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Elridge A. Stafford
Executive Director-
Federal Regulatory

U S WEST

September 17, 1992

Mr. H. Franklin Wright
Office of Engineering and Technology
Frequency Liason Branch
2025 M Street, N.W., Room 7326
Washington, D.C. 20554

RE: U S WEST COMMUNICATIONS, INC.
Call Sign KK2XCC; File No. 3630-EX-ML-93
SIXTH QUARTERLY REPORT
PCS Experimental License for Boulder, CO

Dear Mr. Wright:

Enclosed please find U S WEST's sixth quarterly report addressing the above referenced authorization for PCS field trials in Boulder, Colorado.

Should you have any questions or require additional information, please contact me.

Sincerely,

Elridge Stafford

Enclosures

MEMO

TO: Ira Barron, Mark Beckner, John Boe, Annette Bouta, Chris Butler, Tom Dodds, Ed Fontenot, Dave Jones, Ray Nettleton, Doug Reudink, Beth Spellicy, Marty Dickerson

FROM: Marty Feuerstein, Scott McClatchey

DATE: September 8, 1993

SUBJECT: Quarterly Report for FCC Experimental License KK2XCC

The attached report describes field testing performed under FCC Experimental License KK2XCC for Boulder, CO, during the quarterly period from June 5 through September 5, 1993. The report is a draft copy produced by Advanced Technologies. A conference call with U S WEST's legal staff is scheduled for Thursday, September 16, 1993, to edit the report before final submission to the FCC. In light of our upcoming petition to the FCC for an experimental license extension, we may need to alter the sections of the report discussing plans for fourth quarter 1993 and into 1994. For this reason, please do not distribute this draft copy to anyone outside of U S WEST.

The work discussed in the report was truly a cooperative venture between a number of parties, including Advanced Technologies, Personal Communications Development, USW Communications, Bellcore, DDI Corporation, and the NTIA. We would like to acknowledge the outstanding contributions of everyone involved with the testing effort.

Curt Goehring and Dave Robinson assisted with the field measurements and data processing for the PHP system. Ruvin Lerman performed the laboratory calibration of the PHP equipment. The following PHP personnel from Japan were involved with the initial setup of the test equipment: Mr. Sugawara and Mr. Kishi of DDI Corporation; Mr. Taromalu of Panasonic; Mr. Kojima of Kyocera; Mr. Kobayashi and Mr. Honda of Masushita; Mr. Komura of Nitsuko; Mr. Yasuda of Mitsubishi. Mr. Kishi of DDI Corporation was present during all the field tests, where his assistance was invaluable.

For the WACS field tests, the following personnel from Bellcore were instrumental to the measurements: Nelson Sollenberger, Rob Zeigler, Ali Afrashteh, and Alex Lui. Ira Barron coordinated the testing from the Bellcore side. Once again, Curt Goehring's field work and expertise with a bucket truck made these tests successful.

The data services demonstrations of the WACS system were orchestrated by Steve Nowak and Iain Stewart. The following additional Bellcore personnel participated in the data services tests: Mike Kramer, Rich Wolff, Dan Chukorov, Tony McAuley, Gerardo Ramirez, and Henri Tohme. The data services section of the FCC report was prepared by Iain Stewart.

Sergio Aguirre was responsible for the building penetration work performed jointly by NTIA and USWAT. The section of the FCC report discussing results of the propagation study was written by Sergio.

If you have any comments, please contact Marty at (303) 541-6764 or Scott at (303) 541-6795.

U S WEST
Wireless Personal Communications
Experiments

Quarterly Progress Report
FCC Experimental License
KK2XCC

September 8, 1993

Submitted to

Federal Communications Commission
Frequency Liaison Branch
Room 7326
Washington, DC 20554

Prepared by

U S WEST Advanced Technologies
Wireless Communications Services
4001 Discovery Drive
Boulder, CO 80303

Table of Contents

Executive Summary

U S WEST has conducted two system trials and one propagation study during this quarterly period. In addition, plans have been developed for expanding the Boulder PCS testbed facility to allow more comprehensive experiments using different radio environments, transport infrastructures, and switching architectures. The system trials included tests of the Personal Handy Phone (PHP) system and the Wireless Access Communications System (WACS). The propagation study evaluated the penetration of radio signals from lamp post height microcells into residential and urban buildings.

Testing of the Personal Handy Phone system included a voice quality test and a more detailed propagation study where bit error rate and received signal strength were recorded. Base station antenna heights of 43 and 57 feet were used to emulate typical rooftop antenna installations. Based on the bit error rate measurements, the range covered by the prototype system was 400 to 500 meters non-line-of-sight radius from the base station. Building penetration coverage into a shopping mall was also measured from a base station in the parking lot. Most interior areas of the shopping mall, including interior corridors, were covered with acceptable bit error rates.

The field trials of the Wireless Access Communications System were divided into two parts: first, coverage and handoff tests, and second data services demonstrations. Two radio ports were installed and connected to radio port controllers through HDSL links over copper loops. During the outdoor coverage tests, word error rates and subjective voice quality estimates were recorded for both the radio ports. Coverage contours were plotted based on these measurements. Results indicated that outdoor coverage along streets with line-of-sight to the radio ports was 2 to 2.5 blocks. Coverage in non-line-of-sight conditions was limited to 1 to 2 blocks from the radio port.

Inbuilding penetration studies were conducted by evaluating subjective voice quality in a number of street-side small businesses within the coverage area. Results showed that adequate voice quality was obtained in businesses within 1.5 blocks of the base station, where the entrance to the business was line-of-sight to the radio port. Coverage was poor to unusable for businesses more than 1.5 blocks from the base, or in locations where the building entrance did not have line-of-sight to the radio port.

Handoff tests of the WACS system were conducted with handoff hysterisis levels of 3, 5,and 7 dB. The numbers of handoffs encountered while traversing designated walking routes were recorded as functions of hysterisis level. Hysterisis levels of 5 and 7 dB produced approximately the same average number of handoffs, while the 3 dB level comparatively had four times the number of handoffs. Excessive "ping-ponging" between the two radio ports was noted with the 3 dB hysterisis level. Results confirmed that hysterisis levels as low as 5 dB can be used successfully in the WACS system.

Specially modified versions of the WACS equipment were used to demonstrate data services over the radio link. Two services were trialed: Call Command and Simple Messaging. Call Command allowed a nomadic wireless computer user to route incoming voice phone calls via a software interface. Messages or announcements could be sent from the computer user to the voice caller using a text-to-speech converter. The Simple Messaging application allowed electronic mail messages to be transferred between two wireless computer users.

A building penetration propagation study was conducted jointly between U S WEST and the National Telecommunications and Information Administration (NTIA). Radio experiments were conducted to quantify building penetration losses at three frequencies: 910 MHz, 1920 MHz, and 5990 MHz. The experiments were conducted in typical residential areas in Boulder, CO and urban (high rise buildings) environments in Denver, CO. The sample population included seven typical houses and five multistory office buildings with various degrees of window areas and differing construction materials. A variety of situations were tested, including line of sight and non-line of sight conditions. The experiments are intended to determine the viability of providing indoor coverage using outdoor base stations, with antennas at lamp post height.

In general, and as expected, higher penetration losses were experienced at the higher frequencies. Mean penetration losses per house varied from 7.4 dB to 12.5 dB at 1920 MHz with standard deviations ranging from 5.3 dB to 10.7 dB. Considering all the residential measurements taken, median penetration losses at 912, 1920, and 5990 MHz were 7.7 dB, 11.6 dB, and 16.1 dB respectively. At the 90% level, the losses were 13.0 dB, 23.0 dB, and 28.8 dB respectively. Median high rise building penetration losses for all the buildings measured at 912 MHz, 1920 MHz, and 5990 MHz were 17.5, 18 dB and 26 dB respectively. At the 90% level, the measured penetration losses for all the high rise buildings were 27.5 dB, 34 dB, and 37.5 dB respectively.

1 Introduction

This report describes field testing which U S WEST Advanced Technologies performed under FCC Experimental License KK2XCC for Boulder, Colorado, during the quarterly period from March 5 through June 5, 1993.

U S WEST has conducted two system trials and one propagation study during this quarter. In addition, plans have been developed for expanding the Boulder PCS testbed facility to allow more comprehensive tests using different radio environments, transport infrastructures, and switching architectures. The radio trials included tests of the Personal Handy Phone (PHP) system and the Wireless Access Communications System (WACS). The propagation study evaluated the penetration of radio signals from lamp post height microcells into residential and urban buildings.

Testing of the PHP system included a voice quality test, and a more detailed propagation study where bit error rate and received signal strength were recorded. Base station antenna heights of 43 and 57 feet were used to emulate typical rooftop antenna installations. Building penetration coverage into a shopping mall was also measured from a base station in the parking lot.

The field trials of the WACS system were divided into two parts: first, coverage and handoff tests, and second data services demonstrations. During the outdoor coverage tests, word error rates and subjective voice quality estimates were recorded for a two radio port configuration. Coverage contours were plotted based on these measurements. Inbuilding penetration studies were conducted by recording subjective voice quality in a number of street-side small businesses in the coverage area. Handoff tests of the WACS system were conducted with handoff hysterisis levels of 3, 5,and 7 dB.

Specially modified versions of the WACS equipment were used to demonstrate data services over the radio link. Two services were demonstrated: Call Command and Simple Messaging. Call Command allowed a nomadic wireless computer user to route incoming voice phone calls via a software interface. Messages or announcements could be sent from the computer user to the voice caller via a text-to-speech converter. The Simple Messaging application allowed electronic mail messages to be transferred between two wireless computer users.

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Section 2 of this report describes U S WEST's plans for expanding the Boulder PCS testbed facility to include additional radio ports and expanded transport facilities. Measurement results from trials with the Personal Handy Phone system are detailed in Section 3. In Section 4, results from the tests of the Wireless Access Communications System are discussed. Measurements of coverage and handoff characteristics are presented, along with observations from the wireless data services demonstrations. Preliminary analysis from the radio propagation study of building penetration are presented in Section 5. Finally, future research plans are outlined in Section 6.

2 Expansion of Boulder PCS Testbed

A large scale expansion of the Boulder PCS testbed has been initiated this quarter. A number of new radio ports are being installed to enhance the coverage of the testbed in residential, light urban, and heavy urban areas. The new base station locations include a mixture of street lamp mounts and building rooftop installations. The combination of different antenna heights will provide a mechanism for testing overlay and underlay scenarios with micro/macro cells. The transport infrastructure, which provides connections to the radio ports, is being upgraded to include a broadband fiber and cable distribution plant. The current transport infrastructure makes use of HDSL, T-1, analog line, and X.25 modem links. The network switching hardware is being expanded to test various switch architectures and interfaces.

2.1 Network Infrastructure Equipment

In addition to the radio testing that was conducted during this quarter, substantial effort went into expanding the testbed infrastructure in preparation for upcoming PCS radio system trials. Network switching hardware is being installed in laboratories on 28th Street in Boulder and on Pierce Street in Lakewood, as indicated in Figure 2-1. The Intelligent Service Peripheral (ISP) is a platform that provides PCS access management functions for mobile control. The Integrated Service Control Point (ISCP) provides the home location register containing handset and call routing information. Radio Port Controllers (RPCs) are PC-based applications software systems providing radio port management and call routing functions. For operations support, the Bellcore PCS Operations Support Prototype (BPOP) may be installed at the 28th Street laboratory. The installation of the laboratory hardware and the associated communications links is expected to be complete by early October of this year.

2.2 Radio Base Station Expansion

Also included in the testbed expansion is the addition of approximately 40 new radio base station sites. With these new base station locations, significant flexibility will be added in terms of the radio systems and propagation environments that can be tested using the Boulder PCS testbed. The facilities to support these new base stations, including all transport infrastructure, are scheduled to be in place by the end of 1993. Figures 2-2 and 2-3 show the locations of the new base station sites being added to the testbed in Boulder and Denver, respectively. Descriptions of the new base station sites, grouped by area, are provided below.

Light Urban Area With Conventional Transport Backbone

Thirteen low-tier, or microcellular, base station sites will be installed directly east of the initial nine sites along Pearl Street, extending eastward as far as 28th Street. Like the nine low-tier sites already in place, these thirteen sites will be mounted on existing public lighting structures or traffic signal poles. Standard twisted pair copper wires provide the backbone connections into the telephone switching network.

