High Data Rate Indoor Wireless Communications Using Antenna Arrays

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Abstract

In this paper, we consider the feasibility of indoor wireless communications at very high data rates (up to multi-Gbps). In particular we wish to use one base station to cover the entire floor of an office building, which may have in excess of 60 dB propagation loss relative to 1 meter. This feasibility depends on two factors: received signal power margin and delay spread. Based on results using the propagation-prediction techniques of [1], supported by experimental results up to 622 Mbps, we conclude that neither multicarriers, equalization, nor antenna arrays with less than 1600 elements at one end of a communication link are economical methods for increasing the data rate substantially above 10 to 20 Mbps for multiple room indoor wireless coverage. However, based on the propagation-prediction techniques of [1] and verified by our experimental measurements using directive antennas (15° beamwidth) at both ends of a link between the center of the Crawford Hill building to an end laboratory, we have shown that high-speed ubiquitous communication is feasible. Using antenna arrays with 50 to 200 elements at both the transmitter and receiver, we expect to obtain entire floor coverage at data rates in excess of 1 Gbps.

1. Introduction

In this paper, we consider the feasibility of indoor wireless communications at very high data rates (up to multi-Gbps). In particular we wish to use one base station to cover an entire floor of an office building.

This feasibility depends on two factors: received signal power margin and delay spread. Previous measurements have shown that the maximum propagation loss for a single floor in several office buildings, including the Crawford Hill building, is typically 60 dB (relative to 1 meter, averaged over the multipath fading), while the rms delay spread is typically on the order of 100 ns [2,3]. This rms delay spread limits the maximum data rate to about 1 Mbps. Current proposals consider equalization or multicarrier processing to increase this data rate to 20 Mbps, but the circuitry is near the complexity limit for an economical system and maintaining reasonable outage probability with a 60 dB propagation loss (relative to 1 meter) may be difficult to achieve.

Here we consider the use of phased arrays (tested in our experiment by using directive antennas) to increase the power margin and decrease the delay spread of the signal at the receiver, thereby permitting data rates in excess of 1 Gbps. Note that if the multipath in a building generated signals at the receiver that were uniformly distributed in power and delay spread with respect to angle-of-arrival, antenna arrays would not be useful. However, results using the propagation-prediction techniques of [1] for in-building propagation over an entire floor of the Crawford Hill Building show that this is not the case. In particular, our results show that arrays at the transmitter and receiver with 25° beamwidths can isolate one ray, with high probability, and thereby achieve nearly the full gain of the antennas and eliminate delay spread. To support this conclusion, we present experimental results for 622 Mbps at 19 GHz from several locations within the Crawford Hill building, using manually-scanned directive (15° beamwidth) horn antennas. We have investigated ways of economically fabricating antenna arrays with these beamwidths, which, based on our results, would make entire floor coverage at high data rates economically feasible.

In Section 2 we discuss the data rate limitations due to power margin and delay spread. The effect of antenna arrays is studied in Section 3, using both propagation-prediction results and experimental data.

0-7803-3002-1/95 $4.00

2. Data Rate Limitations

Consider first the received signal power margin. The margin is given by

$$Margin = \frac{E_b}{N_o} - \left.\frac{E_b}{N_o}\right|_{req} , \qquad (1)$$

where $\frac{E_b}{N_o}$ is the energy per bit to noise density ratio at the receiver and $\left.\frac{E_b}{N_o}\right|_{req}$ is the ratio required to achieve a given bit error rate (BER). Now,

