MULTI-FREQUENCY RADIOWAVE PROPAGATION MEASUREMENTS IN THE PORTABLE RADIO ENVIRONMENT

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ABSTRACT

Time delay spread and signal level measurements were made in two dissimilar office buildings at 850 MHz, 1.7 GHz and 4.0 GHz. No significant statistical difference in time delay spread was found at the three frequencies. The maximum rms time delay spread at the three frequencies did not exceed 270 nanoseconds at the larger building and 100 nanoseconds at the smaller building. Attenuation, while very nearly the same at the three frequencies, decreased slightly with increasing frequency, within the limits of the experiment's accuracy. The variation of the received signal level with distance could be characterized by free space propagation together with attenuation per unit distance. This attenuation coefficient decreased slightly with increasing frequency. The fractional error was found to be a useful measure of the spread of the data.

INTRODUCTION

Universal digital portable communications requires radio equipment which will work reliably within buildings in an environment which has multipath propagation, shadow fading, and moderate motion [1]. The intersymbol interference produced by this radio channel is related to the root mean square (rms) time delay spread of its impulse response [2] [3].

The first measurements of time delay spread at three office buildings and two residences were reported earlier by Devasirvatham [4] [5] [6] [7]. These studies, at 850 MHz, consistently measured root mean square time delay spreads under 100 ns within the buildings when there was a direct path between the transmitter and receiver. In the absence of a direct path, rms delay spreads of as much as 250 ns were seen. Other measurements in offices and factories have also been reported [8] [9].

The first time delay spread measurements at both 850 MHz and 1.7 GHz inside a metropolitan office building were reported by Devasirvatham, Murray and Banerjee [10]. This paper reports the results of the first measurements conducted at 850 MHz, 1.7 GHz and 4.0 GHz, inside two other dissimilar office buildings.

THE EXPERIMENT

Details of the experimental setup to measure the impulse response of the radio propagation channel have been reported earlier [5] [6]. Briefly, an 850 MHz, 1.7 GHz or 4.0 GHz carrier, bi-phase modulated by a 40 Mbit/s pseudonoise code, is broadcast by a transmitter. The signal suffers time-smear in the propagation channel and is then correlated at the receiver with an identical pseudonoise code, running 4 kbit/s slower. As the codes sweep past each other, the receiver traces out the power-delay profile of the channel and its envelope is recorded.

The transmitting and receiving antennas were wideband omni-directional units, at heights of 1.5 m and 2 m, respectively. At every measurement location the receiver antenna was rotated through a horizontal 1.2 m (4 foot) diameter circle. Eight power-delay profiles were obtained at equally spaced positions around the perimeter of this area. For each profile, 2048 points, representing either 2048 or 4096 ns depending on the time scale, were digitized and stored after verifying that there was no signal at greater time delays. The eight individual profiles were then power averaged at each time delay to calculate an averaged power-delay profile. After noise clipping, the area under the curve gives the received power level, while the square root of its second central moment, the rms time delay spread, is the measure of channel dispersion that has the most significant effect on the digital error rate [2] [3].

A total of 50 averaged power-delay profiles were obtained at each frequency in Building OFC/NCO and 28 at Building OFC/NST.

SITE DESCRIPTIONS

The experiment was conducted in one large and one medium sized office building. The larger building, henceforth referred to as OFC/NCO, was the Corporate Headquarters of NYNEX Corporation in White Plains, New York. This large four-floor L-shaped structure measures 121 x 75 m in plan. The building is shadowed to the north by a hill and to the south-east by another large building of the same height. The south and west faces are open. Offices and conference rooms opening off corridors in the longer arm are partitioned using sheet rock walls. The shorter arm is laid out mostly with office cubicles. Usually, line of sight was found only in the aisles and corridors. The floors are constructed using reinforced concrete. The metallized glass outer walls are shaded with venetian blinds. All the measurements were made on the top floor.