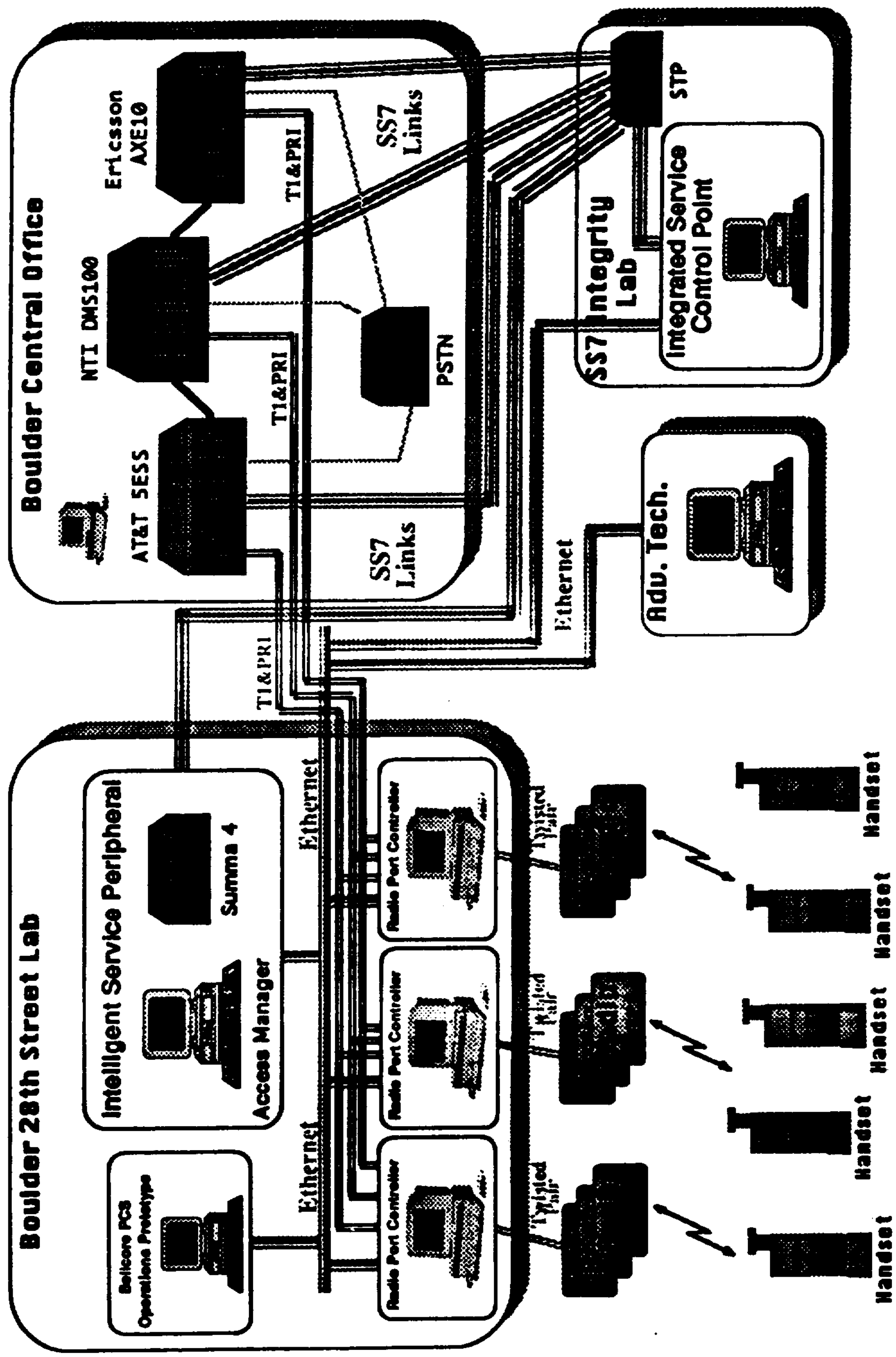

Figure 2-1. Boulder PCS testbed infrastructure

Figure 2-2. Testbed base station locations in Boulder, Colorado

Downtown Denver, Colorado

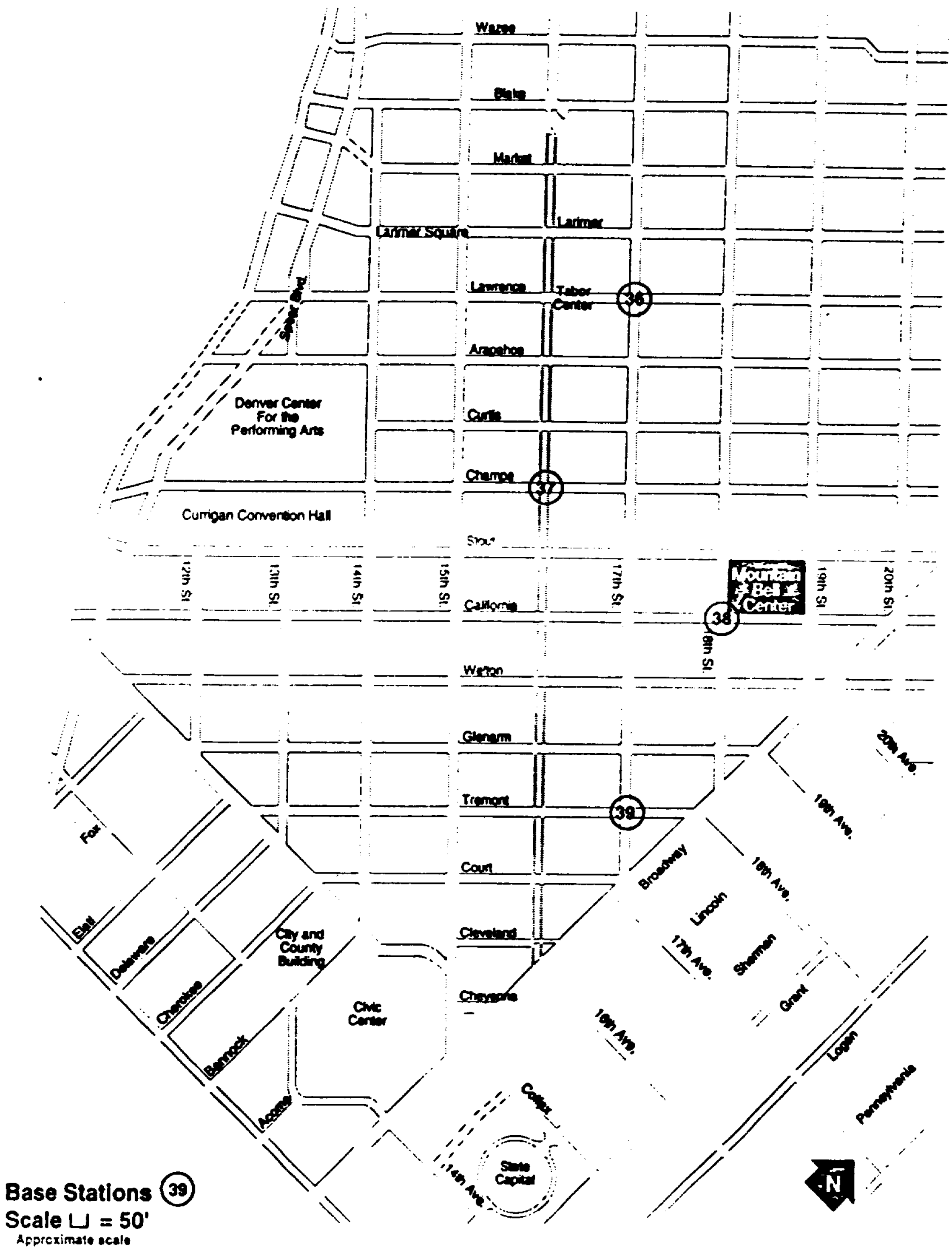

Figure 2-3. Testbed base station locations in Denver, Colorado

Light Urban Area With Broadband Transport Backbone

Eleven low-tier base station sites will be added north of the Pearl Street Mall. Unlike the initial nine stations along the Pearl Street Pedestrian Mall, these new stations will be connected to the telephone switching network using a broadband infrastructure consisting of fiber optic and coaxial cables. As with the initial nine sites already installed, these eleven sites will be mounted on existing light or signal poles.

High-tier PCS Using Rooftop Base Stations

Five high-tier, or macrocell-size, PCS base station sites are planned for rooftop installation on buildings near downtown Boulder. These high-tier cells overlay the smaller microcells formed by the base stations located on light or signal poles. In this way, U S WEST can test both low-tier and high-tier PCS radio systems within the same propagation environment.

Indoor Shopping Mall and Parking Lot

Several PCS base stations will be installed inside the Crossroads Shopping Mall to determine the viability of offering PCS service inside heavily traveled buildings. In addition, base stations may be added on the roof of the Crossroads Mall to measure coverage and handoff characteristics in the parking lot and in adjoining buildings.

Heavy Urban Area In Downtown Denver

Four low-tier base station sites are being installed in downtown Denver to provide PCS testing capability in a heavy urban environment characterized by high-rise buildings. These base sites will be mounted on existing public lighting structures or traffic signal poles at the intersections indicated in Figure 2-3. T-carrier links from the Boulder Main Central Office (C.O.) to the Denver C.O. will be used to access the testbed equipment installed in the remote laboratories shown in Figure 2-1.

3 Personal Handy Phone Tests

A prototype version of the Personal Handy Phone (PHP) system was tested in the Boulder PCS testbed. The prototype equipment consisted of a propagation test set and a speech quality demonstration unit. The prototype equipment was first calibrated in the laboratory and then field tested in residential, light urban, and shopping mall environments. Base station antenna heights of 43 and 57 feet were evaluated to simulate typical rooftop installations.

The propagation test set was used to characterize the coverage of the PHP system based on received signal strength (RSS) and bit error rate (BER) readings. Building penetration from the exterior to the interior of a shopping mall was also measured. The speech demonstration unit was used to subjectively evaluate the voice quality of the system. Due to the extremely limited coverage range of the speech demonstration unit, only limited over-the-air voice recordings were made during the testing.

3.1 Measurement Procedure and Equipment Description

The prototype PHP test system included the following two components: a speech quality demonstration unit and a propagation test set. The speech quality demonstration unit consisted of a rack mounted base station and a portable unit with an attached handset. The initial plan was to use the speech demonstration unit to record uplink/downlink voice quality while simultaneously recording signal strength and word error rate on the propagation test set. Several uplink voice recordings, using Harvard sentence source tapers, were successfully made over short distances (less than 10 feet).

Unfortunately, the coverage range of the speech demonstration unit was extremely limited because the equipment was an early vintage prototype. With the base station antenna mounted at 43 feet above ground level, the coverage of the speech demonstration unit was approximately 150 feet line-of-sight. Because of the limited coverage area, subjective voice quality tests were performed, but voice recordings were not simultaneously made.

Equipment Description

The propagation test set consisted of a combination of prototype hardware and commercial bench test equipment. Figure 3-1 is a block diagram of the PHP propagation test transmitter. The heart of the transmitter is a vector modulator with variable modulation parameters. The parameters for the digital modulator were set to a bit rate (R_b) of 384 kbps using $\pi/4$ DQPSK; square root raised cosine filtering was selected with a rolloff factor of 0.5. The modulation parameters were chosen to match the air interface for the PHP standard. The modulator was driven with a 1904.15 MHz carrier signal at a 0 dBm level output derived from a signal synthesizer. The modulated data stream was a periodic pseudo-random pattern (PN Code), where the pattern was known *a priori* at the receiver.

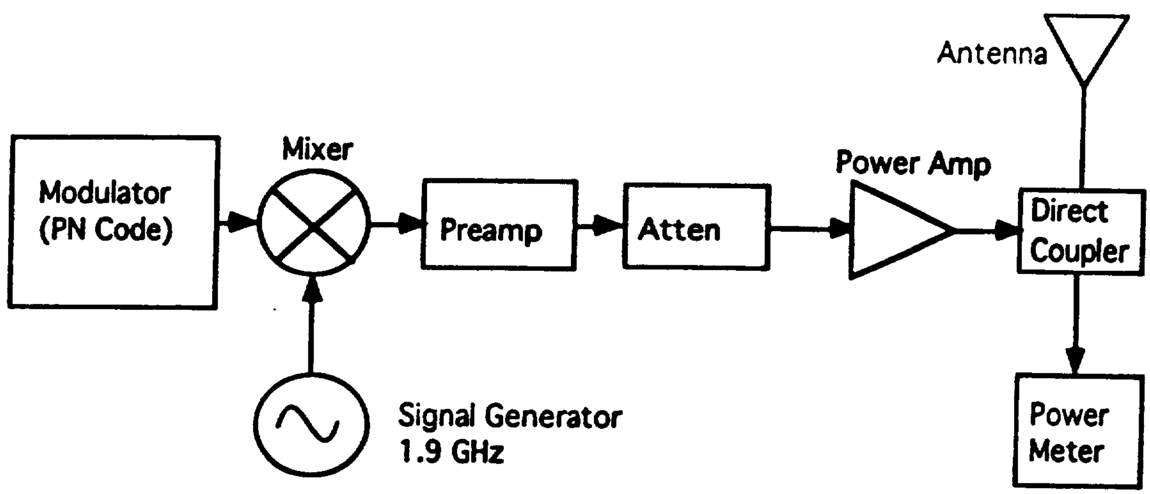

Figure 3-1. Block diagram of PHP propagation test set transmitter

The signal output from the modulator was passed through a pre-amplifier, step-attenuator, and to a GaAs high power amplifier. The power amplifier output was passed through a 30 dB directional coupler to the antenna; the monitor output from the directional coupler was connected to a bolometer power sensor and a power meter. The transmitter output power was varied by adjusting the drive level output from the modulator.

The PHP bit error rate (BER) measuring receiver is shown in Figure 3-2. The radio frequency (RF) circuitry consists of a low noise amplifier and a heterodyne receiver. The received signal strength is monitored by measuring the automatic gain control (AGC) voltage in the receiver. The intermediate frequency output from the RF circuitry is passed to the demodulator which performs clock recovery and data demodulation. The recovered clock and data signals were fed to a bit error analyzer. The bit error analyzer correlated the received pseudo-random sequence with the known transmitted sequence to determine the number of bit errors. An MS-DOS personal computer was used to monitor the received signal strength (RSS) through an analog-to-digital converter connected to the receiver AGC; the bit error rate (BER) was also monitored through a General Purpose Interface Bus (GPIB) card interconnected to the bit error analyzer.

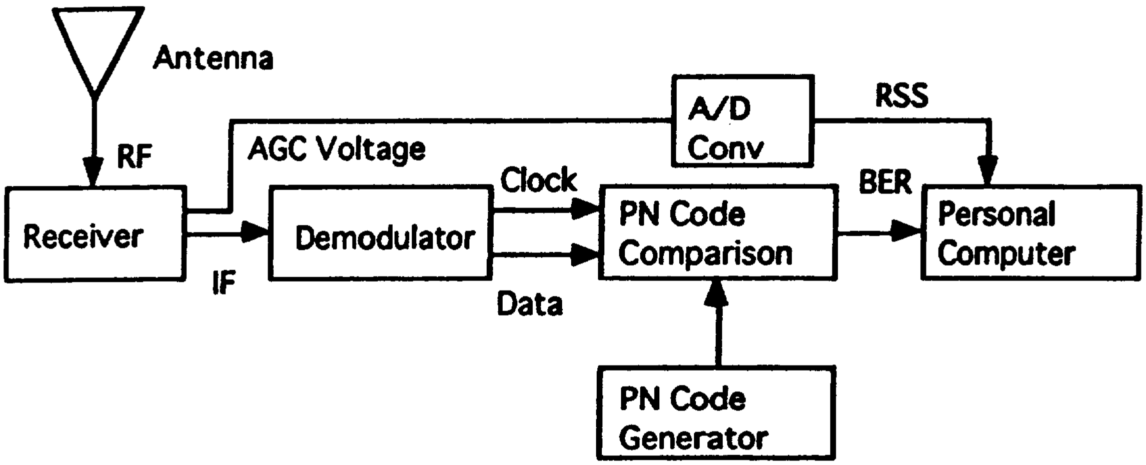

Figure 3-2. Block diagram of PHP propagation test set receiver

Laboratory Calibration

Prior to the field testing, the PHP propagation test receiver was characterized and calibrated in the lab. In the initial test setup, the transmitter in Figure 3-1 was directly connected to the receiver in Figure 3-2. The signal level out of the modulator was varied from -53 to -98 dBm, and the RSS and BER were recorded.

With the modulator directly connected to the receiver there is a possibility of leakage radiation from the modulator reaching the receiver and biasing the measurement results. One method of alleviating this artifact would be to place the receiver in an electromagnetic screened room to perform the measurements. Since no screened room was available for these tests, an alternate method of isolating the transmitter and receiver was used. A mixer and local oscillator were placed between the modulator and receiver. The mixer and local oscillator combination was used to frequency translate the signal, such that the transmitter and receiver were tuned to different channels. By frequency offsetting the transmitter and receiver, leakage radiation effects were mitigated.

The results of the laboratory calibration are shown in Figure 3-3, where the solid line depicts the direct connection and the dashed line is for the mixer connection. The receiver's performance characteristics were measured over a dynamic range from -50 dBm to -100 dBm. At signal levels greater than -50 dBm, the receive AGC voltage reaches saturation. The measurements for the direct and mixer connection are within approximately ± 2 dB. As expected, the direct connection produced consistently larger RSSI voltage outputs, due to a small level of leakage radiation.

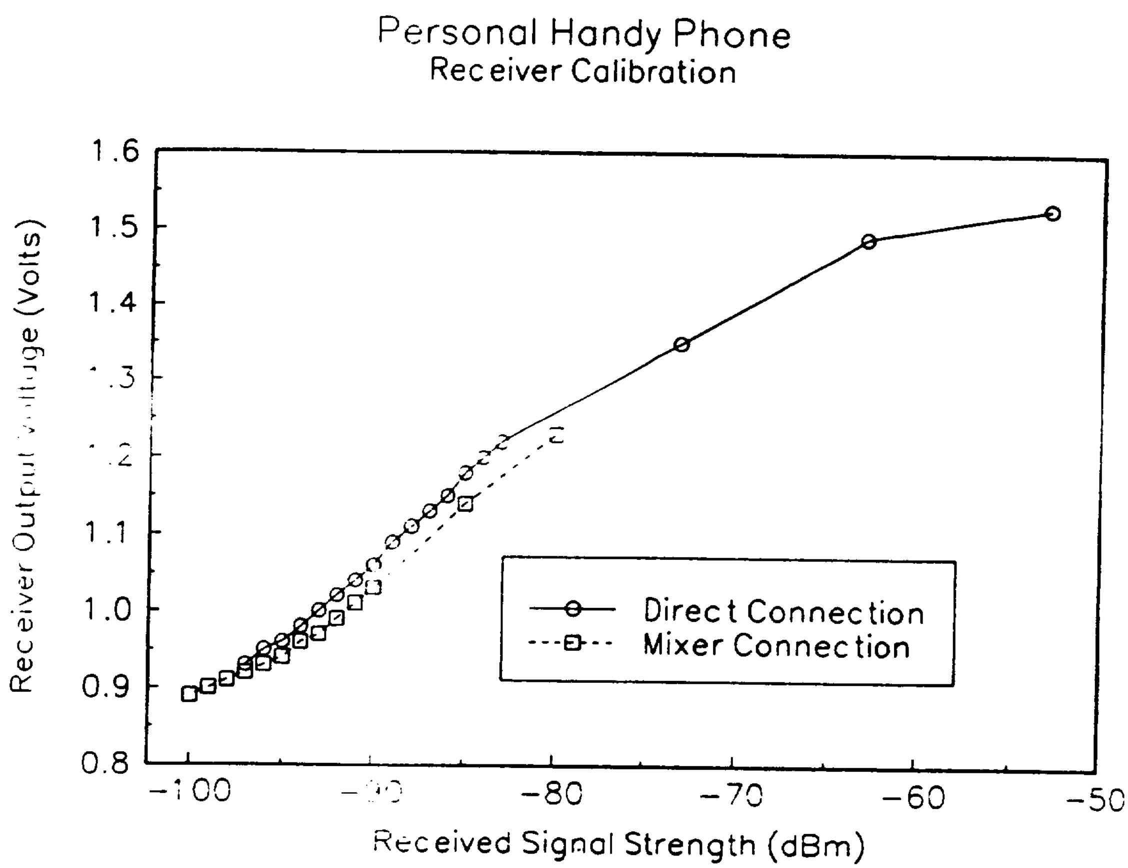

Figure 3-3. Laboratory calibration results for PHP system

The bit error rate performance of the receiver, as a function of received signal level, was also measured. The results are illustrated in Figure 3-4, where the solid curve is the direct connection and the dashed curve is the mixer connection. The PHP receiver exhibited an irreducable BER of approximately 5.2×10^{-8} at signal levels higher than -83 dBm. Once again, leakage effects were minimal, as the two curves were within ± 2 dB of one another.

