THE MPRG RESEARCH PROGRAM - SOME RECENT PROPAGATION RESULTS

Theodore S. Rappaport
Mobile and Portable Radio Research Group
Bradley Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0111

ABSTRACT

The Mobile and Portable Radio Research Group (MPRG) is a relatively new research group at Virginia Tech. Founded in the Spring of 1990, it is conducting basic and applied research in the areas of radio propagation measurement and prediction, communication system design using real-world channel models, and digital simulation of various modulation, diversity, and equalizer techniques. This paper provides an overview of the MPRG propagation research, and provides references for readers interested in further details of our work.

I. INTRODUCTION

The burgeoning wireless communications business has created an interesting problem for U.S. wireless manufacturers and service providers. Because the field of cellular radio and personal communications is changing rapidly, and since the field involves system concepts seldom taught at universities, our nation's wireless companies are having difficulty finding entry level graduates with sufficient education to make an immediate contribution in research or design. Consequently, recruiters are forced to "raid" competing companies for more senior personnel, and resign themselves to spending 6 months to 2 years training new graduates in the art and science of mobile radio.

MPRG was founded last year to increase the research base in wireless personal communications, and to concurrently provide a quality education for graduate and undergraduate electrical engineering students who wish to pursue careers in mobile and portable radio communications. Our hope is to provide an educational experience that allows a new graduate to possess a solid understanding of the theory and practice of cellular radio. After one year, the results appear to be good. Five M.S.E.E. students have graduated with expertise in RF filter design, indoor radio propagation, adaptive noise-cancellation techniques, and urban radio propagation prediction. Several analysis and simulation software tools have been developed by MPRG researchers, and are presently being used internally and by several companies and universities for R&D. Furthermore, a graduate course dedicated to the topics of cellular radio and personnel communications was offered in Spring 1991, and enjoyed an enrollment of 34 students, making it the most popular graduate course in the EE curriculum at Virginia Tech last semester. When one considers that Virginia Tech has one of the largest EE programs in the U.S., it becomes clear that MPRG will be able to fulfill its mission of providing a significant number of graduates with a solid understanding of wireless communications. It is believed that these graduates will be able to make immediate contributions in industry and academia because of their interest and background.

While the research and educational mission of MPRG concerns itself with more than just propagation, the group received its first research contracts in the area of propagation measurement and prediction. It seems there is extreme interest in propagation measurements and models for the proper design of emerging wireless services such as PCN. However, the U.S. wireless industry generally finds conducting their own measurements and propagation research to be a time consuming and expensive task, and many industrial players view it as an expensive luxury which involves high priced consultants. Virgnia Tech has emerged as a sensible alternative, since MPRG has an established equipment arsenal and offers research expertise in the area of propagation measurement and prediction. As a university, we can provide research and measurement expertise at low cost. By pooling resources in an Industrial Affiliates program, we are generating useful tools and basic propagation models that can be shared by all Affiliates, and the resulting value of the research is much greater than the cost to an individual affiliate member. Since we are a research university, we publish our results so the entire research community can benefit from the knowledge base.

This paper focuses on MPRG radio propagation modeling and prediction activities underway or recently completed. The paper presents results from cellular radio measurements in urban channels, microcellular measurements, and indoor measurements. New results showing the effects of antenna polarization are also included. The paper concludes with an outline of future plans, which include integrating the extensive propagation data bases into new tools for wireless system design.

II. PROPAGATION MEASUREMENT AND PREDICTION

A large part of MPRG work has dealt with measuring, and then statistically modeling, the path loss and time dispersion of multipath radio channels. Measurements and models have been made in many different environments: traditional urban cellular radio channels with base station antenna heights exceeding many tens of meters [1], [2], urban cellular radio channels with lower antenna heights, on the order of 15 - 20 meters [2], in-building channels within sports arenas, factories, and office buildings [3],[4], and open plan office buildings [5].

For urban mobile radio channels, it has been reported that the coherence bandwidth (the bandwidth over which the received signal strength will likely be within 90% of any other frequency from the same source) is between 10 kHz to 500 kHz [6]. Consequently, to sufficiently resolve multipath components that cause frequency selective fading, a channel sounder for urban channels should possess an RF bandwidth several times larger than the maximum coherence bandwidth. This thinking led us to use a 500 ns probing pulse (4 MHz RF bandwidth) in [1],[2]. For indoor measurements, we have used probes that have durations on the order of 5 ns, thereby providing measurements than span over 400 MHz. (the baseband pulse is DSB modulated so there is a bandwidth expansion factor of two at RF). Broadband antennas have been used to ensure no pulse spreading is attributed to impedance mismatch. Figure 1 illustrates important parameters when measuring time dispersion in multipath channels. The rms delay spread (σ_τ) and excess delay spread (X dB) are good measures for comparing different channels and determining approximate bit error rates for digital modulation schemes. Figure 2 shows different time dispersion and path loss results for measurements reported in [2]. The exponent value represents the best-fit average power law at which signal power decays with respect to a free space measurement at some close-in reference distance. The standard deviation σ in dB represents the best-fit deviation from the large scale power law. Figure 3 shows the raw data from which the values in Figure 2 were computed.

