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September 4, 1992

BY CERTIFIED MAIL

Frequency Liaison Branch
Federal Communications Commission
Room 7326
2025 M Street, N.W.
Washington, D.C. 20554

RE: Experimental Radio Station Licenses KK2XBA and KK2XBB
Six Month Progress Report

Dear Sir/Madam:

Enclosed for your files is the first six month progress report required under Special Condition #2 of each of the above-referenced licenses. If you have any technical questions relating to this report, you may contact Eric Barnhart at (404) 894-8248. Please give me a call at (404) 894-4812 for any administrative questions.

Sincerely,

Gail Gunnells

E. Gail Gunnells
Attorney

Enclosure

cc: Eric Barnhart

INTERIM TECHNICAL REPORT
NUMBER 1
EXPERIMENTAL LICENSE:
KK2XBA and KK2XBB

By
Michael L. Witten
Leslie W. Pickering
Eric N. Barnhart

August 26, 1992

Communications Laboratory
GEORGIA TECH RESEARCH INSTITUTE
Georgia Institute of Technology

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1.0 INTRODUCTION

On January 3, 1992 the Federal Communications Commission granted experimental licenses KK2XBA and KK2XBB to the Georgia Institute of Technology (GTRI). The license was requested for the purpose of taking measurements to characterize the in-building propagation channel to support development of indoor wireless communications technology. Specifically, the objectives of the program are as follows:

(1) Advancing the body of knowledge in indoor propagation as applied to wireless, digital communications;

(2) To establish a technology basis for development of indoor wireless communications technology and services;

To meet these objectives, the Georgia Tech Research Institute (GTRI) is engaged in an effort to collect, assess and document data related to indoor propagation for indoor wireless applications. This report documents the following key sub tasks of the effort:

(1) Definition of the methodology and measurement procedures including frequencies, modulations, and locations to be included in the data collection;

(2) Design of the measurement apparatus and definition of required instrumentation and recording equipment to support data collection;

(3) Determination of data reduction procedures and formats for correlation and presentation of data;

(4) Construction of the measurement apparatus and instrumentation including software development as required for instrumentation control and data collection;

(5) Collection of the propagation data;

(6) Normalization and preliminary assessment of the data collected.

1.1 Overview

The GTRI approach to channel characterization of the indoor wireless propagation path was to make a direct measurement of the channel transfer function in the frequency domain by transmitting thousands of discrete frequency tones over the channel and recording the amplitudes and phases of these tones at the receiver. The time-domain multipath profile was then developed by obtaining the Discrete Fourier Transform (DFT) of the frequency-domain data.

In an earlier program, an analysis had been done to determine the frequency spacing of the tones used to probe the channel. This parameter selection has been validated by all subsequent measurements. It should be pointed out that data collected to date (as can be seen in later sections of this report) indicates strongly that the frequency domain is the domain in which continuity can be observed. Probing signal bandwidths are not yet large enough (and probably would have to be considerably larger) to generate an observable continuity in the time domain.

Measurement results presented in this report are valuable and unique by virtue of three facts: (1) There is a serious dearth of channel transfer function measurements on the indoor channel; (2) There are no channel transfer measurements in the important 1850 to 1990 MHz passband (except those reported by Georgia Tech); (3) There are no channel transfer function measurements covering a bandwidth as large as the 1850 to 2200 MHz band used for some of the measurements in this report.

The need for channel transfer function measurements is unarguable. Important and popular communication system simulation models, for example, require the definition of a channel transfer function. In those cases where distortion is not important, the transfer function may be as simple as a single complex number (one amplitude and delay that applies to all frequency components).

In the most complex multipath fading environments, exemplified by the indoor radio channel, complicated statistical models that reflect the strong frequency dependence of amplitude and phase must be used. To validate such models, they must be compared with benchmark measurements of the type presented in this report, i.e. with direct measurements of indoor channel transfer functions across the band of interest. In the same vein, benchmark communication simulations, in their reflection of true performance, can do no better than using actual measured channel transfer function data.

The collected data described in this report and the statistical data that will result from the extensive processing efforts will lead to a channel model. The individual series of measurements, the uses they will be put to, and the degree to which preliminary examination of the data validate their original promise are discussed below.

A series of *Coarse Grain Fade Statistics* measurements were made. These were made over a number of different rectangular grids, with antennas spaced at 50 cm increments. These data will be processed to achieve the fundamental statistical characterizations that will be the building blocks of the statistical channel model. Such statistics, e.g. multipath spread and correlation bandwidth, are fundamental to communication channel modeling.

A preliminary review of the data collected in this measurement series indicates that the expected rough independence of samples from point to point on the grid has indeed been obtained. This achieves the goal of maximizing the number of useful samples available for the statistical processing. Additionally, it should be pointed out that the measurements in this series were taken in a variety of locations. This, of course, will allow investigators to relate statistical parameters to the geometry and character of the locations and physical surroundings. Such environmental characterizations will be inputs to the channel model of the Cell Evaluation Tool.

A series of *Fine Grain Fade Statistics* measurements was made with the goal of determining the spatial behavior of the channel transfer function, i.e. that behavior exhibited when one or both of the antennas is moved to a new location. These measurements were made over a grid with 10 cm spacing. The data so obtained will be used to evaluate the performance of space diversity schemes, sensitivity to antenna placement, and time variability of the channel due to pedestrian walk-through of the spatial patterns. The 10 cm spacing of these measurements was used to obtain a broad view of spatial behavior over longer distances, rather than the detailed view over shorter distances described in connection with extra fine grain measurements. (The experimental data validates this approach in that the series manifests the moderate degree of correlation expected from sample to sample.) These data will allow calculations of the spatial correlation function over distances that are relatively great with respect to the distances covered by the extra fine grain track measurement series. The primary statistical quantity that will be calculated from the data is the spatial correlation function, which will provide important information relative to spatial diversity (horizontal placement of antennas) and time-dependent fading effects.

A series of measurements on a *track* with much closer spacing of antenna placement locations (1cm and 2 cm apart) was made. This is called the *Extra Fine Grain Track*. Like any *track* measurement it is meant to serve two primary functions: (1) Approximate the path a phone-carrying pedestrian might walk; (2) Provide a measurement path that will show some dependence of measured parameters on distance. This series, like the fine grain measurements, will be used to determine the spatial behavior of the channel transfer function. In contrast, however, the measurements here are spaced closely enough to display continuity, and they follow a single track rather than range over a grid. This choice will provide detailed plots of the spatial correlation functions at high-to-moderate values of correlation. Observations of the data validate this up-front expectation. Channel transfer measurements made at subsequent locations along the track show the expected high degree of correlation and continuity, whereas measurements made at the *ends* of the track show enough differences to indicate that a full cycle of variability has been experienced. These measurements, directly mappable into a fine-grained depiction of time-variability, will be unique in the insights they provide; there is currently nothing that can compare to them in the journal literature relating to indoor wireless communication.

The measurements in the *Fine Grain Track* series seek the middle ground between the measurements made in the extra fine grain track series described above and the coarse grain track series described below. As in the fine grain fade statistics series described earlier, the 10 cm spacing used for these track measurements was to obtain a broad view over longer distances, rather than the detailed view over shorter distances. Although not finely detailed, spatial variability is still of importance in this series, with the sample separation chosen to lie between a value known to give continuity (extra fine grain) and one that gives independence of samples (coarse grain).

A series of measurements (*Extra Fine Grain Vertical Diversity*) was made to characterize spatial variation in the vertical direction, a variability that *must* be characterized in order to evaluate or model spatial diversity. The primary statistical quantity of interest, here, is the spatial correlation function (in the vertical direction). The degree of decorrelation characterizing the fading experienced by the same transmitted signal at two different receiving diversity antennas is the primary performance indicator of spatial diversity systems. Without knowing, or being able to estimate this correlation, there is no way to model the potential of spatial diversity as a technique for combating multipath fading. An examination of collected data show the required continuity from sample to sample. This continuity is sufficient to calculate the spatial correlation function in the vertical direction, and thus, after statistical processing, will be used to determine the degree of decorrelation.

The measurements described above all relate to distortion on the indoor wireless communication channel. Such distortion can be enormous. The means by which any communication scheme deals with that distortion must be considered in any viable comparison of candidates. In this regard, there are three major functions to which the data described in this report can be applied: (1) Provide channel transfer data that can be directly used in simulations; (2) On the basis of a statistical breakdown of the data, develop *statistical* channel models for use in communication evaluation tools; (3) Based on a firm foundation of measurements and physical principles, develop a *physical* model of the propagation channel. The basic thrust of (2) is to develop a mathematical model of the channel that, in similar specified environments, has the same statistics as the real channel. The approach in (3) is to develop a model that draws on environment descriptions and calculates the parameters of the ray paths (and hence the transfer function) from fundamental electromagnetic principles.

1.2 Organization of This Report

Section 2 of this report addresses the measurement test plan, the instrumentation and software developed to conduct and process the in-building propagation measurements. Details of the measurements locations appear in Section 3. In Section 4 of this report, the results of the tests are reviewed and key elements of the data are summarized. The data discussed include both frequency and time domain representations (transfer functions and impulse response) of the multipath channel. Trends in the data are identified, leading to the presentation of conclusions and recommendations in Section 5.

Additional detail beyond the scope of this report in the areas of background and the basis for the measurements conducted in this program are provided in Reference [1], which is the interim report produced by GTRI under this program entitled "Test Plan for Hitachi In-Building Communications Channel Characterization Design and Measurement Plan for Propagation Characterization."

2.0 INSTRUMENTATION AND DATA COLLECTION SYSTEM

2.1 System Hardware

To directly measure the path and multipath losses of the office environment in the frequency domain, an approach based on a Network Analyzer (NWA) was used. The transmit and receive antenna were placed at various locations in the building. The NWA treated the path between the two antennas as a network, and generated the system transfer function directly by sweeping through a set of frequencies and comparing the received signal to the transmitted one. Both amplitude and phase data were directly measured and recorded.

