficient. For example, if S has $D = 1$ m and $f = 18$ GHz, any $r_{TS} < 12$ m meets this criterion by at least a factor of 10. The conducting reflectors may be walls with metal-backed whiteboards, metallized windows, desks, filing cabinets, or electronic equipment with smooth metal surfaces.

B. Size of Critical Region

In this section, we evaluate the size of the critical region as a function of the antenna beamwidth. The critical region near

[1] The essential idea is that the multipath components may add in voltage such as to reduce the data eye opening. At high data rates where the symbol time $T \ll \tau_1$, the multipath will arise from data bits other than the current bit. The smallest eye opening occurs when all multipath voltages add in antiphase to the direct path voltage. This concept does not apply for the case of nonlinear modulation schemes such as FSK.

[2] More precisely, we can determine the region in the α_1, θ_1 plane for which the data eye opening is closed, by determining the function $\alpha_1(\theta_1)$ such that the eye is just closed. We can then define the probability of eye closure $p(\alpha_1^*)$ for a given α_1^* as $1/2\pi$ times the range of θ_1 for which $\alpha_1(\theta_1) < \alpha_1^*$. The probability of link outage P_{out} may be obtained by averaging over $f(\alpha_1^*)$ (the pdf of α_1^* for the propagation environment in question), i.e., $P_{out} = \int p(\alpha_1^*) f(\alpha_1^*)\, d\alpha_1^*$. This has been done for various modulation/demodulation schemes in [9], including coherent PSK with data directed and pilot tone carrier recovery, differential PSK, and amplitude shift keying (ASK) with envelope detection. Nonlinear modulations such as FSK would require a different analytical method.

[3] The same results are obtained with the alternate criterion $|\alpha_1| > x_1$ for $x_1 < 0.1$. For larger x_1 and a given ϵ_2, 20 log x_1 is 1–3 dB less than 20 log x_0.

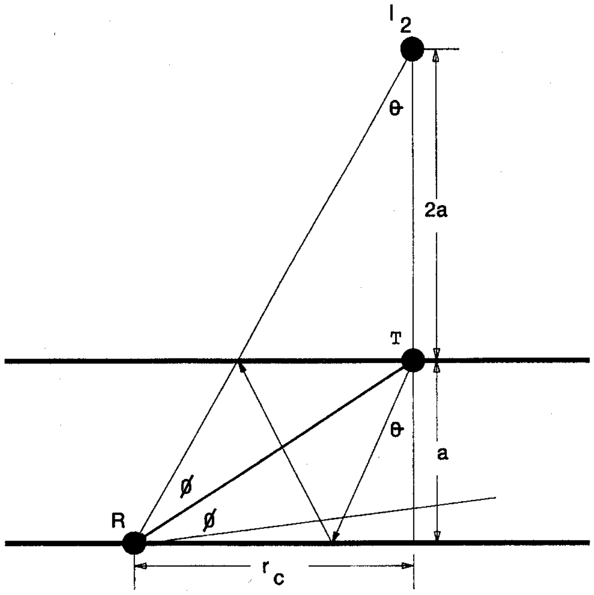

Fig. 3. Critical region.

R_A is that region for which the image I_2 falls within the full beamwidth Φ of the antenna pointed at T. Fig. 3 shows the geometry, where the half-beamwidth $\phi = \Phi/2$ is shown. For an (impractical but useful) cone-shaped beam with no response outside the cone of full beamwidth Φ, we calculate the radius of the critical region as

$$r_c = \alpha \frac{1 - \sqrt{1 - 3\tan^2\left(\frac{\Phi}{2}\right)}}{\tan\left(\frac{\Phi}{2}\right)}. \tag{4}$$

This expression for r_c is found using Fig. 3 with $\tan(\theta + \Phi/2) = r_c/a$, $\tan\theta = r_c/(3a)$ and solving for r_c in terms of Φ. For small Φ, $r_c \simeq 3a\Phi/4$ is valid within 10% for $\Phi/2 < 17°$.

For practical antenna patterns, the boundary of the critical region cannot be precisely defined by the beamwidth Φ for which the pattern is some value x dB below the main lobe. This is because the value of x will depend on the amplitude of a multipath ray relative to the direct ray (as determined by the reflectivity of the walls), and on the strength of the multipath needed to close the eye [9]. Thus x, and the corresponding beamwidth, depends on the particular situation (environment and modulation scheme), and may be in the range from 3–20 dB. In addition, there may be sidelobes which are less than x dB below the main lobe.

If we define Φ to be the nominal (3 dB) full-beamwidth, and assume that x may be greater than 3 dB in many situations, then we arbitrarily approximate for small Φ, the radius of the critical region $r_c \simeq a\Phi$ instead of $3a\Phi/4$. This is equivalent to assuming that x for a typical environment and modulation scheme is such that the corresponding beamwidth is approximated to be 4/3 greater than the 3 dB beamwidth. This approximation, while crude, is sufficient for our purposes, since the actual value of r_c in a particular situation is not likely to vary by more than a factor of two.

