3/15/93

U S WEST COMMUNICATIONS

1005 17th Street, Room 1750
Denver, Colorado 80202-2002
March 16, 1993

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

RE: U S WEST COMMUNICATIONS, INC.
FOURTH QUARTERLY REPORT
PCS Experimental Licenses:
KK2XCC (File Number 3306-EX-ML-92) - Boulder, CO
KK2XCD (File Number 2149-EX-PL-91) - Portland, OR

Dear Mr. Wright:

Enclosed please find U S WEST's fourth quarterly report addressing the above referenced authorization for PCS field trials in Boulder, Colorado. At this time we have yet to implement experimental trials in Portland, Oregon.

Should you have any questions or require additional information, please contact Beth Spellicy at (303) 896-7576.

Sincerely,

Sambran Sandoval
Manager - Network Technology Transport Services

ENCLOSURES

U S WEST Wireless Personal Communications Experiments

Quarterly Progress Report
FCC Experimental Licenses
KK2XCC and KK2XCD

March 5, 1993

Submitted to

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

Prepared by

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

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Executive Summary

This report describes field testing which U S WEST Advanced Technologies has performed under FCC Experimental Licenses KK2XCC for Boulder, Colorado and KK2XCD for Portland, Oregon. The report covers the quarterly period from December 5, 1992, through March 5, 1993. Initial results from testing of a frequency hopping microcell system are documented in the report. Coverage contours for word error rate and received signal strength are presented as functions of space, time, and frequency diversity.

U S WEST has constructed a Personal Communications Service (PCS) microcell test bed in Boulder, Colorado. The ultimate objectives of the test bed experiments include the following: first, to comparatively evaluate the performance of different PCS technologies; to develop implementation guidelines and software tools for the design of optimized microcellular systems; to gain technical knowledge which can be used to drive the adoption of industry standards for PCS.

The test bed currently consists of 9 flexible outdoor base station sites located in and around the Pearl Street pedestrian mall in downtown Boulder. Each base site contains a weatherproof equipment enclosure prewired with electrical power and twisted pair telephone interconnections. In addition, each base location is equipped with two antenna mounts and low-loss coaxial cable wired back to the equipment enclosure. Some of the base sites are located on lamp posts and street lights, while others are located on buildings mounts. The twisted pair telephone connects at the sites are wired back to the Boulder Main Central Office where a Radio Port Control Unit (RPCU) and additional network switching equipment are located. The geographic locations of the outdoor base sites are marked on the map shown in Figure 1. The test bed also contains a number of indoor base locations for testing wireless PBX and wireless LAN technologies.

Several different microcell PCS technologies have been evaluated at the test bed [1-3]. Initial tests were conducted with equipment using the CT-2 common air interface in the 866-868 MHz band [1,2]. A prototype version of the Bellcore Wireless Access Communication (WAC) air interface was tested in the 2.1 GHz frequency division duplex bands [2]. During December 1992 through July 1993, a frequency hopping system developed by Tadiran, Ltd. is being tested [3]. The system operates in the 902-928 MHz band using time, space, and frequency diversity. Through the use of an engineering menu, it is possible to selectively enable or disable each of the diversity modes. The handsets and base stations are capable of recording received signal strength, word error rate, antenna diversity selection information, and other operating statistics.

The first step in testing the Tadiran equipment involved careful laboratory testing and calibration. The majority of the field testing was to be performed outdoors during the Winter in Boulder, Colorado. For this reason, the temperature dependence of the receiver and transmitter performance characteristics were measured for the handsets and base stations. The transmitter and receiver performance for the handsets was also characterized as a function of battery voltage. Finally, accurate calibration curves were measured at several frequencies in the operating band. The calibration curves were used to correct the received signal strength readings logged by the equipment during the field tests.

In parallel with the equipment calibration, a field measurement campaign was conducted. A symmetric grid of measurement points spaced one-half block apart was defined. At each measurement point, the handset and base station performance was measured. Several combinations of time, space, and frequency diversity were measured. First, a set of

measurements was collected with the system operating in a full functionality mode with dual slot time diversity, antenna diversity, and frequency hopping. From the first set of measurements it is possible to determine the performance of the system with no time diversity. A second run was conducted with no antenna diversity but with time diversity on. A final set of measurements was collected with no frequency hopping but with antenna diversity turned on.

The results of the field measurement campaign are the heart of this report. Coverage contours for word error rate and received signal strength are presented for each of the diversity conditions. By selectively turning on and off space, time, or frequency diversity, it is possible to ascertain the effects of each type of diversity independently. Thus it is possible to weigh the benefits and complexity tradeoffs of diversity schemes such as dual antenna diversity, time slot retransmission, and frequency hopping.

Initial tests of the frequency hopping system operating in the 902-928 MHz band have been conducted. A series of measurements have been taken at one of the base station locations in the Boulder test bed. The effects of adaptive time diversity, antenna diversity, and frequency hopping have been evaluated. Processing of these data are continuing in order to develop propagation models and software prediction tools for the microcellular environment.

In general, the word error rate (WER) and received signal strength (RSS) coverage contours are diamond shaped. In some cases, for example with no antenna diversity, the coverage contours become more cross shaped. The effects of local topographical features, such as large buildings, hills, valleys, and open areas are clearly evident in the measured coverage contours.

The measured coverage contours distinctly point out the importance of local topography upon the coverage of microcellular systems where antenna heights are below the surrounding buildings. Without knowledge of the surrounding environment, both man-made and natural, it is not possible to optimize the coverage and performance of a microcellular system. For this reason, U S WEST Advanced Technologies is involved with the development of PCS system design guidelines and software tools which make use of information about the local environment. Geographical Information Systems (GIS) are being utilized to store and manipulate topographical information about the propagation environment. Information about user demographics (user densities, income levels, etc.), telecommunications infrastructure (fiber, coaxial cable, twisted pair, etc.), and the electric power plant are being incorporated in the database system.

Field test results indicate that dual slot time diversity improves the 1% WER coverage by approximately three-fold. This dramatic improvement is critical to the performance of a frequency hopping system in the presence of frequency selective fading and narrow band interferers. The tradeoff is obviously in terms of system capacity; the more time slots that are used for retransmission - the less that are available for additional users. The increase in high quality coverage area with time diversity is significant enough to warrant including time slot retransmission in the common air interface for a frequency hopping system.

Antenna diversity improves the coverage of the system by approximately 0.5 to 1.5 blocks in non-line-of-sight conditions. Coverage is improved only marginally under the line-of-sight conditions in the measurement area. The single antenna 1% WER coverage contours are much closer to the shape of a cross, while the antenna diversity case more closely resembles a diamond shape. This difference is critically important for the deployment pattern of PCS microcellular systems. Antenna diversity can significantly improve coverage in directions other than the cross streets at which the base station is located.

Frequency hopping produces coverage contours, both in terms of WER and RSS, which are significantly smoother and less erratic than the single frequency measurements. Again, this is important for the layout and design of microcellular systems. The smoother coverage contours with frequency hopping are due to the frequency selective nature of the fading and the inherent frequency averaging associated with frequency hopping. Coverage contours are much closer to diamond shaped for the frequency hopping case compared to the single frequency case.