Details of the hardware implementation of the measurement system appear in Figure 2-1. The major components of the measurement system were as follows:

HP8510C	Network Analyzer
HP8360	Synthesizer/Sweeper
HP8511	4 port Test Set
HP37204	GPIB Bus Extender (2 ea.)
ZHL-4240	MiniCircuits Broad band Amplifier, 40dB gain (as needed)
ANAREN 40710	RF Splitter
ORTEL3510B	Fiber Optic Transmitter (6GHz bw)
ORTEL4510B	Fiber Optic Receiver
PC Clone/486	Personal Computer
Kreko: D300-A	(Modified) Broad Band Discone Antenna (2 each)
EMCO 3115	Double Ridged Guide Antennas (2 each, as needed)

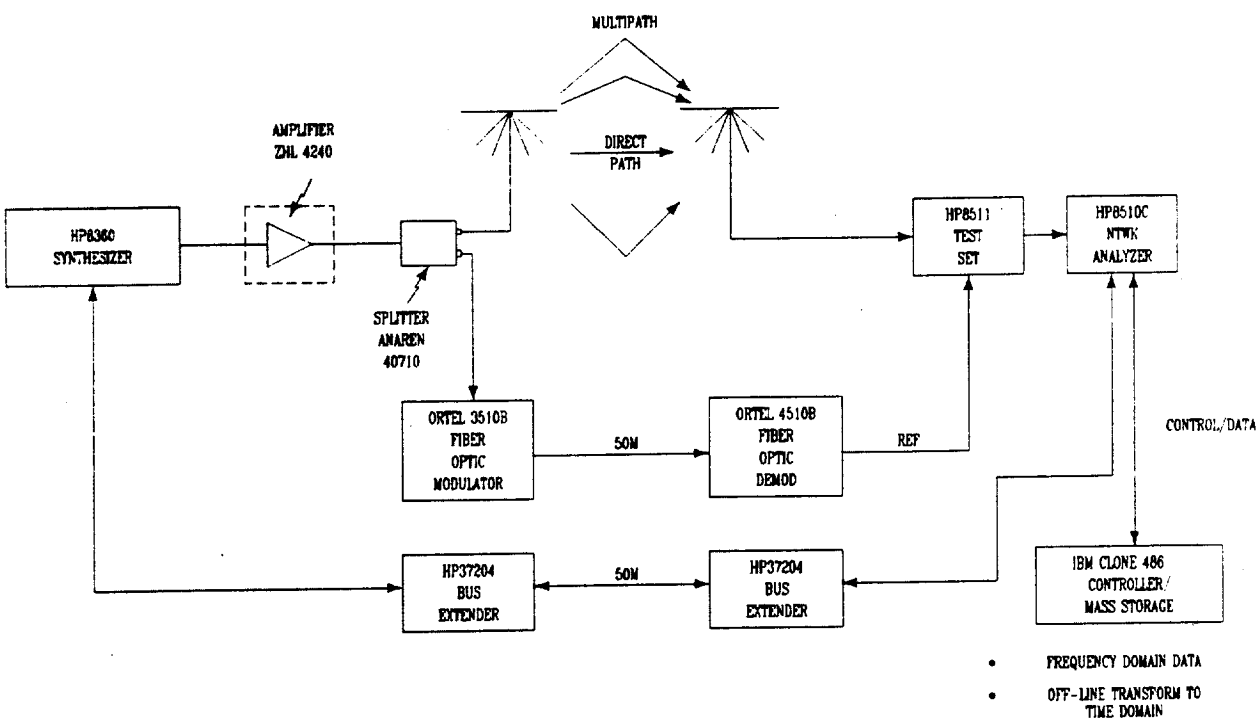


Figure 2-1 Measurement System Hardware Configuration.

To protect against RF leakage that could corrupt the measurements, double shielded coax was used for all RF cable runs greater than 4 feet in length. Shorter interconnects were made with semirigid cable whenever possible. When the goal of the measurement was to characterize multipath, the two discones were used. When the goal was to measure only path loss and to minimize the multipath effects, the EMCO ridged horns were used. The ridged horn antenna provides gain and directionality, both of which are desirable in this case. RF Absorber was used liberally on the antenna poles and on the carts containing measurement equipment to minimize reflections from these surfaces.

To take a measurement, the control computer commands the NWA to take a sweep of 801 points. The NWA in turn commands the synthesized source to step through the frequencies of interest. Commands to the synthesizer are passed through the GPIB bus extender. The synthesizer output was amplified and split with part of the signal being sent to a discone antenna, and part being sent to the reference port of the HP8511 test set through either a highly shielded cable or a broad band Fiber Optic transmitter/receiver pair. The fiber optics are used for the multipath measurements. The NWA locks on this reference signal and compares the received signal to that of the reference. The magnitude and phase of this difference are stored for each point. Once the measurement is complete, the NWA dumps the data set, provided as real/imaginary complex pairs, to the control computer. The control computer then initiates the next sweep at a new set of frequencies. This process repeats until the desired band was measured.

The configuration used here was designed to minimize errors caused by RF cable leakage and by measurement system nonlinearities. The signal source was placed close to the transmit antenna to minimize the effects of cable leakage on the connecting cable. Since the NWA must (in this configuration) be near the test set and therefore the receive antenna, a bus extender was required to pass control information between the units.

This configuration also constrains the network Analyzer to be in "Step" mode for the sweeps, forcing the system to step through and lock on discrete frequencies one at a time. This was actually the more desirable mode (as opposed to "ramp" mode), as it provides greater precision in the measurements. All measurements were subject to at least 128 point averaging for each frequency measured.

To minimize the effects of nonlinearities in the system, the reference signal should ideally be taken from the last active component in the system. In this case, that would be the output of the amplifier, if any, or the synthesizer if no amplifier is present. This signal must then be connected back to the test set. This was the approach used by GTRI. To minimize cable leakage, a broad band fiber optic system was used to return the reference to the test set. This system provided a high quality reference for the network Analyzer, with minimal leakage and the ability to track minor variations in synthesizer or amplifier output.

2.2 System Calibration and Data Processing

Since the RF power to the amplifier and therefore the fiber optic system are constant from sweep to sweep, system nonlinearities, connector and cable losses (except for antenna effects) are accounted for by making regular calibration sweeps. These sweeps are performed with the antennas removed from the system, and the antenna cables connected directly through a coupler as shown in Figure 2-2. An attenuator was also placed in line to prevent overload of the test set inputs. With the antennas removed, a sweep was then made and stored to be used as a reference for that specific hardware configuration. The attenuators are assumed to be linear, and their effects are removed directly during processing. These calibration sweeps are taken any time system components are changed, as well as on a daily basis.

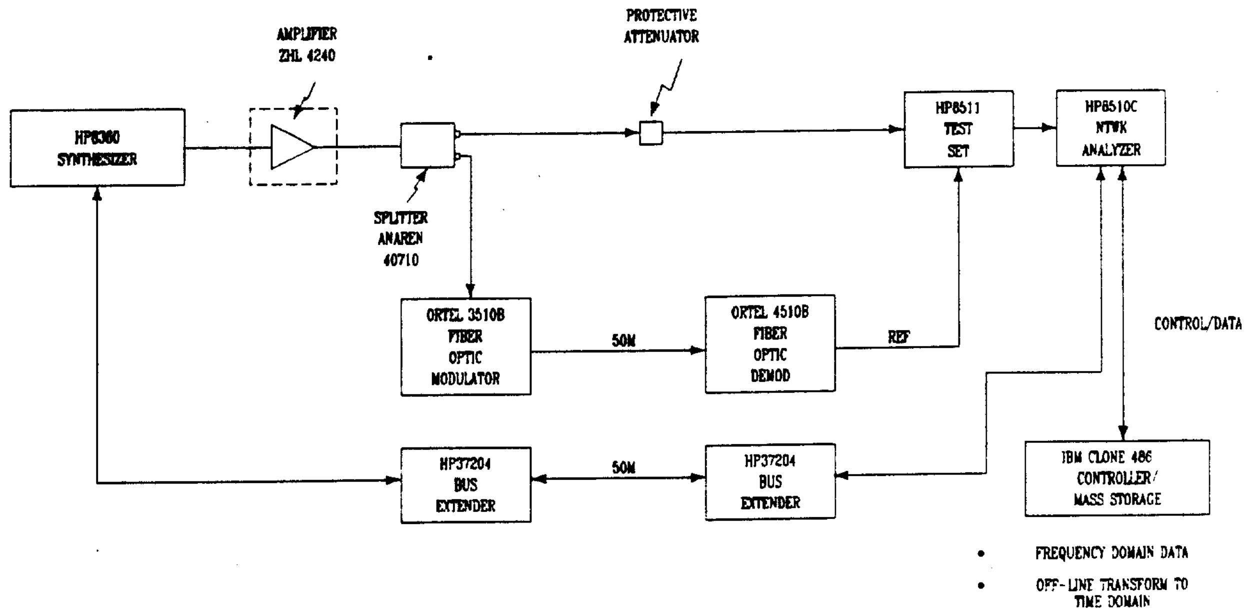


Figure 2-2 Measurement System Through Calibration Configuration

Raw data collected during the measurement process was corrected for variations in configurations and other major day-to-day system differences by correction with these through calibration sweeps. During data processing, each sweep was divided by the appropriate calibration sweep (in the frequency domain) to yield a data set that contains only the effects of path/multipath losses (the channel) and antenna effects.

After the data has been corrected with the through calibration, the data is normalized to account for antenna effects such as gain and VSWR. To do this, a sweep was made with the antennas in an anechoic chamber at a fixed distance of 2 meters. This measurement, being in the far field of the antennas, was used as the absolute reference for all other measurements. This data, with its own "through" calibration information removed, was then divided into the corrected raw data to normalize for the antenna effects. The resulting data is the system transfer function with respect to a pair of isotropic antennas separated by 2 meters.