Our measurement systems use a simple time domain technique for easy assembly, test, and rapid deployment. They provide instantaneous channel measurements with excellent time delay resolution. Our approach, though, requires more peak power than the direct sequence systems used in [7], [8], and [9] for a specified coverage distance.

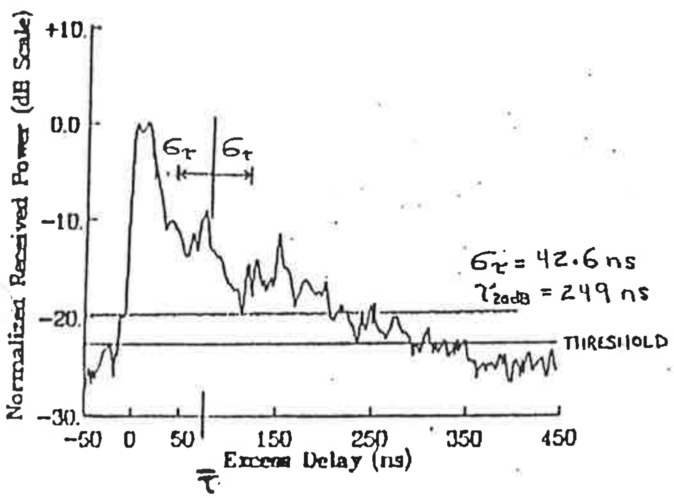


FIG. 1 IMPORTANT TIME DISPERSION PARAMETERS.

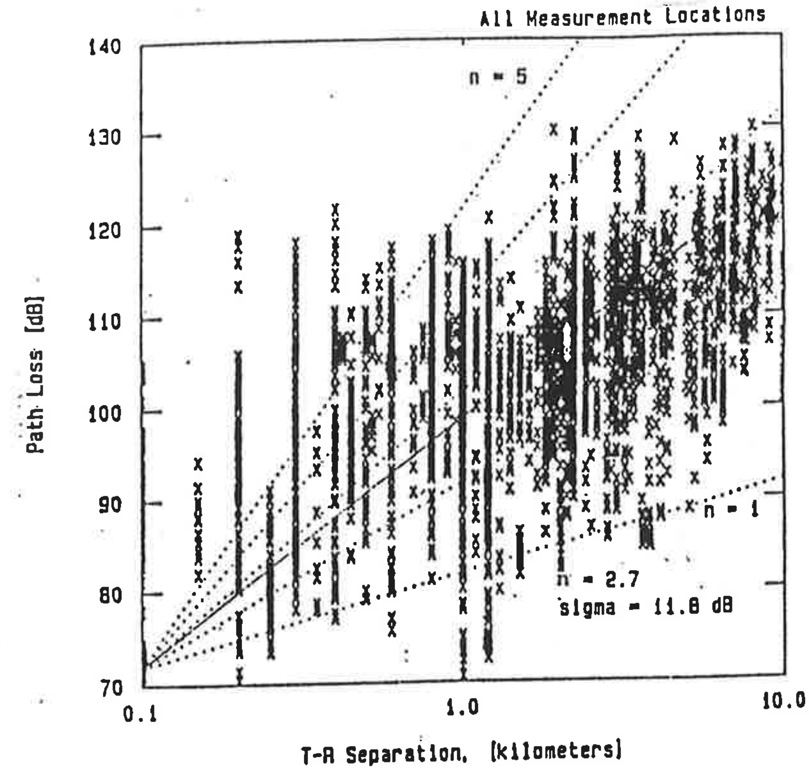


FIG. 2 SCATTER PLOT OF WIDE BAND MEASUREMENTS MADE IN CELLULAR AND MICROCELLULAR CHANNELS IN EUROPE [2].

FIG. 3 TABLE INDICATES THE BEST FIT PATH LOSS EXPONENT AND THE TIME DISPERSIVENESS OF SEVERAL MEASURED CHANNELS [2]