The medium sized office building, referred to as OFC/NST, was the NYNEX Science and Technology Center at White Plains, New York. It is a rectangular two-level structure, with a hill to the north. It measures 104 x 47 m in plan. Inside, the two floors have been divided, using rectangular layouts, into aisles, corridors, laboratories and rooms utilizing metallic partitions with a 0.67 m high glass upper portion. Once again, line of sight was only found in the same aisle or corridor. The floor is constructed of concrete and raised false floors are provided throughout the facility. There is a significant amount of laboratory equipment in the rooms. The building's conventional 1950's stone and brick facade has been completely replaced by an aluminum panel system with large metallized glass windows which have metallic venetian blinds. All the measurements were made on the second floor.

In both locations, the receiver was placed, in an aisle or corridor, often at an intersection. The transmitter was moved to locations in aisles, corridors and office rooms. Laboratories were also included in the measurements at OFC/NST.

RESULTS

An averaged power-delay profile at 850 MHz in OFC/NCO is shown as the solid curve in Figure 1. The dotted curve shows the averaged profile at 1.7 GHz and the dashed curve that at 4.0 GHz at the same place, taken immediately afterward. Each curve has been separately normalized to the peak power value of a power-delay profile received at that frequency at a reference distance of 0.3 m in free space. This corrects for frequency dependent system parameters such as transmitted power and antenna gains, and path loss to the reference distance. These three profiles match very closely, indicating that they suffer the same impairments over the multiple echo paths in this location. The higher receiver noise tails at 1.7 GHz and 4.0 GHz are artifacts of the normalization, since the absolute received signal levels were lower at those frequencies and hence closer to the noise floor of the receiver.

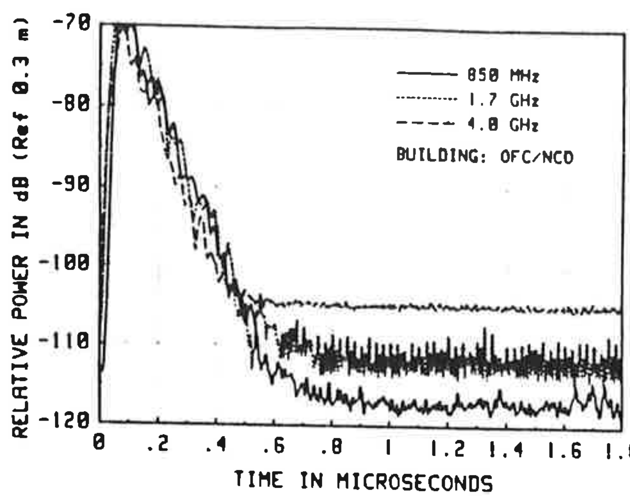

Figure 1. Typical averaged power-delay profiles at 850 MHz (solid curve), 1.7 GHz (dashed curve), and 4.0 GHz (dotted curve) at a location in Building OFC/NCO.

The rms time delay spread measured inside the buildings OFC/NCO and OFC/NST, respectively, was calculated at the three frequencies for all locations measured. The maximum rms delay spread in OFC/NCO at 850 MHz was 270 ns, while it was only 150 ns at 1.7 GHz and 130 ns at 4.0 GHz. This significant anomaly was found at a single location where the 850 MHz profile was much wider than the other two. It appeared that echoes from outside the building were visible at 850 MHz, but not at the other two frequencies. This result is puzzling, but repeatable at that spot.

The rms delay spread did not exceed 100 ns at any frequency at OFC/NST. It was also seen that, excluding the above-mentioned single anomaly at 850 MHz, the three distributions plotted from the data at each site were quite similar. The worst-case value is much less than the worst-case results measured in other larger buildings. Many locations had blocked direct paths, since the transmitter was positioned in conference rooms and in individual suites separated from the main area by walls. The fact that the worst-case results are still not much greater than the direct-path results seems to indicate that the interior walls and partitions are quite transparent at these frequencies.

Figures 2 and 3 show the rms time delay spread at 1.7 GHz and 4.0 GHz, plotted against the rms time delay spread at 850 MHz at the same positions of the transmitter and receiver in the two buildings.