A somewhat simplified mathematical representation of the whole calibration/ normalization process appears below. The following definitions apply:

H_m	=	Transfer function of the data measurement.
H_r	=	Transfer function of the reference path.
H_{c1}, H_{c2}	=	Transfer functions of receive/transmit cabling.
H_{a1}, H_{a2}	=	Transfer functions of the antennas.
H_s	=	Transfer function of the environment (what we want)

H_{sc} = Transfer function of the ideal chamber environment with the antennas spaced 2 meters apart.

H_{tcal} = Measured through (no antenna) calibration.

H_{ccal} = Measured and corrected chamber calibration. For the removal of the cable and reference path effects, the measured data point (H_m) was divided by the measured through calibration (H_{tcal}):

$$H_m = H_r H_{c1} H_{a1} H_s H_{a2} H_{c2}$$

$$H_{tcal} = H_r H_{c1} H_{c2}$$

$$\frac{H_m}{H_{tcal}} = \frac{H_r H_{c1} H_{a1} H_s H_{a2} H_{c2}}{H_r H_{c1} H_{c2}}$$

To remove antenna effects, $H_{a1} H_s H_{a2}$ was divided by a calibration factor which includes the effects of the antennas and a 2 meter path in an echoic chamber (H_{ccal}). H_{ccal} (after processing as in the step above) = $H_{a1} H_{sc} H_{a2}$.

$$\frac{H_{a1} H_s H_{a2}}{H_{a1} H_{sc} H_{a2}} = \frac{H_s}{H_{sc}}$$

H_s/H_{sc} was the final result, which was the channel transfer function referenced to a pair of isotropic antenna with a 2 meter free space path distance. Additional information on how this processing was implemented is discussed in Section 2.3 below.

2.3 Software

The data acquisition and processing software are written in the "C" programming language. Standard subroutine packages were used to perform the inverse Fourier transform (IFFT), data conversion and plotting functions. The GPIB was programmed with subroutines provided by the GPIB interface manufacturer (National Instruments).

All processing and data storage was performed in the control computer. The results were stored both as raw data (as provided by the NWA) and as fully corrected data. All data is stored in the frequency domain.

Data processing consisted of correcting with the calibration files as described above, plotting magnitudes and phases of the frequency data, and converting the sweeps to the time domain. As received from the Network Analyzer, the data was in byte reversed, 32 bit IEEE standard floating point Cartesian point pairs (real, imaginary). Immediately after the data was received and the next portion of the Network Analyzer sweep (if any) was started, the data was byte swapped to make it usable. Once all the data for a given frequency sweep was collected, the data was viewed and stored.

Each raw file, as stored, contains a header with software revision level ID, a character array containing a one line description of the file, run power levels and other information needed for later processing. The description was provided by the operator at the time the data was taken. The other information was taken directly from the stored setup used by the computer to run the measurement. This information was then followed by the real/imaginary complex pairs of data.

Processing of the data involves a number of steps. First, a point-by-point complex division with the regular or "through" calibration run data was performed. Second, the data was divided again by the appropriate chamber measurement run (already corrected for its through calibration) to yield the "fully corrected" file. Detailed discussion of this calibration process is covered in Section 2.2 above. The corrected complex data was converted to Log Magnitude data (20log(data), Phase) and both magnitude and phase are plotted as desired.

2.4 General Measurement Procedures

Most measurements were taken in the Hitachi Telecom Norcross facility. Multipath measurements were taken in a variety of locations throughout the building. The remainder of the measurements were taken in the Hemphill warehouse facility on the Georgia Tech Campus. License constraints in effect at the beginning of the measurement period necessitated the inclusion of the Georgia Tech site. Nevertheless, this site represented a typical warehouse structure similar to that at the Hitachi Norcross facility.

2.4.1 Multipath Measurements

The frequencies measured were those allowed by the FCC license in effect, 1850-1990 MHz for the first few weeks, and 1850-2200 MHz for the remainder of the period. The narrower 140 MHz bandwidth provided a time domain resolution of 7.14 ns. Two 800 point sweeps were used to cover the band, yielding 1600 data points per measurement. Each sweep took approximately 54 seconds, yielding a measurement time of about 2 minutes per data set. With the acquisition, display and header entry process, each measurement took on the order of 2-3 minutes.

The 1850-2200 MHz sweeps represent the bulk of the measurements. This 350 MHz bandwidth provided a time domain resolution of 2.86 ns. Five 800 point sweeps were used to cover the band. Acquisition time, including header entry, storage and display averaged approximately 5 minutes per sweep.

Since the license allowed transmission on a non-interfering basis only and a number of local businesses had receivers within "range", maximum output power was adjusted to the minimum required for a given measurement location. Power output levels ranged from approximately 0 dBm up to +20 dBm. The different levels, accounted for in the various calibration measurements and in the reference path, only serve to move the noise floor up or down.

The noise floor was measured at least once for each receive antenna position. These ambient measurements are made by terminating the transmit antenna cable into a load and performing a run as usual. This data was used to verify that measurements were well above the average level of the noise floor.

Measurement system accuracy depended somewhat on the particular measurement. In general, the following tolerances apply:

MEASUREMENT ACCURACY

Antenna Position (absolute)	+/- 2. cm
Antenna Position (relative, base moved)	+/- .5 cm
Antenna Position (relative, base not moved)	+/- .1 cm
Antenna Position (high resolution)	+/- 2. mm
Frequency	+/-10. Hz
Power	+/- 1.5 dB

The base of the transmit antenna was constructed with loaded bearing slide rails that could be very accurately positioned. The rail length was 50 cm. For this reason, if two measurements were made without moving the base, just by sliding the table, the much higher relative precision figure shown above could be achieved.

The anechoic chamber antenna-antenna calibration run used to correct the multipath measurements was made at a range of 2 meters. For this reason, all multipath results and plots in this report are presented with respect to ideal isotropic antennas separated by 2 meters.

To verify system accuracies, periodic re-runs of calibrations and measurements were performed. These measurements demonstrated repeatability consistent with the accuracies listed above.

A typical measurement was conducted as follows:

(1) The receive antenna was placed in the desired position, usually a pre-determined standard location used for most of the measurements. Absorber was placed on the receive cart as necessary.

(2) A transmit antenna location was selected, generally one of a series of locations pre-marked on the floor. Absorber was used to cover the antenna-facing side of the cart if necessary. The cart location was also selected to minimize its effect on the measurement.

(3) The computer initiated a run, setting the start and stop frequencies over which the 801 points were to be taken and starting the sweep. The typical first sweep covered the range 1850-1920 MHz.

(4) When the NWA signaled completion of data acquisition, the computer read the sweep from the NWA, set the next set of frequencies (1920-1990 MHz) and triggered the sweep. The computer then performed the byte-swap on the first set of data. This process was repeated until the full band had been measured.

(5) The NWA again signaled completion, and the last sweep of data was collected from the computer, byte-swapped and stored.

(6) A copy of this data was converted to log magnitude format and displayed. This gave the operator a chance to verify that no major glitches occurred during the run.

(7) The operator was queried for one line of header information. The file name was a three character series ID, an a, b or c depending on the frequency band being measured (1850-2200, 866-869, 902-928) and month and day of the run, followed by a three character extension representing the number in sequence that the file was for that day. For example: HIBA0205.006 was the 6th file taken on February 5, was a 1850-2200 MHz sweep, and was a measurement of the HIB series. The file was stored to disk. Pertinent run information was recorded in the written run log.

(8) At a later time, off site, the data was corrected and normalized to the daily through calibration run and antenna-to-antenna chamber calibration using the procedure described in the preceding section.

(9) If desired, the results were plotted in log magnitude and phase plots in the frequency domain, and (after the IFFT) with a magnitude stick plot in the time domain. Samples of these plots appear in Section 4.

3.0 DETAILED MEASUREMENT DESCRIPTIONS

In the actual measurement period of January 6 through March 4, 1992 in excess of 1000 multipath and calibration measurements were performed in and around the Hitachi Telecom facility in Norcross (FCC License KK2XBA), Georgia as well as the Georgia Tech Central Receiving warehouse on Hemphill road, Georgia Tech Main Campus (FCC License KK2XBB). A detailed rational for the physical layout of the measurements appears in [1]. Detailed descriptions of the measurement topologies appear below.

Any statistical processing of data referred to in the text of this section is for reference only. Such processing will be the focus of ongoing indoor channel model development work.

The measurements have been divided into 4 groups based on their topologies. Unless otherwise noted, all measurements were made with the receive antenna in a fixed location and the pattern (grid, linear series) formed by moving the transmit antenna.

All measurements in figures are metric. The figures are provided to give relative feature placement only and are not to scale. The origin of grid and high resolution track measurements are marked with an enlarged dot.

3.1 Coarse Grain Fade Statistics

The statistics that will result from data processing of these measurements will be the building blocks of the statistical model under development. These statistics are fundamental to communication channel modeling. In addition to the simple average received signal level, they include among other things: (1) Distribution of fade depths and spectral widths of fades; (2) Multipath Spread; (3) Correlation bandwidth; (4) Frequency domain correlation functions and; (4) Joint probability density functions for fade levels in frequency diversity channels. The reason that the measurements are coarse, i.e. separated by such a large distance, is to guarantee rough statistical independence of the samples. This maximizes the number of independent samples. The greater the number of independent samples the greater the statistical reliability of the resultant data.