Field Test Procedure

For the experimental field tests, the PHP transmitter was located at a fixed base station site, either in the test van or in a building. The PHP receiver equipment was mounted on a portable push-cart, which was accompanied by a portable 110 volt power generator. In all cases, the transmitter remained fixed at the base site, while the receiver was moved to the measurement locations for coverage testing. The receiver cart was stopped at each test location, and the personal computer was used to record average BER and RSS over a period of 150 seconds. The 150 second average stored on the computer was the average over 15 sample periods of 10 seconds each.

Ideally, the receiver push-cart would have been moved throughout a several wavelength local area during the 150 second measurement period. Moving the receiver push-cart would have produced the local mean signal level, by averaging out the effects of small scale fading. Due to the extreme weight of the equipment cart and generator, it was not possible to move the push-cart during the measurements; therefore, the receiver cart remained stationary during the entire averaging period. Thus, the measurements recorded during the 150 second interval represent time averaged results without any spatial averaging.

Coverage tests of the PHP system were performed for the following three base station locations: 14th and Spruce Streets, Boulder Main Central Office Building, and 28th and Arapahoe Streets in the parking lot of the Crossroads Shopping Mall. Outdoor measurements were made in line-of-sight and non-line-of-sight conditions in residential, light urban, and shopping mall environments. Building penetration measurements were recorded inside the shopping mall complex.

3.2 Measurement Results

The following section presents the results field tests at three different base station locations.

14th and Spruce Street Base Station

The PHP transmitter was located in the test van which was parked at the Northwest corner of 14th and Spruce Streets. The van was parked as close as possible to the permanent base station enclosure mounted on the lamp post at the intersection. The transmitter equipment in the van was powered by line power obtained from the base station enclosure. The 6 dBi transmitter antenna was mounted on the extendable hydraulic mast on the van, and the mast was extended to 42 feet above ground level. At a height of 42 feet, the transmitter antenna was approximately level with the surrounding building rooftops.

The environment around the 14th and Spruce site consists of a light urban and commercial district to the South and a residential area to the North. The field testing was conducted in the residential area within two blocks North and six blocks East of the base station site. Measurements were recorded in one block intervals at the street intersections.

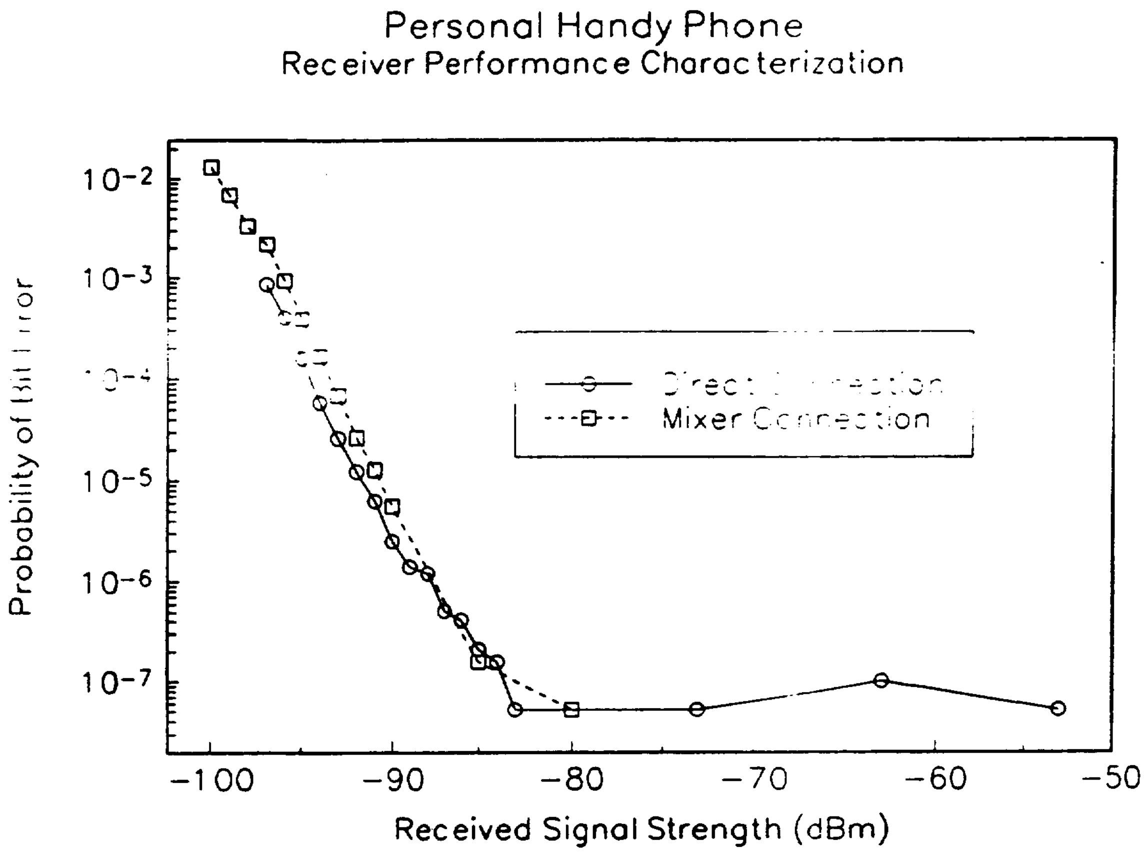

Figure 3-4. Receiver characterization results for PHP system

Bit error rate (BER) and received signal strength (RSS) results are illustrated on the map in Figure 3-5. The first number located adjacent to each measurement location is the BER, while the second number is the RSS in units of dBm. The base station site is located near the lower left corner of the map. A total of 16 measurements were made in a roughly 1 block by 6 block rectangular area. For the frame structure associated with the PHP system, a BER of 10^{-5} translates into an approximate word error rate (WER) of 1%. Therefore, using a WER threshold of 1% for acceptable voice quality, the coverage of the system from Figure 3-5 is on the order of 350 to 400 meters non-line-of-sight. These initial tests were performed without compensating for cable losses incurred at the transmitter and for performance limitations in the prototype receiver noise figure. All subsequent tests included 10 dB of additional transmitter power to compensate for these two factors.

Boulder Main Central Office Building Base Station

The PHP transmitter was placed near the rooftop of the Central Office (CO) building located at the Northwest corner of Walnut and 16th Streets. A coaxial cable was routed from the transmitter to the antenna located on the roof of the building. The antenna was mounted on a chimney vent at a height of 57 feet above ground level. Power for the transmitter was obtained from commercial line power within the CO building. The receiver cart was pushed over an area Northwest and Northeast from the base station. Measurements were made in one block intervals at the street intersections.

The environment to the Northeast of the base station is light commercial and residential. The area to the Northwest is light urban, and is residential further North. The measurement results are illustrated on the map in Figure 3-6. A total of 61 measurement locations were used , primarily in areas North and East of the base station site. The base station location is marked near the lower right corner of the map. From the figure, it is possible to estimate the coverage of the system for 10^{-5} BER. The coverage radius of the PHP equipment was found to range from a low of 174 meters to a high of 1060 meters, depending on the surrounding environment. The typical 10^{-5} coverage radius was found to be approximately 800 meters.

Crossroads Shopping Mall Parking Lot Base Station

The PHP transmitter was located in the test van which was parked in the Southwest part of the Crossroads shopping mall parking lot. The transmitter antenna was placed on the hydraulic mast which was extended to 42 feet. Power for the transmitter was obtained from a gas-powered generator.

Measurements were made at locations on the exterior and interior of the shopping mall. For the exterior measurements, the receiver cart was pushed around the shopping mall's parking lot. Measurements were recorded at approximately 50 meter intervals around the perimeter of the mall. Performance was also recorded in the corridors and hallways within the shopping mall to determine how well the signal penetrated the building structure. A total of 19 measurements were made around the exterior of the mall and 16 measurements were made in the interior.

The measurement locations for the exterior of the mall are shown as the circles in Figure 3-7, where the base station is shown as the inverted triangle at the lower right corner. From the measurements, distances up to 644 meters from the base station were covered with word error rates of 6×10^{-5} or better.

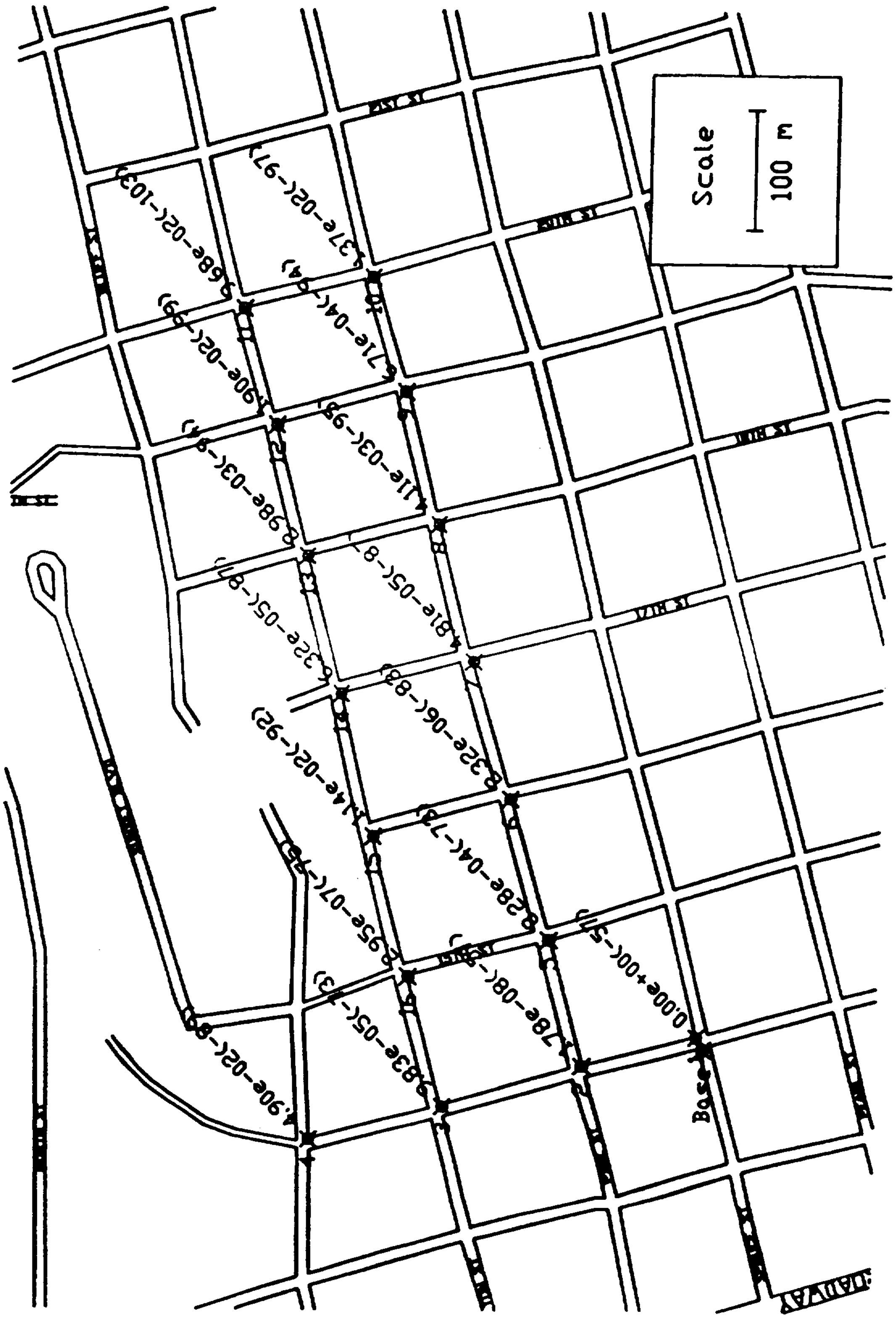

Figure 3-5. Word error rate and received signal strength (in parenthesis) in dBm for base station at 14th and Spruce Streets

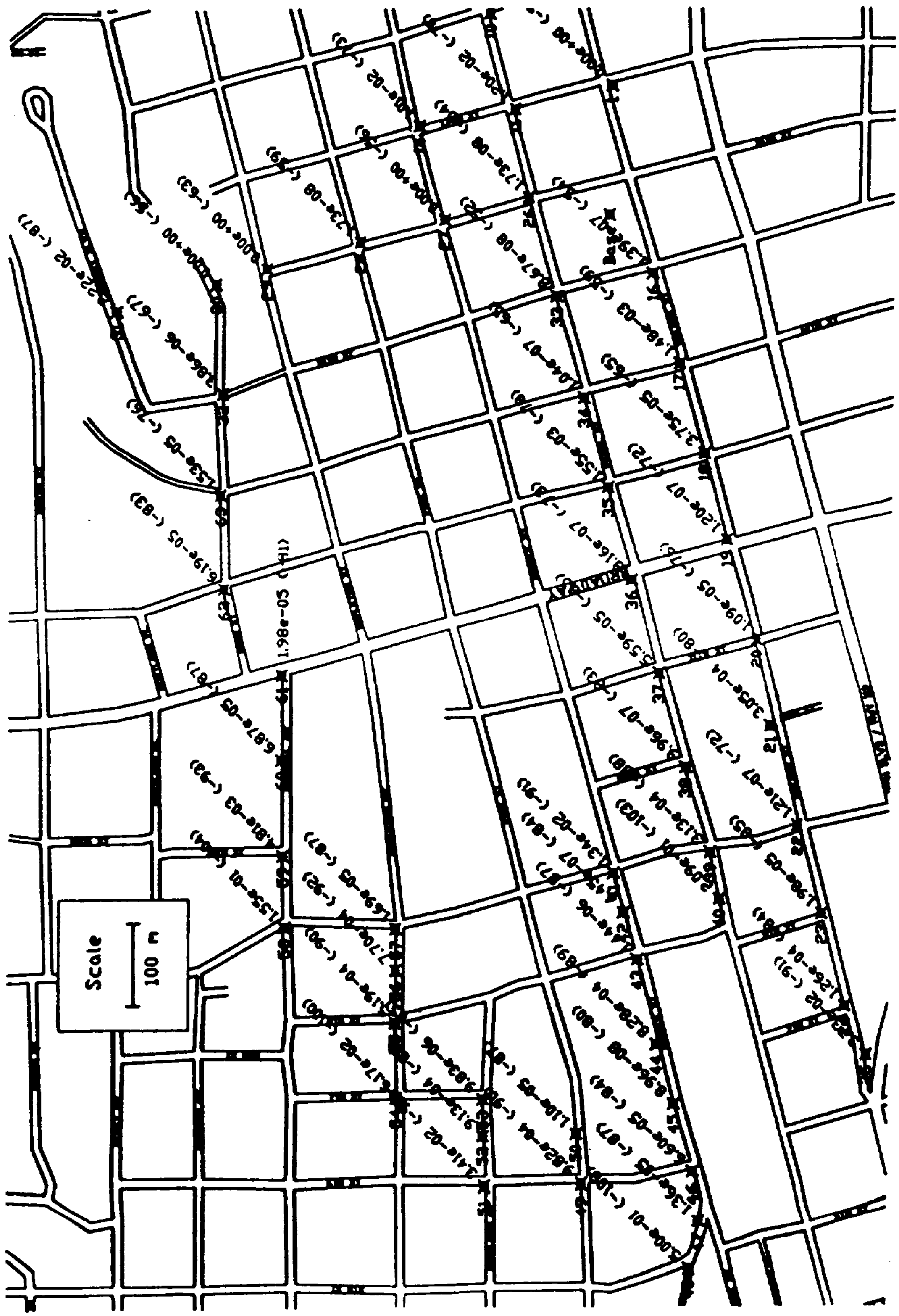

Figure 3-6. Word error rate and received signal strength (in parenthesis) in dBm for base station at Boulder Main Central Office located at 16th and Walnut Streets