These important conclusions regarding the use of time, space, and frequency diversity in the design of common air interfaces for PCS systems are being presented by U S WEST to appropriate standards bodies and industry organizations. It is hoped that this technical information will lead to the standardization of common air interfaces for future PCS systems. Space, time, and frequency diversity can be important elements in such a common air interface.

U S WEST Advanced Technologies will continue testing the frequency hopping system in the 902-928 MHz band. The field test data will be processed further to determine appropriate propagation models for the prediction of system coverage. Additional field tests including handoff, system loading, interference, and jamming will be conducted. Several other PCS technologies will be evaluated at the Boulder test bed in 1993, including systems operating at 1.9 GHz and 2.1 GHz.

1 Introduction

This report describes field testing which U S WEST Advanced Technologies has performed under FCC Experimental Licenses KK2XCC for Boulder, Colorado and KK2XCD for Portland, Oregon. The report covers the quarterly period from December 5, 1992, through March 5, 1993. Initial results from testing of a frequency hopping microcell system are documented in the report. Coverage contours for word error rate and received signal strength are presented as functions of space, time, and frequency diversity.

U S WEST has constructed a Personal Communications Service (PCS) microcell test bed in Boulder, Colorado. The ultimate objectives of the test bed experiments include the following: first, to comparatively evaluate the performance of different PCS technologies; to develop implementation guidelines and software tools for the design of optimized microcellular systems; and to gain technical knowledge which can be used as input to standards bodies.

The test bed currently consists of 9 flexible outdoor base station sites located in and around the Pearl Street pedestrian mall in downtown Boulder. The base station sites are located in a light urban environment. Each base site contains a weatherproof equipment enclosure prewired with electrical power and twisted pair telephone interconnections. In addition, each base location is equipped with two antenna mounts and low-loss coaxial cable wired back to the equipment enclosure. Some of the base sites are located on lamp posts and street lights, while others are located on buildings mounts. The twisted pair telephone connections at the sites are wired back to the Boulder Main Central Office where a Radio Port Control Unit (RPCU) and additional network switching equipment are located. The geographic locations of the outdoor base sites are marked on the map shown in Figure 1. The test bed also contains a number of indoor base locations for testing wireless PBX and wireless LAN technologies.

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The first step in testing the Tadiran equipment involved careful laboratory testing and calibration. The majority of the field testing was to be performed outdoors during the Winter in Boulder, Colorado. For this reason, the temperature dependence of the receiver and transmitter performance characteristics were measured for the handsets and base stations. The transmitter and receiver performance for the handsets was also characterized as a function of battery voltage. Finally, accurate calibration curves, relating received signal strength readings versus actual input power, were measured at several frequencies in the operating band. The calibration curves were used to correct the received signal strength readings logged by the equipment during the field tests.

In parallel with the equipment calibration, a field measurement campaign was conducted. A symmetric grid of measurement points spaced one-half block apart was defined. At each measurement point, the handset and base station performance were measured. Several combinations of time, space, and frequency diversity modes were tested. First, a set of measurements was collected with the system operating in a full functionality mode with dual slot time diversity, antenna diversity, and frequency hopping. From the first set of measurements it is possible to determine the performance with no time diversity. A second run was conducted with no antenna diversity but with time diversity on. A final set of measurements was collected with no frequency hopping but with antenna diversity and time diversity turned on.

The results of the field measurement campaign are the heart of this report. Coverage contours for word error rate and received signal strength are presented for each of the diversity conditions. By selectively turning on and off space, time, or frequency diversity, it is possible to ascertain the effects of each type of diversity independently. Thus it is possible to weigh the benefits and complexity tradeoffs of diversity schemes such as dual antenna diversity, time slot retransmission, and frequency hopping.

This report describes the equipment used in the field testing, the laboratory calibration procedures, the field test results, and directions of future experimental work. Section 2 of the report provides specifications for the microcell equipment used during the testing this quarter. In Section 3, the procedures used to calibrate and test the equipment are discussed. The experimental field measurement procedures and results are presented in Section 4. The direction of future experiment work is described in Section 5. In Section 6, the conclusions from the experimental work this quarter are summarized.

2 Description of Microcell Equipment

In December 1992, Tadiran, Ltd. provided U S WEST with an engineering prototype PCS system. U S WEST currently has 5 base stations and 15 handsets for use in field trials. The prototype system is an extremely flexible platform for performing field experiments. The equipment contains an engineering menu which provides control of operating modes, diversity schemes, integration times, recorded statistics, and other relevant parameters. The prototype equipment records received signal strengths, word error rates, diversity selection statistics, and other operating information.

A description of the common air interface implemented by the Tadiran, Ltd. equipment was presented in reference [3]. Multiple access is achieved through a time division multiple access (TDMA) scheme. Transmit and receive duplexing are implemented through time division duplexing (TDD). There are 5 full duplex TDMA slots per radio channel. Each 2 millisecond TDMA/TDD frame consists of 5 reverse channel time slots followed by 5 forward channel time slots. The over the air bit rate is 468 kbps with each traffic channel allocated 32 kbps for voice data and 4.5 kbps for control information.

The modulation used is Frequency Shift Keying (FSK) with a digital modulation index of slightly less than one-half. Therefore, the modulation scheme closely approximates Gaussian Minimum Shift Keying (GMSK). The system transmits a maximum of 30 milliwatts from the handsets and 100 milliwatts from the base stations. The handsets and base stations are capable of dynamic power control over a total dynamic range of 28 dB.

The following sections discuss the diversity schemes which are implemented by the prototype equipment. Frequency hopping is used to provide frequency diversity. Dual antenna diversity is implemented to provide spatial diversity. Time slot retransmission is used to provide time diversity.

2.1 Frequency Hopping

The Tadiran Ltd. equipment is capable of transmitting on any one of 51 channels within the 902 to 928 MHz band. Each of the channels occupies a 500 kHz 20 dB bandwidth, with the first channel's carrier frequency at 902.5 MHz and the fifty-first channel's carrier frequency at 927.5 MHz. The system is capable of frequency hopping at a rate of 500 hops per second. A pseudo-random sequence is used to define the fixed hopping pattern, which repeats every 102 milliseconds. By hopping throughout the 902 to 928 MHz band, the system is able to achieve frequency diversity to combat interference and fading.

2.2 Antenna Diversity

Antenna diversity is implemented at the base station only. The antenna diversity involves two antennas spaced several wavelengths apart connected to dual receivers. The base station uses a diversity selection algorithm to choose the best data block from one of the two receivers. The base station uses only one transmitter whose output is adaptively switched to the antenna which provided the best signal from the given handset on the same hop. Data to a specific handset is transmitted through the same antenna that was chosen to receive from that handset earlier in the TDD frame. Since the first half of the 2 millisecond TDMA/TDD frame consists of 5 slots of reverse channel (handset to base) traffic, the transmit antenna selection for the forward channel (base to handset) is based on the best receive antenna selection from the handset transmission 1 millisecond earlier.