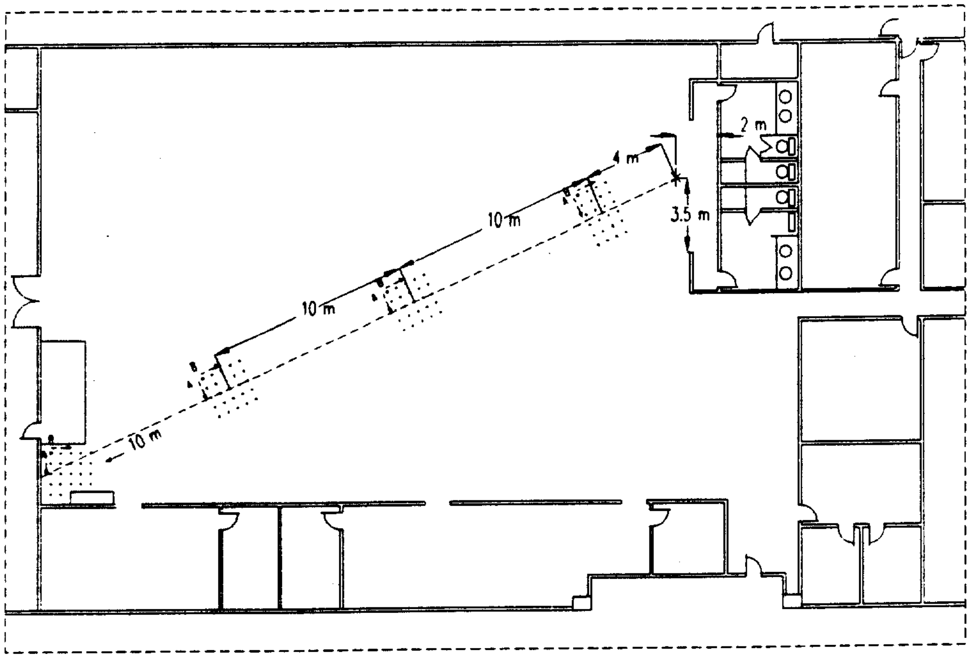
The reason for taking measurements in so many, diverse locations is to allow for relating of the statistical characterizations that will result from statistical data processing to the geometry and character of the locations, the characterizations of which will be inputs to the channel model required of the Cell Evaluation Tool.

Our previous experience shows that a cluster or grid of measurement points about a central location provides the best method of generating these statistics. The grid parameters represent a compromise between the sample spacing that assures reasonable independence and the maximum displacement from the center point that can be tolerated without introducing a dependence on variation of the transmit-receive antenna distance. The "coarse grain" grid of approximately 25 samples in a 5 x 5 square pattern 2 meters on a side (50 cm sample spacing) was selected to meet these criteria.

Coarse grid measurements were taken in a variety of locations to provide broad applicability of the results. Details of each set are described below. Individual measurement topologies were occasionally modified because of the realities of wall placement and other physical constraints that limit the available antenna placement locations. For each grid, one corner was designated the reference origin, and grid coordinates (in cm) are used to identify each location. The coordinate A050, B100, for example, represents a measurement point 50 cm in the "A" direction and 100 cm in the "B" direction away from the origin.

3.1.1 Assembly Area

Four sets of measurements were made with both antennas in the assembly area as shown in Figure 3-1. The sets were designed to minimize distance dependence within each sample set, and to emphasize the difference dependence between sets. The four sets were taken over grids centered every 10 meters, beginning 4 meters from the receive antenna. Each set consisted of samples spaced at 50 cm intervals oriented as follows:



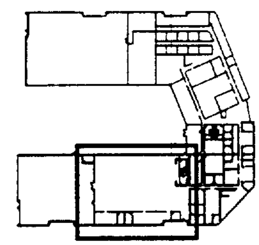


Figure 3-1 Assembly Area Measurement Grid Locations.

1) The closest grid was made up of 24 samples from a 1.5 m x 2.5 m grid. The 1.5 m dimension was perpendicular to the antenna path to minimize the local distance dependence.

2) The two intermediate grids were made up of 25 samples taken on a 2 m square grid of 5 x 5 samples.

3) The fourth or furthest grid was made up of 21 samples set approximately in a square. The grid was offset approximately 20 cm, and 4 samples could not be taken because of room size and clutter constraints.

3.1.2 Warehouse

Measurements were performed on two coarse grids in the warehouse on the GTRI campus. This warehouse approximates a standard warehouse environment, and was available to us under licensing in effect at the beginning of the measurement period. Approximate locations of the two grids appear in Figure 3-2.

Each grid was made up of 25 samples in a 5 x 5 grid. The two major sample sets were positioned to give a direct path partially obstructed by boxes, crates and other items typical to the warehouse environment.

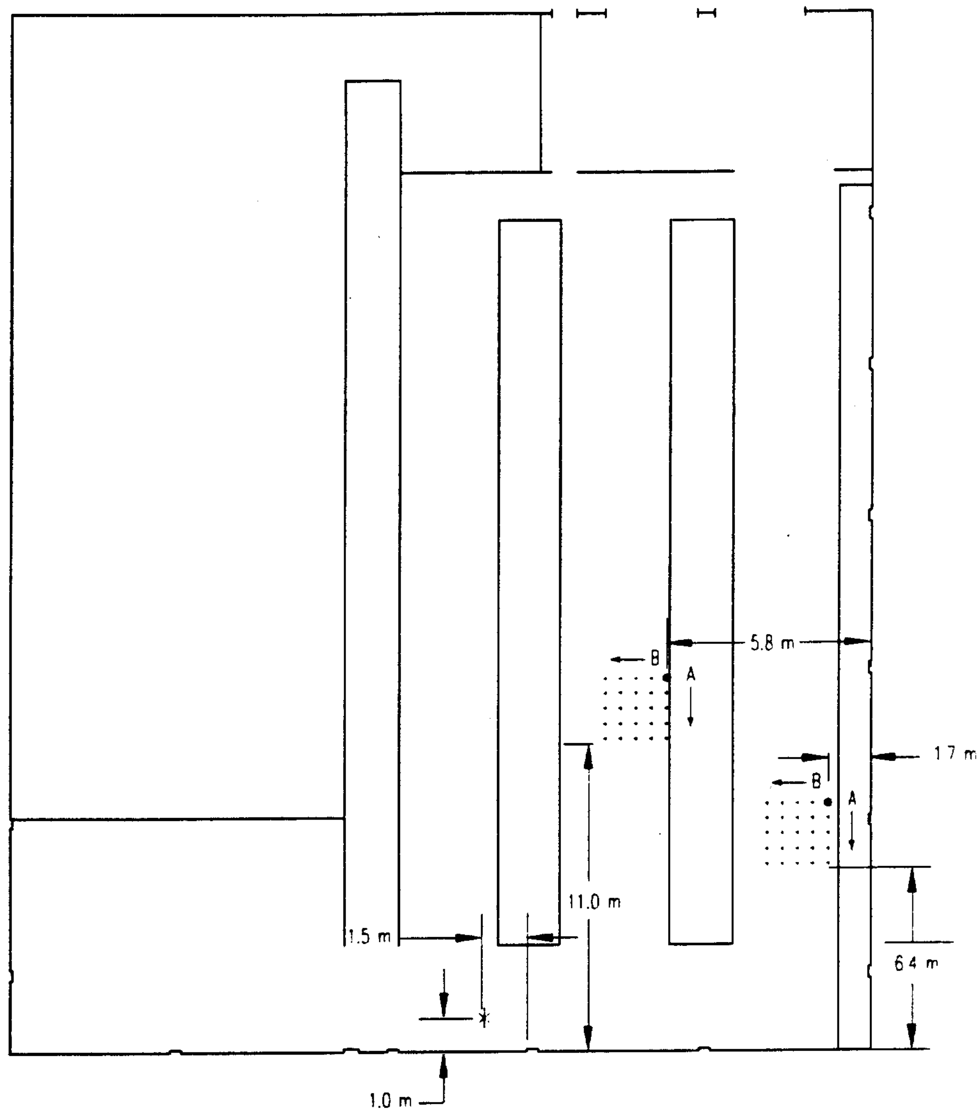
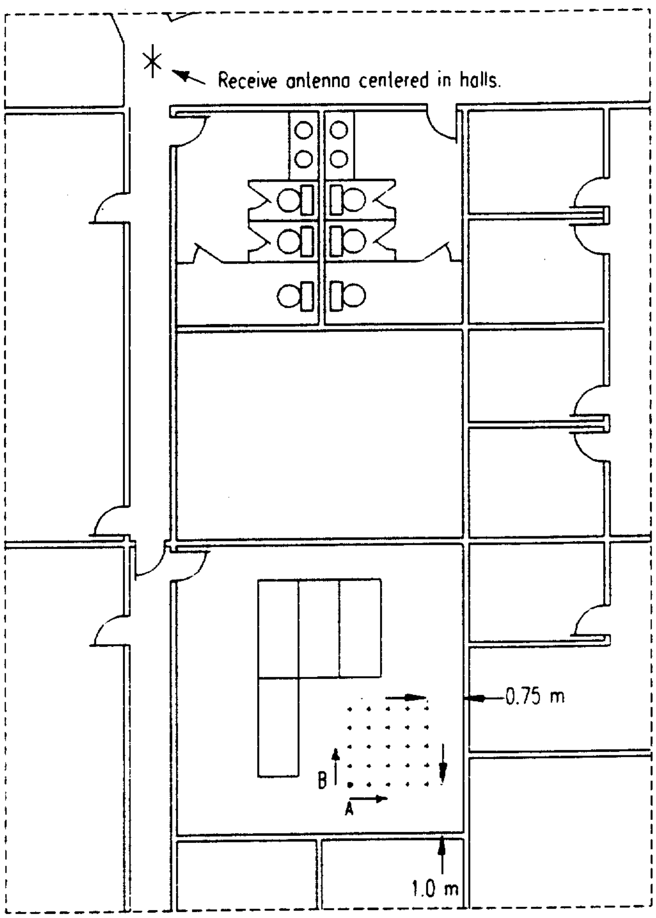


Figure 3-2 GTRI Warehouse Grid Locations.