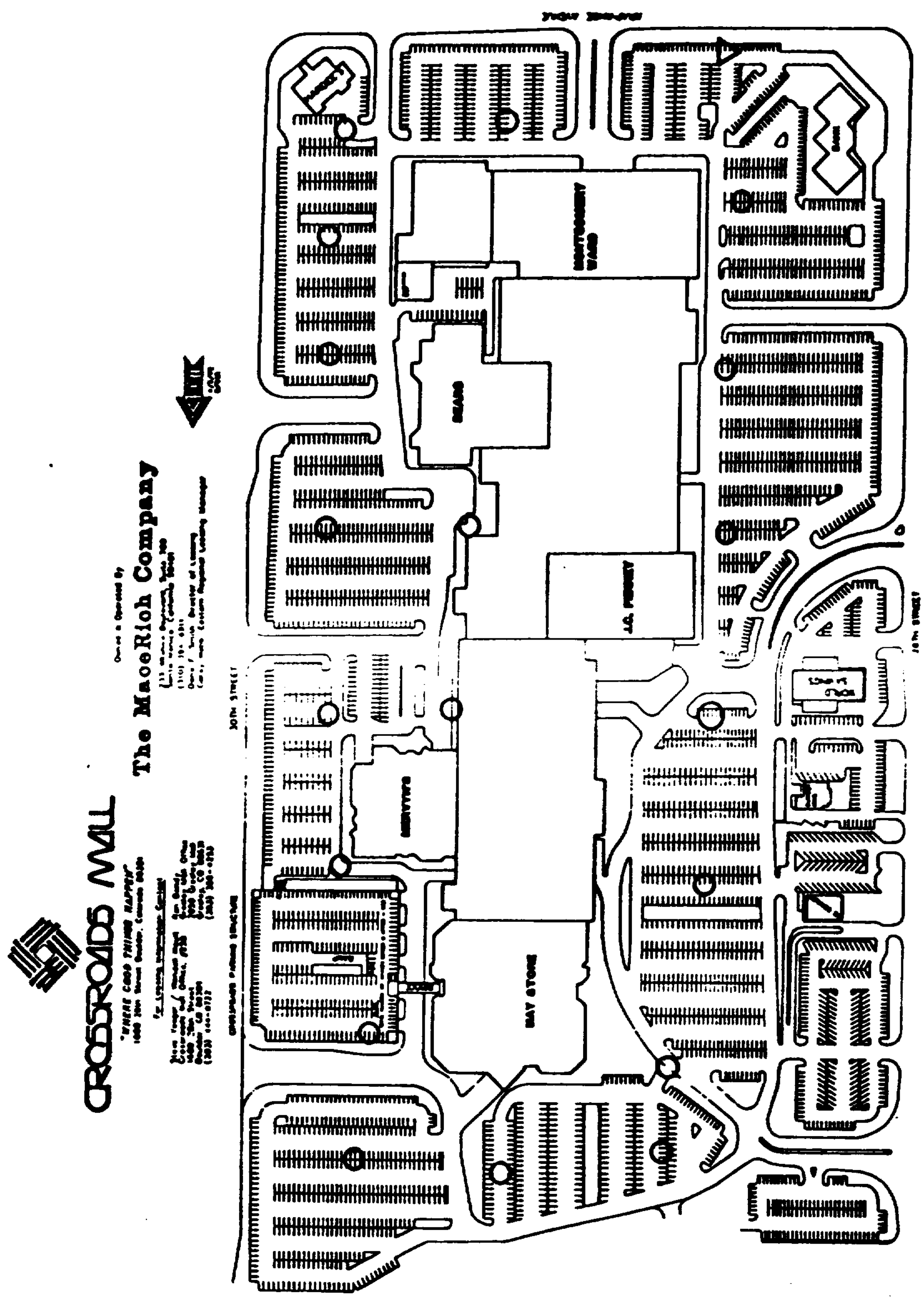

Figure 3-7. Measurement locations, shown as circles, in perimeter parking lot of Crossroads Shopping Mall

The measurement locations in the interior of the shopping mall are shown as circles in Figures 3-8a and 3-8b. Of the 16 measurements taken inside the mall, 5 provided word error rates in excess of 10^{-5}. The measurements with BERs in excess of 10^{-5} are shown as solid circles in the figures. The measurements with the high BER values were primarily on the extreme North end of the mall, in side hallways and service corridors.

Results of the shopping mall measurements indicate that the exterior base station was able to cover the complete parking lot for the mall. Approximately 2/3 of the interior measurements had acceptable BER coverage. The main corridor of the mall was covered from the external base stations. Some locations in side hallways and service corridors, on the end of the mall farthest from the base station, did not provide adequate BER for acceptable voice quality.

4 Wireless Access Communications System Tests

Two separate trails were conducted this quarter using the Wireless Access Communications System (WACS) as proposed by Bell Communications Research (Bellcore). Complete details of the WACS air interface are provided in reference [1]. Briefly, the system is a low power TDMA approach with frequency division duplexing. QPSK modulation is employed with raised cosine filtering using a rolloff factor of one-half. The transmission rate is 450 kbps using a 16 ms frame structure, which supports 9 channels of 32 kbps ADPCM voice coding plus a control channel.

Two radio ports were installed on lamp posts in the Boulder testbed. The radio ports were connected back to a pair of radio port controllers at the Boulder Main Central Office via HDSL links over copper loops. The radio ports were positioned such that several handoff zones existed between them.

The first test of the system was a radio trial measuring outdoor coverage, building penetration, and handoff frequency. For the outdoor coverage, word error rate and subjective voice quality were recorded at an irregular grid of points spaced approximately one-half block apart. By plotting contours of constant error rate and voice quality, it was possible to assess the coverage of the two radio ports. Subjective voice quality was monitored in selected street-side buildings in the coverage area to determine building penetration characteristics. Finally, the numbers of handoffs were recorded over two pedestrian routes as functions of hysterisis level.

The second set of tests was a demonstration of data services over the WACS air interface. Two applications were demonstrated in the trial: Call Command and Simple Messaging. Call Command allows a nomadic wireless computer user to control the routing of incoming voice calls via a software interface. The Simple Messaging services allows two wireless computer users to exchange messages over the radio interface.

4.1 Coverage and Handoff Measurements

The objective of the coverage tests was to determine the range over which the microcells provide acceptable voice quality grade of service. Outdoor coverage contours were plotted based on word error rates and subjective voice quality scores. Indoor building penetration was characterized based on subjective voice quality for street-side businesses. For the handoff testing, the goal was to determine appropriate hysterisis thresholds based on the number of handoffs observed over pedestrian routes.

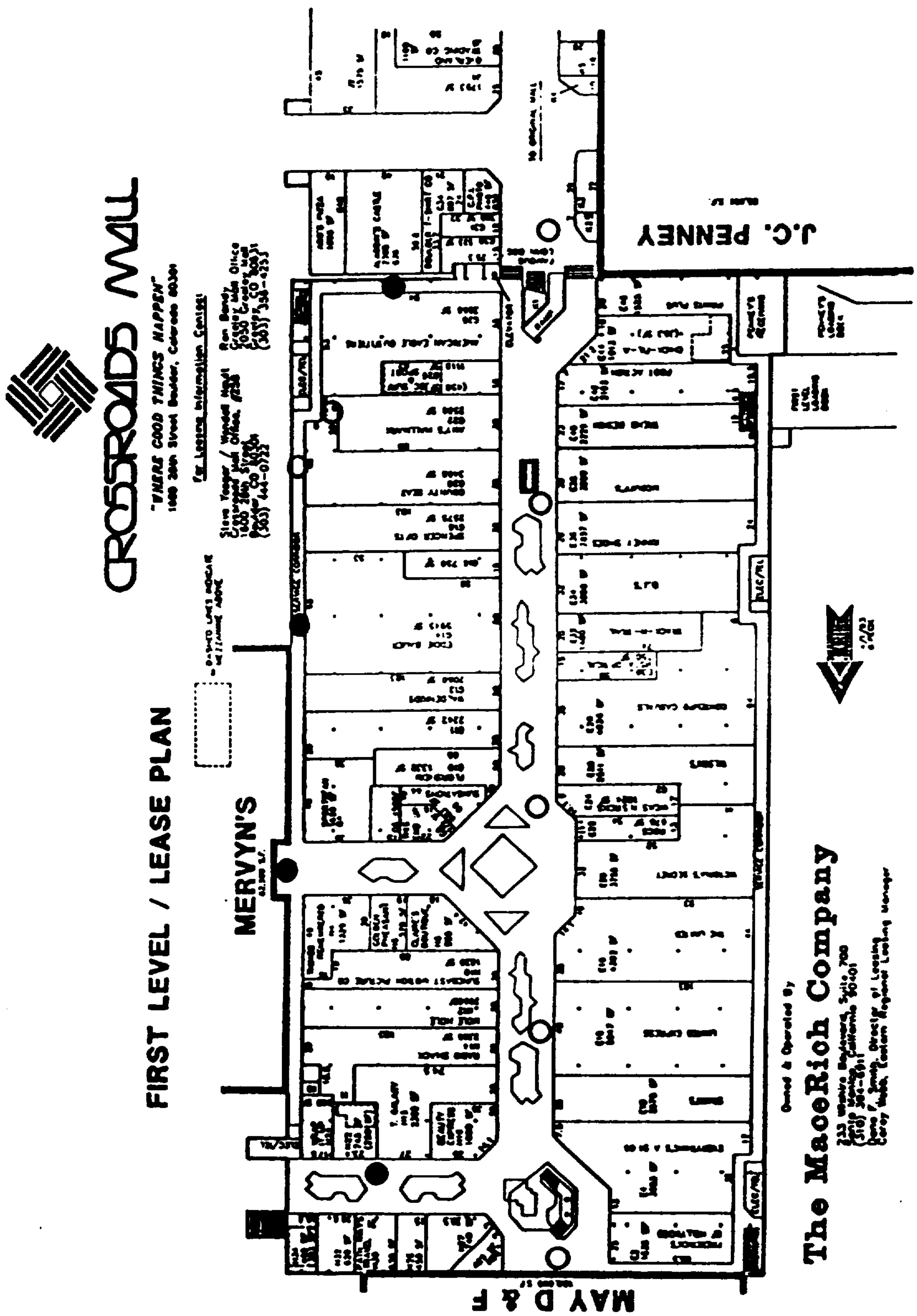

Figure 3-8a. Measurement locations, shown as circles, in interior of Crossroads Shopping Mall. Locations with bit error rates greater than 10^{-5} are shown as solid circles.

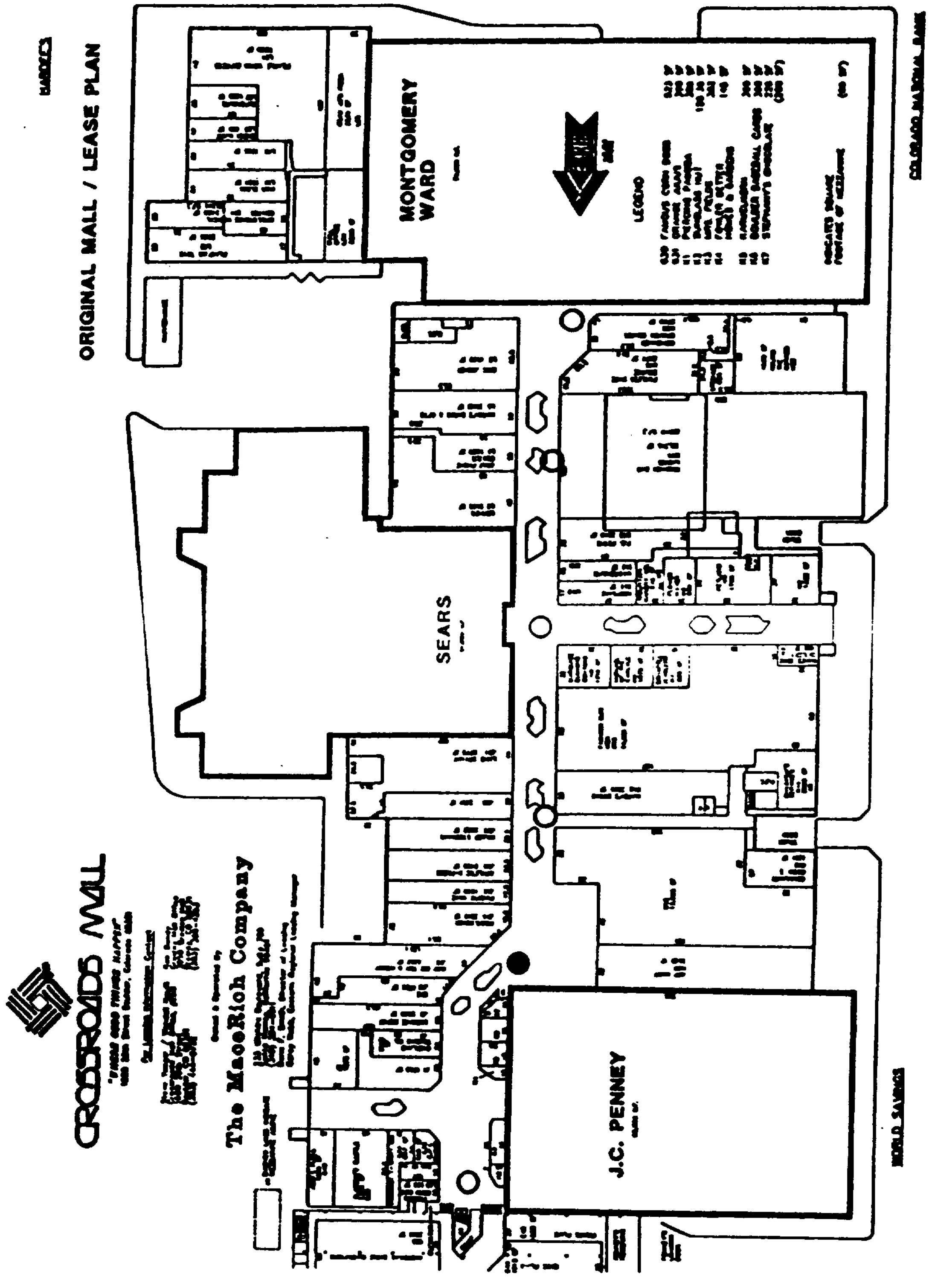

Figure 3-8a. Measurement locations, shown as circles, in interior of Crossroads Shopping Mall. Locations with bit error rates greater than 10^{-5} are shown as solid circles.

A prototype portable transceiver was used for all of the tests. The unit consisted of an electronics box which could be carried using a shoulder strap. The electronics box was connected to a mock handset via a set of interconnection cables. The mock handset contained a microphone, speaker, and two antennas.

Outdoor Coverage Tests

In order to estimate the coverage of the two test microcells, measurements were made at an irregular grid of points spaced one-half block apart. Due to the limited time available for field testing, an incomplete grid was measured; in other words, a measurement was not made at every location on the grid. For these tests, only outdoor tests were made at the measurement locations. Inbuilding penetration tests were performed separately, and are discussed in a later section of this report.