$$\frac{E_b}{N_o} = \frac{P_{rec}}{N} , \qquad (2)$$

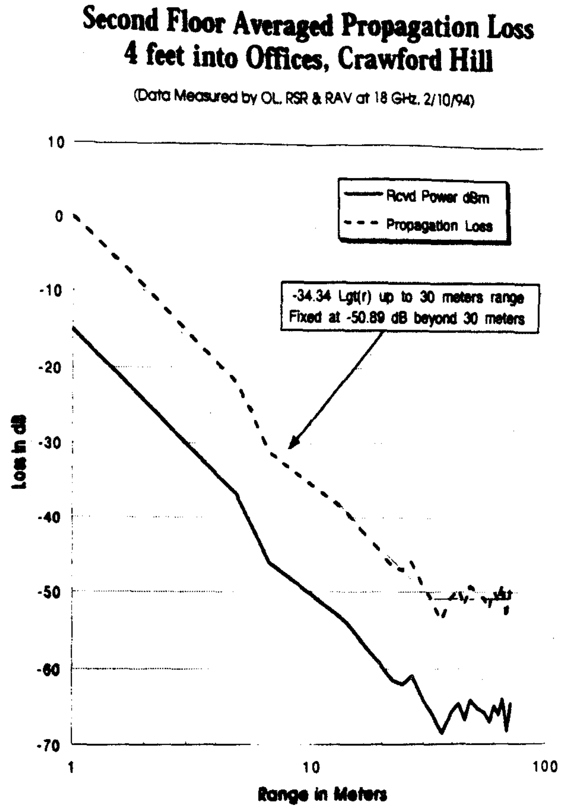
where P_{rec} is the received signal power given by [6, p. 490]

$$P_{rec} = P_a \cdot L_{CT} \cdot G_t \left[\frac{\lambda}{4\pi}\right]^2 \cdot L_P \cdot G_r \cdot L_{CR} , \qquad (3)$$

N is the noise power given by

$$N = kTB \cdot NF , \qquad (4)$$

and P_a is the power out of the transmit amplifier, L_{CT} is the loss of cable to the transmit antenna, G_t is the transmit antenna gain, λ is the wavelength, L_P is the propagation loss relative to 1 meter free space, G_r is the receive antenna gain, L_{CR} is the loss of cable from the receive antenna, k is Boltzmann's constant (1.38×10^{-20} mW/Hz/°K), T is the system noise temperature, B is the bandwidth, and NF is the noise figure of the receiver. In (4), we assume that the signal bandwidth is equal to the data rate. Let us consider typical values for the following parameters: P_a=23 dBm, L_{CT}=1 dB, L_{CR}=1 dB, T = 290 °K, and NF = 6 dB. To operate with data rates up to Gbps, the carrier frequency must be in the range of 19 GHz (or higher), or $\lambda = 3\times10^8/1.9\times10^{10}$ m. Now, the prediction techniques of [1], along with experimental measurements [1], have shown that in several buildings, including Crawford Hill (which has sheetrock interior walls), with a suitably-placed base station, the maximum propagation loss, L_P, on one floor is equal to 60 dB. In particular, Figure 1 shows propagation loss measurements of the Crawford Hill building made by R. S. Roman, O. Landron, and R. A. Valenzuela at 18 GHz using omnidirectional antennas. These results show the loss, averaged over the multipath fading by moving the antenna over an area with a radius of several wavelengths, for transmission from the center of the main hallway to 4 feet inside each room (i.e., no line-of-sight). The maximum loss is seen to be less than 60 dB. Thus, with a 60 dB loss, from (2)


Second Floor Averaged Propagation Loss
4 feet into Offices, Crawford Hill

(Data Measured by OL, RSR & RAV at 18 GHz, 2/10/94)

Figure 1 **Propagation loss versus range for the Crawford Hill building.**

$$\frac{E_b}{N_o} = 71 \text{ dB} - 10\log_{10}(B) + G_t + G_r \qquad (5)$$

where G_t and G_r are in dB. If we assume that a BER of 10^{-8} is required, with coherent detection of binary phase shift keying $\left.\frac{E_b}{N_o}\right|_{req}$ = 12 dB [6, p. 380], and the margin is given by (from (1) and (5))