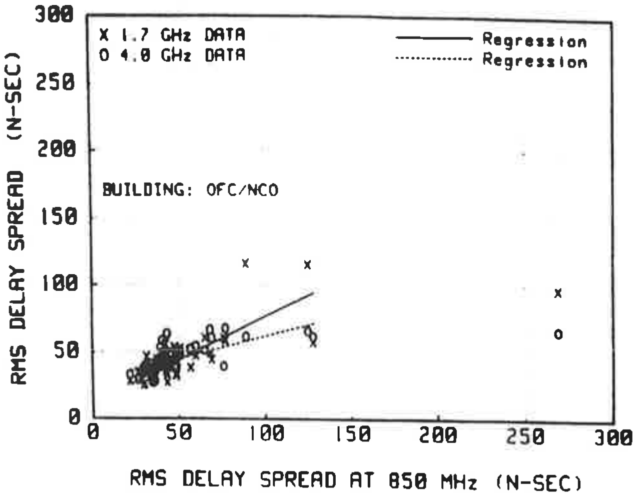

Figure 2. Root mean square time delay spread at 1.7 GHz (X symbols) and 4.0 GHz (O symbols) plotted against the results at the same locations at 850 MHz in OFC/NCO. The regression line for all the data is shown as the central solid curve (1.7 GHz) and dotted curve (4.0 GHz).

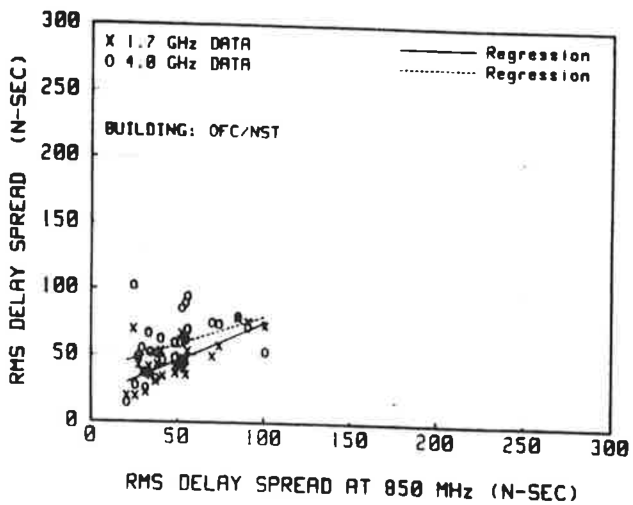

Figure 3. Root mean square time delay spread at 1.7 GHz (X symbols) and 4.0 GHz (O symbols) plotted against the results at the same locations at 850 MHz in OFC/NST. The regression line for all the data is shown as the solid curve (1.7 GHz) and dotted curve (4.0 GHz).

The solid curve is the regression line through all the points at 1.7 GHz, while the dotted curve is the regression line for the 4.0 GHz results. The single outlying point at 850 MHz is excluded from the regression.

These regression results are not very meaningful, quantitatively. This is because the data are clustered about small values of delay spread. The few larger delay spread values exert a disproportionate influence on the regression lines. Nevertheless, it may be said that as the frequency ratio increases, the delay spreads at a particular location tend to be less correlated. Furthermore, the worst-case rms delay spreads at the higher frequencies are not larger, statistically. This also agrees with earlier results at 850 MHz and 1.7 GHz inside a metropolitan office building [10] . This is a very useful result since it suggests that rms delay spread will not, by itself, limit the use of the higher frequencies for a communications system operating within a large building. More data in buildings that produce large delay spreads are needed, however, to confirm this.

Figures 4 and 5 show the received relative power at 1.7 GHz ('X' symbols) and 4.0 GHz ('O' symbols) plotted against the corresponding power at 850 MHz for the same locations of the transmitter and receiver in the two buildings. The power levels are normalized to the power received at each frequency at 0.3 m (1 foot), a convenient distance. This normalization removes system dependent parameters such as transmitted power and antenna gains from the results and gives a measure of the relative path loss at each frequency. The relative power levels range from -35 dB to -95 dB at OFC/NCO and -22 to -85 dB at OFC/NST. The regression lines for all the data at each frequency are shown in the figures as the center line of the set of three lines shown at that frequency. The line above and below it are a set of bounds, which will be discussed below.