During each of the tests, the prototype portable unit was carried to the outdoor measurement location, where a call was placed to an operator at radio port controller. A data collection computer at the radio port controller was then used to record data while the portable operator walked in a random pattern over a five foot local area. The received signal strength and word error rate were recorded at the base station for the uplink path. The portable was moved over a small area in order to average out the effects of small-scale fading so that the local mean could be recorded. The portable was moved and data recorded for at least 32 seconds at each measurement location. Subjective voice quality, as observed by the operators at the radio port and the portable, was logged on a scale of 1 to 4 (4:Good, 3:Fair, 2:Poor, 1:Unusable).

Measurements were recorded at a total of 40 outdoor locations. Figure 4-1 is a scatter plot of WER versus subjective voice quality score. As expected, there is clearly a strong trend towards lower subjective voice quality associated with higher WER. For Good quality voice (i.e., voice score = 4) the WER must be less than approximately 3%. For voice quality in the Good to Poor range (i.e., voice score = 4, 3, or 2) the WER must be less than approximately 10%. The WER coverage contours for the WACS system have therefore been presented in terms of 3% and 10% contours.

Figure 4-2 shows the WER coverage contours for the two base stations which were tested. The base stations are shown as solid inverted triangles, while the measurement locations are solid circles. The streets in the measurement area are very close to a regular grid with 100 meters per block. Thus, the grid lines in the figure closely approximate the cross streets. The curves in the figure represent the constant value contours for 3% and 10% WER. The contours were calculated based on a fitting a cubic spline to the 3-dimensional data. The contour lines were then extrapolated from the fitted spline function.

Before interpreting the results illustrated in Figure 4-2, two important facts must be mentioned. First, the measurements used to generate the contours were outdoor tests only; therefore, the coverage contours are only valid for outdoor coverage. The contours cannot be used to accurately predict indoor coverage. Second, an irregular grid of measurement points was used to develop the cubic spline model. The fitted spline is not accurate in areas where no measurement points were taken; therefore, the contour lines are not valid in areas where no measurements were recorded (i.e., areas distant from the solid circles in Figure 4-2).

From Figure 4-2, several important observations can be made regarding the two cell configuration of the WACS system. First, line-of-sight coverage for 3% WER along cross streets with the base stations was approximately 275 meters (2.5 blocks) radially. The 3%

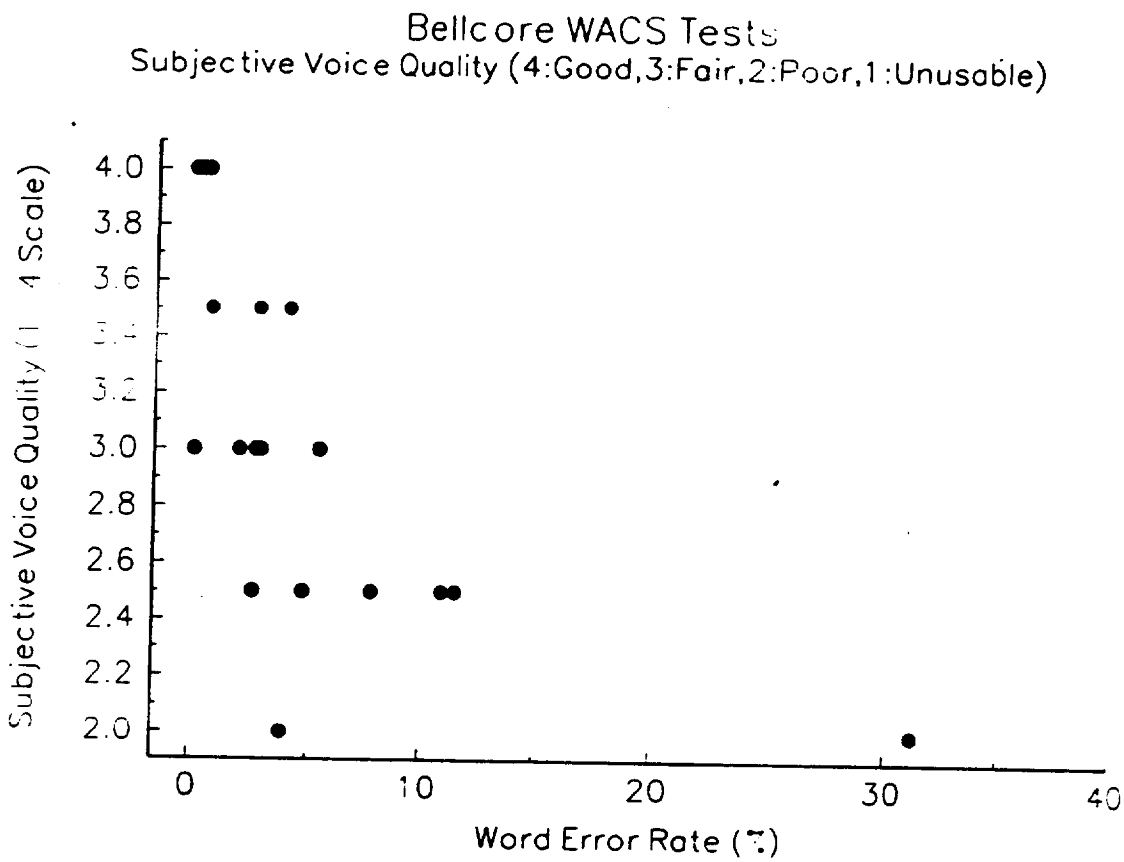

Figure 4-1. Word error rate versus subjective voice quality score for all outdoor measurements.

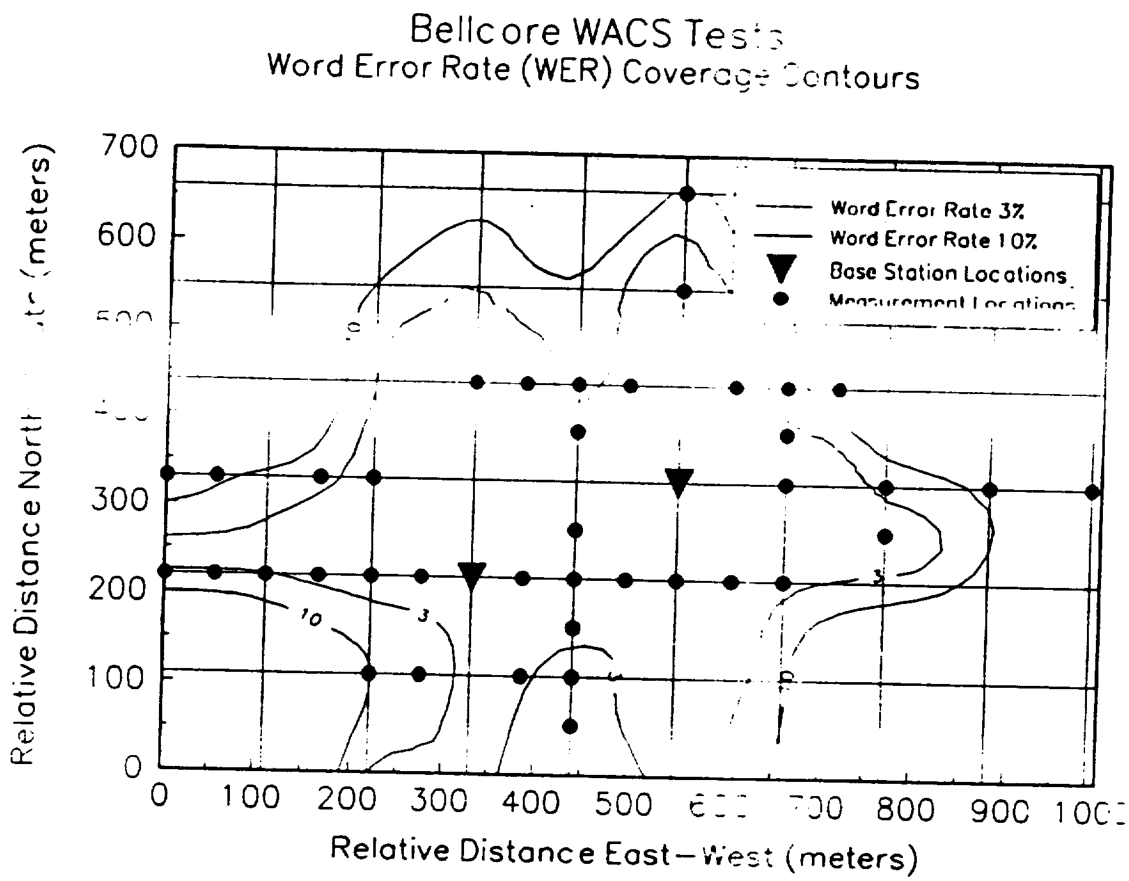

Figure 4-2. The 3% and 10% outdoor word error rate contours as a function of position. Solid circles are measurement locations and inverted solid triangles are radio port locations.

WER coverage non-line-of-sight to the base stations was from 50 to 160 meters, depending upon the building topography. This means that the WACS system was able to provide Good quality voice coverage at least 2 blocks line-of-sight, but coverage non-line-of-sight was less than 1 block.

Figure 4-3 shows the coverage contours based on subjective voice quality score for Fair and Poor voice quality (i.e., scores of 3 and 2, respectively). Again, results are for outdoor measurements and the contours are invalid far from the measurement locations. As expected from Figure 4-1, the 3% and 10% WER contours on Figure 4-2 roughly correspond to the Fair and Poor voice quality contours in Figure 4-4. Based on Figure 4-4, the coverage of the WACS base stations is at least 2 blocks line-of-sight for Fair voice quality. Coverage non-line-of-sight is somewhat less than 1 block.

Building Penetration Coverage Tests

Due to the limited time available for testing, the building penetration coverage tests were conducted in an informal fashion based on subjective voice quality. The portable unit was carried into a number of small businesses located within the coverage area of the two microcells. Some of the businesses had a line-of-sight path from the front entrance of the business to the base station, while others were non-line-of-sight. The operator entered the business and then walked the portable unit around different areas of the premises. Subjective opinions of voice quality were recorded as the operator canvassed the building interior. Voice quality was rated on a scale of good, fair, poor, unusable.

A total of 23 businesses were tested for building penetration coverage. Figure 4-4 shows the inbuilding coverage observed during the tests. The crosshatched areas represent businesses where voice quality was consistently good to fair within the building. The spotted areas show locations where voice quality was in the poor to unusable range within the buildings. By examining Figure 4-4, it is possible to make some general observations regarding building penetration into street-side business from the WACS base stations. First, there is a good probability of covering businesses within 1.5 blocks (approximately 165 meters) if the entrance to the building has a line-of-sight path to the base station. This can be seen from the coverage along Broadway and 14th Streets in the figure. Businesses which are more than 1.5 blocks away from the base station, or which do not have line-of-sight from the entrance to the base station, were observed to be less likely to have acceptable voice quality. This can be seen from the measurements on Broadway North of Pine Street and the measurements along 13th Streets in the figure.

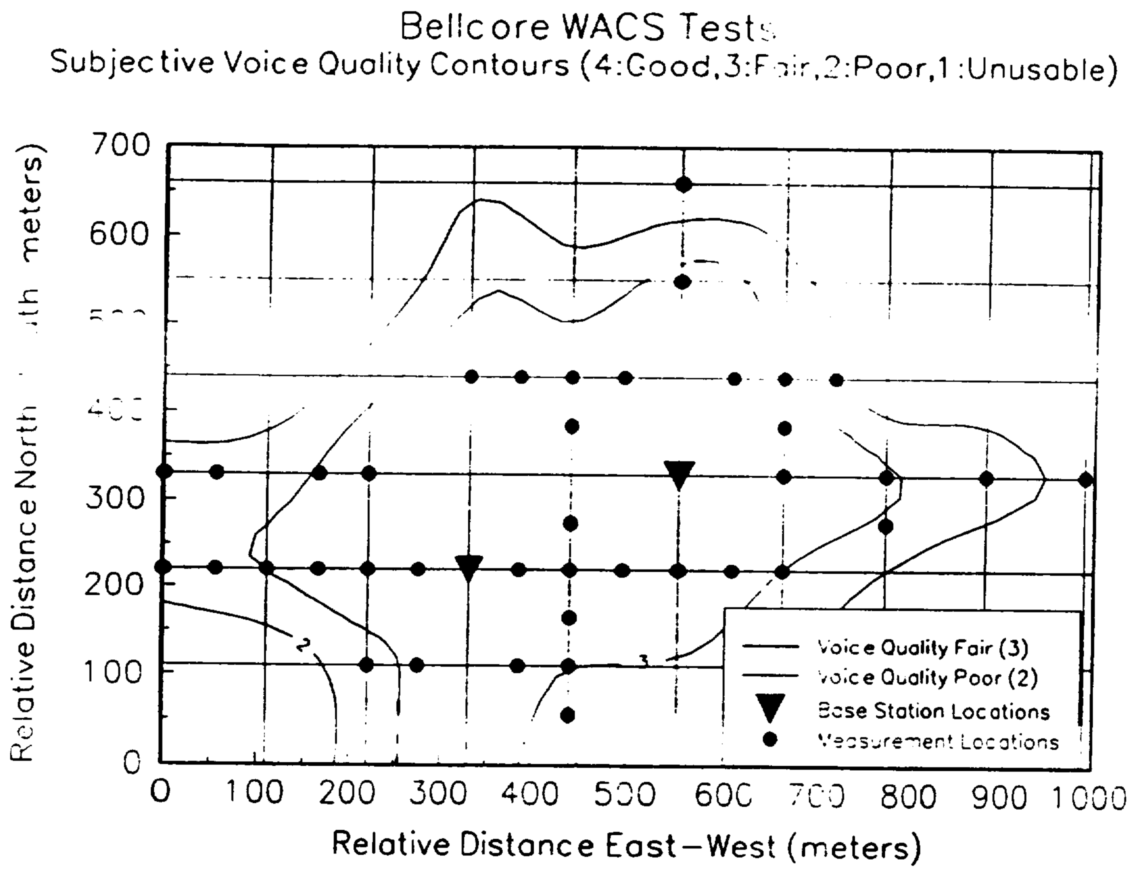

Figure 4-3. **The Fair** (voice **score** = 3) **and** Poor (voice **score** = 2) **outdoor subjective** voice quality score **contours as a function of** position. Solid **circles are** measurement locations and inverted **solid triangles are** radio **port** locations.

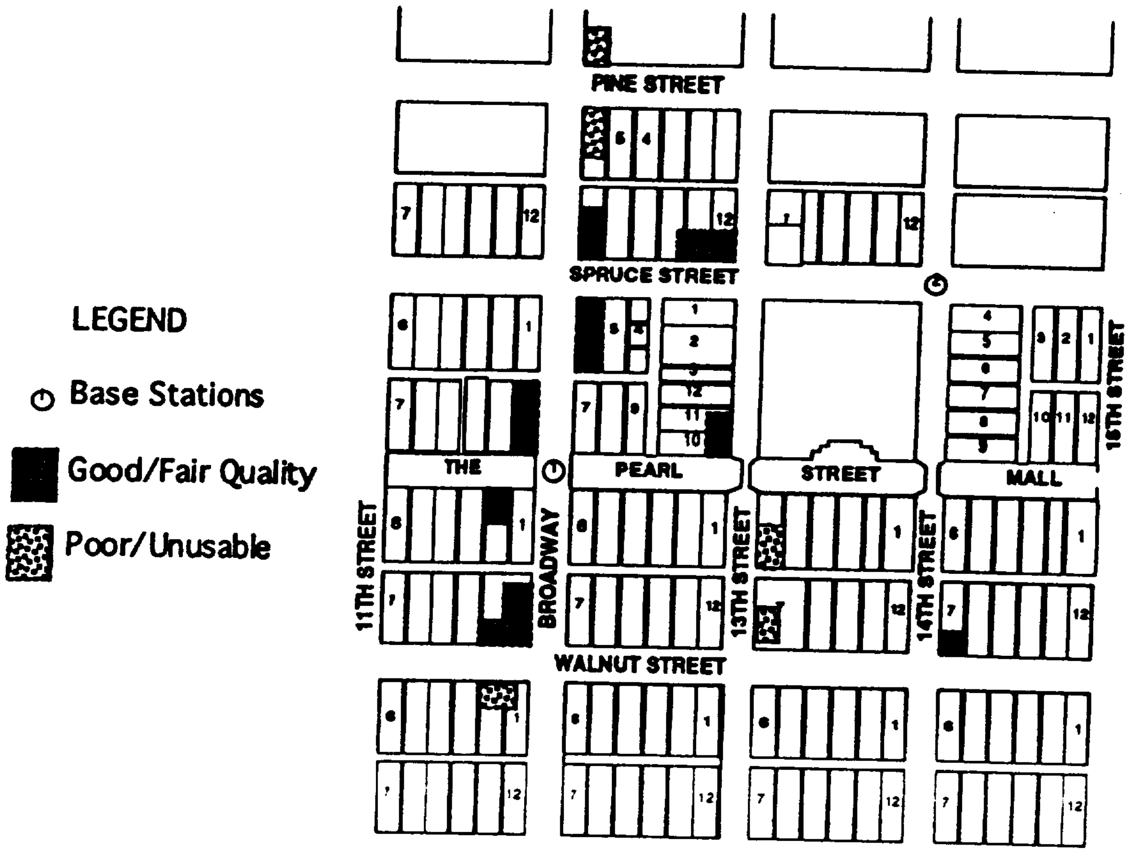

Figure 4-4. In building coverage quality into selected street-side businesses

Handoff Tests

During the handoff tests, the portable unit was carried over a fixed pedestrian route in an area where the two base stations had comparable signal levels. After the route was traversed, the number of handoffs was recorded based on a handoff counter in the prototype portable WACS transceiver.