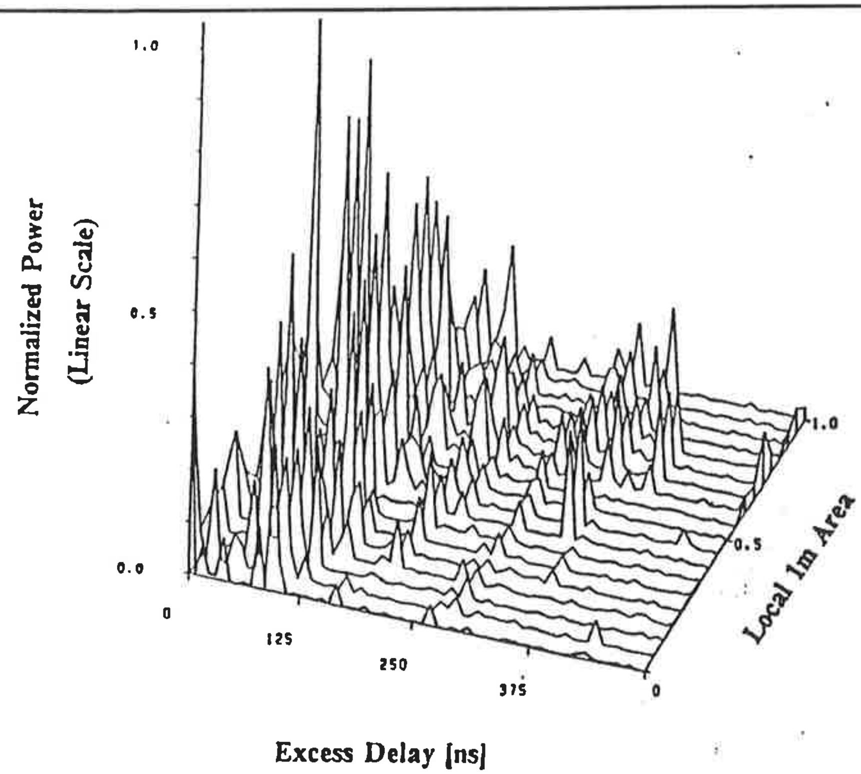
	Antenna Height (m)	n	σ(dB)	Maximum T-R Separation (km)	Maximum Rms Delay Spread (μs)	Maximum Excess Delay Spread(μs) (10 dB)
Hamburg	40	2.5	8.3	8.5	2.7	7.0
Stuttgart	23	2.8	9.6	6.5	5.4	5.8
Dusseldorf	88	2.1	10.8	8.5	4.0	15.9
Frankfurt (PA Bldg.)	20	3.8	7.1	1.3	2.9	12.0
Frankfurt (Bank Bldg.)	93	2.4	13.1	6.5	8.3	18.4
Kronberg	50	2.4	8.5	10.0	19.6	51.3
All (100 m)		2.7	11.8	10.0	19.6	51.3
All (1 km)		3.0	8.9	10.0	19.6	51.3

From Seidel, Rappaport, and Singh, IEE Electronics Letters 9/26/90

From the large number of measurements collected in [1], we have developed a statistical simulator called SMRSIM (Simulation of Mobile Radio Statistical Impulse Response Measurements), which reproduces spatially-varying complex impulse responses comparable to measured data. MPRG graduate students Victor Fung and Weifeng Huang are using SMRSIM for design and simulation of modulation and equalization techniques. SMRSIM is used in addition to the worst case two-ray, Rayleigh fading model often used in simulation work [12]. Although the phases of individual signals were not measured, we use a physically-motivated synthesis technique described in [10] to reconstruct the phases and spatial variation of the phases in outdoor channels. Our model is different from Hashemi's SURP model for the phases of individual multipath components, since we model the phases of each multipath component to be changing deterministically from a randomly located fixed scatterer, rather than assuming [11] that the phases of each multipath component are uncorrelated over less than a wavelength. The Doppler shift actually places an upper bound on the rate of change of phase of a discrete multipath component, and we use the Doppler information to determine the rate of change of phase. When CW fading signals are reconstructed from SMRSIM, the fading statistics, including level crossing rate, fade rate, and fading distribution, are very representative of measurements.

Extensive indoor measurements are being conducted, with the long term goal of deriving site-specific models based on building blue prints. Along the way, we have used the statistical modeling procedure in [10] to reproduce, on a personal computer, extensive factory impulse response measurements given in [13]. Also, more recent measurements [3], [4], and measurements reported in the literature [14] have been used to generate, on a computer, impulse response and path loss measurements in traditional partitioned office buildings, and soft partitioned (Herman-Miller office partitions) office buildings. Statistical models are useful for designing, on a computer, appropriate data rates or modulation, coding, diversity, and equalization methods. The simulator, called SIRCIM (Simulation of Indoor Radio Channel Impulse response Measurements), is a valuable research tool for MPRG equalization and antenna diversity work, and has been purchased by over 25 companies and universities. MPRG plans to update the software as more measurements become available, and as customer feedback dictates. A useful result from [3] is that propagation characteristics are very similar at both 1.3 GHz and 4.0 GHz, which means the SIRCIM models (based on measurements around 1 GHz) will hold up to at least 4.0 GHz, and probably at somewhat higher frequencies. At the time of this writing, MPRG measurement capabilities are limited to frequencies below 4 GHz, although new measurement equipment is being pursued for measurements at much higher frequencies. Typical examples of the data produced by SIRCIM are shown in Figure 4. Data files that contain the amplitudes, phases, time delays, and path loss for individual multipath components are produced by SIRCIM and written to disk for later use in simulation programs.