By rotating Fig. 3 in the third dimension, we see that the critical regions may be approximated as cones [Fig. 4(a)–(c)] with the base of radius $a\Phi$ on the wall or floor (shaded in the figures), and the tip at T. It is assumed that one surface in each of the three pairs of parallel surfaces is a conductor (or has a conductor of sufficient size at the reflection point), so that the multipath is significant. If not, then the corresponding critical cones are deleted. The cones may be reduced in size if we assume that R is located only in the top half of the room nearest the ceiling. Note that these cones arise from the directional properties of the antenna at R, regardless of the pattern of T.

By admitting a finite beamwidth Φ, multipath from a single reflection from a smooth object parallel to but offset from the LOS path and within the beamwidth of T and R can also create critical regions, provided that the excess path length exceeds $\lambda/4$.

C. Fractional Outage Ratio

We define a link outage probability in terms of the fractional outage ratio o_f. By assuming that the receiver may occupy any point in the room with equal probability, o_f is defined as the ratio of the size (volume) of the critical region cone to the size of the room. The volume of each critical region cone is given by

$$\begin{aligned} V &= \frac{K}{3}\pi(r\Phi)^2 r \\ &\simeq K r^3 \Phi^2 \end{aligned} \tag{5}$$

where r is the distance from T to the wall, $r\Phi$ is the radius of the base of the cone, and $K = 1.0$, 0.5, or 0.25 is the shape of the base (full-, half-, or quarter-circle).

For example, from Fig. 4(a)–(c) for T_1 in the center of the ceiling

$$\frac{V_1}{\Phi^2} = 2(0.5)\left(\frac{a}{2}\right)^3 + 2(0.5)\left(\frac{b}{2}\right)^3 + (d)^3 \tag{6}$$

for T_2 in the corner

$$\frac{V_2}{\Phi^2} = (0.25)(a)^3 + (0.25)(b)^3 + (0.25)(d)^3 \tag{7}$$

and for T_3 in the center of the wall of length b[4]

$$\frac{V_3}{\Phi^2} = (0.5)(a)^3 + 2(0.25)\left(\frac{b}{2}\right)^3 + (0.5)(d)^3. \tag{8}$$

The fractional outage ratio can be computed as

$$\begin{aligned} o_f &= \sum \frac{V_i}{V_T} \\ &= q\Phi^2, \quad i = 1, 2, 3 \end{aligned} \tag{9}$$

where $\sum V_i$ is the sum of the volumes of all critical region cones for T_i, $V_T = abd$ is the total volume of the room, $q \simeq 1$

[4] If T_3 is not placed in the center of the wall of length b, but offset from the center by α, then $V_3/\Phi^2 = (0.5)(a)^3 + (0.25)(b/2+\alpha)^3 + (0.25)(b/2-\alpha)^3 + (0.5)(d)^3$ which is minimum for $\alpha = 0$.