By changing the firmware in the prototype portable transceiver, it was possible to test different hysterisis levels. As the hysterisis level gets smaller, more handoffs are observed between the base stations due to fading. The objective of the testing was to determine appropriate hysterisis levels which avoided excessive "ping-ponging" between the base stations.

Two different walking routes were used for the handoff tests, as shown in Figure 4-5. For each route, hysterisis levels of 3, 5, and 7 dB were tested. At each hysterisis level, three separate 4 to 5 minute passes were made along the route. The average number of handoffs for the two routes are shown in Figure 4-6 as a function of the hysterisis level. From the figure, hysterisis levels of 5 and 7 dB provided an average of approximately 5 handoffs for each pass. The 3 dB hysterisis level provided an average of 20 handoffs per pass for the two routes.

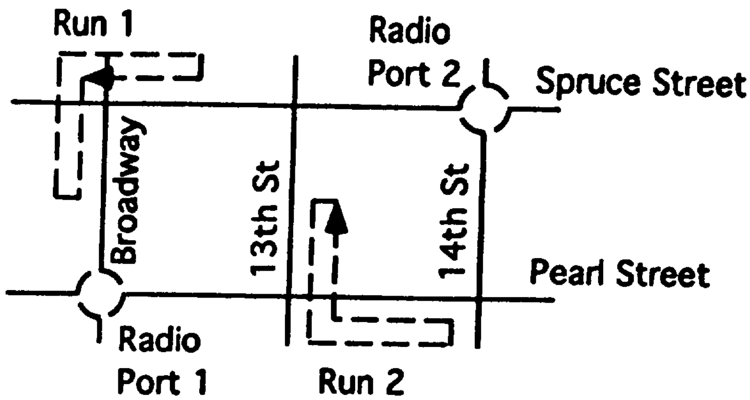

Figure 4-5. Illustration of handoff test runs in relationship to radio ports

In the current prototype implementation of the WACS system, a handoffs can result in a 50 millisecond disturbance in the voice signal. This audible disturbance is heard as a "click" or "pop" in the voice path. The disturbance results from synchronization changes as the portable unit hands off from one base to another. Because the radio ports are unsynchronized with one another, the handoff causes a change in the clock timing. The clock timing change is manifest in a clocking shift to the vocoder, which causes the audible distortion. In a commercial implementation of the WACS system, it is likely that this audible distortion could be lessened or eliminated by implementing a special vocoder which is capable of handling these clock shifts.

In the handoff tests, the hysterisis level of 3 dB resulted in an objectionable number of handoffs during the 4 to 5 minute pass. "Ping-ponging" between base stations was clearly audible at certain location along the walking path, as distinguished by audible "clicking". The 5 and 7 dB hysterisis tests had approximately one-quarter the number of handoffs compared to the 3 dB tests. Handoffs were audible during the 5 and 7 dB runs, but no significant "ping-ponging" was noted. These results indicate that handoff hysterisis levels as low as 5 dB can be used with the WACS system.

4.2 Data Services Demonstrations

Data applications tend to fall into two main categories, transaction-oriented requiring quick bursts of data, and bulk data transfer involving the exchange of large amounts of textual or imaging information. Applications in the former category include point of sale, alarms, telemetry, calendaring and messaging whereas applications in the latter category include transfer of faxes, files of text, images, and digitally encoded speech. Complicating the picture still further are expectations of latency which impose additional restrictions upon an already complex area.

It is becoming increasingly apparent that the deployment of data is likely to present a formidable array of issues, marketing as well as technical. Several points of consensus have begun to emerge:

- Data capabilities should be seen as complementary to voice, particularly if both functions can be lodged within the same device.
- Emergent wireless data applications are likely to have bandwidth needs as varied as those of wireline applications, ranging from an average of a few bits per second to

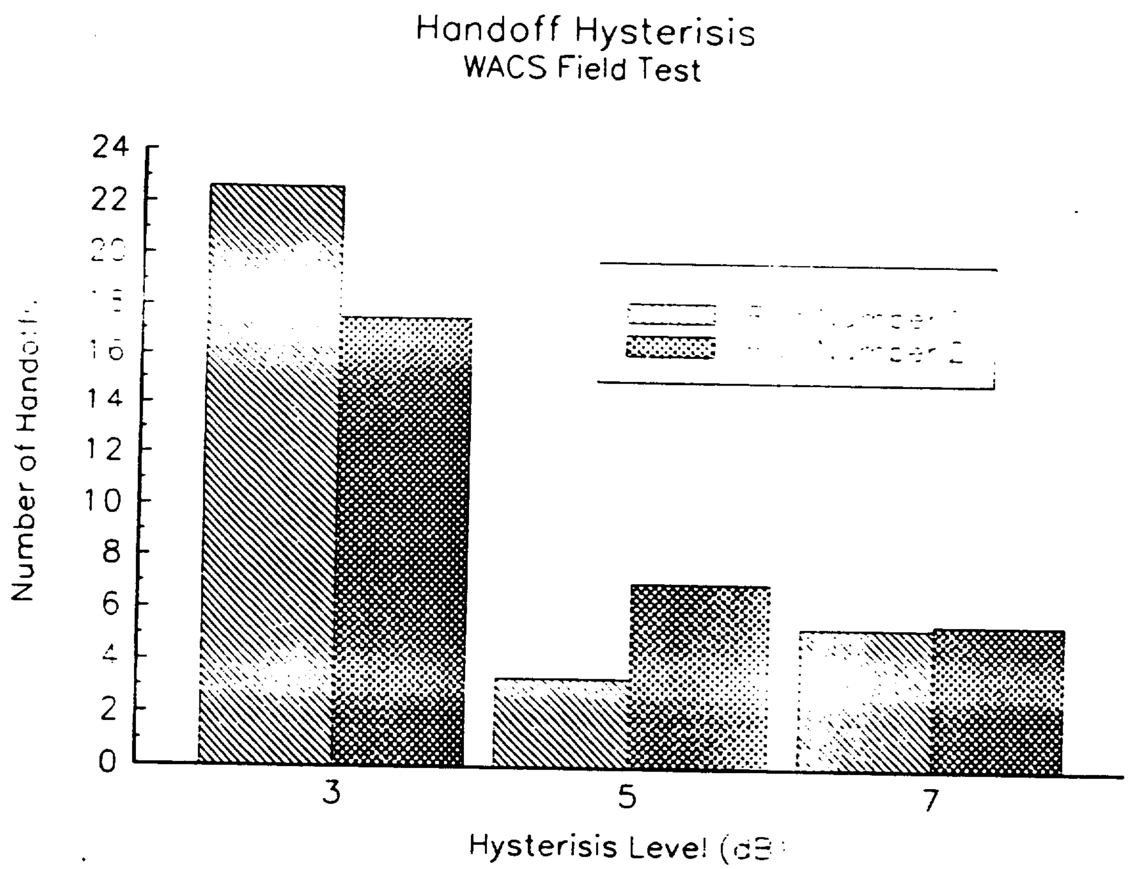

Figure 4-6. Average number of handoffs versus hysterisis level for Runs 1 and 2

(potentially) hundreds of kilobits per second. Any infrastructure capable of supporting a wide variety of data rates, fixed as well as varying, will possess a distinct advantage.

- Applications possess widely differing latency needs. Most transaction-oriented applications are relatively tolerant of transmission delays, while others demand real-time responsiveness.
- A circuit-switched fabric can satisfy all needs, but at a cost of reduced efficiency for applications whose latency requirements are more relaxed, or whose bandwidth requirements are variable. A packet-based approach is likely to yield better resource utilization in these circumstances. Any infrastructure which can potentially support packet as well as circuit access will possess an advantage.

One of the objectives of the wireless personal communications experiments in the Boulder PCS testbed is to explore the feasibility of wireless data on outdoor PCS. PCS provides a number of unique characteristics which have the potential of transforming the way people communicate. Although voice remains the primary imperative behind PCS, it is increasingly evident that to be successful, PCS must be capable of leapfrogging existing technologies to provide support for a wide variety of commercial data communication applications.

The Wireless Access Communications System (WACS) Data Trial has been undertaken with these needs in mind. Work has been split into three main phases -

- *Phase 1*: (July '93) Demonstration of basic data capability.
  Perform System Integration of WACS radio equipment, TPE communication layer, and two applications
  Demonstrate Simple Messaging Application
  Demonstrate Call Command application.

- *Phase 2*: (Expected November '93) Quantitative measurements and demonstration of further applications
  Gather Bit Error Rate statistics for Markov model
  Demonstrate Point Of Sale Application (Credit/Debit/ATM)
  Demonstrate Fax transfer w/ALT
  Demonstrate Enhanced Messaging with image capability.

- *Phase 3*: (Expected Summer '94) Investigation of transaction-oriented application requirements
  Investigate optimization of circuit-like access protocol for transaction-oriented data applications
  Demonstrate computer-supported collaboration applications (e.g. shared image or text).

Enhancements to Standard Equipment

Two WACS handsets were modified to provide data access from an external RS232 port into the voice channel. Additional software modifications included buffering, framing, and rate adaptation.

The interface between the radio port and radio-port controller comprised an HDSL interface running across twisted pair. Typical analog line interfaces were used to connect the radio port controller to the PSTN.

Demonstration of Data Services

For Phase 1, two applications were selected - one involving call routing and one involving simple messaging. The demonstration called for two mobile PCs, each attached to a specially-modified WACS handset, and one fixed PC. SCO Unix was used on all platforms to facilitate application development. One platform was configured to run an integrated Call Command/Simple Messaging application while the other platform ran Simple Messaging alone. During Phase1, the communication layers were integrated with each application as a library to simplify development.

In addition to the applications running on the mobile platforms, a server application was also developed at the fixed Gateway at the Central Office (see Figure 4-7) to route messages between the platforms. This application was also developed to run under SCO Unix. For cosmetic reasons, all applications made impressive use of X-window screens to achieve their objectives of demonstrating a clean, tidy user interface.

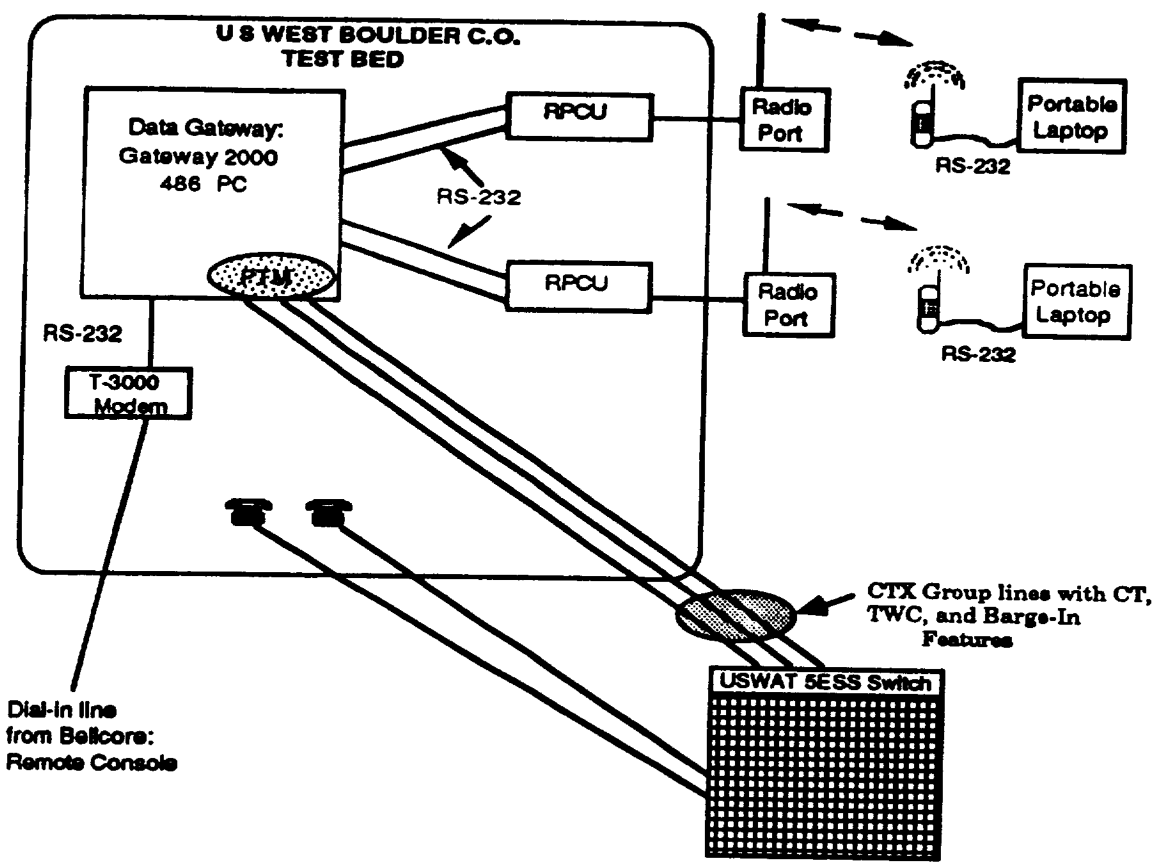

Figure 4-7. Architecture Overview of Bellcore Data Prototype

To support the applications, a communication layer, TPE, was implemented by Bellcore to run on the Server and each mobile platform. In Phase 1, the responsibilities of TPE were limited to packet framing, assembly and disassembly, sequencing, error detection and retransmission. In Phase 2, these responsibilities will be expanded to include Forward Error Correction (FEC).

In Phase 1, messaging was essentially hard-wired between the two mobile data terminals and the Server while Call Command was restricted to a single terminal. By this expedient, addressing issues were relegated to a later stage to allow more focus upon protocol and application issues.

One interesting perspective to emerge with the prototype involved the coexistence of independent voice and data on the same wireless voice circuit. The data connection running across the digital voice interface actually runs concurrently with, but independently of, voice. Data packets take precedence over voice in 'blank and burst' mode which causes a slight but very temporary degradation of the voice circuit as voice packets are hijacked and diverted for data use. Interestingly enough, none of the voice callers found this temporary phenomenon objectionable, although a different impression might have been gained if bulk data transfer had occurred over an extended period.

Call Command

A logical view of the Call Command application is shown in Figure 4-7. Call Command (previously named "Personal Telephone Management" or PTM) was selected as an example of the type of application which demonstrates the way in which a small amount of data and intelligence can exert considerable control over traditional voice communications. It was selected because it does not appear to be a data application in the conventional sense, but uses data communications more discretely to achieve its objectives.