2.3 Time Diversity

The equipment is capable of implementing an adaptive time diversity algorithm to combat fading or interference. The time diversity mechanism is based on a sliding window repetition of the same data block from the vocoder. If less than the full 5 time slots are in use at a given base station, then the adaptive time diversity algorithm can be implemented. Any unused slots within the TDMA/TDD frame can be used to retransmit data from previous hops. This redundant transmission provides improvement in the case when a particular hop, or a series of hops, is corrupted by interference or fading.

In the current software revision of the time diversity algorithm, only dual slot diversity is implemented. In other words, in dual diversity mode each TDMA/TDD frame will contain the current output of the vocoder as well as a repetition of information which was transmitted on the previous hop. This mechanism is extremely effective at removing interference from narrow band fixed-frequency interference sources. The time diversity is also effective at combating frequency selective fading if the frequency spacing from one hop to the next hop exceeds the coherence bandwidth of the channel.

3 Equipment Testing and Calibration

The engineering prototype equipment from Tadiran, Ltd. was designed to be a functional PCS microcell system, not a laboratory grade measurement system. For this reason, the manufacturer had not calibrated the equipment or determined the sensitivity of the equipment readings to temperature, battery voltage, or operating frequency. In order to assure that the field test results were valid, U S WEST conducted an extensive calibration procedure.

The goal of the laboratory test procedure was to determine the effects of battery voltage, temperature, and operating frequency on the transmit power, received signal strength indication, and word error rate readings. In addition, calibration curves were determined for each handset and base station.

3.1 Laboratory Calibration Procedure

A block diagram of the test setup is shown in Figure 2. A mixer and local oscillator are used to provide a frequency translation between the base station and handsets. In this manner, the base station operates on one radio channel, while the handsets operate on a different radio channel. The frequency shift between the base station and handsets assures that no radio frequency leakage occurs between the transmitter and receiver. Leakage of this type can be a critical problem when measuring receiver sensitivity without the use of a screened room.

A three way splitter was employed so that two handsets could be calibrated at a time. A spectrum analyzer monitored the signal which was being fed to the handsets. A calibrated variable attenuator provided a known signal level into the handsets. The received signal strength (RSS) indication on the handset was then compared with the actual power input to the handset. Correction factors relating handset RSS readings to actual power input could then be determined.

The curves in Figure 3 show the RSS readings at the handset versus the actual input signal power for 5 representative handsets. The response curves for the five handsets are clustered within about 10 dB and are well correlated with one another. Handsets 4, 8, 10, and 16 exhibit a dead zone at approximately an RSS of - 62 dBm. In other words, these handsets read - 62 dBm over a range of approximately 5 dB in input power. The exact cause of the dead zone has not been determined. In order to avoid possible inaccuracies associated with this phenomenon, handset number 12 was used for all measurements discussed in this report.

3.2 Sensitivity to Battery Voltage

During the field testing, the handsets were operated using battery power. Is was therefore important to determine how sensitive the handset readings were to the battery voltage. Figure 4 shows the RSS reading versus input power for handset number 12. Two different battery voltages are illustrated in the figure, the solid black squares represent a fresh battery pack (5.5 Volts) and the white triangles represent a low battery pack (4.9 Volts). The fresh battery readings and the low battery readings are within ± 2 dB of each other. Therefore, it does not appear that battery pack voltage impacts the field test readings significantly. During the field testing the battery voltage was monitored frequently; fresh battery packs were used to replace any low batteries.

3.3 Sensitivity to Operating Temperature

The field test results presented in this report were collected during the Winter months in Boulder, Colorado. Outdoor temperatures during the measurement campaign ranged from approximately 60° F to 10° F (without wind chill). Tests were performed to determine how the operating temperature affects signal strength and word error rate readings from the equipment. Figure 4 shows the input signal level versus RSS reading for handset number 12. The readings were taken in the middle of the frequency band at 915 MHz. Two cases are shown in the figure, the solid black squares represent readings at room temperature (approximately 68° F) and at the freezing point of water (32° F). The readings show less than 1 dB change with temperature. It does not appear that operating temperature has a significant impact on the RSS readings from the field test equipment.

3.4 Sensitivity to Carrier Frequency

The Tadiran, Ltd. equipment is capable of operating on any one of 51 channels in the 902 to 928 MHz band. It was necessary to determine the effect of carrier frequency upon the RSS readings provided by the test equipment. Figure 5 shows RSS correction as a function of the displayed RSS for handset number 12. The RSS correction is the number which must be added to the handset RSS reading to obtain the actual input power to the handset. In other words, the RSS correction is the difference between the actual input power to the handset and the RSS reading on the handset. There is approximately a 5 dB spread in the RSS correction factor over the operating frequency band. Individual calibration curves were obtained for the high, middle, and low ends of the frequency band; these curves are shown in Figure 5.

3.5 Signal Strength Calibration

When the equipment is operated in the frequency hopping mode, the transmitter and receiver change frequencies at 500 hops/second. The RSS readings logged by the equipment are averaged over time (integration times are user selectable from 0.1 to 100 seconds). The RSS readings are thus averaged over all 51 hopping frequencies. In order to obtain a single calibration curve to apply to the handset readings, a weighted average of the high, middle, and low frequency readings (shown in Figure 5) was used. The RSS correction curve for full-band frequency hopping is shown in Figure 6, where the results have been rounded to the nearest decibel. The calibration offset was applied to the received power data files which were collected during the field testing.

3.6 Front End Interference Filtering

The system under test operates in the 902 to 928 MHz frequency band. This band is directly adjacent to paging transmissions which use frequencies above 929 MHz. There are several paging towers located in downtown Boulder in close proximity to the PCS base station sites. The paging transmissions represent potential interference to channels at the high end of the 902-928 MHz band. The main concern with the paging transmissions is that they are time varying in nature (i.e. the paging transmitters are not continuously turned on). In order to avoid time varying effects on the results of the field measurements, notch filters were added to the receiver front end of the PCS handsets and base stations. The notch filters provided greater than 10 dB of attenuation at the pager frequencies from 929 to 932 MHz. Measurements indicated that the filters were able to remove any interference effects that from the paging transmitters.

4 Field Test Results

A series of field tests were performed at the test bed in Boulder, Colorado. Base station location number 1 (see Figure 1) at the corner of Pearl Street and Broadway Street was used for all of the tests reported here. Measurements were taken in a one-half block spaced grid pattern. Coverage contours were then interpolated from the grid measurements. At each measurement location received signal strength, word error rate, and antenna diversity selection statistics were recorded.

The first measurement run consisted of a full functionality tests with dual slot time diversity, antenna diversity, and full-band frequency hopping. From the full functionality data it was possible to determine the word error rates for the use of two time slots (time diversity) or with only one slot (no time diversity). A second test run was conducted with only a single antenna (no antenna diversity) but with time diversity and frequency hopping turned on. The final test run was with no frequency hopping at a carrier frequency of 903 MHz but with time diversity and antenna diversity turned on. From these test data it was possible to independently assess the effects of space, time, and frequency diversity.