$$Margin = 59 \text{ dB} - 10\log_{10}(B) + G_t + G_r \quad . \qquad (6)$$

Thus, with isotropic antennas (G_t=G_r=0 dB), the maximum data rate is about 800 kbps. (Note that to increase the data rate limitation due to power margin, coding could be used to permit a higher raw BER. For example, with BER = 10^{-2}, and coding to reduce this to 10^{-8}, an additional 4.3 dB margin can be obtained. Thus, from (6), the maximum data rate would be 2 Mbps.) This is the maximum data rate considering the loss averaged over the multipath fading, however. Multiple paths from various directions produce fades in signal strength which vary with distance at wavelength intervals. In practice, additional margin (with a correspondingly lower data rate) must be considered because of this fading. For example, with a single receive antenna and Rayleigh fading (note, however, that our results in Section 3 indicate that the fading is Rician in our building), 10 dB of additional margin is required for 90% availability and 20 dB is required for 99% availability, which lowers the data rate limit to 80 and 8 kbps, respectively, for full, single-floor, building coverage. Of course, at millimeter wavelengths a user would only have to move the receive antenna by a fraction of an inch to move out of a fade, and therefore might not need this margin. However, even though the user antenna may be stationary, the environment changes, which makes this method not practical, and may mean that even a 99% availability would be unacceptable due to frequent, but short, outages. Diversity can be used to greatly reduce this additional margin, though, with two receive antennas cutting the margin required for a given availability in half (in dB).

Next consider delay spread. For many buildings, the rms delay spread is on the order of 30 to 250 ns [2,3]. Since without equalization, a BER of less than 10^{-8} requires an rms delay spread less than about 10% of the symbol period, this rms delay spread results in a data rate limitation of about 1 Mbps. Note that this is similar to the limitation due to power margin (without the multipath fade margin), and thus both factors need to be reduced to operate at very high data rates.

3. Antenna Arrays

First, consider the use of higher gain antennas to increase the margin. Note that if the multipath causes the received signal to be uniformly distributed in power with respect to angle-of-arrival, increased receive antenna gain does not increase the margin. In this case the increase in receive antenna gain is cancelled by the loss of power from the signal outside the beamwidth. Similarly, transmit antenna gain would not increase the margin. However, results using the propagation-prediction techniques of [1], for transmission to users up to 4 rooms away, show that even though the signal received by a user can arrive via hundreds of rays at different angle-of-arrivals, about 50% of the signal energy, i.e., total power from all rays, which is approximated by the multipath-averaging in the measurements mentioned before, is usually concentrated in one ray. Thus, directive antennas should provide an increase in multipath-averaged received signal power over isotropic antennas within 3 dB of their directive antenna gain. For an antenna with a beamwidth in azimuth and elevation (assumed equal) of θ in degrees, the gain for small θ is given by (see also [7])

$$G \approx 10\log_{10}\left[\left\{\frac{360}{\theta}\right\}^2 \frac{1}{\pi}\right] \quad . \qquad (7)$$

Note that this beamwidth and gain can be obtained by an array of M antennas, with the gain, G=10log$_{10}M$. For example, from (6) (which assumes L_P = 60 dB), to obtain enough receive power to support 155 Mbps (with a ray with power 3 dB less than the total received signal power) requires an antenna gain G=26 dB, or, from (7), a 400-element (θ=10°) base station array with omnidirectional antennas at the users. Note that the required gain is given by the product of the gain of the receive and transmit antennas. Thus, we could also use a 100-element (θ=20°) base station antenna with a four-element handset, or a 20-element (θ=45°) array at both ends. Thus, for example, antenna arrays with 15° beamwidths (183 elements) at the transmitter and receiver should support up to 10 Gbps (if delay is not an issue).

Note that these results do not consider additional fade margin due to multipath fading as in the omnidirectional antenna case. We do not consider the multipath fading to be a concern with directive antennas for two reasons. First, an isolated ray should have no fading, since multiple rays are required for fading and the single ray should remain relatively constant in amplitude over many wavelengths. However, although the prediction techniques of [1] may generate only a single ray, the environment may actually generate multiple rays that are closely spaced, rather than a single ray, which could result in fading, albeit with longer fading intervals than with omnidirectional antennas. This fading would typically be Rician, though, with a large K, which greatly reduces the required fade margin. Second, the prediction technique of [1] shows that, at least with the Crawford Hill building, there are typically seven isolated rays, with low delay spread and sufficient power. In this case, we obtain seventh order diversity, which reduces the required fading margin even further. Therefore, we expect the required fade margin to be substantially less than with omnidirectional antennas and will therefore not consider it.