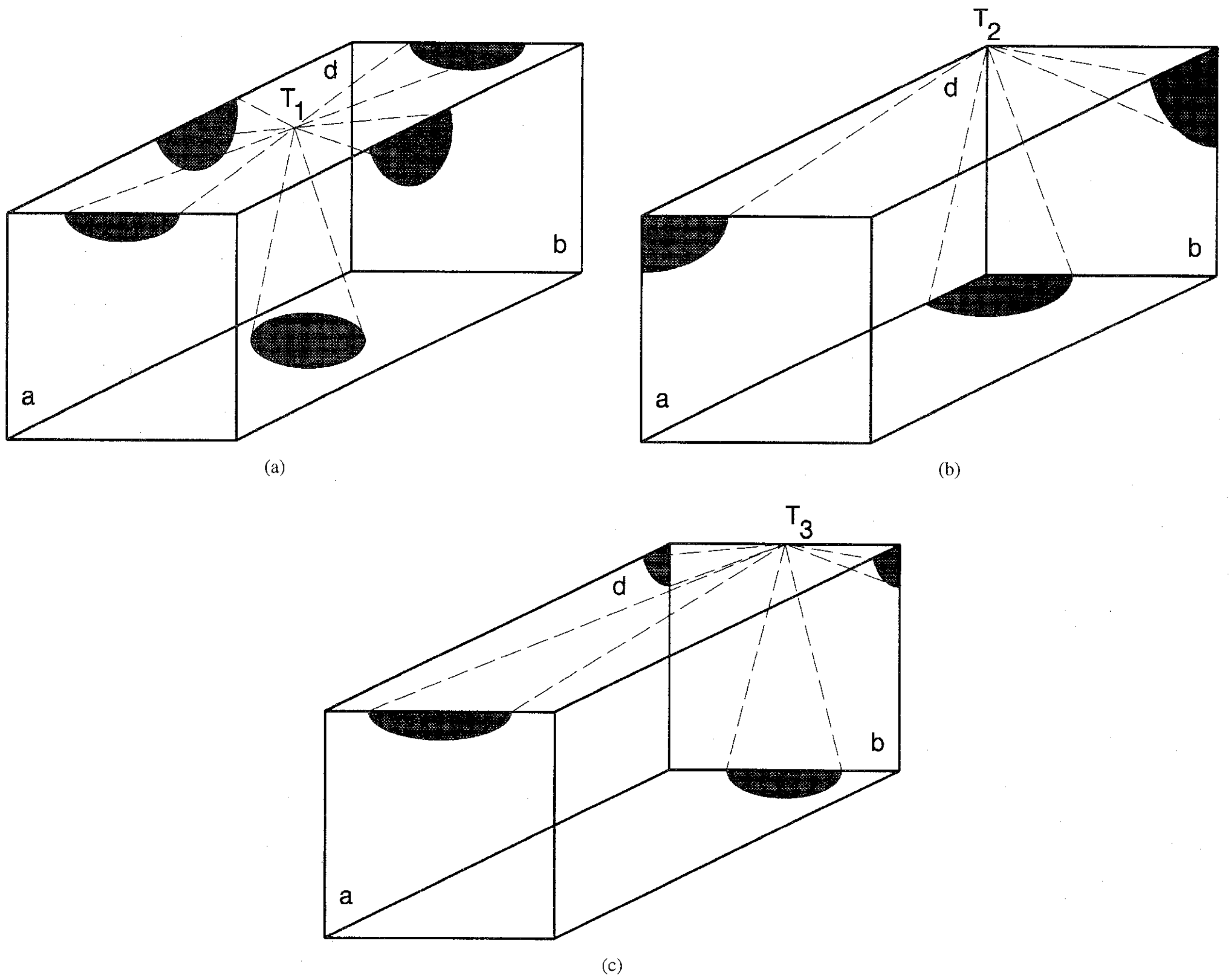

Fig. 4. (a) Critical region cones for T_1. (b) Critical region cones for T_2. (c) Critical region cones for T_3.

TABLE I
NORMALIZED FRACTIONAL OUTAGE CONSTANT $q = o_f/\Phi^2$ FOR DIFFERENT T LOCATIONS AND ROOM DIMENSIONS

Example No.	1	2	3	4	5	6
T Location						
T_1	1.25	0.75	1.06	1.06	1.25	1.12
T_2	0.75	1.12	1.25	1.25	2.16	0.50
T_3	1.06	1.25	0.75	2.28	1.06	0.56
Best Location	T_2	T_1	T_3	T_1	T_3	T_2

is a constant depending on the room dimensions a, b, d, and the T_i location in the room. For example, if $a = b = d$ and T_1 (center of the ceiling) is selected, then $q = 1.25$. Thus, for $\Phi = 0.1$ (6°, antenna size $D = \lambda/\Phi = 5$ cm at 60 GHz), o_f is in the range of 10^{-2}. However, by incorrect selection of location, o_f may be increased by a factor of two to four. Also, o_f may be reduced if only one or two of the three pairs of surfaces contain a conductor. o_f may also change if we assume a nonuniform probability distribution of receiver locations, e.g., R is located only in the top half of the room nearest the ceiling, or R is more likely to be near the center of the room than near the walls.

The outage o_f for each location T_i can be compared by choosing specific values for a, b, d. We consider the following six examples, and calculate o_f for each T_i and select T_i with the smallest o_f: 1) cubical room, 2) cubical room, R only in top half of room nearest the ceiling, 3) one wall twice as long as the other, T on long wall, 4) one wall twice as long as the other, T on short wall, 5) one wall twice as long as the other, R only in top half of room nearest the ceiling, T on long wall, and 6) cubical room, one pair of nonconducting parallel walls (pair normal to a). The results are given in Table I.

In each of these examples except the last one, we assumed that one surface in each of the three pairs of parallel surfaces is a conductor. If not, then the corresponding critical cones are deleted, and the preferred locations and corresponding o_f may be different. In the last example, the pair of walls normal to a are both nonconducting, and all terms involving a are dropped.

These calculations may be repeated for other room dimensions. From these examples, the guidelines for placement of T are to avoid T locations on short walls, and avoid T locations on parallel surfaces of which one is a conductor. These calculations could be refined by considering more realistic antenna patterns in place of the cone patterns used here, but the results are not expected to change significantly. For any reasonable room dimensions where the ratio of wall lengths is less than two (i.e., a room rather than a hallway), the essential result is that q is in the range from one to two. If $q \simeq 1$, then $o_f \simeq \Phi^2$, which is conservative by no more than 2:1 in predicting outage probability.