It is apparent, when looking at the data, that the spread of the data from the regression line increases as the relative signal level decreases. This behavior is commonly seen in other measurements also [11] . In order to study this behavior, the ratio of the deviation of the data point from the regression, to the regression value, itself, was taken. This was called the "Fractional Deviation" of the data. Therefore, the fractional deviation of the power, $d_f(P_{dB})$, was defined as,

$$d_f(P_{dB}) = \frac{(P_{dB} - P_{dBreg})}{P_{dBreg}} \qquad (1)$$

where P_{dB} is the received power relative to the received power at 0.3 m, in decibels, and P_{dBreg} is the regression value of relative received power in decibels. The rms value of all d_f values will be denoted by σ_d.

We note that the fractional deviation of power is implicitly dependent on the reference power relative to which the denominator is calculated. Intuitively, one may postulate that it should be measured close to the transmitter. In our measurements, this reference was at 0.3 m. Fortuitously, it gave good results. No other justification is given.

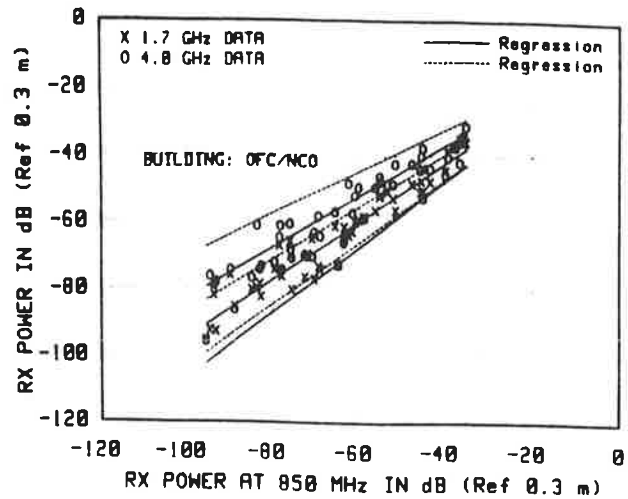

Figure 4. Relative received power normalized to the power at 0.3 m separation at 1.7 GHz (X symbols) and 4.0 GHz (O symbols) plotted against the results at the same locations at 850 MHz in OFC/NCO. The regression line for all the data is shown as the central solid curve (1.7 GHz) and central dotted curve (4.0 GHz). The corresponding lines on either side show ± two fractional deviations.

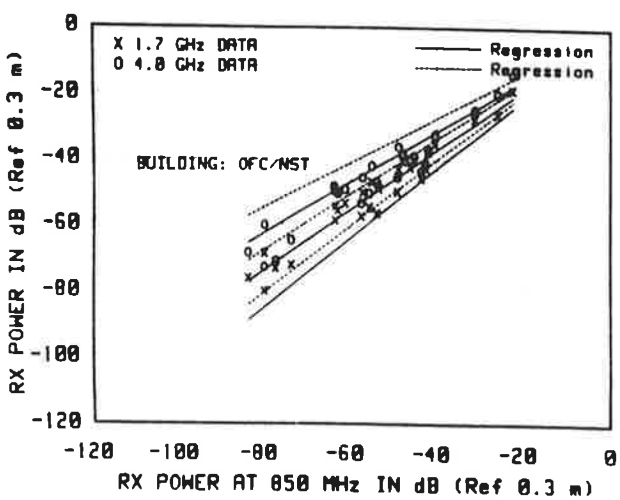

Figure 5. Relative received power normalized to the power at 0.3 m separation at 1.7 GHz (X symbols) and 4.0 GHz (O symbols) plotted against the results at the same locations at 850 MHz in OFC/NST. The regression line for all the data is shown as the central solid curve (1.7 GHz) and central dotted curve (4.0 GHz). The corresponding lines on either side show ± two fractional deviations.