Next, consider antenna arrays to reduce the delay spread problem (see also [4], which also considers directive antennas at both ends of the link to reduce delay spread, but for line-of-sight systems). Since the data rate limitation due to margin (without an additional fade margin) and delay spread are about the same and arrays are needed to increase the maximum data rate due to the margin limitation, we would hope that an M-element array would increase the data rate limitation due to delay spread by the same factor as that due to power margin. Similar to our above results, if the distribution of received power and delay spread was uniform with respect to the angle-of-arrival, directive antennas will not increase the data rate limitation due to delay spread. However, as stated above, the prediction techniques of [1] show that the power of the received signal is not uniformly distributed in angle-of-arrival. However, the range of signal delays can remain large even for small beamwidths as shown below.

An example of this problem is shown in Figure 2, where with omnidirectional transmit and directive receive antennas the delay spread is large even when the receive beamwidth is small. As a result, higher directivity reduces the total power of the weaker rays with respect to the strongest ray within each beam, but not necessarily the delay spread of the signals in the beam. Therefore, the maximum data rate remains below 1 Mbps until the power of the weaker rays becomes small enough. At this point the delay spread limitation is essentially removed. Thus, as the antenna directivity is increased, the data rate is limited to 1 Mbps by the delay spread until the directivity exceeds some value at which point the data rate dramatically increases to the power margin limitation. Furthermore, as discussed above, additional margin due to multipath fading is no longer needed.

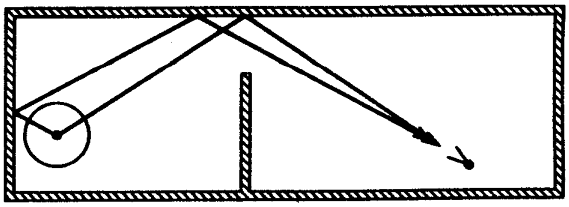


Figure 2 **An example case of omnidirectional transmit and directive receive antennas where the delay spread is large even when the receive beamwidth is small.**

Note that under these conditions, neither multicarrier techniques nor equalization can significantly increase the data rate. Until the beamwidth is sufficiently narrow, the number of carriers or the length of the equalizer must increase linearly with the data rate, independent of the antenna directivity. These techniques become very complex and expensive for data rates greater than 20 Mbps.

The critical parameter is therefore the directivity required for high data rates. Consider first an omnidirectional transmit and directive receive antenna, as in Figure 2. Using [1], Figure 3 shows the beamwidth required at the receiver versus the number of equalizer taps (see below) for 90% coverage at a 1 Gbps data rate. These results were generated for the model of the Crawford Hill building (see Figure 4), using ray tracing to determine all rays received with up to 3 reflections. To show the most optimistic results for the

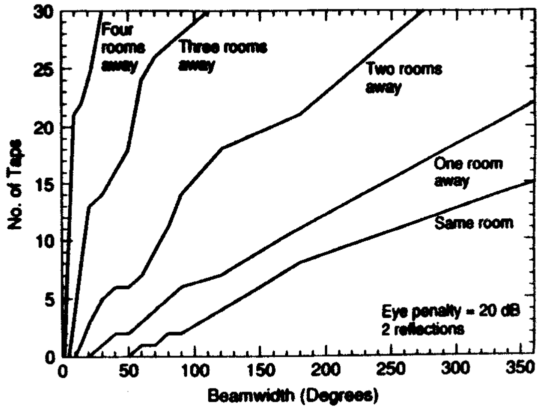


Figure 3 **The beamwidth required versus the number of equalizer taps for 90% coverage with omnidirectional transmit and directive receive antennas.**