4.1 Experimental Test Procedure

One of the Tadiran, Ltd. base stations was installed at base station location number 1, which is located at the corner of Broadway and Pearl Streets on Figure 1. The antennas for the base station are located on a traffic signal arm which extends Eastward across Broadway from the West side of the street. An aerial view of the site showing the antenna locations is shown in Figure 8. Antenna number 1 is located on an 18 inch standoff at a height of 16 feet above ground level. Antenna number 2 is located on the traffic signal arm approximately 20 feet from the West sidewalk at a height of 20 feet. For the antenna diversity tests, both antennas were used. For the single antenna tests, only antenna number 2 located in the middle of Broadway Street was used. The base station antennas are both 5 dBd gain with omnidirectional horizontal radiation patterns.

Measurements were taken in a square grid pattern in one-half block intervals over the area in which a call could be maintained between the handset and base station. No measurements could be made at grid points where a call could not be maintained. All the measurement locations presented here are outdoor locations. Additional measurements were made at a series of indoor locations to study penetration of the signals into buildings. The results of the building penetration measurements will be reported in future FCC Experimental License progress reports.

Handset number 12 was used for all of the tests described in this report. At each grid location, the antenna for the handset was held at approximately 6 feet off the ground. The antenna was placed in at this height to simulate a typical pedestrian PCS phone user. All measurement results were averages obtained over a 10 second integration period. During the integration period, the antenna was moved slowly in a 1 meter circle to provide local area averaging.

At the end of the 10 second integration time, the following data were recorded. At the handset Received Signal Strength (RSS) mean, minimum, maximum and Word Error Rate (WER) mean, minimum, maximum were displayed. At the base station Word Error Rate with time diversity (DWER) mean, minimum, maximum and Word Error Rate with no time diversity (SWER) mean, minimum, maximum were recorded. In addition, the base station also logged the percentage of hops that antenna 2 was selected by the antenna diversity algorithm. The current revision of software in the base station does not allow RSS to be recorded at the base station. Therefore, it was not possible to obtain reverse link RSS readings for the set of measurements described in this report.

The measurement readings at each grid location were entered into a database along with the location of the measurement point. The data were then exported to AutoCAD® and combined with a digitized map of the Boulder area. Contour lines were interpolated between the grid locations at which measurements were taken. Some of the contours lines for high word error rates (25% and 50%) and low signal strengths (-85 dBm and -95 dBm) were truncated in the East-West direction along Pearl Street due to the limited area of the measurement grid. The truncated contours are well beyond the coverage of the system for acceptable voice quality.

4.2 Word Error Rate Coverage Contours

Base station receiver word error rate (WER) contours were generated for 1%, 10%, 25%, and 50% error rates. The 32 kbps Adaptive Differential Pulse Code Modulation (ADPCM) vocoder used in the system provides a threshold of acceptable grade of service somewhere between 1% and 10% WER. From the WER plots it was possible to determine the area of acceptable coverage for a given system configuration. In addition, the coverage areas were be compared as functions of the three different diversity schemes.

Figure 1 illustrates the downtown Boulder geographic area where the field measurements were recorded. Base station location number 1 was used for the measurements reported in the following sections of this report. East and West of base site 1 along Pearl Street is an outdoor pedestrian mall, which is closed to vehicular traffic. The Pearl Street mall is decorated with both deciduous and non-deciduous trees in the 20 to 40 foot height range. The center of the Pearl Street Mall contains a number of small buildings (public restrooms, street vendor facilities, and bus stops). The Mall also contains a number of statues and information kiosks (less than 8 feet tall). The buildings surrounding the Mall are in the 2 to 4 story height range. North and South of base site 1 along Broadway Street is a typical light urban environment. The environment becomes more residential proceeding North of Pine Street along Broadway Street.

It is important to note several topographical features in the field measurement area which strongly influence the coverage from base site 1. The base location is on the Southwest corner of the intersection at Pearl and Broadway Streets. The base site antennas are obstructed by buildings on the Southwest corner of the intersection as one proceeds West on Pearl Street. North and South of the base site along Broadway, the base antennas are line of sight over the measurement area. The terrain North of the base site rises in elevation North of Pine Street. The terrain South of the base site dips in elevation South of Canyon Boulevard where Boulder Creek crosses Broadway Street.

There is a park three blocks South and one block East of the base station location. The park is at the Southeast corner of Canyon Boulevard and Broadway Street. The park is open wooded land with a small band shell and a locomotive engine display. Several large buildings are located along 14th Street both North and South of Pearl Street. A three story parking garage is located on the Southeast corner at the intersection of 11th Street and Spruce Street.

4.2.1 Full Functionality Performance

The base station receiver 1%, 10%, 25%, and 50% WER coverage contours for the full functionality test run are shown in Figure 9. For this test the system was operating with dual time slot diversity, antenna diversity, and frequency hopping simultaneously. The 1% WER coverage contour extends approximately 2.5 to 3 blocks in the East-West direction along Pearl Street and 4 to 6 blocks in the North-South direction along Broadway Street.

There are two reasons for the reduced coverage in the East-West direction: first, the shadowing of the base station antennas due to buildings obstructions; and second, attenuation due to obstructions (trees, buildings, kiosks) on the pedestrian mall.

The basic shape of the 1% WER contour is roughly a diamond shape. In the directions off of the Pearl and Broadway intersection the 1% WER contour covers approximately 1 block. A parking garage at the Southeast corner of Spruce Street and 11th Street causes the lack of 1% WER coverage at that intersection. Coverage is extended Southeast of the base station due to the open-area park near Broadway Street and Canyon Boulevard.

4.2.2 Performance without Time Diversity

Figure 10 shows the base station receiver WER coverage contours for the use of a single time slot with no time diversity. Antenna diversity and frequency hopping were employed for the tests. It is obvious from the figure that the 1% and 10% WER contours shrink dramatically without the time diversity. The 25% and 50% WER contours are not significantly altered by the use of time diversity. Figure 11 is a comparison of the 1% WER contours for the full functionality tests (from Figure 9) and the tests without time diversity (from Figure 10). The 1% WER coverage without time diversity is approximately 1 block along Pearl and Broadway Streets. Coverage is slightly less than 1 block in the East-West direction and slightly more than 1 block in the North-South direction.

It is apparent that the dual slot time diversity increases the 1% WER coverage by at least three-fold. The tradeoff is that adaptive time diversity can be utilized less as the loading of the system increases. When the system is fully loaded with 5 users per radio channel, then no time diversity can be employed. The increase in 1% WER coverage with time diversity is sufficient to warrant designing time slot retransmission into the common air interface for frequency hopping systems. This is particularly true for a system which will be operating in an unlicensed band with multiple interferers, such as the Part 15 unlicensed band at 902-928 MHz.