D. Effect of Omni or Broadbeam Antenna at One End of the Link

With an omni antenna at T, the image locations are unchanged. Thus to receive a signal, the directional R antenna can be pointed at any image instead of at T, (i.e., at the last reflection point along the ray path from T to R associated with that image). If several such images fall within the beamwidth of R, then multipath will result. Thus, by using an omni at T, there are more ray paths besides the LOS path which can be exploited to establish a link. For example, if T with an omni is placed in the center of the room, then a singly reflected ray[5] will arrive at R from the same direction as T.

With an omni at T, the effect of objects near T becomes more pronounced. In particular, additional ray paths arising from single reflections from objects near T become "active," and multipath may arise which would not occur with a directional antenna at T. Such multipath can be readily eliminated by using a broadbeam (but not omni) antenna with beamwidth of 90–180° and a carefully controlled pattern which does not illuminate the immediately adjacent walls or ceiling.

It is preferable to use the omni at T rather than R, because the user may place R in a cluttered environment with nearby objects (thus, activating additional ray paths), whereas the location of T may be chosen carefully away from the clutter (e.g., on the ceiling), thus avoiding objects near T.

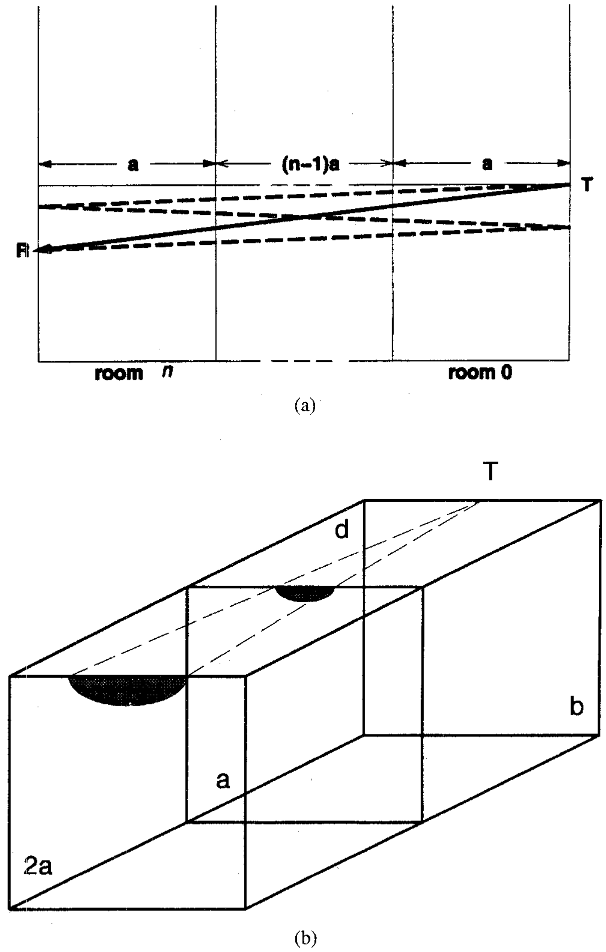

Fig. 5. Critical regions in an adjacent room. (a) Ray paths. (b) Critical region cones.

III. Non-LOS Links to Adjacent Rooms

In this section, we investigate the consequences of using a base station in one room to serve adjacent rooms also. In this case, fewer base stations are required to serve a given area, and those rooms without a base station are served by NLOS links.

For empty rooms, significant multipath is found only when two parallel surfaces are both perpendicular to the direct ($T-R$) path, where at least one surface is a conductor. For adjacent rooms, the common wall is a third parallel surface. For R in a "NLOS room" adjacent to the "LOS room" containing T, there are several ray paths which potentially contribute to the multipath within the critical region. However, for low values of Γ_i, the power transmission coefficient through the ith wall is $\tau_i = 1 - \Gamma_i > \Gamma_i$, and thus, the ray path with the fewest reflections will be the strongest. Fig. 5(a) shows a side view of the rooms. For adjacent rooms, $n = 1$ so that there is only one intervening wall. We label the intervening wall $i = 0$, and the other walls $i = 1, 2$ as before. The direct path is attenuated by τ_0, and the dominant multipath ray is attenuated by $\tau_0^3\Gamma_1\Gamma_2$. Thus, $|\alpha_1|^2 = \tau_0^3\Gamma_1\Gamma_2/9\tau_0 = \tau_0^2\Gamma_1\Gamma_2/9$. The multipath is attenuated by an additional factor τ_0^2 due to the intervening wall. Depending on the value of τ_0, the multipath may fall below the threshold x_1, and the critical region disappears in this case. The size of the critical areas in the adjacent "NLOS rooms" is such that if $a = b = d$, and T is in a corner, $o_f = 1.75\Phi^2$ which is more than twice that for the "LOS room."