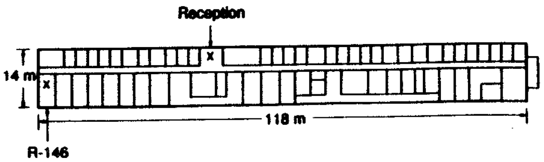


Figure 4 **The bottom floor of the Crawford Hill building.**

effect of equalization and arrays, we only considered delay spread and used a coverage requirement of a 20 dB eye penalty (nearly closed eye) as given by a 1/.9 ratio of the power of the strongest ray (plus other rays within ±.5 of the symbol period) to the sum of the powers of the other rays (with delays outside of ±.5 of the symbol period) within the beamwidth. Furthermore, we considered an N-tap decision feedback equalizer that eliminated the rays in either the strongest N precursor or N postcursor symbol intervals. Figure 3 shows that, even under these overly optimistic conditions, coverage within a distance of four rooms requires 5° beamwidths, and equalization does not significantly reduce the required beamwidth. Thus, a 1650-element array is needed, which appears to be impractical with today's technology.

Therefore, consider using directive antennas at both the transmitter and receiver. Note that the example given in Figure 2 would benefit greatly from this strategy. On the other hand, the example given in Figure 5 shows that even with directive antennas at both ends a small beamwidth may not always reduce the delay spread. However, we would hope that these cases are rare. Therefore, to further improve performance we consider searching over all rays to find the beam direction with the lowest BER due to thermal noise and delay spread. Thus, we could choose a beam with a ray with lower power than the strongest ray, but with less delay spread.

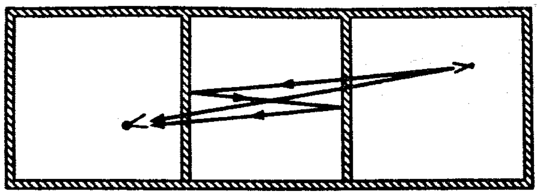


Figure 5 An example case of directive transmit and receive antennas where the delay spread is large even when the beamwidth is small.

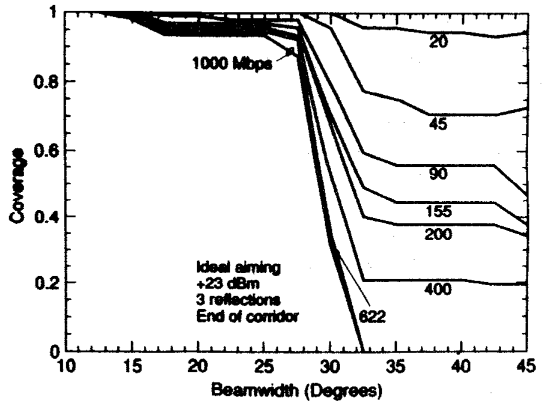
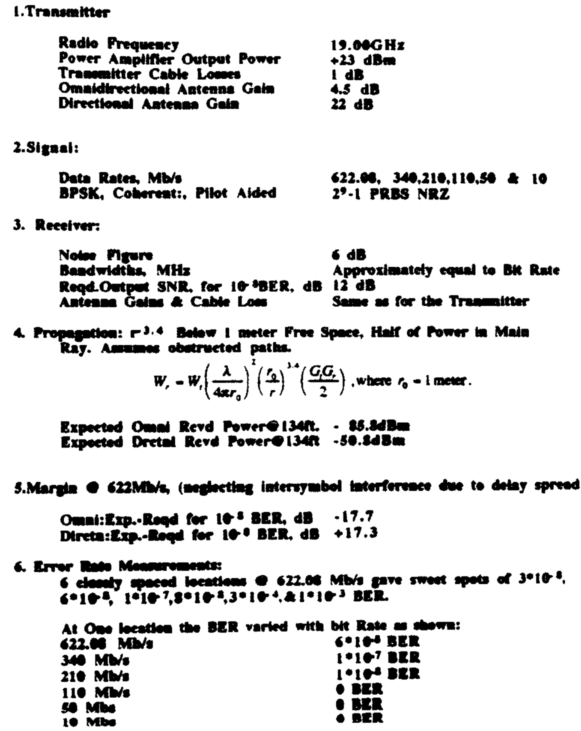


Figure 6 Availability versus beamwidth for several data rates for transmission to the edge of the coverage area using the propagation-prediction techniques of [1] for the Crawford Hill building with rays with up to 3 reflections.