Figure 6 shows the fractional deviation of power for the 1.7 GHz - 850 MHz pair of data at the building OFC/NCO, plotted against the power at 850 MHz. It is seen that the spread is now independent of the received

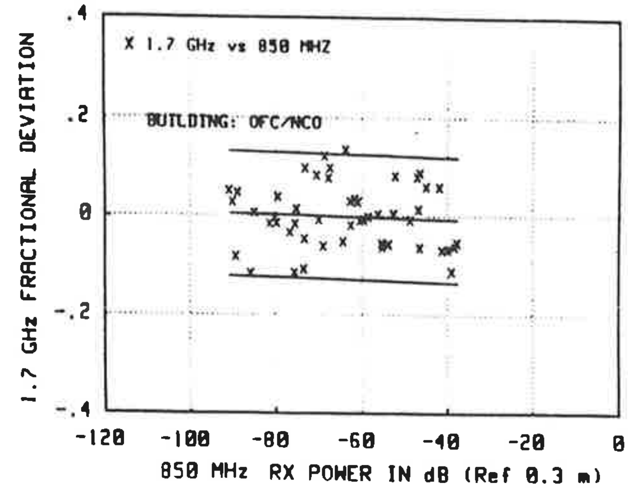

Figure 6. Fractional deviation of power at 1.7 GHz from the regression line, plotted against the power in dB at the same locations at 850 MHz in building OFC/NCO.

relative power. It was found, using statistical analysis, that the spread was not Gaussian, but was better approximated by a uniform distribution. The rms fractional spread, $\sigma_{d(P_a)}$ for this data was 0.064 . It was further found, experimentally, that curves drawn at $\pm 2\sigma_{d(P_a)}$ about the regression curve enclosed virtually all the data points at each frequency at each building. These curves are also drawn in Figures 4 and 5. This is a new and useful result that enables reasonable bounds to be estimated for the propagation data.

The regression results are tabulated in Table 1. They clearly show a small but significant departure from the 45 degree line as the frequency increases. While the lines converge to common values at the higher power levels, i.e., close in, somewhat unexpectedly they deviate so that the relative received power is higher at the higher frequency as the path loss increases.

The 4.0 GHz data lie, in general, at higher relative power values than the 1.7 GHz points or 850 MHz data. The differences in some cases are as much as 15 dB. It is also useful to note that the enhancement of relative level above the 850 MHz data occur where the signals are the weakest (i.e., where the path loss is greatest). Since the frequency-related free space path loss would increase only about 6 or 12 dB at 1.7 or 4.0 GHz, respectively, absolute signal levels could be higher at the higher frequency as well, in this region. This agrees with visual observations at 4.0 GHz on several occasions while making the measurements. The enhancement of the 1700 MHz signal is not as great, and was not obvious during the measurements.

While the intercepts for 1.7 and 4 GHz regression lines are close at each building, the deviation of the intercepts from zero at OFC/NCO is puzzling. There may be some error introduced in extrapolating the data into the close-in region, since this extrapolation must be extended further at OFC/NCO.

Next, the variation of relative received power with distance was studied. Figures 7 and 8 show examples of the relative power, referenced to the power at 0.3 m, at two frequencies in building OFC/NCO. The distance is plotted on a logarithmic scale. As expected, the power falls off with distance. Characterizing this fall-off was somewhat challenging. Piecewise linear approximations, as well as a two-path model together with an attenuation term, were considered. Neither model is intuitively satisfying in this cluttered environment. Hence the approach taken was to apply a simple free space + linear path attenuation model. The signal clearly expands from the transmitting antenna. It passes through walls and other obstructions. As the number of these obstructions increase, their effect may be approximated by some attenuation coefficient in dB/m.

When this model was applied to the data, the results were as good or better than the first two approaches outlined above over the span of the data. Since this model is also closer to the physical reality, it was decided to use it on all the data. However, it must be borne in mind that the model may not apply outside the range of the data, and that it should be used only inside the building.

In figures 7 and 8, the model fit was optimized by varying the attenuation coefficient alone. No offset to the free-space portion of the model was allowed. The model regression lines and suggested upper and lower bound lines, based on twice the rms fractional deviation from the regression for that data, are shown as well. Table 2 shows the regression parameters for the free space + linear path attenuation model, at these locations.