4.2.3 Performance without Antenna Diversity

The base station receiver WER coverage contours for the tests without antenna diversity are shown in Figure 12. Figure 13 is a comparison of the 1% WER contours for the full functionality tests (from Figure 9) and tests without antenna diversity (from Figure 12). The antenna diversity improves coverage primarily in the non-line-of-sight conditions off of Pearl and Broadway Streets. In general 1% WER coverage is increased by approximately one-half block in most non-line-of-sight conditions. The 1% WER coverage is increased by approximately 1 block in the open-area park near Broadway and Canyon. Coverage is increased by almost 1.5 blocks in West along Pearl Street with antenna diversity because of shadowing of antenna number 2 at the base site. The performance in line-of-sight conditions is improved much less significantly due to the antenna diversity.

There are two points on the contours in Figure 13 where the 1% WER coverage without antenna diversity extends slightly beyond the coverage with antenna diversity (Northwest and Southeast of the base station location). The diversity algorithm in the base station chooses the best output of the dual receivers connected to the diversity antennas. The two locations where a single antenna performs better than antenna diversity are most likely due to the repeatability of the measurements. The two measurement runs were made on different days.

4.2.4 Performance without Frequency Hopping

In the tests where the system was not frequency hopping, the equipment was operating with a fixed carrier frequency of 903 MHz. The base station receiver WER coverage contours for the fixed frequency tests are shown in Figure 14. Figure 15 compares the 1% WER contours for the full functionality tests (from Figure 9) with the non-hopping tests (from Figure 14). It is apparent from the figures that frequency hopping does not universally increase the 1% WER coverage contour. The coverage West along Pearl Street is increased by almost 1.5 blocks. In several areas, particularly North of the base station, the coverage area is slightly larger with the single frequency compared to the hopping.

The 1% WER coverage contours without frequency hopping are more erratic than the comparable contour with frequency hopping. This is due to the frequency selective nature of the fading. The frequency hopping measurements provide an average WER over the entire 26 MHz band, while the non-hopped curve represents measurements at only a single frequency. One advantage of the frequency hopping is the manner in which the hopping provides a smoother, more predictable coverage contour. The coverage areas for the 10%, 25%, and 50% contours are decreased markedly without the frequency hopping.

4.3 Received Signal Strength Coverage Contours

Receive Signal Strength (RSS) measurements were recorded at the handset only, because the current revision of the base station control software does not display or record RSS. The transmit power at the base station for the field tests was 20 dBm. A diversity pair of 5 dBd antennas with omnidirectional horizontal patterns were used at the base station. RSS readings were not evaluated for the time diversity on/off case because the equipment does not provide RSS information as a function of the time diversity mode.

4.3.1 Full Functionality Performance

Handset RSS coverage contours for the full functionality tests with time diversity, antenna diversity, and frequency hopping are shown in Figure 16. The contours are displayed in 10 dB steps from -95 dBm to -45 dBm. A comparison of Figures 9 and 16 indicates that the -75 dBm contour reasonably approximates the 1% WER coverage contour. Once again, signal strength coverage is reduced in the East-West direction along Pearl Street compared to the North-South direction along Broadway Street. This is due to building shadowing and attenuation due to obstructions along the pedestrian mall. The coverage contours are roughly diamond shaped.

The tear drop shaped -75 dBm contour, approximately 5.5 blocks North of the base location, is due the rise in elevation as one proceeds North along Broadway Street. The tear drop contour is located at the peak of the hill and thus provides enhanced signal strength coverage. The pair of thin tear drop -65 dBm contours South of the base station location are due the lower elevation in the area where the Boulder Creek crosses Broadway Street. South of Boulder Creek, the elevation of Broadway Street increases, providing improved coverage.

4.3.2 Performance without Frequency Hopping

Figure 17 illustrates the handset RSS coverage contours for the measurements without frequency hopping. The system was operating at a fixed carrier frequency of 903 MHz with time diversity and antenna diversity. Figure 18 compares the -65 dBm coverage contours for the full functionality case (from Figure 15) and the non-hopping case (from Figure 17). Frequency hopping clearly increases the coverage area in terms of received signal strength. In the North, West, and South directions -65 dBm coverage in increased by approximately 1 block. Coverage is increased less than 0.5 blocks in non-line-of-sight conditions off of Pearl and Broadway Streets. Similar to the WER coverage contours presented earlier, the RSS contours are more erratic without the frequency hopping. This is due to the frequency selective fading and the inherent averaging (frequency diversity) provided by hopping over the entire 26 MHz band.

4.3.3 Performance without Antenna Diversity

The RSS coverage contours for the single antenna case are shown in Figure 19. A comparison of the -65 dBm contours for full functionality (from Figure 15) and without antenna diversity (from Figure 19) is shown in Figure 20. From Figure 20, it is clear that antenna diversity improves the -65 dBm coverage, particularly in non-line-of-sight cases. Coverage is improved by approximately 0.5 blocks in the West direction along Pearl Street, where the base station antennas are obstructed by buildings. Coverage is also increased by almost 0.5 blocks South of the base station in the elevation dip, where the Boulder Creek crosses Broadway Street.

5 Future Experiments

Field experimentation on the Tadiran, Ltd. will continue from March until July of 1993. Coverage contours will be measured at additional base sites to determine the effects of local topographical features upon the system coverage. Because the system currently operates in the Part 15 unlicensed band, there is the potential for interference from other users of the band. Interference and jamming tests will be conducted to determine the robustness of the frequency hopping and time slot retransmission schemes. The performance of the adaptive time diversity technique is highly dependent upon the loading of the system. As the traffic loading increases, fewer time slots are available for the time diversity scheme. Loading and capacity tests will be performed to determine at what point the time slot retransmission becomes ineffective. Tadiran, Ltd. is currently in the process of developing system firmware to provide handoff capability. Tests will be conducted to examine the performance of the handoff algorithm in the presence of jamming and heavy system loading.

5.1 System Coverage as a Function of Local Topography

Coverage contours have been measured for the Tadiran, Ltd. system at base site number 1. Additional coverage contours will be measured at the other 8 base station sites. The received signal strength measurements will be used to determine path loss propagation models. Propagation models which take into account local topography, including terrain and buildings, will be compared with the measured path losses.

The first stage of the field testing will involve mapping the coverage zones for each of the base sites. Contours of received signal strength, word error rate, and subjective voice quality will be recorded. Signal coverage on streets and into buildings will be measured. The resulting performance contours will be used to determine a set of PCS microcell implementation guidelines to be used for the deployment of future systems. The effects of shadowing from buildings, trees, cars, and other objects will be assessed. Time variable effects due to the motion of people and vehicles will be determined.

5.2 Interference and Jamming Tests

The performance of the Tadiran system will then be determined in the presence of interference and jamming. Several wide band and narrow band interferers will be strategically placed around the Boulder test bed area. The jammers will include fixed frequency sources as well as frequency hopped sources. These tests should determine the performance of the system under harsh interference conditions as might be encountered in an unlicensed band. The effects of high power interferers, such as Industrial, Scientific, and Medical (ISM) devices will also be measured. The interference tests should give a realistic assessment of the performance of the system in a heavily congested unlicensed band or in a band sharing arrangement.