To illustrate these results, and determine the critical antenna size, consider the data rate limitation given by directive beams for one floor of Crawford Hill (see Figure 4) with a 10^{-8} BER requirement. Specifically, for each ray, using the prediction techniques of [1] with rays with up to 3 reflections, we determined if the receive $\frac{E_b}{N_o}$ was greater than 12 dB and, for all the rays within the beamwidth, the rms delay spread was less than 10% of the symbol period. For a given receiver location, an outage occurs if no ray can be found that meets these requirements. For each beamwidth, we chose 60 locations, at the edge of the coverage region, and determined the availability at a given data rate. Figure 6 shows our results for the availability versus beamwidth (with data points taken at 2.5° intervals) for several data rates. These results show that for data rates greater than 20 Mbps, the availability depends primarily on the beamwidth. Availability greater than 90% requires a beamwidth less than 30° (≈50 elements) for 45 Mbps, but 1 Gbps requires only a 25° beamwidth. Thus, if the beamwidth is narrow enough to isolate at least one ray for 45 Mbps operation, data rates up to 1 Gbps and higher are also feasible. For a 13° beamwidth (244 elements), the maximum data rate exceeds 1 Gbps with 100% availability. Thus, in all 60 locations 13° antennas find an isolated ray with enough power to support Gbps data rates. In fact, our results show that about 7 isolated rays (in different 13° beams) with sufficient power are usually found for each location.

To support our conclusions, we performed the following experiment, which is summarized in Table 1. Using the LuckyNet [5] setup, we transmitted up to 622 Mbps at 19 GHz within Crawford Hill. For Table 1, radio link factors are given in [5-7]. The propagation loss is determined as 3 dB less than free space (assuming half the total power in one beam, as above) minus 3.4 power law excess loss (from Figure 1). The transmitter was located in the hallway near the library and reception area on the first floor and the receiver was positioned about 12 feet inside room R146 at the end of the corridor (see Figure 4). Although this is the short end of the corridor (about half the length from the reception are to the other end of the corridor), propagation measurements (see Figure 1) show that the propagation loss (L_P) is similar to that for the longer end, i.e., an average of about 50 dB. The transmit and receive antennas were 15° beamwidth horn antennas, which could be manually scanned.

BER measurements were made at a combination of 6 locations by moving the antenna height or lateral position within a few feet at both ends of the link. At each location, both antennas were manually scanned to try to jointly find the best transmit and receive angles. Note that there are over 33,000 possible transmit/receive angle combinations with 15° beamwidths, and therefore it was not practical to exhaustively search for the best angle. However, since the transmitter was located down a long corridor, we assumed that pointing the transmit antenna toward R146 would be most likely to give the good performance. With this general direction for the transmit antenna, the receive antenna was manually scanned to find a reasonable BER, and the transmit angle was then adjusted slightly to try to improve this performance. We found that good receive angles could not be determined *a priori*, e.g., pointing at the door did not always result in a satisfactory BER. The strongest receive signal had a propagation loss of 51 dB, compared to the predicted propagation loss with omnidirectional antennas of 50 dB. This is in agreement with our expected result of the strongest ray containing about half of the total receive power.