Narrow band measurements show how the path loss exponent, and the deviation about the best-fit average path loss model, can be affected by building type, or location within a building. Table 1, extracted from [5], shows how that in different buildings, the floors can offer different values of attenuation. Figures 5 - 6 present measured attenuation factors for various obstacles in indoor environments [4],[5]. In [5], a simple two parameter statistical model was developed to model the loss due to each partition or each wall encountered between a transmitter and receiver inside an office building. Figure 7 shows a scatter plot of measurements made on three floors of two different office buildings, and the best-fit line which provides about a 4 dB standard deviation. The transmitter antenna was mounted 1.8 m above ground, and the receiver was located at desk height, shadowed by the soft partitions. Using a very simple model, it becomes possible to come close to predicting signal strength contours. Figures 8-10



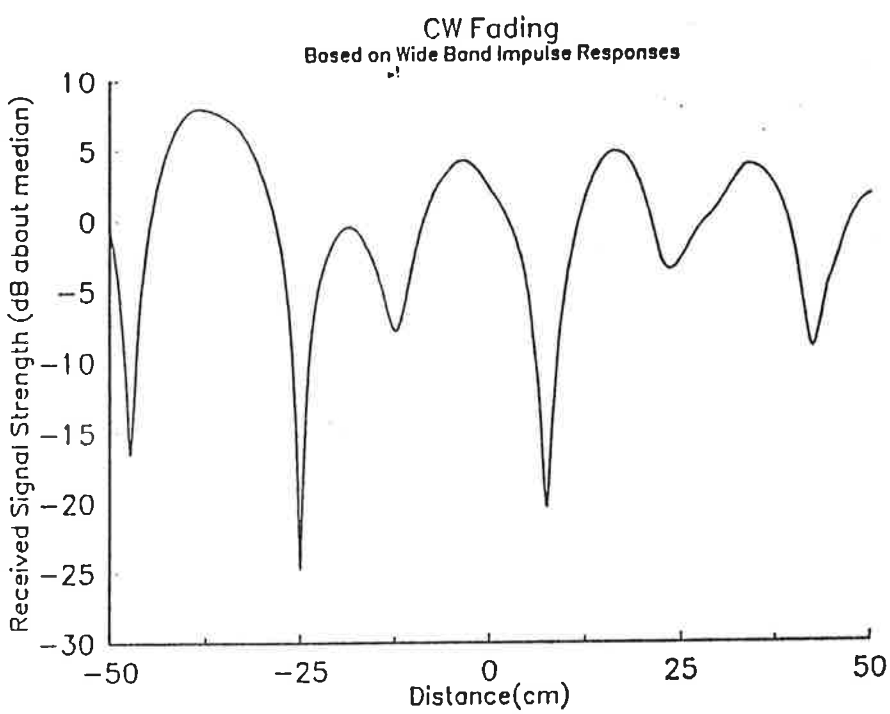
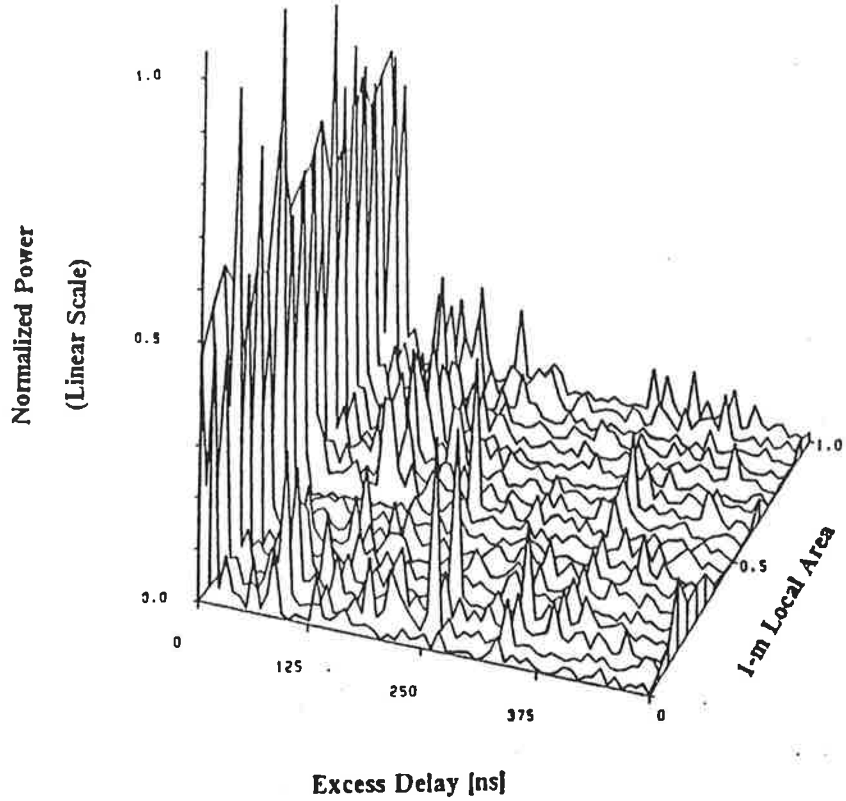
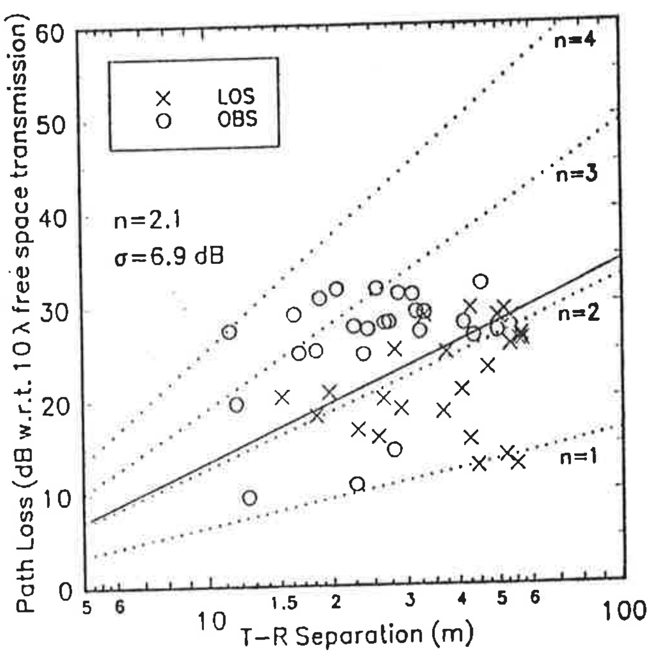