3.1.3 Conference Room

Measurements were performed on one 5x5 sample grid in the main conference room (see Figure 3-3). This series of measurements was made with the door closed, and had no path available that did not penetrate a wall. No direct or reflected-direct paths existed for this series.



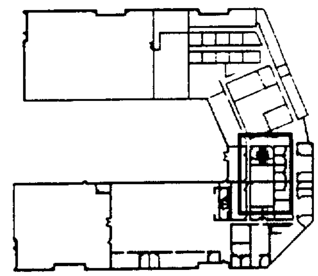


Figure 3-3 Conference Room Grid.

3.1.4 Center Hall

Measurements were performed on a large grid in the hall running from the front to the rear of the building near the main entrance as shown in Figure 3-5. The 50 cm grid data obtained was a subset of the more 10 cm sample grid measurement series discussed in Section 3.2 below.

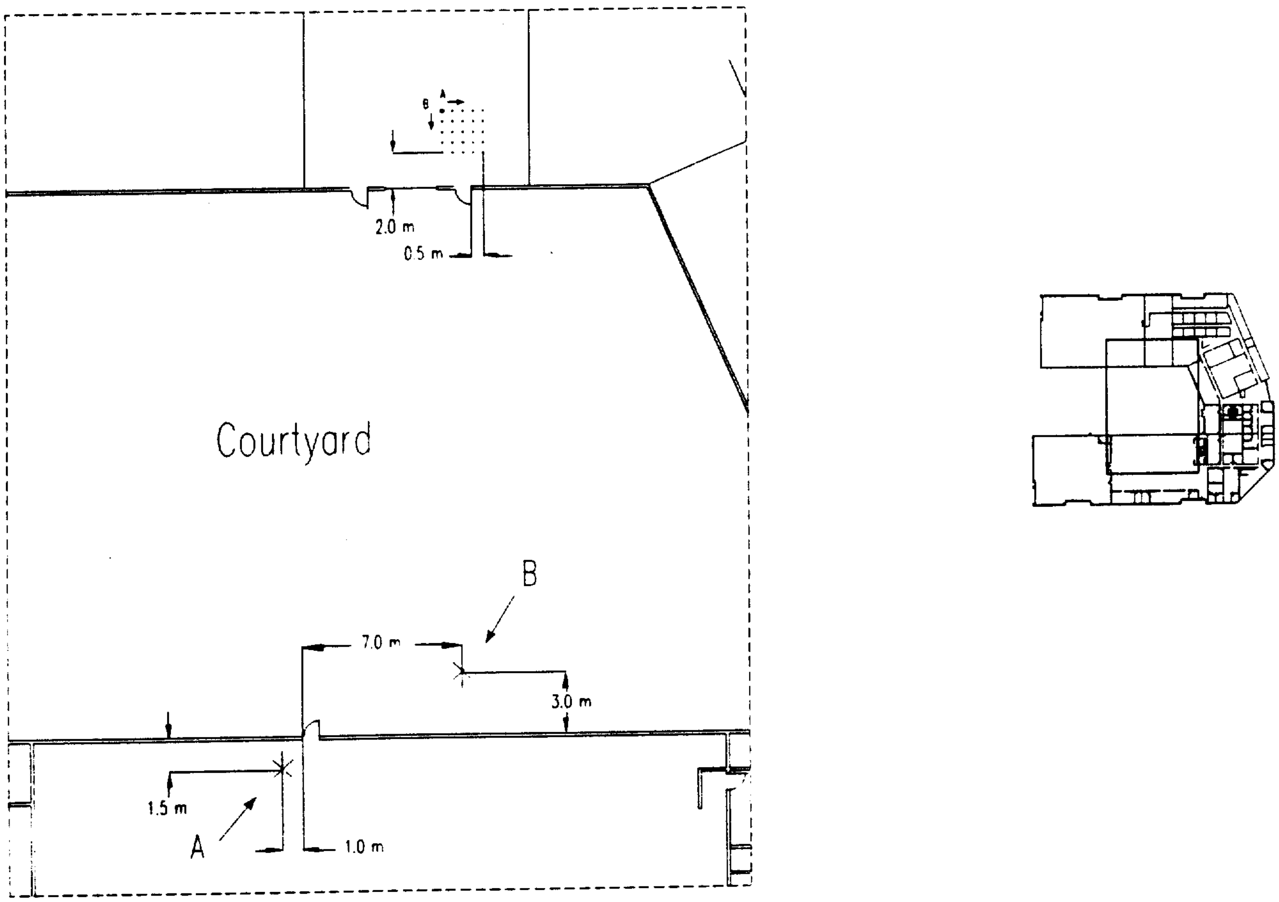


Figure 3-4 Across and From Courtyard Series.

3.1.5 Cross-Courtyard

One measurement set on a 5x5 grid was performed across the courtyard between the assembly area and a storage area. For this set, the grid was located in the storage area, and the receive antenna was in the assembly area as shown in Figure 3-4. The receive antenna location for this series is marked "A". This series represents a no direct or reflected-direct path measurement series, with significant distance and penetration losses.

3.1.6 Courtyard to Storage Area.

The grid used in the storage area described in Section 3.1.5 above was used again, but this time with the receive antenna in the courtyard. This series is also shown in Figure 3-4, with the receive location marked "B". This series represents a no direct or reflected-direct path measurement with moderate distance and penetration losses.

3.2 Fine Grain Fade Statistics (10 cm grid spacing)

Spatial behavior of the channel transfer function, i.e. that behavior exhibited when one or both of the antennas is moved to a new location, has important ramifications relative to the performance of space diversity schemes, sensitivity to antenna placement, and time variability of the channel. Time variability is connected to spatial variability, of course, because the dominant time variability in operational systems will be due to callers experiencing time variations of the channel transfer function as they carry phones through *spatial* patterns.

A large grid of measurements was made with a topology allowing the calculation of the near spatial correlation of each measurement set. The grid consists of a 6 x 6 array, with measurements made at each grid location, as well as 10 and 20 cm away from each grid location (see Figure 3-5). Evaluation of this grid will later yield correlation information for sample spacings of 10, 20, 30, 40, ... 250 cm. Intermediate spacings representing diagonal elements may also be calculated. The grid was located in the cross hall near the main entrance (see Figure), with the receive antenna out of the line-of-site.

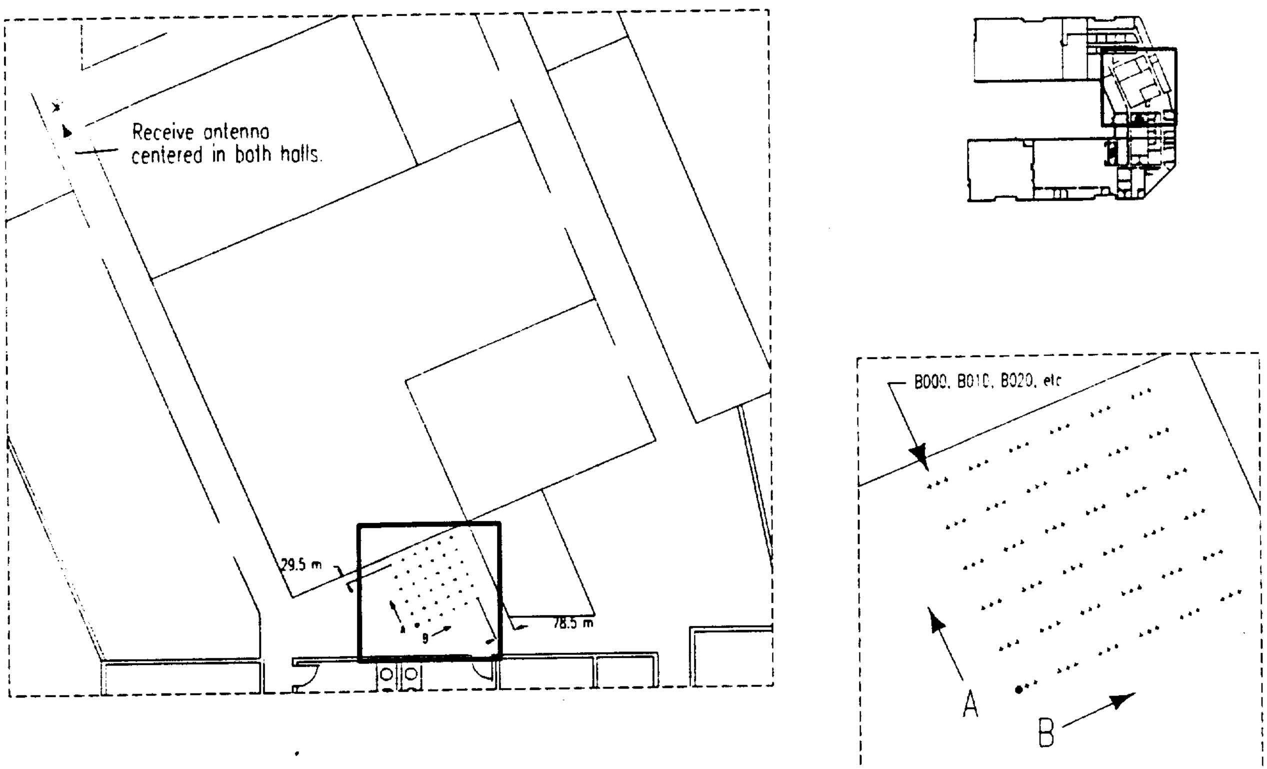
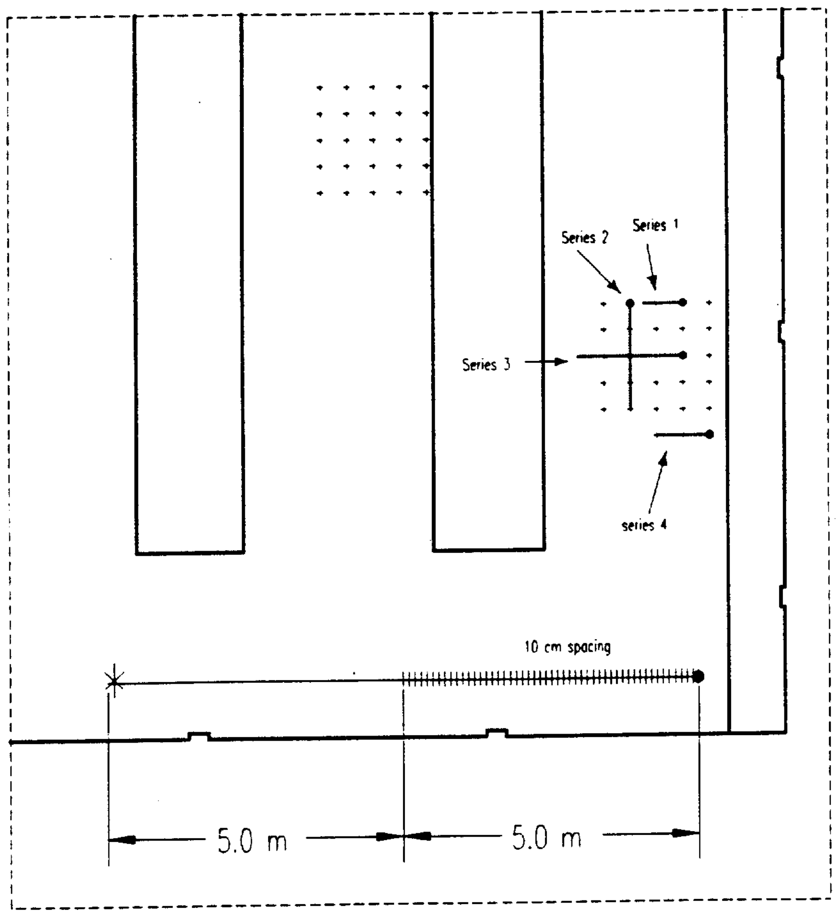