1.Transmitter

Radio Frequency	19.00GHz
Power Amplifier Output Power	+23 dBm
Transmitter Cable Losses	1 dB
Omnidirectional Antenna Gain	4.5 dB
Directional Antenna Gain	22 dB

2.Signal:

Data Rates, Mb/s	622.08, 340,210,110,50 & 10
BPSK, Coherent:, Pilot Aided	2^9-1 PRBS NRZ

3. Receiver:

Noise Figure	6 dB
Bandwidths, MHz	Approximately equal to Bit Rate
Reqd.Output SNR, for 10^{-8}BER, dB	12 dB
Antenna Gains & Cable Loss	Same as for the Transmitter

4. Propagation: $r^{-3.4}$ Below 1 meter Free Space, Half of Power in Main Ray. Assumes obstructed paths.

$$W_r = W_t\left(\frac{\lambda}{4\pi r_0}\right)^2\left(\frac{r_0}{r}\right)^{3.4}\left(\frac{G_tG_r}{2}\right), \text{where } r_0 = 1 \text{ meter}.$$

Expected Omni Rcvd Power@134ft.	- 85.8dBm
Expected Drctnl Rcvd Power@134ft	-50.8dBm

5.Margin @ 622Mb/s, (neglecting intersymbol interference due to delay spread):

Omni:Exp.-Reqd for 10^{-8} BER, dB	-17.7
Drctn:Exp.-Reqd for 10^{-8} BER, dB	+17.3

6. Error Rate Measurements:

6 closely spaced locations @ 622.08 Mb/s gave sweet spots of $3*10^{-8}$, $6*10^{-8}$, $1*10^{-7}$,$8*10^{-8}$,$3*10^{-4}$,& $1*10^{-3}$ BER.

At One location the BER varied with bit Rate as shown:

622.08 Mb/s	$6*10^{-8}$ BER
340 Mb/s	$1*10^{-7}$ BER
210 Mb/s	$1*10^{-8}$ BER
110 Mb/s	0 BER
50 Mbs	0 BER
10 Mbs	0 BER

Table 1 Indoor Wireless Error Rate Measurement

The BER results for 6 locations are shown in Table 1 and range from 3×10^{-8} to 10^{-3}. Note that even a 10^{-3} BER is acceptable since with coding the error rate could easily be reduced below 10^{-8}. Table 1 also shows the variation in BER with bit rate at one location. Except for the highest data rate measured, 622 Mbps, we did not have a clock recovery circuit and used a coaxial line to feed the clock to the receiver. Data rates were adjusted slightly to synchronize the coaxial-line-fed clock to that of the signal received by radio. The BER is nearly constant for data rates greater than 210 Mbps, which implies an irreducible BER (albeit, low BER, $\leq10^{-7}$) that is independent of the data rate, i.e., the received signal consisted of one strong ray with much weaker rays with delay spreads in excess of 5 nsec. Thus, with sufficient receive power, data rates in excess of 1 Gbps should be possible.

This experiment only presents anecdotal results at a few closely-spaced locations to support our conclusions. The propagation loss was 10 dB less than is required for full floor coverage (with a maximum 60 dB propagation loss), but we did not exhaustively search all transmit/receive angles. Even a computer-controlled exhaustive search with directive horns would take many hours for each location, so experimental measurement of availability awaits the construction of phased array antennas.

4. Conclusions

Economically-fabricated antenna arrays with about 100 elements which determine and track the optimum combination of transmit and receive beams, along with networking issues, are complex problems that require further research. However, assuming such technology were available, we make the following conclusions. Based on the propagation-prediction techniques of [1], supported by experimental measurements, neither multicarriers, equalization, nor antenna arrays at one end of a communication link are economical methods for increasing the data rate substantially above 20 Mbps for multiple room indoor wireless coverage. However, based on propagation-prediction techniques and verified by our experimental measurements using directive antennas at both ends of a link between the center of the Crawford

Hill building to an end laboratory, we have shown that high-speed ubiquitous communication is possible. Using antenna arrays with 50 to 200 elements at both the transmitter and receiver, we can expect to obtain entire floor coverage at data rates in excess of 1 Gbps.

Acknowledgements

We gratefully acknowledge R. S. Roman and O. Landron for providing the experimental results presented in Figure 1, and A. A. M. Saleh for proposing the high-speed data measurements.

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