FIG. 4 THESE WAVEFORMS ARE EXAMPLES PRODUCED BY SIRCIM. SIRCIM PROVIDES THE USER WITH DATA FILES THAT CONTAIN AMPLITUDES, PHASES, AND TIME DELAYS OF THE CHANNEL IMPULSE RESPONSE, AND COMPUTES FADING STATISTICS, LARGE SCALE PATH LOSS, BEST FIT EXPONENT AND STANDARD DEV. USER CAN SPECIFY BUILDING TYPE, TOPOGRAPHY (LOS or OBS), AND T-R SEPARATION DISTANCE. SIRCIM IS BASED ON EXTENSIVE MEASUREMENTS MADE



EXAMPLE OF SIRCIM OUTPUT IN LOS OPEN PLAN BUILDING



EXAMPLE OF SCATTER PLOT PRODUCED BY SIRCIM IN AN OPEN PLAN BUILDING - 50% LOS, 50% OBS

FIG 4. ADDITIONAL EXAMPLES OF OUTPUT GENERATED BY SIRCIM. ALL DATA ARE STORED ON DISK FOR LATER USE IN ANALYSIS OR SIMULATION.

TABLE 1: a) Floor Attenuation Factors measured in two office buildings

b) Best fit path loss exponents, and corresponding std. dev. for measurements in several types of buildings [5].

	FAF(dB)	σ(dB)	# Locations
Office Building 1 :			
Through 1 floor	12.9	7.0	104
Through 2 floors	18.7	2.8	18
Through 3 floors	24.4	1.7	18
Through 4 floors	27.0	1.5	18
Office Building 2 :			
Through 1 floor	16.2	2.9	40
Through 2 floors	27.5	5.4	42
Through 3 floors	31.6	7.2	40

	n	σ(dB)	# Locations
All Buildings :			
All Locations	3.14	16.3	646
Same Floor	2.76	12.9	501
Through 1 Floor	4.19	5.1	144
Through 2 Floors	5.04	6.5	60
Through 3 Floors	5.22	6.7	58
Grocery Store	1.81	5.2	89
Retail Store	2.18	8.7	137
Office Building 1 :			
Entire Building	3.54	12.8	320
Same Floor	3.27	11.2	238
W. Wing 5th Floor	2.68	8.1	104
Central Wing 5th	4.01	4.3	118
W. Wing 4th Floor	3.18	4.4	120
Office Building 2 :			
Entire Building	4,33	13.3	100
Same Floor	3.25	5.2	37

It is possible to account for obstructions when computing coverage zones. The following tables provide representative attenuation factors for obstacles, based on extensive measurements by Virginia Tech MPRG personnel.

Item	Loss (dB)
IN OFFICE BUILDINGS	
Concrete Block Wall	13
Loss From One Floor	20-30
Loss From One Floor and One Wall	40-50
Fade observed when transmitter turned a right angle corner in a corridor	10-15

FIG 5. MEASURED SIGNAL LOSS DUE TO COMMON OBSTRUCTIONS IN BUILDINGS. THESE DATA WERE COLLECTED BY COMPARING SIGNAL STRENGTH ON EITHER SIDE OF THE OBSTRUCTION.