5.3 Loading and Capacity Tests

The next phase of testing will involve fully loading the system and stress testing the components. All of the 15 handsets will be utilized to simulate a congested high traffic area. The performance of the radio ports as well as the port controller will be monitored. A base station simulator will be used to simulate additional fully loaded base stations connected to the radio port controller. The test will determine the functional limitations of the radio port controller developed by Advanced Technologies. The tests will also assure that the Tadiran base stations are capable of operating under fully loaded conditions.

5.4 Radio Channel Simulation

The radio air interface will then be tested using a Hewlett-Packard fading simulator. A set of representative channel models will be programmed into the simulator. The performance of the link between the handset and base station will be monitored under various channel conditions. The channel simulator will provide a stable, repeatable platform for comparing the performance of different vendor's PCS systems. The simulator can also be used to test the system in urban or rural areas which have different channel characteristics than those which can be observed in the Boulder test bed.

5.5 Handoff Performance

The final testing of the Tadiran system will involve the performance of the handoff algorithms. Various multiple-handoff scenarios will be tested. The performance of the radio link, base station software, and port controller will be monitored. Proper signal strengths and word error rates for high quality handoffs will be determined. The effects of interferers on the handoff process will be measured.

5.6 User Interface Human Factors

The human factors issues associated with the user interface will be tested. The handsets will be given to a sample of users and their responses to questions regarding the functionality of the interface will be scored. The Tadiran handset interface will be compared to typical cellular telephone handset interfaces. In addition to the Tadiran handset evaluation, the human factors work will also examine the human interface issues related to Personal Digital Assistant (PDA) devices.

5.7 Microcell System Design

The results of this field research are being used to develop microcell implementation guidelines. These guidelines will allow the efficient, optimized design of full scale microcellular systems. Software tools will be developed based on Geographical Information Systems (GIS) databases. Propagation prediction will be performed to determine expected coverage areas. Optimized microcell layout can be performed based on propagation considerations, user demographics, telephone and electrical power infrastructure, and economic constraints.

Implementation guidelines will be developed for the widespread deployment of PCS systems. The implementation guidelines will serve as a reference for system planners wishing to design a microcell radio system. The primary purpose of the guidelines will be to address outdoor base station antenna siting for radio coverage. The report will discuss street coverage in suburban residential areas, light urban, and heavy urban areas. Indoor coverage of office buildings will also be discussed. Different antenna placement options along streets will be compared (street lamps, building corners, free standing masts). The effects of antenna radiation patterns (omni versus directional) and antenna heights (10 to 30 feet) will be presented. The proper placement of diversity antennas in different scenarios will be discussed. Minimum antenna separations and proper diversity orientations will be discussed.

6 Conclusions

Initial tests of a frequency hopping system operating in the 902-928 MHz band have been conducted. A series of measurements have been taken at one of the base station locations in the Boulder test bed. The effects of adaptive time diversity, antenna diversity, and frequency hopping have been evaluated. Processing of these data are continuing in order to develop propagation models and software prediction tools for the microcellular environment.

In general, the word error rate (WER) and received signal strength (RSS) coverage contours are diamond shaped. In some cases, for example with no antenna diversity, the coverage contours become more cross shaped. The effects of local topographical features, such as large buildings, hills, valleys, and open areas are clearly evident in the measured coverage contours. The local environment can cause changes in received signal strength of much greater than 10 dB.

The measured coverage contours distinctly point out the importance of local topography upon the coverage of microcellular systems where antenna heights are below the surrounding buildings. Without knowledge of the surrounding environment, both man-made and natural, it is not possible to optimize the coverage and performance of a microcellular system. For this reason, U S WEST Advanced Technologies is involved with the development of PCS system design guidelines and software tools which make use of information about the local environment. Geographical Information Systems (GIS) are being utilized to store and manipulate topographical information about the propagation environment. Information about user demographics (user densities, income levels, etc.), telecommunications infrastructure (fiber, coaxial cable, twisted pair, etc.), and the electric power plant are being incorporated in the database system.

Field test results indicate that dual slot time diversity improves the 1% WER coverage by approximately three-fold. This dramatic improvement is critical to the performance of a frequency hopping system in the presence of frequency selective fading and narrow band interferers. The tradeoff is obviously in terms of system capacity; the more time slots that are used for retransmission - the less that are available for additional users. The increase in high quality coverage area with time diversity is significant enough to warrant including time slot retransmission in the common air interface for a frequency hopping system.

Antenna diversity improves the coverage of the system by approximately 0.5 to 1.5 blocks in non-line-of-sight conditions. Coverage is improved only marginally under the line-of-sight conditions in the measurement area. The single antenna 1% WER coverage contours are much closer to the shape of a cross, while the antenna diversity case more closely resembles a diamond shape. This difference is critically important for the deployment pattern of PCS microcellular systems. Antenna diversity can significantly improve coverage in directions other than the cross streets at which the base station is located.

Frequency hopping produces coverage contours, both in terms of WER and RSS, which are markedly smoother and less erratic than the single frequency measurements. Again, this is important for the layout and design of microcellular systems. The smoother coverage contours with frequency hopping are due to the frequency selective nature of the fading and the inherent frequency averaging associated with frequency hopping. Coverage contours are much closer to diamond shaped for the frequency hopping case compared to the single frequency case.

These important conclusions regarding the use of time, space, and frequency diversity in the design of common air interfaces for PCS systems are being presented by U S WEST to appropriate standards bodies and industry organizations. It is hoped that this technical information will lead to the standardization of common air interfaces for future PCS systems.

U S WEST Advanced Technologies will continue testing the frequency hopping system in the 902-928 MHz band. The field test data will be processed further to determine appropriate propagation models for the prediction of system coverage. Additional tests of handoff, system loading, interference, and jamming will be conducted. Several other PCS technologies will be evaluated in the Boulder test bed in 1993, including systems operating at 1.9 GHz and 2.1 GHz.

References

[1] Federal Communications Commission First Quarterly Report for Experimental Licenses KK2XCC and KK2XCD, U S WEST Advanced Technologies, May 20, 1992.

[2] Federal Communications Commission Second Quarterly Report for Experimental Licenses KK2XCC and KK2XCD, U S WEST Advanced Technologies, September 5, 1992.

[3] Federal Communications Commission Third Quarterly Report for Experimental Licenses KK2XCC and KK2XCD, U S WEST Advanced Technologies, December 14, 1993.