These results may be generalized for the nth adjacent NLOS room to help establish how many rooms there can be in between T and R without introducing significant multipath. We define the NLOS room adjacent to the LOS room to be called the 1st adjacent room, so that the nth adjacent room will have n intervening walls between T and R. As before, the multipath is attenuated by the additional factor τ^2, where in this case, τ is the aggregate transmission coefficient through the n walls. If $a = b = d$, the fractional outage ratio for T_2 in a corner is

$$\begin{aligned} o_f &= (0.25)[(n+1)^3 - n^3]\Phi^2 \\ &= (0.25)[3n^2 + 3n + 1]\Phi^2 \\ &\simeq 0.75n^2\Phi^2. \end{aligned} \tag{10}$$

Similarly, we find for both T_3 in the center of the wall, and T_1 in the center of the ceiling, $o_f \simeq 1.5n^2\Phi^2$.

[5]That is, a ray from T departing away from R (in the opposite direction from the LOS path to R) and then reflecting back toward R.

We conclude that NLOS links may be usable, provided that: 1) there are no reflectors within the beamwidth of T and R which would yield a singly reflected multipath in addition to the direct NLOS path, 2) the size of the critical region as a function of n is a reasonably small fraction of the room size, 3) the intervening wall or walls do not introduce significant multipath due to multiple reflections within their thickness, 4) the link budget can accommodate the attenuation of the direct path, and 5) the receiver is not placed in the critical region.

IV. Experimental Work

A. Equipment Description

Experiments using a 19-GHz 622-Mb/s BPSK [and 1.244-Gb/s quaternary phase shift keying (QPSK)] radio link [8] equipment have been performed in a building with offices and laboratories on either side of a long hallway, plaster walls and metallized windows. The equipment setup includes a 622-Mb/s data generator and bit error rate test set (BERT). The multipath delay profile (magnitude of the channel impulse response) is measured using the BERT with a repetitive sequence of a 1 b followed by 63 0 b, thus achieving a time resolution of about 0.5 symbol periods (0.8 ns or 24 cm distance), a maximum unambiguous delay of 100 ns or 30 m (64 symbols) and a dynamic range of about 20 dB. For the antenna at T, a broadbeam antenna (a 45° 3 dB beamwidth horn or an open-ended waveguide) was used to illuminate the rooms to be covered, and the antenna at R is a horn with 15° 3 dB beamwidth. With the open-ended waveguide at T, transmit power of +11 dBm, and receiver noise figure of 5.5 dB, a 20 dB link margin is available to overcome excess path losses (wall attenuation) above the free space loss on a 10 m path.

B. Experimental Methods

For the experiments, various links are set up (LOS, NLOS direct, NLOS indirect via reflectors). Results include a *qualitative part* in which both the impulse responses and the BER are recorded to obtain general impressions of the link behavior, and a *quantitative part* in which many BER measurements are taken at regularly spaced intervals within a room to obtain link outage statistics.

Since the QPSK BER is much more sensitive to weak multipath than the BPSK BER [9], QPSK BER measurements are also taken for locations where the BPSK BER is zero. The QPSK BER measurement may be considered as a crude uncalibrated "multipath detector" for regions where the BPSK BER measurement does not detect multipath (i.e., the BPSK BER is zero).

For the quantitative part, since the BER depends critically on the exact RF phase of the delayed path compared to that of the direct path, it is important to take a sufficient number of spatial samples so that the phase distribution is reasonably uniform. This is because any single spatial sample may not be indicative of the performance nearby (within a few wavelengths) of that point. However, since positioning and aligning the antenna for maximum signal and taking a BER measurement at each location may require one minute or more, the time required may be impractical. Since we are primarily interested in the probability of link outage (i.e., whether the link is good or bad, rather than a specific BER), we consider an alternative approach. We take fewer spatial samples, and if the BPSK BER is zero, we search for "bad spots" (error bursts) by moving the antenna randomly (shaking it) over a distance of a few wavelengths, thus covering all phases fairly uniformly. This approach yields data samples with three possible outcomes: nonzero BER, zero BER, zero BER with error bursts on shaking. The aggregate of all samples in a given room thus yields a coverage map with bad, good and "medium" regions (i.e., link outage, reliable link, usable but error-prone link).

The measurements showed that for most of the BPSK zero BER samples, if the QPSK BER was zero also, then there would be no BPSK errors on shaking, and if the QPSK BER was nonzero, there would be errors on shaking. Thus, the "medium" regions may be loosely defined by the presence of either a nonzero QPSK BER or BPSK error bursts on shaking.

For certain bad spots, the impulse response was recorded and some qualitative testing (e.g., rotating the antenna slightly and observing changes in the impulse response) was done to identify the multipath causing the link to fail.

The fractional outage ratio o_f is estimated as the ratio of the nonzero BER points to the total number of points n. This estimate is conservative, in that a BER exponent of eight or nine is deemed to be an outage. The estimate is approximate, in that only 25 to 90 data points were taken per room.