	Loss (dB)		Loss (dB)
Light Textile Inventory	3-5	Heavy Textile Inventory	8-11
Chain link fenced in area 20 ft. high which contains tools, inventory, and people	5-12	area where workers inspect metal finished products for defects	3-12
Metal Blanker 12 square feet	4-7	metallic inventory	4-7
Metallic Hoppers which hold scrap metal for recycling 10 square feet	3-6	Large I-beam 16-20 in.	8-10
Small Metal Pole 6 in. diameter	3	Metallic inventory racks 8 square feet	4-9
Metal Pulley System used to hoist metal inventory 4 sq. ft.	6	Empty Cardboard inventory boxes	3-6
Light Machinery < 10 square feet	1-4	Concrete Block Wall	13-20
General Machinery 10-20 square feet	5-10	Ceiling Duct	1-8
Heavy Machinery > 20 square feet	10-12		
Metal catwalk/stairs	5		
Light Textile	3-5		

Shadowing Effects of Common Factory Equipment	
Obstacle Description	Attenuation (dB)
2.5 m storage rack with small metal parts (loosely packed)	4-6
4 m metal box storage	10-12
5 m storage rack with paper products (loosely packed)	2-4
5 m storage rack with paper products (tightly packed)	6
5 m storage rack with large metal parts (tightly packed)	20
Typical N/C machine	8-10
Semi-automated Assembly Line	5-7
0.6 m square reinforced concrete pillar	12-14
Stainless Steel Piping for Cook-Cool Process	15
Concrete wall	8-15
Concrete floor	10

FIG 6. MEASURED SIGNAL LOSS DUE TO COMMON OBSTRUCTIONS IN FACTORY BUILDINGS.

illustrate how the simple model, which assumes a loss of about 1.4dB/soft partition and 2.4dB/concrete wall, can accurately predict coverage throughout the work space. Although this model is preliminary, it gives us hope that simple statistical models, used in conjunction with descriptions about the building topography, could be used to predict coverage areas and interference zones with good accuracy. MPRG researchers plan to continue a measurement campaign that will lead to accurate site specific models, and incorporate them into an automated system design tool that will optimally locate base stations for minimum interference and consequently maximum capacity. That is, we hope to exploit knowledge of the channel to improve system installation without measurements.

Work in [4] has shown that antenna polarization can play a big part in reducing the delay spread (i.e. improving the bit error performance). In [15], Cox describes the Bellcore UDPC system as using polarization diversity to open the eye in digital modulation techniques. Our work [4] shows that, indeed, polarization diversity can be used to select the best channel at a particular location. Our work also shows that circular polarized (C-P) directional antennas, when used in line-of-sight channels, can provide a much lower delay spread than linear polarized antennas with similar directionality. We have also seen this on cross-campus links which may illuminate several buildings at a time. In outdoor links especially, it appears that when aligned off-axis, directional C-P antennas offer much more multipath resistance than linear polarized antennas. We have good physical reasoning for this phenomenon, and believe it offers insight to appropriate antenna design for emerging PCN systems. Further, it indicates an accurate ray tracing prediction tool must consider polarization effects.

III. FUTURE WORK IN PROPAGATION

Presently we are conducting narrow band measurements around the Virginia Tech campus. A first round of measurements was recently conducted by MPRG undergraduate researchers at 900 MHz, and these data are being compared with campus elevation and building maps to determine appropriate knife-edge and ray tracing modeling techniques. A recent paper shows the viability of ray tracing and shadowing for accurate propagation prediction for microcellular systems [16], and our initial models show that in fact only a few rays and simple diffraction methods can be used most of the time to get surprisingly good prediction (within 3 dB) of measured signals. Tom Russell and Kurt Schaubach are presently working the problem, and are investigating good models that predict the effects of buildings that obstruct and reflect.

Additional 900 MHz and 1900 MHz measurements around campus will provide data for building penetration into several buildings, floor-to-floor loss for different shaped buildings, and the correlation of signal strengths over small distances. Also, further measurements will enhance the partition models presented in [5], and will reveal additional modeling parameters.

An enormous site-specific data base was gathered in [4], and subsequent work will determine ray-tracing and diffraction models for accurate signal strength and time dispersion prediction within buildings. We will include polarization and antenna directivity in our models, and integrate them into a system design tool for indoor wireless communications.

IV. ACKNOWLEDGEMENTS

The author expresses his gratitude to the MPRG Industrial Affiliates companies, and to the hard-working MPRG staff.