Figures

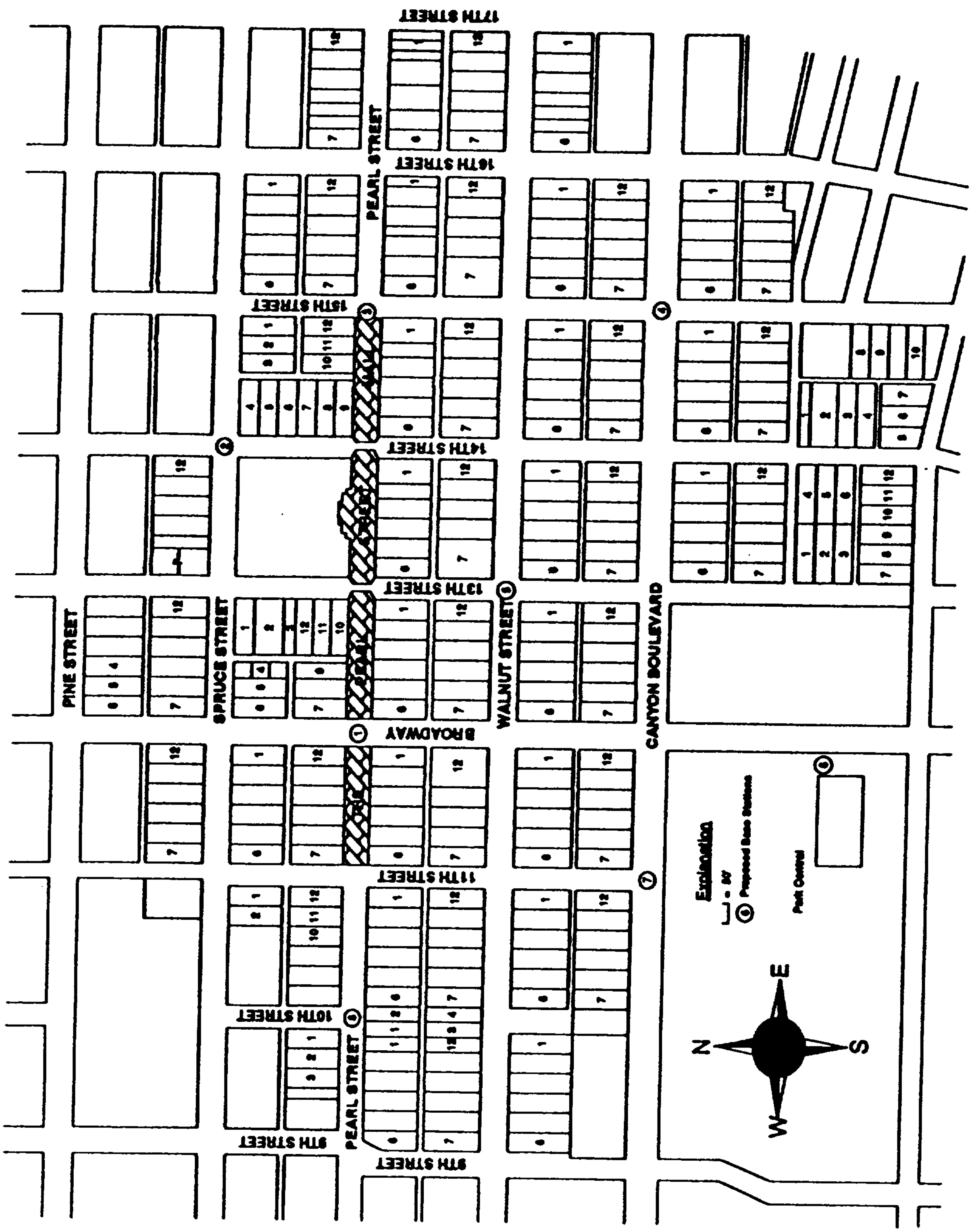

Figure 1. Map of Boulder, Colorado (NL 40 00 38; WL 105 14 31) showing locations of microcell base station sites. Central part of the map represents a light urban environment and pedestrian mall.

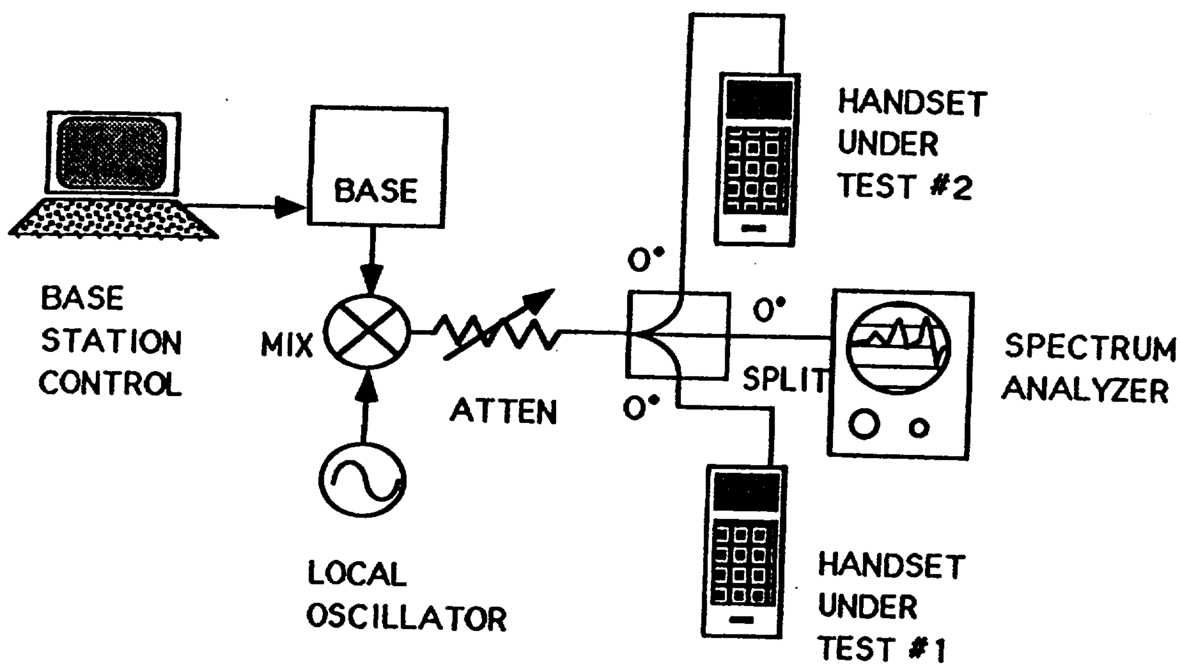

Figure 2. Block diagram of equipment setup for handset and base station received signal strength and word error rate calibration.