The figures and table 2 show that the model fits the data satisfactorily. The variation of the linear attenuation coefficient with frequency is small, yet consistently decreasing with increasing frequency. Their effect in dB over long distances is sufficient to account for the observed reduction in path attenuation with increase in frequency. Their values at each frequency are also somewhat different for the two buildings. The building OFC/NST, with more metallic walls and partitions, shows smaller attenuation coefficients at corresponding frequencies. This may imply that the propagation in this building is more by reflection than direct transmission through walls.

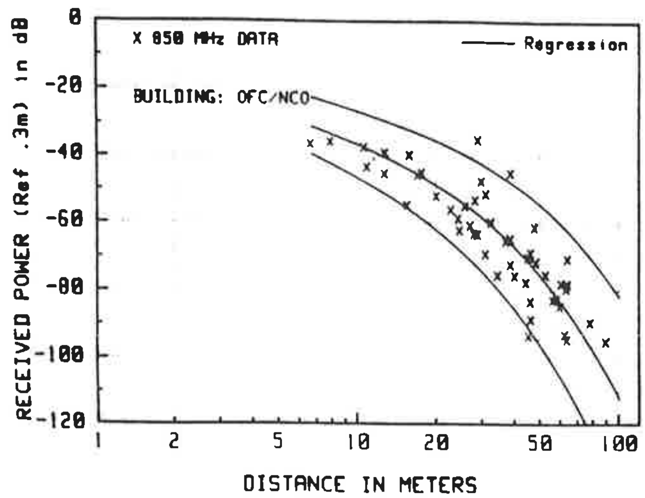

Figure 7. Received power at 850 MHz in OFC/NCO, relative to the power at 0.3 m shown against the distance on a logarithmic scale. The central curve is the model regression line. the side curves are the ± two fractional deviation bounds.

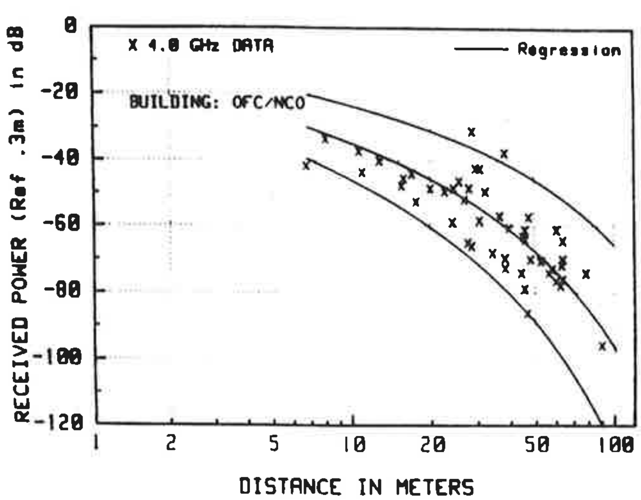

Figure 8. Received power at 4.0 GHz in OFC/NCO, relative to the power at 0.3 m shown against the distance on a logarithmic scale. The central curve is the model regression line. the side curves are the ± two fractional deviation bounds.

The standard deviation of the power data from the regressions are all between 8 and 10 dB. This difference is not significant for practical purposes. Since the data again exhibits increasing spread as the distance between the transmitter and receiver increases, the rms fractional deviation was found to be a more useful parameter in bounding the data. The data bounds drawn in these figures are also at $\pm 2\sigma_{d}$, chosen conservatively to enclose most of the data points. The few points that lie significantly above the upper bound line were found to be direct line-of-sight data.

The variation in the standard fractional deviation is slightly larger in OFC/NST. This may be due to the smaller data sample in this building.

DISCUSSION

Universal portable communications could be provided with low power transmitters and low antenna heights, using relatively small coverage areas compared to today's mobile radio systems. In such a system, a densely inhabited area such as a multi-story office building would have a large number of small coverage areas located within the building, perhaps a few per floor. Therefore, interference between neighboring buildings or other floors is a significant concern.

The two buildings under study, while different in interior construction, were covered with metal or metallized glass skins. This may explain the relative similarities in the delay spread results. Observation of the delay-spread profiles indicated that the signals appeared to be mostly confined inside the buildings, especially at the higher frequencies. At 850 MHz, some small returns at larger distances were occasionally visible. Thus the delay spread profiles would essentially measure the size of the buildings. In the absence of interior "cavity-like" effects, the delay spread numbers would also be bounded. This may explain why the rms delay spread results are quite low for these two buildings. This would also indicate that interference between adjacent buildings may not be great. Furthermore, the interference may be reduced by operating at the higher frequencies.