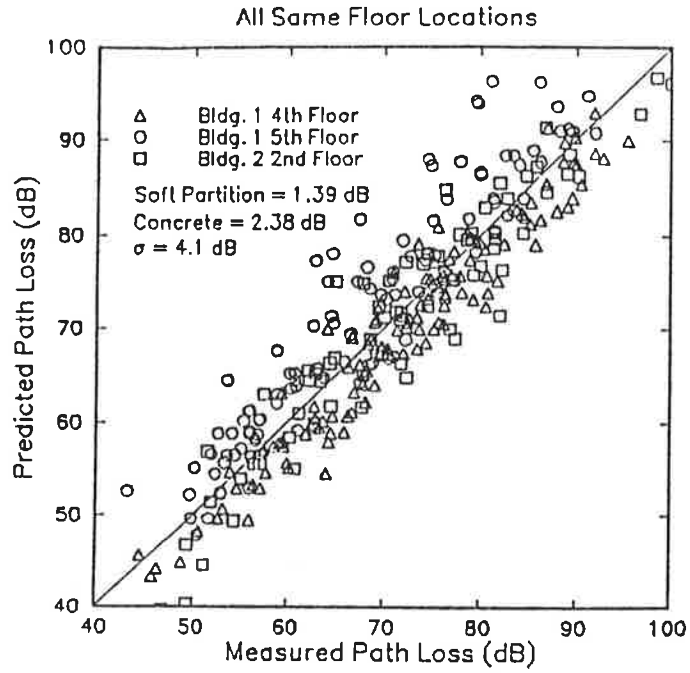


FIG. 7 BEST FIT LINE FOR A SIMPLE TWO PARAMETER MODEL USED TO PREDICT SIGNAL LOSS DUE TO OBSTRUCTIONS.

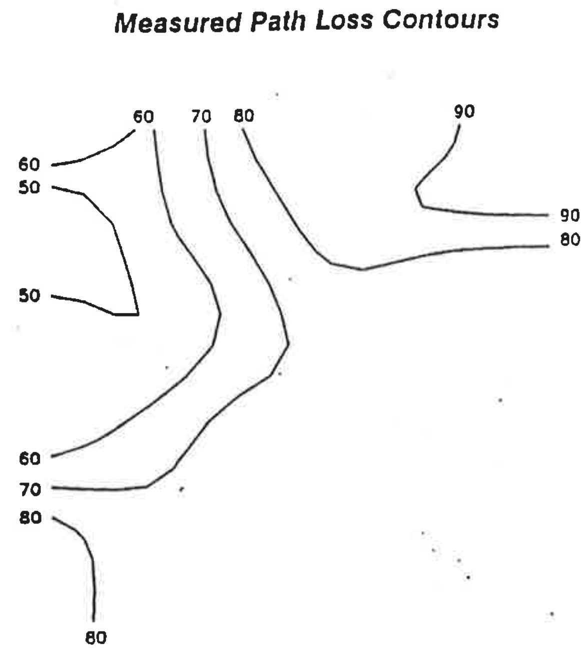


FIG. 8 CONTOUR PLOT OF MEASURED SIGNA STRENGTH AT 900 MHZ INSIDE AN OPEN PLAN BUILDING WITH SOFT PARTITIONS.

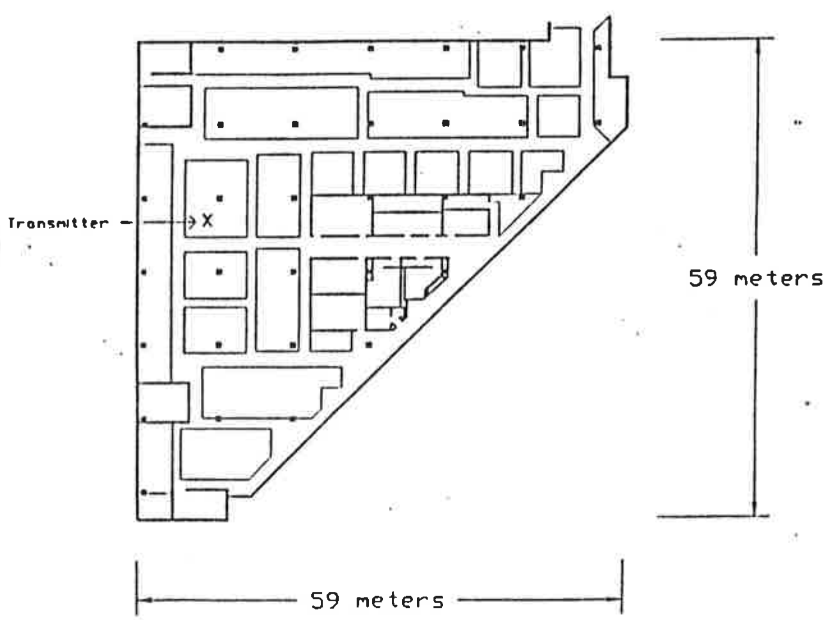


FIG. 9 BLUE PRINT OF OPEN PLAN BUILDING MEASURED IN FIG. 8. NOTE THAT THE NUMBER OF PARTITIONS COULD BE COUNTED USING SIMPLE COMPUTER TECHNIQUES.