A call is forwarded using conventional switch capabilities at the Central Office to a line presence terminated in the data Gateway. This comprises a DigiTalk card integrated into a PC. When the call arrives at the card, the Server senses its arrival and routes a message to the PTM application resident on the Portable Laptop. This is transmitted across the WACS digital voice interface using the underlying TPE protocol layer developed specifically for the purpose.

On the arrival of the message from the Server, the PTM application on the Laptop immediately presents the called party with a window informing them that a call has arrived. A menu of alternative actions is also presented which include routing the caller directly to voice mail, routing to a telephone number selected by the called party, or entering a short message to be converted to speech.

A command message is then sent from the PTM application back to the Gateway. If this includes the destination number to which the call is to be routed, the Gateway reroutes the call via the CO Switch. If this includes a short message, the DigiTalk card performs a text-to-speech conversion which is then played back to the caller, such as ..."I'm busy right now...I'll call you back in 20 minutes...".

In this way, the PTM application enables nomadic end users to manage incoming calls. The caller is kept informed by means of clear voice instructions "...attempting to locate Jane Doe..." while the (nomadic) called party is presented with a set of alternative actions by means of a screen-based menu. By using this approach, PTM (Call Command) meets four basic call management needs of mobile subscribers: location independence, real-time call screening, real-time call redirection, and real-time programming convenience. The value of these attributes became much more apparent as the demo progressed.

Simple Messaging

The architecture required for simple messaging is considerably simpler than that required for Call Command. By clicking a mouse on the appropriate Icon, a nomadic user can prompt the display of a screen in which they can enter a simple message destined for the other portable.

Referring to Figure 4-7, the message is sent by the Messaging application across the air interface to the Radio Port. As mentioned earlier, voice packets are hijacked for data and the data packets arriving at the Radio Port are diverted from the packets associated with any voice call which may be operating at the same time. The data packets are then relayed from the Radio Port at the Base Station across an HDSL interface to the Server at the C.O. The Server receives the data packets from one air interface, reassembles them, and resends them across the other air interface. Each air-interface operates independently of the other and therefore obliges packets to descend the protocol stack before ascending again. TPE handles this transparently to the application.

The arrival of a message at the receiving Laptop provokes the immediate appearance of a message arrival window. X-windows helps here in allowing the juggling of different windows. Although the message arrived silently and unannounced, it could be configured to announce its presence with a short beep.

Although the addressing was simplified for the purposes of the Phase 1 demo (effectively a nailed-up data connection between the two Laptops), the essential elements were satisfactorily demonstrated.

TPE Layering

TPE is the communication protocol used to transport the TPDUs (Transport Protocol Data Units) across the air interface. Current implementations have collapsed Link Layer and Transport Layers into a single protocol Layer as shown in Figure 4-8. The Network layer is missing in this Phase 1 implementation, since addressing is essentially hard-wired with Call Command (PTM) packets destined for the Server while Messaging packets are repackaged by the Server for relay to the other nomadic station.

Although TPE has been simplified for the Phase 1 implementation, it is nevertheless a richly-featured, fully operational, communication layer providing segmentation from TPDUs into 'chunks', SLIP framing, full 32-bit CRC error detection, acknowledgment and retransmission. All control information including CRC is maintained in the 8-byte 'chunk' header which is transported in a virtual in-band control channel independently of the data.

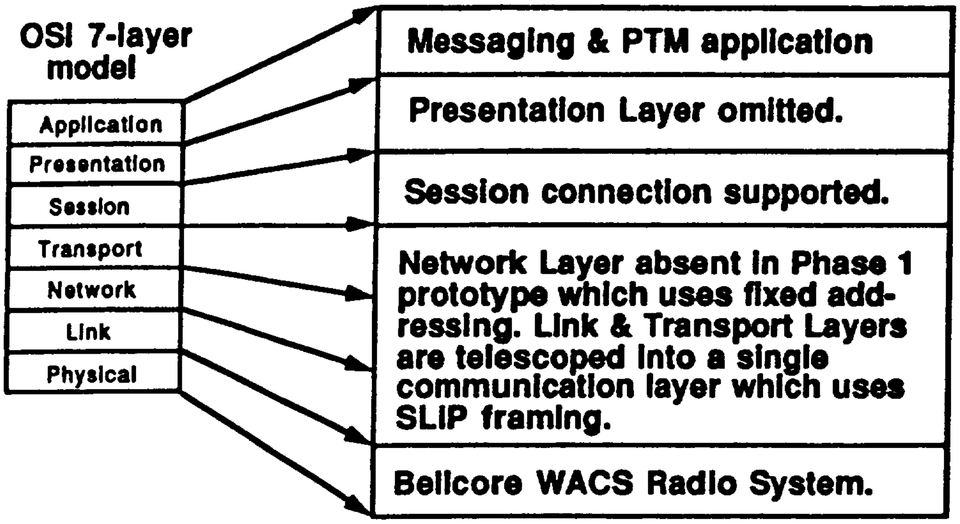

Figure 4-8. The Phase 1 TPE protocol stack

TPE only controls those Voice Timeslots (upper part of Figure 4-9) which are marked as being populated with data. TPE does not control any of the voice timeslots.

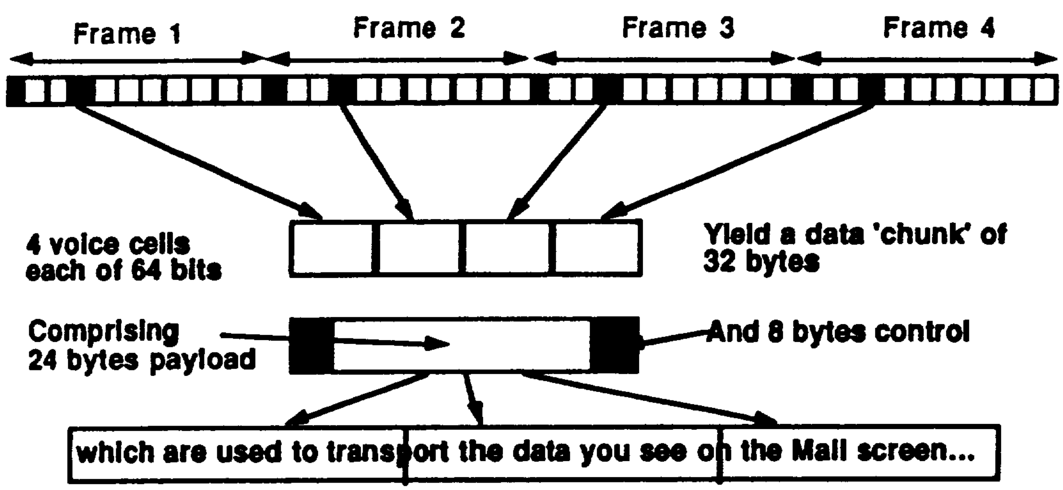

Figure 4-9. Data Segmentation from WACS to application

Each of the timeslots is actually 100 bits in length, of which 64 bits constitute voice or data payload. The other 36 bits comprise voice synchronization and control as well as a 12-bit CRC check.

Under the TPE layer, there is actually a further LAPR layer (Radio Link Access Protocol) which does perform simple error detection by means of its 12-bit CRC and could also undertake responsibilities for cell (64 bits) retransmission. In Phase 1, this 12-bit error detection CRC was simply used to drop cells in which errors have been detected.

TPE Resilience

Initial trials with the data prototype indicated underlying radio error rates far higher than anticipated. In addition, bit errors appear to have bled through to the TPE layer to its severe detriment. Error rates as high as 20 - 40% peaking at 70 - 90% were measured using a Bellcore utility program. TPE was not designed to handle error rates as high as this initially but, after some last-minute tuning , was able to recover gracefully from error rates as high as 70 %. TPE also showed evidence of having to cope with bit errors at a rate exceeding the falsing rate associated with the underlying 12-bit LAPR CRC. This might seem to indicate an error source outside the air-interface.

Further evidence seemed to implicate hardware as a source of errors. On hot days, errors were particularly prominent. Some stability was achieved after all equipment at the C.O., including HDSL cards, were reset and brought up in sequence following a power outage. Improved application stability was noted which permitted the Phase 1 demonstrations to proceed.

In addition, TPE will have some Forward Error Correction (FEC) capable of correcting some of the bit errors which escaped the 12-bit CRC possessed by LAPR. Some thought should be given as to whether LAPR should be trashing cells based upon its error detection mechanism. There is an extremely high probability that the FEC scheme adopted by TPE will actually fix random bit errors in packets which have already been trashed by LAPR. Consequently, in the protocol stack, FEC should always operate at a lower level than ARQ (retransmission) to give the maximum opportunity for packet recovery.

Since the objective even in Phase 2 is to harvest appropriate bit error rate statistics and experiment with protocol ingredients rather than to produce a deployable protocol solution, it might be better to disable the CRC in LAPR for data packets rather than detect errors and throw them away.

Forward Error Correction will only be able to correct a few bit errors per cell, or per chunk if bit interleaving is attempted, so ARQ will always be required for deep fades. However, ARQ imposes variable delays (depending upon error rates and system latency) so it is possible that a light-duty FEC could allow applications to run with lower average latencies over more variable propagation conditions. The only way of testing this proposition is by collecting Bit Error Rate statistics and applying in conjunction with mathematical modeling.

This approach would be consistent with an approach which allows applications maximum flexibility in defining the services they require from the underlying protocol layers in terms of throughput, latency, error correction and so on.

An alternative scheme, better for deployment, but less good for measuring errors involves ARQ at the LAPR level. Ultimately, this is likely to be the layer in which most error compensation is performed.

Decoupling of Applications

In the Phase 1 demo, applications were fully integrated with the TPE communication layer. In Phase 2, TPE will be decoupled from the applications and will run as a separate process (or process group) under UNIX.

Restructuring of Server

The Server used in Phase 1 was never intended to be extremely robust and be capable of standalone operation. The server depended upon the remote applications being brought up in a particular sequence within a minute or two of the server itself. If the server was brought up and left to run for longer periods without client communications, it would inevitably fail again through receipt of multiple chunks of inappropriate lengths appearing randomly from the radio system.

In Phase 2, the Server must be capable of allowing an application to connect at any time, even in the middle of existing sessions and must also be sufficiently robust to tolerate high error rates and incorrect chunk sizes.

5 Building Penetration Propagation Study

A series of radio propagation experiments was conducted during the spring of 1993 in Boulder and Denver, CO. The goal of the experiments was to quantify signal building penetration losses by houses and multistory office buildings. The immediate application of the results is to determine the viability and to statistically characterize the indoor coverage in houses and office buildings using street microcells.

The experiments were conducted jointly by U S WEST Advanced Technologies and The National Telecommunications and Information Administration (NTIA) under a cooperative research agreement.

To conduct the measurements, three separate narrowband continuous waves (CW) at 912, 1920, and 1920 MHz were combined, amplified, and transmitted simultaneously via a single wideband omnidirectional antenna. A single-antenna receiving system was used to monitor the three frequency sources, which were analyzed and recorded simultaneously. The measurements used a fixed outdoor transmitter and a mobile indoor receiver. Vertically polarized transmitter and receiver antennas were used for all the experiments.

Seven houses, typical of those encountered in the region where the measurements were taken, were used to collect the data in residential areas. Four high rise buildings, populated by offices and soft partitions, were used to conduct the experiments in a typical urban area.

A statistical characterization of building penetration losses with street microcells is presented in this section. A comparison in propagation characteristics at the three frequencies studied is also discussed.

5.1 Measurement Procedure and Equipment Description

The measurements were taken inside six residential buildings and four high rise buildings. The transmitter antenna used a vertical polarization and was positioned at a height of 5 m, which is approximately the height of the top of a traffic light. This height was selected to emulate typical street microcell base stations mounted on existing structures such as traffic lights or lamp posts.

The distances involved between the transmitter locations and receivers were restricted to 120 m to remain within the dynamic range of the equipment used. Line of sight paths and non-line of sight paths were established to conduct the tests and investigate various propagation modes. Building penetration was accomplished mainly through walls and windows. Base antenna height can potentially have an impact on building penetration losses when a significant portion of signal energy penetrates a building through the roof.

Within the buildings, the measurements were made by moving the receiving antenna in a zig-zag pattern through the measurement area. This pattern allows the computation of more reliable mean values. In a typical house, four to six rooms were used to measure the received signal strength. The power measurements were done with three (one per frequency) spectrum analyzers, which via interface buses, were connected to a PC for data storage.

In the high rise buildings, received signal levels (RSL) were measured at the four corners of selected floors, using zig-zag patterns.

Reference measurements were made on the sides of each building by tracing a zig-zag pattern in front of the outside walls of the buildings.

Transmitter Equipment

A van was used to house the transmitter equipment. The three frequencies, 912, 1920, and 5990 MHz were radiated simultaneously by one antenna. The transmitter was powered by a diesel generator. The transmitting omnidirectional antenna was mounted on a telescopic mast and positioned at a height of approximately 5 m above ground level. The transmitter position was fixed for the duration of the experiments for each measurement site.

The three transmitted signals were generated by three different signal generators, the signals were amplified separately to avoid intermodulation distortions, filtered individually, and combined by a quadriplexer (with the unused input terminated). The signals were then fed through a low-loss cable to a single wideband omnidirectional (in azimuth) vertically polarized antenna. The transmitted effective isotropic radiated power (EIRP) levels were: 15 dBm, 17.2 dBm, 18.6 dBm for 912 MHz, 1920 MHz, and 5990 MHz respectively. Figure 5-1 illustrates a functional diagram of the transmitter equipment.

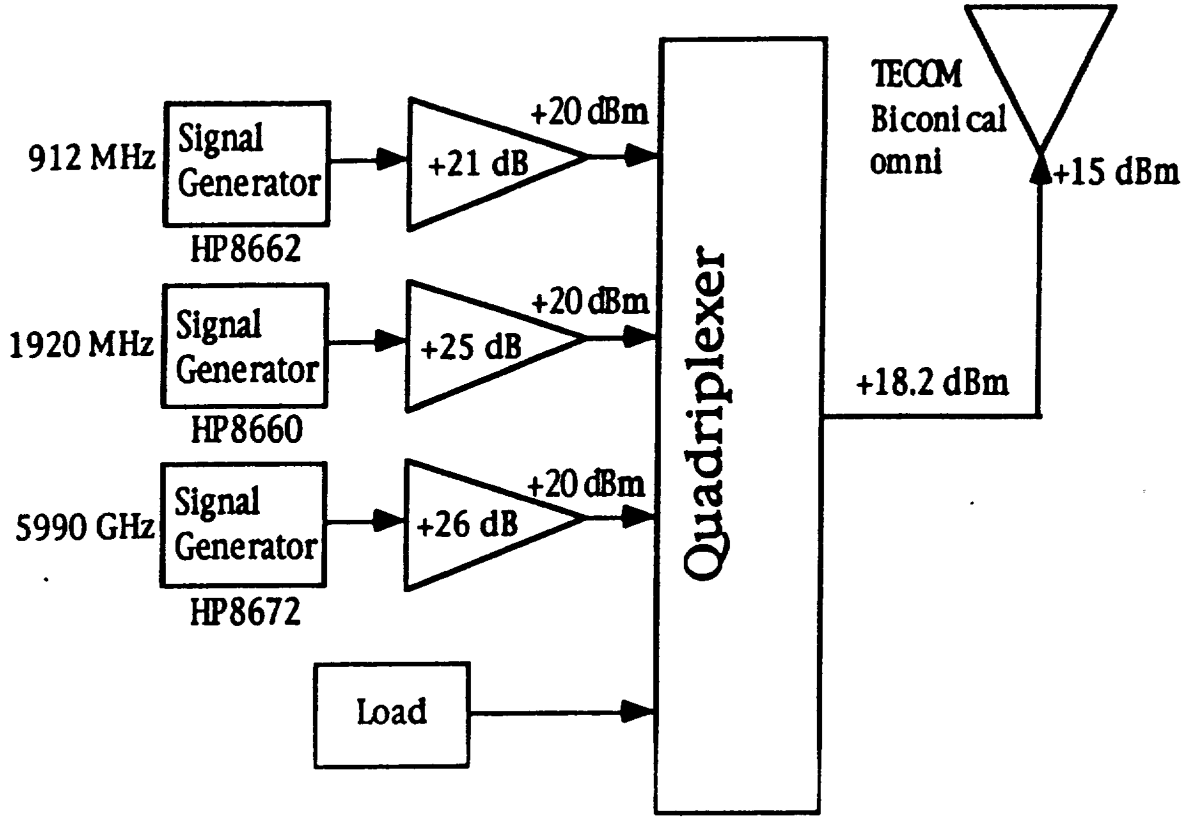

Figure 5-1. Functional block diagram of transmitter equipment

Receiver Equipment

The equipment used at the receiving sites consisted of a single biconical omnidirectional antenna, matched to the transmitting antenna, feeding a quadriplexer, with the unused output terminated. The active outputs of the quadriplexer were individually filtered, amplified, passed through 30 m long coaxial cables and received by three spectrum analyzers. The spectrum analyzers were connected to a PC for data storage through interface buses (HPIB). The 5990 MHz system also included a second low noise amplifier to make up for the higher cable losses at this frequency and overdrive the high noise figure of the spectrum analyzer (i.e., to extend the dynamic range). A functional block diagram of the receiver equipment is shown in Figure 5-2.