Figure 3-5 Large Fine Grain (10 cm) Grid.

3.3 Extra Fine Grain Track Measurements

This series of measurements, like the fine grain measurements addressed in Section 3.2, has the goal of determining spatial behavior of the channel transfer function. Extra Fine grain track measurements are structured to provide a clear picture exhibiting the continuity of the multipath profile in the spatial domain. Measurements are made 1 or 2 cm apart, resulting in a high degree of correlation. The only drawback to such measurement series made on tracks is that the sheer number of measurements limits the distance over which they may be taken.



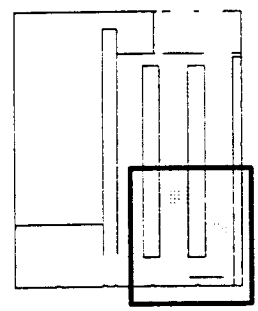


Figure 3-6 Fine and Extra Fine Track Series.

Three sets of extra fine grain measurements were made along four tracks. All three sets were made in the GTRI warehouse facility, and are shown in Figure 3-6. The first set consists of a linear series of 37 measurements on 2 cm spacing. The second set was made up of two perpendicular tracks that cross at the center. The two tracks are each 2 meters long, and were sampled at 2 cm spacing. The third track was sampled at 1 cm spacing, and covered a distance of 1 meter.

3.4 Fine Grain Track Measurements

Fine grain track measurements, measurements with 10 cm spacing, are a compromise between the coarse and extra fine tracks. These measurements are sufficiently correlated to give a moderately detailed picture of the spatial variations in the multipath profile, while being far enough apart to traverse a significant distance in a reasonable period of time.

One series of 50 fine grain track measurements was made in the Georgia Tech Central Receiving warehouse on Hemphill Road, Georgia Tech Campus. The layout of these measurements appear in Figure 3-6

4.0 PRESENTATION AND DISCUSSION OF RESULTS

This section presents a summary of the data collected for each series outlined in Section 3 above. The data was first reviewed , series by series, with sample plots provided as appropriate to illustrate obvious trends and unique features in the data. Discussion of the results is provided, including problems or limitations on the data. This document is intended as a presentation of the results of the data collection process, not a thorough analysis. A brief discussion of how the data will be processed and applied to modeling efforts is also included with each section.

Three types of plots are used in this document. Log magnitude and phase are used to represent the channel transfer function in the frequency domain, while stick plots are used for the time domain impulse response. All frequency domain magnitude plots have been normalized to the RMS for the file (displayed in the upper right corner of the plot) and are plotted on a fixed scale of -30 to +20 dB. Phase plots are plotted on a +/- 180 degree scale. Time domain plots display unnormalized data directly. Only the first 119 samples of the time domain data are plotted, representing approximately 100 meters of path length in free space. Time domain plots are scaled to the highest value plotted.

For each series, the data was corrected with the daily through calibration and normalized with the appropriate antenna-antenna chamber calibration measurement. All plots were generated from this data, with no additional filtering or correction.

4.1 Coarse Grain Fade Statistics

A preliminary review of the data in these series indicate that the expected rough independence of samples from point to point on the grid has indeed been obtained. This, as discussed in Section 3.1, is in keeping with the goal of maximizing the number of useful samples available for the processing that will lead to the statistical characterizations (and their relationship to different environments) that are so essential for the development of the statistical channel model that will be at the heart of the Cell Evaluation Tool (CET).

4.1.1 Assembly Area

Measurements were made located on four grids in the assembly area as shown in Figure 3-1 at 4, 14, 24 and 34 meters average antenna separation. The file names assigned are GRDAS1A.xxx, GRDAS2A.xxx, GRDAS3A.xxx and GRDAS4A.xxx respectively (xxx are the three digit file numbers). Each series or grid of measurements was made in one run, and the measurement environment remained constant (no tables, boxes, etc. were moved) for the duration of the run

The four plots in Figure 4-1 illustrate the goals of this series. The two plots on the left represent the frequency domain log magnitude response, as well as the time domain linear magnitude responses of the channel. This measurement was made at location A000, B000 in the grid 4 m from the receive antenna. The two plots on the right represent the same point on the grid 34 m from the receive antenna.

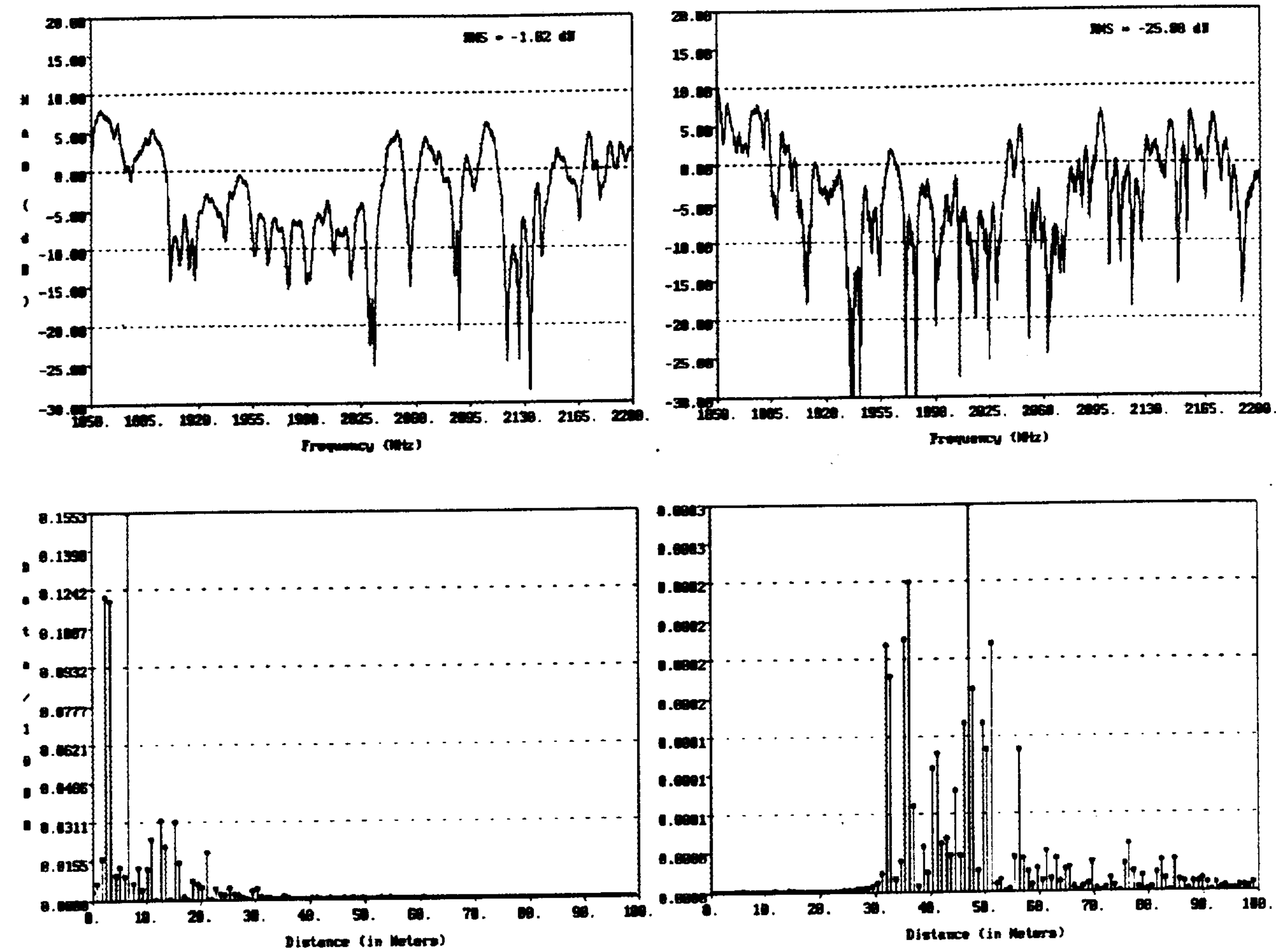


Figure 4-1 Sample Frequency Domain Log Magnitude and Time Domain Magnitude Plots of 4 m and 34 m Assembly Area Grids.