C. Experimental Results

The qualitative experimental tests consider propagation paths in four categories: direct LOS, direct but obstructed NLOS, indirect path reflected from a smooth surface, and indirect path reflected from a cluttered surface. Reliable data transmission could be achieved on all except the last case. In the critical regions, the impulse response measurements clearly showed the expected multipath components at the appropriate delays.

Quantitative tests were done for direct LOS within one room, and direct but obstructed NLOS to the first adjacent room (one intervening wall), and the second adjacent room (2 intervening walls), as outlined below.

LOS tests were conducted in a laboratory which is cluttered with many metal objects, including wall shelves full of parts and equipment, as well as a large metal fume hood on one wall. T was placed on a tripod at a height of 10 ft just below the suspended ceiling at the center of the short wall (windows to outside). R was placed on a tripod at 6 ft height and pointed at the transmitter. Data samples were taken on the points of a 9 in grid determined by the tiles in the room.

With T either a 45° horn or a 70° open-ended waveguide, the BPSK BER was zero in all locations tried. Locations where no data is given could not be tested due to objects in the way (desks, lab benches, fume hood). With T a 45° horn, the QPSK BER was zero or near zero for most locations close to T, and became higher further away (Fig. 6), even though there was plenty of link margin. With the open-ended waveguide at T, the QPSK BER was consistently higher than with the 45° horn.

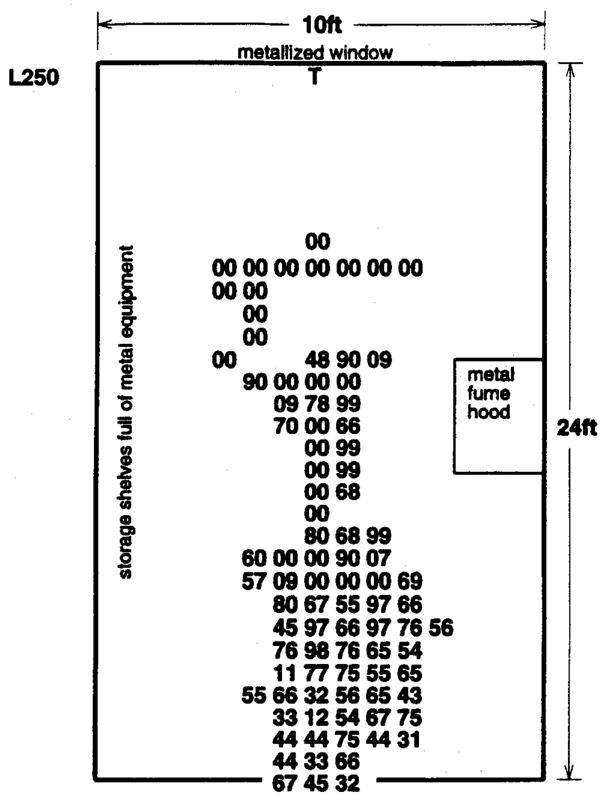

Fig. 6. BER, QPSK, LOS link in single room. Number pairs represent − log(BER) in I and Q channels, 0 means zero errors.

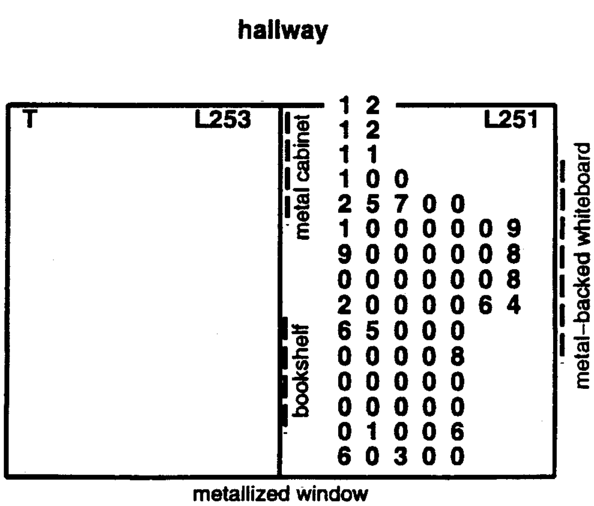

Fig. 7. BER, BPSK, direct NLOS link to adjacent room. Numbers represent − log(BER), 0 means zero errors.

We interpret these results as follows. With the 45° horn, the QPSK error rate increases for R at 17 ft from T. Since the height difference between T and R is four ft, these R locations are near or inside the half-cone critical region in Fig. 4(c). Thus, these measurements tend to support the theory. The BPSK error rate remained zero, even near the half-cone, since the multipath was too weak to close the data eye significantly.

LOS tests were also done in a substantially empty room with highly reflective (metal) walls. This room was chosen to maximize the multipath strength. The BSPK BER results clearly show that the BER degrades inside a conical region with approximate beamwidth of 20°. This result tends to confirm the theory. If perfect wall reflection is assumed, the power in the multipath ray arriving at 20° is approximately 20 dB down compared to the direct ray. This is due to the sum of two effects: the pattern of the 15° horn is approximately 10 dB down from the main lobe, and the distance travelled by the multipath ray is three times longer than the direct path length (i.e., the multipath ray is 20 log 3 = 9.5 dB down). Thus, multipath power 20 dB down is evidently sufficient to cause some BER degradation.