The linear path attenuation also appeared to decrease as the frequency increased. As indicated earlier, even the absolute 4.0 GHz signal level was, on occasion, stronger than the other two frequencies. There may also be "waveguide" effects, especially in OFC/NST which had more metal partitions and walls.

If the primary propagation impairment is absorption as the radio waves travel through the interior walls, any difference in absorption at the two frequencies would show up as a deviation of the slope of the power vs. power regression line from unity. If, on the other hand, the primary mechanism in the propagation channel is reflection from the walls and structures, any differences at the two frequencies would be seen as an offset of the intercept from the origin.

Table 2 seems to indicate that the metallic partitions and walls in OFC/NST reflected all frequencies equally well. OFC/NCO, with its greater use of non-metallic structures, seems to show differences in both the transmitted and reflected components as the frequency increases. However, it must be emphasized that these comments are tentative, and based on relatively small samples. Furthermore these comments are based on extrapolation to short distances where there were no data points.

The behavior of relative path loss with distance was also studied. The present results could be reasonably fitted to a free-space + linear path attenuation model. This approach is intuitively satisfying and does not result in unexplainable distance exponents. Clearly, caution must be exercised if the model is used outside the present range of measurements. It, most certainly, should not be extended to locations outside a building.

It is worthwhile re-iterating that these results are relative to the power received at 0.3 m. The absolute power levels at that reference distance would, of-course, depend on the frequency, transmitter power, and the antennas, and could be easily calculated using Friis' transmission formula.

SUMMARY

Time delay spread and signal level measurements were made at 850 MHz, 1.7 GHz and 4.0 GHz inside two dissimilar office buildings. These are the first reported comparative three-frequency measurements.

The relatively open construction and low absorption of the interior walls, coupled with the strongly attenuating exterior walls, kept the rms time delay spread mostly under 100 ns in OFC/NCO. In OFC/NST, the metallic baffle-like interior construction produced the same result. Rms time delay spreads measured at the three frequencies appear to be statistically equal to a first order, within the observed range of values.

Received power levels, relative to the power at 0.3 m separation, were statistically nearly equal at the three frequencies to a first order. The 4.0 GHz relative signal, however, was often stronger in the more metallic building, OFC/NST.

The power-distance relationship could be represented by a free-space + linear path attenuation model. The fitted model curves showed a smaller linear path attenuation coefficient as the frequency increased. The differences in the attenuation coefficients may reflect the dissimilarities in the buildings.

The rms value of fractional deviation of power from the regression line was a good measure of the spread of the data in all cases, when the power was calculated relative to the received power at 0.3 m.

Overall, it was concluded that radiowave propagation was the same over the range of frequencies studied within these buildings. More measurements are needed to draw generalized conclusions.

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Table 1. Power Regression against 850 MHz Relative Power Data

Relative Power Regression						
Location	Freq.	Slope	Intrcpt dB	Corr.	Std. Dev. dB	Std. Fract. Dev
OFC/NCO	1.7 GHz	0.88	-6.6	0.97	4.1	0.064
	4.0 GHz	0.79	-7.6	0.93	5.6	0.096
OFC/NST	1.7 GHz	0.92	-0.5	0.97	3.8	0.076
	4.0 GHz	0.85	+0.6	0.96	3.9	0.094

Table 2. Free Space + Linear Path Attenuation Model Regression

Path attenuation Regression					
Location	Freq.	Atten dB/m	Corr.	Std. Dev. dB	Std. Fract. Dev.
OFC/NCO	850 MHz	0.62	0.87	8.4	0.13
	1.7 GHz	0.57	0.84	8.5	0.13
	4.0 GHz	0.47	0.82	8.6	0.15
OFC/NST	850 MHz	0.48	0.85	8.0	0.14
	1.7 GHz	0.35	0.77	9.5	0.18
	4.0 GHz	0.23	0.77	8.7	0.19