Comparison of the two magnitude responses demonstrate the differences in the multipath fading at the two locations. The relative fades are both more numerous and somewhat deeper on the average at the longer distances.

The time domain responses both show the difference in the length of the shortest path (the first peak), as would be expected. These responses also show how the received power in the time domain is spread to a greater degree at the greater distance. This indicates that a larger number of reflective paths contribute to the received signal at the greater distance. Far more significant reflected paths exist for the longer antenna-antenna separation distance.

4.1.2 Warehouse

The two series coarse grid locations measured in the GTRI warehouse are shown in Figure 3-2. The processed file names assigned are GRDWH1.xxx and GRDWH2.xxx. The warehouse was in use throughout the measurement period. In general, the physical environment did not change significantly during a particular run or sweep, but changes often occurred between measurements that would be expected to change the multipath environment significantly. As the coarse grids are meant to be treated as independent, uncorrelated samples of the environment, and one arrangement of boxes in a warehouse is as correct as another, these variations in the environment cause no problems. Indeed, they may even be useful in helping determine contributions of such objects to statistics of the environment.

4.1.3 Conference Room

Figure 3-3 shows the single set of coarse grid locations measured in the conference room. The processed files are named GRDCR.xxx. The building was generally unoccupied at the time these measurements were made, so the measurement environment remained constant throughout the grid.

This grid represents a measurement set that forces all paths through a wall, door or other object. No direct path, or reflected direct paths exist. The room was closed for the measurement. Figure 4-2 shows the magnitude response in the frequency domain (top) as well as the time domain response (bottom) of a measurement at grid location A000, B000. The frequency domain response demonstrates the moderately heavy multipath fading in the room. The time domain sample shows the large number of significant reflected paths and their spread. Both plots are reasonable for the environment tested.

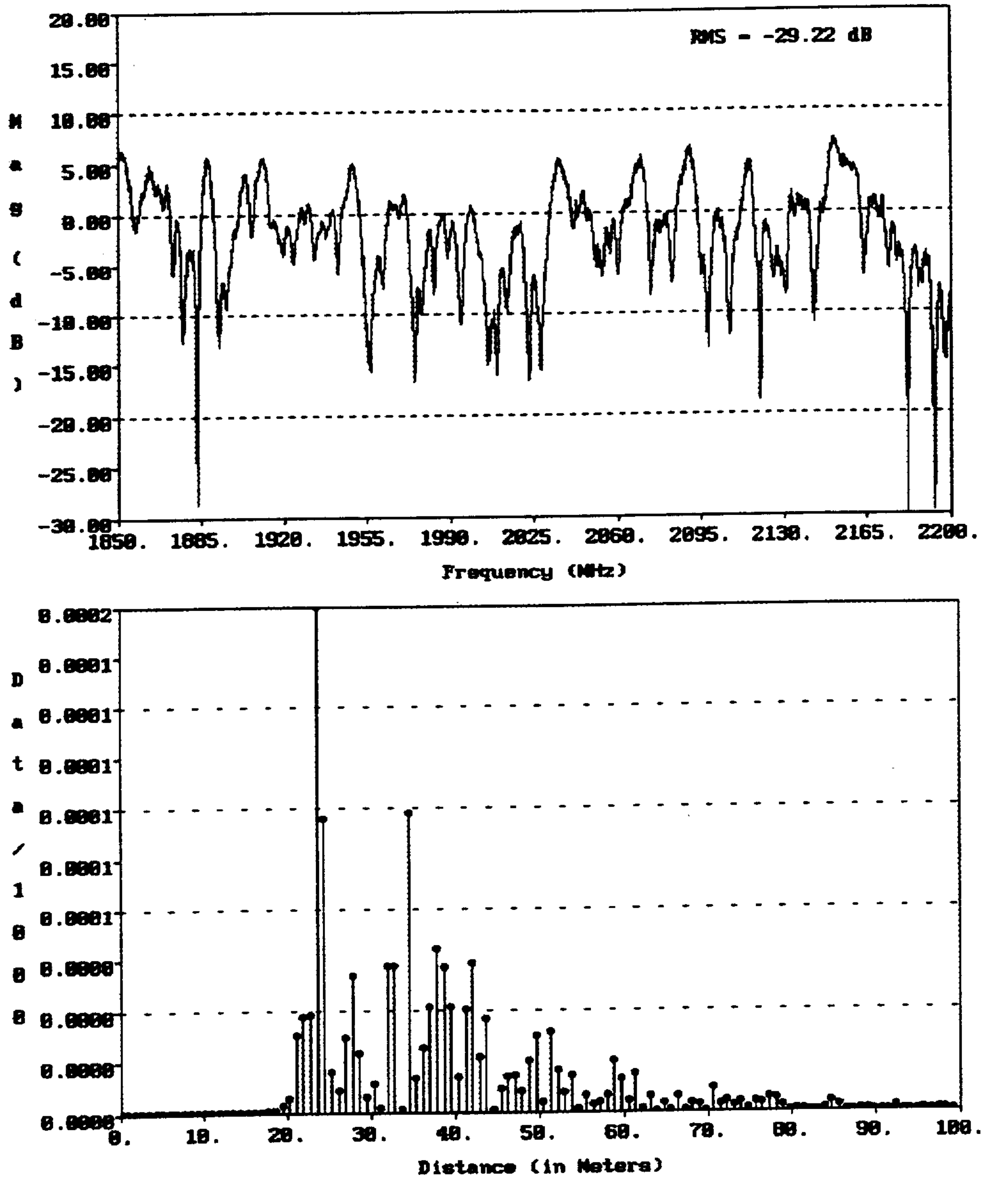


Figure 4-2 Conference Room Sample Response.

4.1.4 Center Hall

The center hall coarse grid represents a subset of the large fine grain measurement set described in Section 4.2. Mention of this series in this section is only provided for completeness, since it will be processed in the same manner as the coarse grids. In addition, correlation statistics will be processed as in Section 4.2.

4.1.5 Cross-Courtyard

This grid was unique in that the signal loss was quite significant. Figure 4-3 illustrates the magnitude of the losses. The RMS was less than -49 dB, as compared to the -25 dB of the upper right sweep in Figure 4-1, the assembly area long path response. This loss was caused by the free-space path loss and the two concrete block walls between the antennas. Also, since the courtyard was open to the sky and one side, little gain could be expected from the channeling effects walls and ceilings might give other paths. For the Hitachi facility, this would be close to representing the worst case.

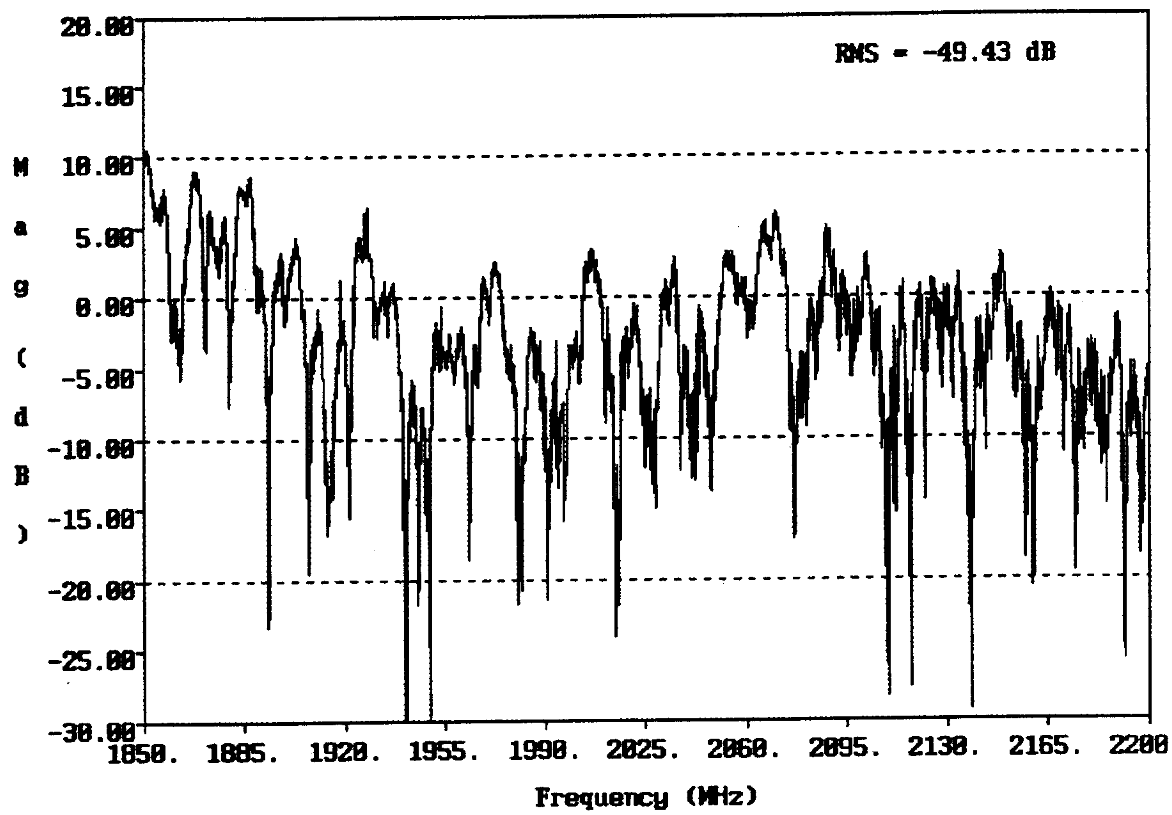


Figure 4-3 Log Magnitude Frequency Response of Cross Courtyard Channel.