The calculated gains of the receiver antennas, relative to a unity gain omnidirectional antenna were 26 dBi, 28.6 dBi, and 40.6 dBi for 912 MHz, 1920 MHz, and 5990 MHz respectively.

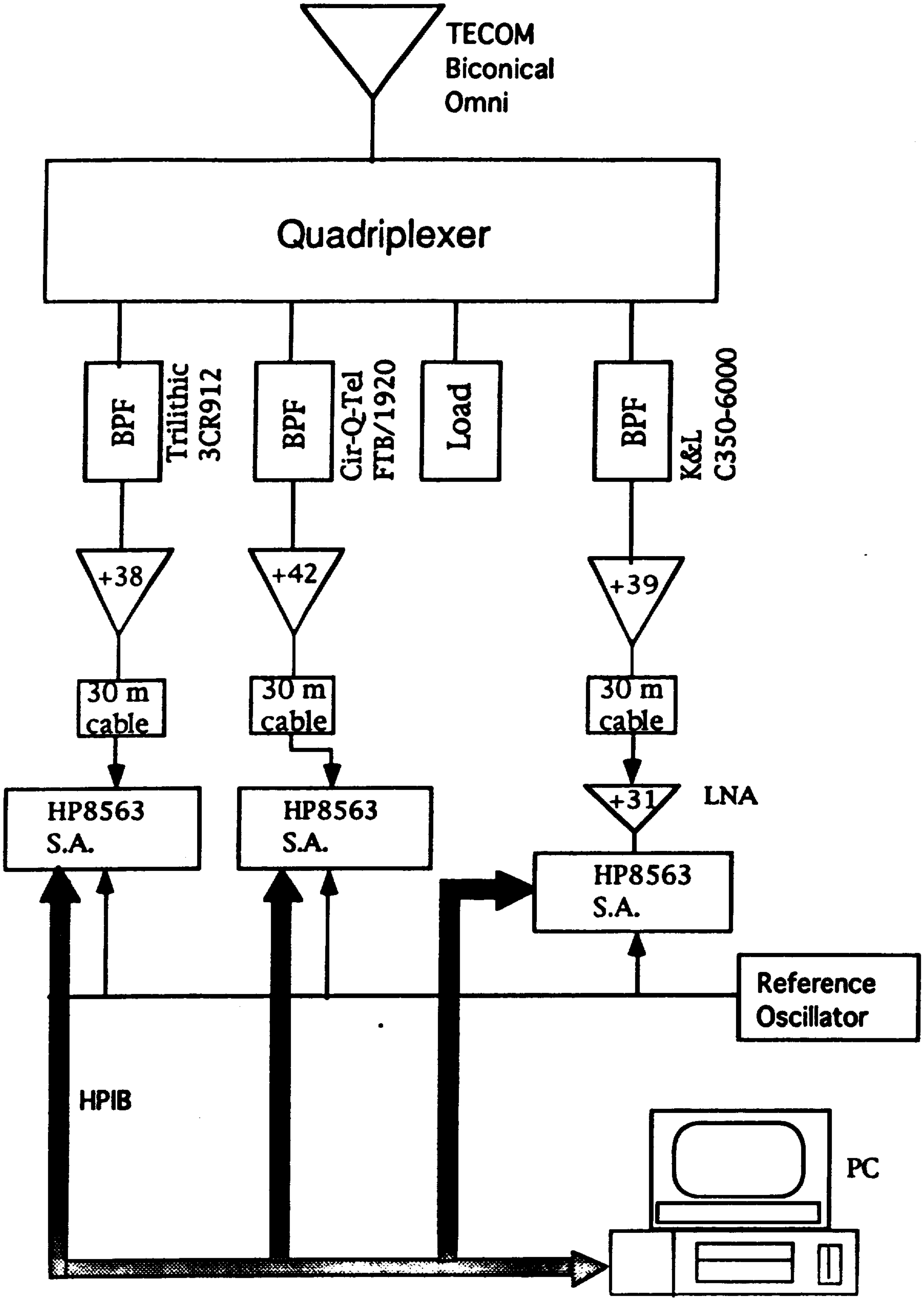

Figure 5-2. Functional block diagram of receiver equipment

Measurement Technique

For consistency, the receiving antenna was supported by a harness worn by a carrier who kept the antenna vertical at all times. The height of the receiving antenna was maintained constant at approximately 1.9 m above ground level, to avoid head shadowing. A zig-zag pattern was traversed across the measurement area of every room used in residential areas, or for the four corners on each floor of the buildings used.

Data Files

To obtain reliable averages, five ten-second sweeps were taken for each room or corner. Thus, a total span of fifty seconds per room or corner per frequency was used to compute average values. This process was repeated in adjacent rooms or corners throughout the measurement sites. The spectrum analyzers used to measure received signal levels were connected to a PC using a Hewlett Packard Interface Bus (HPIB). The data was stored in ASCII format on the hard disk of the PC and downloaded to floppy disks daily. The stored data was in raw form and included "fast" fading, typically modeled as Rician or Rayleigh statistical distribution.

5.2 Office and Residential Building Information

The measurements were made inside seven residential buildings and four multistory buildings with offices and soft partitions. A brief description of the buildings is given below.

Residence # 1

This is a single story brick with mesh and plaster detached home. This house is located on a quiet street with a few cars parked outside. The streets are lined with single story houses with approximately 0.2 acres per house. The trees surrounding the house are approximately 20 years old. Two very large pine trees are located in front of the house. The house has an underground basement that has some small windows. The LOS transmitter was located approximately 63 m away and the NLOS transmitter was located 91 m away.

Residence # 2

This is a tri-level brick veneer and wood detached residence on a quiet street with no cars parked outside. The streets are lined with single and double story houses. The basement is partially underground with large windows. The LOS transmitter was located approximately 85 m away and the NLOS transmitter was located 123 m away.

Residence # 3

This is a single story brick veneer detached residence on a quiet street with no cars parked outside. The streets have single and two-story houses of approximately 0.3 acres per house. A few low height evergreen trees are located around the house. The basement is completely underground with some small windows. The LOS transmitter was located approximately 76 m and the NLOS transmitter 50 m.

Residence # 4

This is a tri-level brick and plaster detached home. Many cars are parked outside on the street. The street is lined with single and two-story houses, with approximately 0.2 acres per house. The vegetation around the house is very low. The basement is half underground with large windows. The LOS transmitter was located 64 m away. The NLOS transmitter was located 88 m.

Residence # 5

This a large two-story (detached) wood and brick veneer residence with thermoply reflective insulation on a quiet neighborhood with no cars parked on the street. The street is lined with double story-houses, approximately 0.5 acres per house, but very few surrounding houses. No vegetation surrounds the house. The basement is completely underground and has large windows. The LOS transmitter was located 43 m away and the NLOS transmitter was located 128 m away.

Residence # 6

This is a two-story aluminum and brick veneer residence (detached) on a quiet street with a few cars parked on the street. The street was lined with single and double story houses, approximately 0.25 acres per house. The vegetation surrounding the house consists of low shrubs and deciduous trees with no leaves. The basement is completely underground with small windows. The LOS transmitter was located approximately 96 m and the NLOS transmitter was located 137 m away.

Residence # 7

This is a two-story wood and brick veneer detached home on a quiet street with a few cars parked on the street. The street is lined with single and two-story houses with approximately 0.2 acres per house. No large trees are located near the house. The basement is completely underground with large windows. The LOS transmitter was located 81 m away and the NLOS transmitter was located 100 m away.

High Rise Building # 1

This is a new 19 story mostly glass high rise building in a busy metropolitan area. The building occupies the entire block and the surrounding streets are busy and lined with parked cars. The first floor is above ground level by approximately 6 m. There are four underground levels for parking. The NLOS transmitter was located approximately 200 m away from the transmitter.

High Rise Building # 2

This is a 65 year old 15 story stone high rise with a few windows. The building comprises one quarter of the block area. The building is surrounded by busy streets and parked cars parked on both sided of the street. There is no surrounding foliage. Most of the floors have an open-face layout with low cubicle soft partitions. The NLOS transmitter was located approximately 97 m away.

High Rise Building # 3

This is a 12 floor stone high rise with a few windows. The building occupies one quarter of the block area and has busy streets and parked cars on two sides. There is no surrounding foliage. Most of the floors have an open-face layout with low cubicle walls. The NLOS transmitter was located was located 97 m away.

High Rise Building # 4

This is a new 50 story concrete building with large windows. The building with its parking garage occupies an entire city block. The high rise is surrounded by busy streets lined with parked cars. The is no surrounding foliage. Most of the floors have open spaces with low cubicle walls. The NLOS transmitter was located 207 m away.

5.3 Measurement Results

Building penetration losses in residential areas are presented in the form of cumulative probability distribution functions (CDF's). Figure 5-3 illustrates the composite results obtained from seven houses and four to six (one per room) mean penetration losses per house.

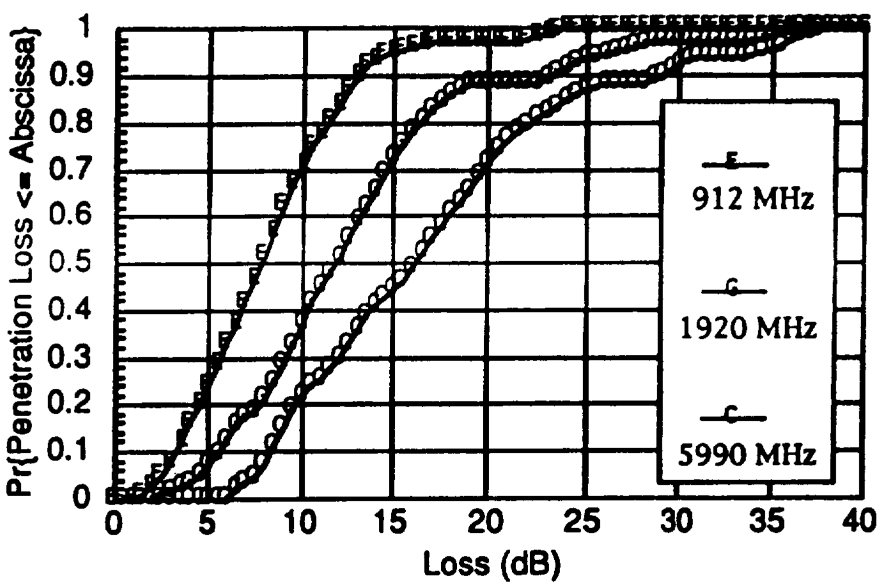

Figure 5-3. Cumulative Probability Distribution Functions of Building Penetration Losses in Residential Areas at 912 MHz, 1.92 GHz, and 5.99 GHz (Non-Line of Sight)

High rise building penetration losses in urban areas are presented in the form of cumulative probability distribution functions (CDF's). Figure 5-4 illustrates the composite results using data from four buildings, six to ten floors per building, and three to four points (mean values) per floor.

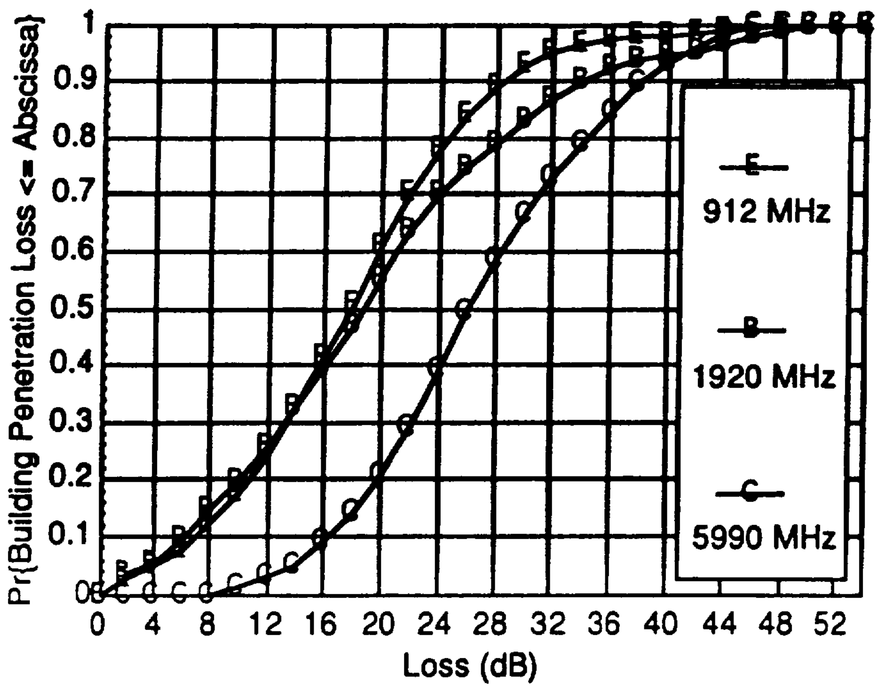

Figure 5-3. Cumulative Probability Distribution Functions of High Rise Building Penetration Losses. Non-Line of Sight Path Between Transmitter and Receiver (The Computed Functions Used All the Data Points From Four High Rise Buildings).

6 Future Research

Additional work is planned in all the areas discussed in this report. First, the testbed expansion efforts will be continued. The bulk of the testbed infrastructure expansion, as described in Section 2, is scheduled for completion by the end of the year. In preparation for continued radio testing, propagation measurements are planned in the expanded areas to fully characterize the radio environments.

The specific wireless systems to be tested next quarter depend on hardware delivery schedules, testbed expansion progress, and availability of vendor personnel & equipment. A production version of the Personal Handy Phone system is scheduled to be installed in the Boulder testbed during the fourth quarter of 1993. The antennas will be placed on building rooftops near the Pearl Street pedestrian mall, with approximately 1 kilometer between base stations. Current planning is that four base stations will be installed and tested.

The four base stations in the PHP installation will allow a more thorough evaluation of the coverage of the system with rooftop antennas. Coverage contour maps can be obtained in light urban and residential areas for use in system design and planning. The performance of the dynamic channel allocation (DCA) algorithm can be evaluated by simulating additional base stations and assessing how efficiently the system assigns new frequencies. The handoff capabilities of the system can be determined; in particular, the blanking time intervals during handoff can be measured. It will be possible to measure the interference to existing microwave point-to-point users from rooftop mounted PCS systems.

Additional phases of data services demonstrations with the Wireless Access Communications System are scheduled for later this year. The Phase 2 trial will include collection of bit error statistics for use in a Markov error probability model. Several new applications will be demonstrated, including point of sale verification, fax transfer, and image messaging. The Phase 2 communications software is expected to be considerably more robust than the Phase 1 prototype algorithms.

Final processing of data from the propagation study of building penetration is expected to be complete in October. A more detailed report of the results from the study should be available at that time. The final analysis will include a breakdown of the results based on individual building structures.

References

[1] D. C. Cox, "A Radio System Proposal for Widespread Low-Power Tetherless Commmunications", IEEE Transactions on Communications, Vol. 39, No. 2, February 1991, pp. 324-335.