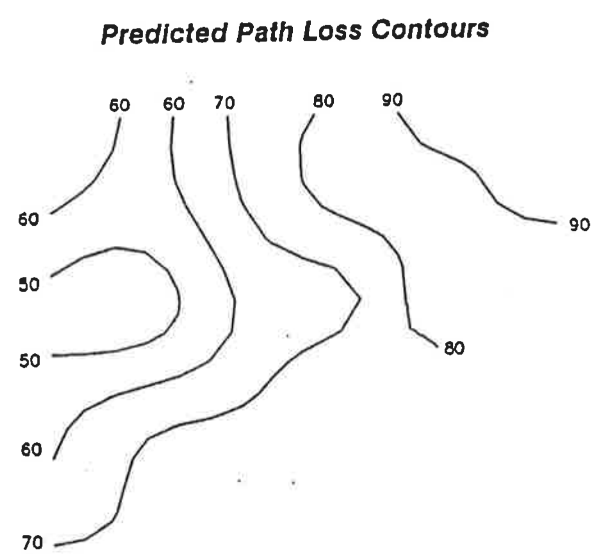


FIG. 10 PREDICTED CONTOUR PLOT OF SIGNAL STRENGTH USING THE BEST FIT MODEL OF FIG. 7. AGREEMENT WITH MEASURED DATA IS GENERALLY GOOD, AND IS MORE ACCURATE THAN JUST USING T-R SEPARATION ALONE [5].

V. REFERENCES

[1] T.S. Rappaport, S.Y. Seidel, R. Singh, "900 MHz Multipath Propagation Measurements for U.S. Digital Cellular Radiotelephone," IEEE Trans. VT., May 1990, pp. 132-139.

[2] S.Y. Seidel, T.S. Rappaport, R. Singh, "Path Loss and Multipath Delay Statistics for 900 MHz Cellular and Microcellular Commuications," IEE Electronics Letters, Sept. 26, 1990, Vol. 26, no. 20, pp. 1713-1715.

[3] D.A. Hawbaker, T.S. Rappaport, "Indoor Wideband Radiowave Propagation Measurements at 1.3 GHz and 4.0 GHz " IEE Electronics Letters, October 10, 1990, Vol. 26, no. 21, pp. 1800-1802.

[4] D.A. Hawbaker, "Indoor Radio Propagation Measurements, Models, and Communication System Design Issues," Masters Thesis in Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, May 1991.

[5] S. Y. Seidel, T.S. Rappaport, "900 MHz Path Loss Measurements and Prediction Techniques for In-Building Communication System Design," 1991 IEEE Vehicular Technology Conference, St. Louis, MO, May 21, 1991.

[6] R. W. Lorenz "Impact of Frequency-Selective Fading on Digital Land Mobile Radio Communications at Transmission Rates of Several Hundred kbit/s," IEEE Trans. Veh. Tech., Vol. VT-35, no. 3, August 1987, pp. 122-128.

[7] R.J.C. Bultitude, "Propagation Characteristics on Microcellular Urban Mobile Radio Channels at 910 MHz," IEEE J. in Sel. Areas Communications, Vol. 7, no. 1, January 1989, pp. 31-39.

[8] D.M.J. Devasirvatham, "Multipath Time Delay Spread in the Digital Portable Radio Environment," IEEE Communications Magazine, Vol. 25, no. 6, June 1987, pp. 13-21.

[9] D.C. Cox, "Time and Frequency-domain Characterizations of Multipath Propagation at 910 MHz in a Suburban Mobile-Radio Environment," Radio Science, Vol. 7, no. 12, December 1972, pp. 1069-1081.

[10] T.S. Rappaport, S. Y. Seidel, K. Takamizawa, "Statistical Channel Impulse Response Models for Factory and Open Plan Building Radio Communication System Design " IEEE Transactions on Communications, to be published May 1991, 13 pages.

[11] H. Hashemi, "Simulation of the Urban Radio Propagation Channel," IEEE Trans. Veh. Tech., Vol. VT-28, pp. 213-225, August 1979.

[12] J.I. Smith, "A Computer Generated Multipath Fading Simulation for Mobile Radio," IEEE Trans. Veh. Tech., Vol. 24, no. 3, August 1975, pp. 39-40.

[13] T.S. Rappaport, "Characterization of UHF Multipath Radio Channels in Factory Buildings," IEEE Trans. Antennas and Propagation, Vol. 37, no. 8, August 1989, pp. 1058-1069.

[14] D. Molkdar, "Review on Radio Propagation Into and Within Buildings," IEE Proceedings-H, Vol. 138, no. 1, February 1991, pp. 61-73.

[15] D.C. Cox, "A Radio System Proposal for Widespread Low-Power Tetherless Communications," IEEE Trans. Comm., Vol. 39, no. 2, February 1991, pp. 324-335.

[16] F. Ikegami, T. Takeuchi, S. Yoshida, "Theoretical Prediction of Mean Field Strength for Urban Mobile Radio," IEEE Trans. Ant. Propagation, Vol. 39, no. 3, March 1991, pp. 299-302.