This series pushed the measurement system to its limit. With the maximum capable power from the transmit antenna, the signal levels were at best 15 to 20 dB above the noise floor. For this reason, care will be needed in the further processing and interpretation of the data from this run.

4.1.6 Storage Area to Courtyard.

Because of the losses through the concrete wall, the power levels used in this set of measurements was maximized. The noise floor was more than 30 dB below the RMS signal level, which is acceptable for its intended purpose.

4.2 Fine Grain Fade Statistics

This series evidences the moderate degree of correlation expected from sample to sample. (Final processing will determine the degree precisely.) As pointed out in Section 3.2, this should allow calculations of the spatial correlation function over distances that are relatively great with respect to the distances covered by the extra fine grain measurements described in subsequent sections. A preliminary examination of the data indicates that statistical processing of it will provide important information relative to space diversity (horizontal placement of antennas) and time-dependent fading effects.

Because of its size, this series had to be taken in two runs. For each run, the environment remained fairly constant, although the multipath environment did change somewhat in the time between runs. A sensitivity experiment showed that even a slight movement of a piece of furniture makes a measurable difference in the location and depth of fades, although preliminary indications are that the actual statistics of the channel don't vary significantly with such changes.

For this reason, some special adaptations were made for these two runs. First, the grid was split in the middle, across the A series axis. All columns of 18 measurements were run on the same day, with the same environment. The two runs took each half grid on a different day. In addition, for the second run, measurements were repeated for the single 50 cm grid points (not the +10 and +20 cm points) made in the first run. With the data taken in this way, each half grid contains a sufficient number of 10-40 cm distance measurements to calculate correlation statistics. With the additional 50 cm measurements, statistics on the larger distances of 50-250 cm can be generated. Data from the first two runs are contained in the FGRD1A.xxx files, while the additional 50 cm repeat measurements are in the FRGD2A.xxx files.

4.3 Extra Fine Grain Track Measurements

The data collected in this series shows superb agreement with objectives. Channel transfer measurements made at subsequent locations along the track, show excellent correlation and continuity, whereas measurements made at the *ends* of the track show enough differences to indicate that a full (or nearly full) cycle of variability has been experienced. These measurements, directly mappable into a fine-grained depiction of time-variability, are unique in the insights they provide and, when finally processed and written up, will be an important addition to the Indoor and Wireless Communications journal literature.

Three of these measurements, from consecutive 1 cm locations, are shown in Figure 4-4. Growth and decay of at least four major fades can be clearly seen in these samples. Statistical processing will give a better idea of the actual correlation.

A number of constraints affected these high resolution track series. The amount of time required to take these measurements necessitated splitting the acquisition process into a number of subgroups taken on different days. As was mentioned in 4.1.2 above, the warehouse was in use during these series, and the environment could change somewhat between measurements. This was even more true of measurements made on different days. For this reason, because of the correlation desired, considerable care must be taken to check the run logs and point-to-point correlations prior to comparing adjacent measurements in intended processing and usage of the data.

Another possible source of error in these measurements was in movement from set to set. Extreme care was taken to assure that the relative (point to point) location of these measurements was extremely accurate and repeatable. The receive antenna base was a precision constructed, rigid platform with two cylindrical shafts and bearings to allow precision linear motion within its 52 cm range of movement. Measurements made within this range, without moving the table, are probably accurate to within +/- 1 mm. When the segment limit was reached, the entire platform was repositioned. Adjacent line segments, or the point to point tolerance between the end of one segment and the beginning of the next will be +/- 5 mm. Again, logs and correlations must be reviewed carefully when comparing adjacent measurement points.

The official Federal Communications Commission (FCC) approval for broad band (1850-2200 MHz) measurements was received part way through the set of 1 cm step track measurements. For this reason, measurements from 0 cm through 74 cm were made with the old 1850-1990 MHz band, while measurements 75 cm through 100 cm used the new bandwidth. Because the frequency sample spacing for each band was identical, the narrower band measurements may be directly correlated with and compared to that segment of the 1850-2200 MHz measurements.

Finally, some RF path hardware component problems occurred with a fiber optic cable and an attenuator used in calibration measurements. As a result of the attenuator failure, all of the 2 cm step track measurements and most of the 1 cm step measurements have been corrected with a daily through calibration file not made the actual day of the measurement. Comparisons of same power through calibration files show that the day-to-day drift of the system was approximately +/- .2 dB worst case. In addition, the 2 cm tracks have an error induced by the use of a different fiber optic reference cable than was used in the through calibration runs used to correct them. Analysis of the available reference information indicates that the error induced by this difference was a fixed difference of approximately 1.5 dB worst case.

The negative effect these errors have on this data was minimal. The differences are quite small, and generally fixed. The net result of this error was to widen the error margin to +/- 3 dB. As most of this error represents a level bias, it should have minimal effect on processing and usage anticipated for these series of data.

4.4 Fine Grain Track Measurements

Corrected and normalized data from the fine grain track series was as saved series FTA.xxx. As with all of the warehouse measurements, some variation in the multipath environment can be expected between runs. This was caused by normal warehouse operations such as moving pallets and crates between runs. Care should be taken in interpretation of correlation estimates between samples.

Processing and uses for this data are similar to the fine grain grid described in section 4.2. The longer track, however, provides information for a longer distance. Measurement correlations are difficult to see with the eye, so statistical processing is required for interpretation. Track measurements may be used directly, however, to model a time varying process such as motion across the floor. In this way, these measurements represent a useful compromise between coarse track independence and the excessive time required for extra fine track samples.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Measurement results presented in this report are unique by virtue, among other things, of their comprehensiveness in an extremely important indoor communication passband for which no other channel transfer function measurements have been made. Even if the measurements covered a less important band, the general dearth of channel transfer measurements for the indoor channel (especially over wide passbands) would make them of considerable value. It should be noted that important and popular Communication system simulation models, e.g. ComDisco's SPW and BONEs, as do the majority of simulation models, require the definition of a channel transfer function. In those cases where distortion is not important, the transfer function may be as simple as a single complex number (one amplitude and delay that applies to all frequency components). In the most complex multipath fading environments, exemplified by the indoor radio channel, complicated statistical models that reflect the strong frequency dependence of amplitude and phase on the channel must be used. All of these, if such statistical models are to have any validity, must be compared with benchmark measurements of the type presented in this report, i.e. with direct measurements of indoor channel transfer functions across the band of interest. In the same vein, benchmark communication simulations, in their reflection of true performance, can do no better than using actual measured channel transfer function data.

The collected data described in this report and the statistical data that will result from the extensive processing efforts will lead to a channel model. The individual series of measurements, the uses they will be put to, and the degree to which preliminary examination of the data validate their original promise are discussed below.

Coarse Grain Fade Statistics These measurements of coarse grain fade statistics (made at 50 cm spacings), will be processed to achieve the fundamental statistical characterizations that will be the building blocks of the statistical channel model. These statistics are fundamental to communication channel modeling. In addition to the simple average received signal level, they include among other things: (1) Distribution of fade depths and spectral widths of fades; (2) Multipath Spread; (3) Correlation bandwidth; (4) Frequency domain correlation functions and; (4) Joint probability density functions for fade levels in frequency diversity channels.

A preliminary review of the data collected in this measurement series indicates that the expected rough independence of samples from point to point on the grid has indeed been obtained. This is in keeping with the goal of maximizing the number of useful samples available for the processing that will lead to the statistical characterizations. The taking of measurements in so many, diverse locations, of course, will allow investigators to relate statistical parameters to the geometry and character of the locations and physical surroundings, the characterizations of which will be inputs to the channel model of the Cell Evaluation Tool.

Fine Grain Fade Statistics (10 cm grid) As determined in this series of measurements, spatial behavior of the channel transfer function, i.e. that behavior exhibited when one or both of the antennas is moved to a new location, will be used to evaluate the performance of space diversity schemes, sensitivity to antenna placement, and time variability of the channel due to pedestrian walk-through of the spatial patterns.

The 10 cm spacing of these measurements was used to obtain a broad view of spatial behavior over longer distances, rather than the detailed view over shorter distances described in connection with extra fine grain measurements. Experimental data validates this approach in that the series manifests the moderate degree of correlation expected from sample to sample. This will allow calculations of the spatial correlation function over distances that are relatively great with respect to the distances covered by the extra fine grain track measurement series. The primary statistical quantity that will be calculated from this data is the spatial correlation function, which will provide important information relative to space diversity (horizontal placement of antennas) and time-dependent fading effects.

Extra Fine Grain Track Measurements This series of measurements, like the fine grain measurements, will be used to determine the spatial behavior of the channel transfer function. In contrast, however, the measurements here are spaced closely enough to display continuity. This choice will provide detailed plots of the spatial correlation functions at high-to-moderate values of correlation.

The data collected in this series will be excellent for this purpose. Channel transfer measurements made at subsequent locations along the track show the expected high degree of correlation and continuity, whereas measurements made at the *ends* of the track show enough differences to indicate that a full cycle of variability has been experienced. These measurements, directly mappable into a fine-grained depiction of time-variability, will be unique in the insights they provide; there is currently nothing that can compare to them in the journal literature relating to indoor wireless communication.

Fine Grain Track Measurements The measurements in this series are a compromise between the measurements made in the extra fine grain track series described above and the coarse grain track series described below. As in the fine grain fade statistics series described earlier, the 10 cm spacing used for these measurements was to obtain a broad view over longer distances, rather than the detailed view over shorter distances. Although not finely detailed, spatial variability is still of importance in this series, with the sample separation chosen somewhere between one that gives continuity (extra fine grain) and one that gives independence of samples (coarse).

6.0 REFERENCE

[1] Witten, M.L., Pickering, L.W., and Barnhart, E.N., "Test Plan for Hitachi In-Building Communications Channel Characterization," Georgia Tech Research Institute Communications Laboratory, August 1991.