BPSK BER's in the first and second adjacent offices are shown in Figs. 7 and 8.

V. Discussion

A. *Qualitative Results*

A variety of reliable 622-Mb/s BPSK indoor radio links at 19 GHz have been demonstrated. Using a receiver antenna with a 15° 3 dB beamwidth, and either a 45° horn or a 70° open-ended waveguide at the transmitter, error-free performance is obtained by pointing the antennas at each other on a direct LOS path in all cases tried. Qualititive tests show that error-free performance can also be obtained on other types of propagation paths, including a direct but NLOS path obstructed by a nonmetallic wall, and an indirect path bouncing off a smooth wall or smooth ceilings. Error rates in the 10^{-1}–10^{-8} range can be obtained by bouncing the signal off a "cluttered" wall with metallic equipment on shelves, depending on the extent of the clutter. These errors may be explained by multipath arising from multiple reflection points spaced in the range of a data wavelength (48 cm).

When the LOS link is blocked (i.e., the transmitter and receiver are in different rooms), then the path loss of a ceiling-reflected link may be much less than that of the blocked direct path, as previously observed in [3]. This result is unfortunately of no help in establishing a data link, since the multipath delay profile shows a cluster of paths for these cases. These clusters, presumably due to the many metallic reflectors (ducts, pipes) hidden behind the suspended ceiling, cause the data eye to be closed on most ceiling-reflected links. Only a few examples of "clean" reflections from the ceiling (with BER = 0) were found.

Unusable links where the eye was closed even with strong signals could be deliberately constructed using smooth (not cluttered) reflectors, by careful placement and orientation of the antennas to create multipath, corresponding to the single and double reflection cases. Such unusable links were constructed by setting up a two-ray link with a LOS and a floor-reflected path, and tilting the antennas so as to obtain roughly equal strength from each path with relative delays on the order of a symbol period (1.6 ns). Other unusable links were constructed by setting up two large parallel reflectors perpendicular to the path, resulting in strong multipath components at delays corresponding to multiples of the spacing

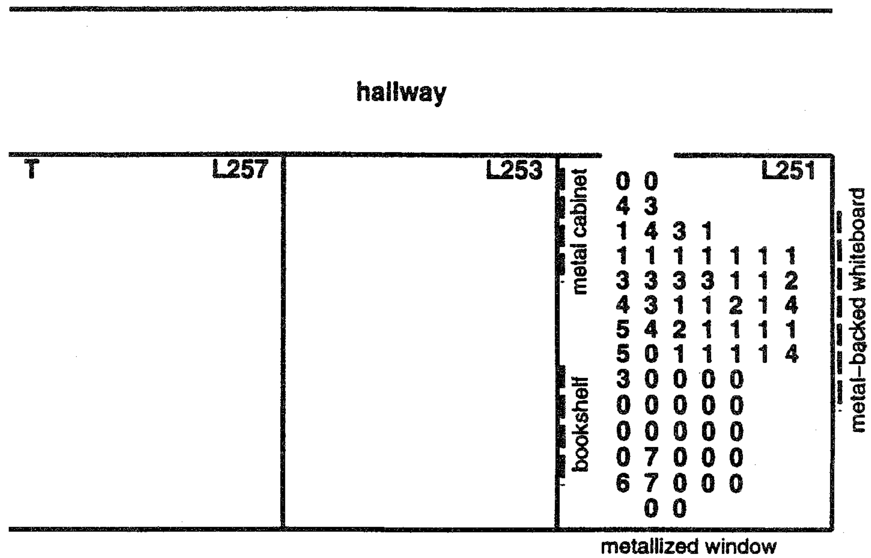

Fig. 8. BER, BPSK, direct NLOS link to second adjacent room. Numbers represent $-\log(\text{BER})$, 0 means zero errors.

between the reflectors. Thus, we confirmed the presence of critical locations (regions) and orientations of the antennas which can cause a link to fail.

B. Quantitative Results

Quantitative results with a broadbeam (70° beamwidth, not omni) antenna at T and the 15° horn at R show reliable BPSK LOS links ($o_f = 0/90$) within a cluttered lab. No errors were found even with the antenna placed in the critical regions, since none of the walls were smooth conductors, so that the multipath power was insufficient to cause BER degradation. This result is very encouraging, since this lab may be considered a near-worst-case for a cluttered environment with many metallic reflectors.

Reliable BPSK NLOS links were observed with the receiver in an adjacent room (one intervening wall) and the second adjacent room (two intervening walls), provided that the direct path was not blocked by a large metal object.

A few impulse response samples taken at selected points revealed multipath which could be explained by the local geometry.

C. Practical Applications

The results may suggest that detailed engineering design of antenna locations may be required to obtain reliable system performance. In practice, however, an *ad hoc* approach may be sufficient. Fixed directional antennas may be acceptable for a lower cost system where the users R are fixed (e.g., desktop workstations), and an antenna can be manually pointed at the base station T. Antennas may be placed by the users on room dividers, shelves or walls (pointing at T) so as to avoid critical regions and minimize the probability of people walking through the beam. If the link performance is unsatisfactory, (i.e., R is in a critical region), then it will be necessary to manually search for an alternate path or to move the antenna.

Adaptive antenna arrays would increase the system flexibility and robustness, and permit the tracking of mobile users. Such adaptive arrays can be programmed to do beamforming, and to find the optimum path at any given time. If the direct path is temporarily blocked, then an alternate path may be used instead. The essential function of the beamforming adaptive array is to scan for and find a single isolated ray among the multiple rays which arrive at the receiver. *A key result of this work is that a* 15° *beamwidth is sufficiently narrow* for this purpose. This beamwidth can be achieved at millimeter waves with small antennas (e.g., a 10×10 patch array). With adaptive arrays, the anti-multipath signal processing has been moved from the time or frequency domain to the space domain. This is an advantage at high bit rates, where time domain processing (e.g., equalization) may be difficult to implement. A topic for future study may be to find an optimum combination between time and space domain processing for a given indoor environment.

VI. Summary

For an indoor wireless system (e.g., a WLAN) with directional antennas, we have identified the primary sources of multipath, and estimated the antenna beamwidth (and thus the frequency for a practical antenna size) above which multipath effects due to reflections from walls, floor and ceiling are negligible. In general, we conclude that smooth conducting surfaces will cause significant multipath and limit the achievable data rate, whereas dielectric surfaces do not (unless ϵ_r is very high). For directional LOS links, any ray paths which contribute multipath components must arrive at R from the same direction as T. Thus, significant multipath was found only:

1) for a single reflection when an object is parallel to but offset from the LOS path, and within the beamwidth of both T and R; and
2) for a double reflection from two parallel surfaces, where both surfaces are perpendicular to the LOS path, and at least one surface is a conductor.

In all other situations, the multipath was negligible.

The specular reflectors (e.g., conductors with reflection coefficient near one) need not be very large, i.e., a size $D > \sqrt{r\lambda/2}$ (near-field) is sufficient. The reflectors may be walls with metal-backed whiteboards, metallized windows, desks, filing cabinets, or electronic equipment with smooth metal surfaces.

The double reflector case results in critical regions which cannot be avoided, but which can be reduced in size by using a smaller beamwidth, and carefully selecting the base station (T) location in the room. These critical regions are cones with tip at T and a base with radius $\simeq a\Phi$ on the wall or floor, where a is the room dimension and Φ is the full beamwidth. Guidelines for placement of T to minimize the size of the critical regions are to: avoid T locations on the shorter of two walls; and to avoid T locations on parallel surfaces of which one is a conductor.

With certain simplifying assumptions, an estimate of the link outage probability is given by the ratio of the critical region volume to the total room volume. If the guidelines for T placement are followed, then the fractional outage ratio is approximately equal to the square of the beamwidth in radians, i.e., $o_f \simeq \Phi^2$. o_f can be further reduced by keeping R outside the critical regions, i.e., by avoiding LOS paths which run perpendicular to the walls or floor. LOS paths which are offset from the perpendicular by at least a half-beamwidth are preferred.[6] To obtain 1% outage ($o_f = 0.01$), the beamwidth $\Phi = \sqrt{o_f} = 0.1$ radians (6°). For a practical antenna area $d^2 = 10 \times 10$ cm, and using $\Phi = \lambda/d = c/fd$, we can obtain a 0.1 radian beamwidth for frequencies above $f = c/\Phi d =$ 30 GHz.

NLOS links may also be usable, provided that the intervening wall or walls do not introduce significant multipath due to multiple reflections within its thickness, and the link budget can accommodate the attenuation of the direct path. For such NLOS links between immediately adjacent offices, o_f is within a factor of two of that achievable on a LOS link. For the nth adjacent office (with $n-1$ intervening offices), o_f increases approximately as n^2.

Experimental results with a 19-GHz 622-Mb/s BPSK indoor radio link using a horn antenna (15° full beamwidth) at the receiver demonstrated that reliable indoor data transmission can be achieved. The link performance may degrade inside the critical regions, but only if the reflections are strong enough.

[6] If the directional antenna is implemented as an adaptive antenna array at T and R, and R is in a critical region, then the system can search for alternate (indirect) paths between T and R, e.g., a single specular reflection from a wall parallel to the LOS path. In this case, it may not be necessary to keep R outside the critical regions, thus further reducing o_f.

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