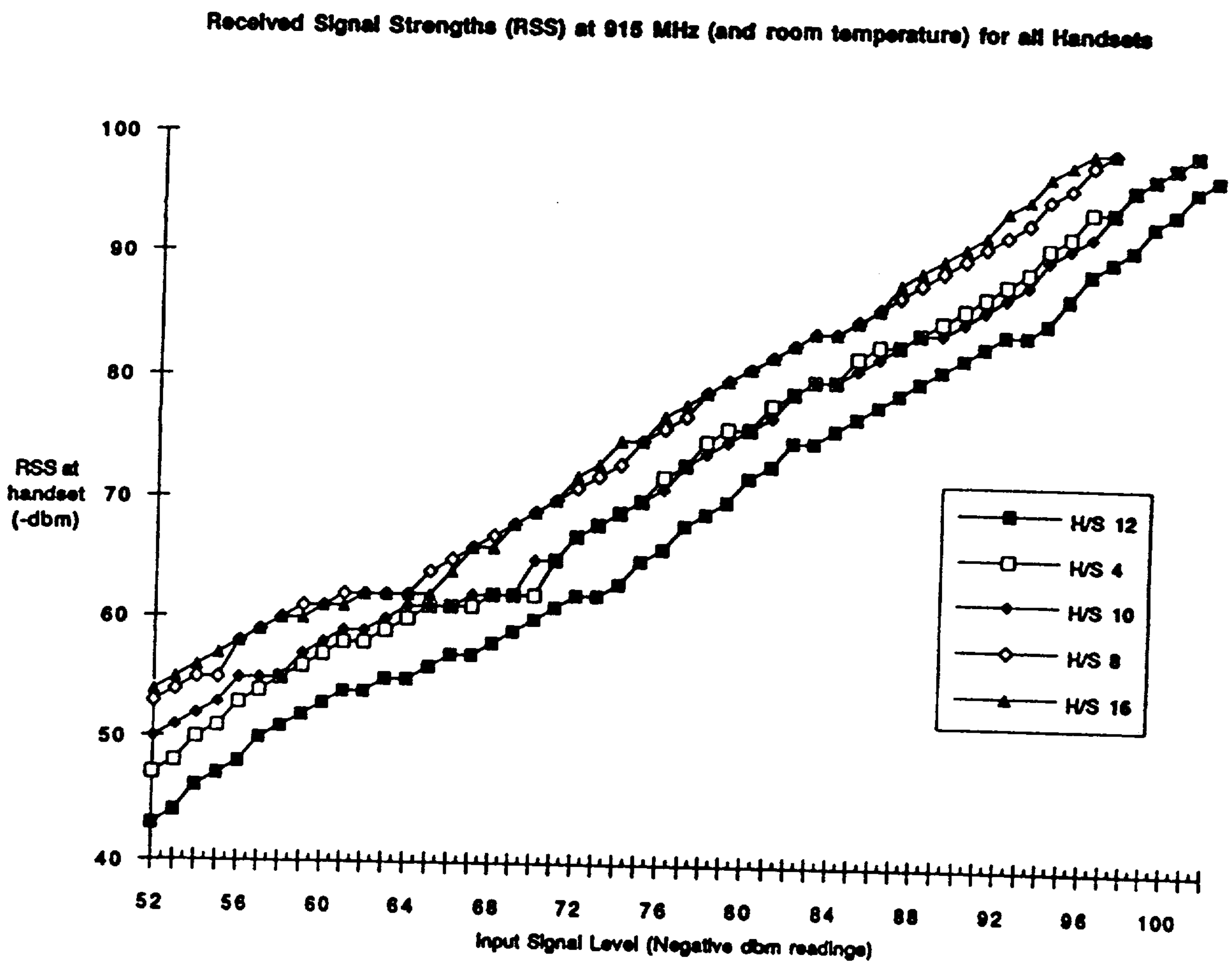

Figure 3. Input signal level versus received signal strength (RSS) readings for five representative handsets.

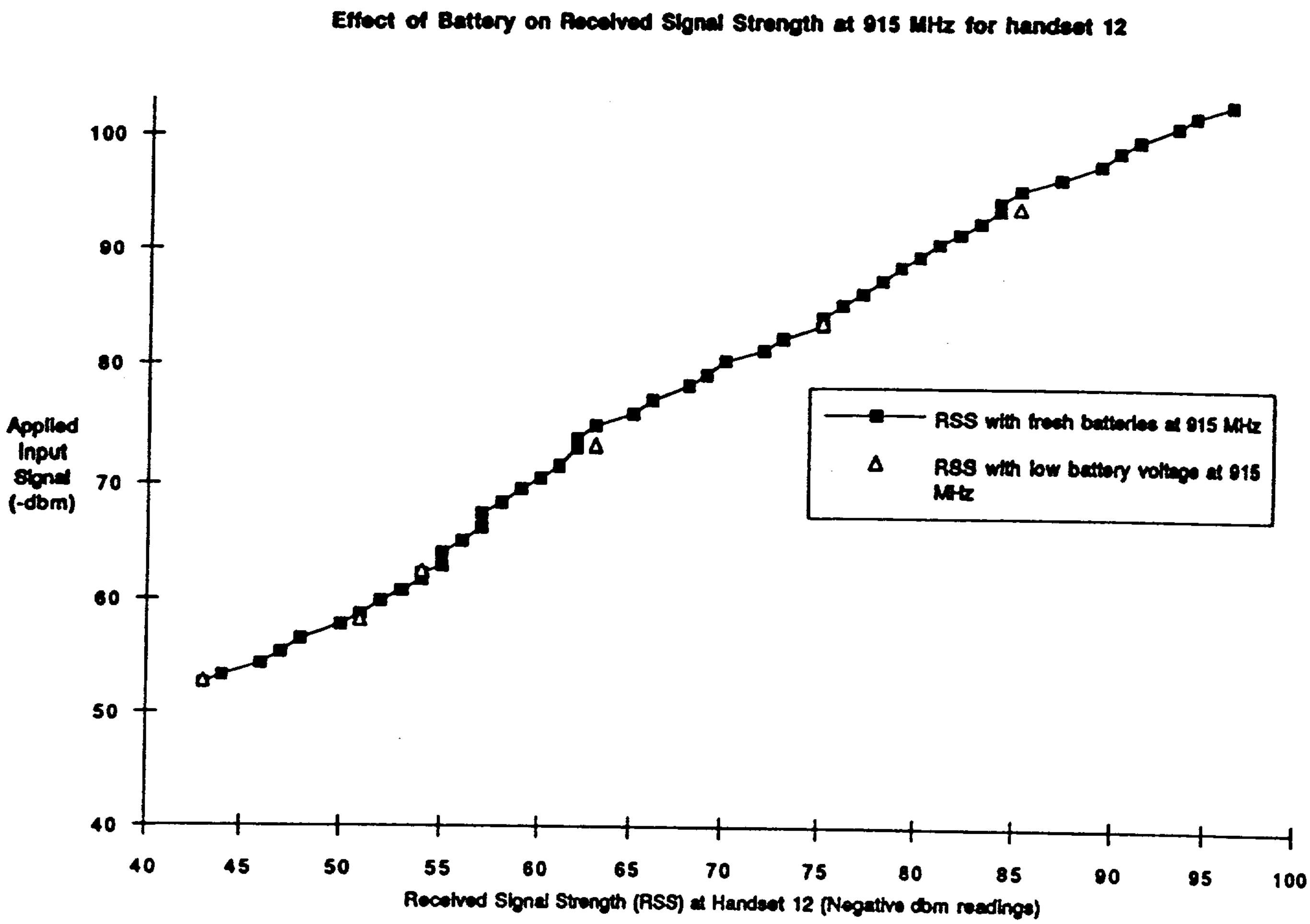

Figure 4. Effect of battery voltage on received signal strength (RSS) readings. Fresh battery voltage represents 5.5 Volts and low battery voltage is 4.9 Volts.

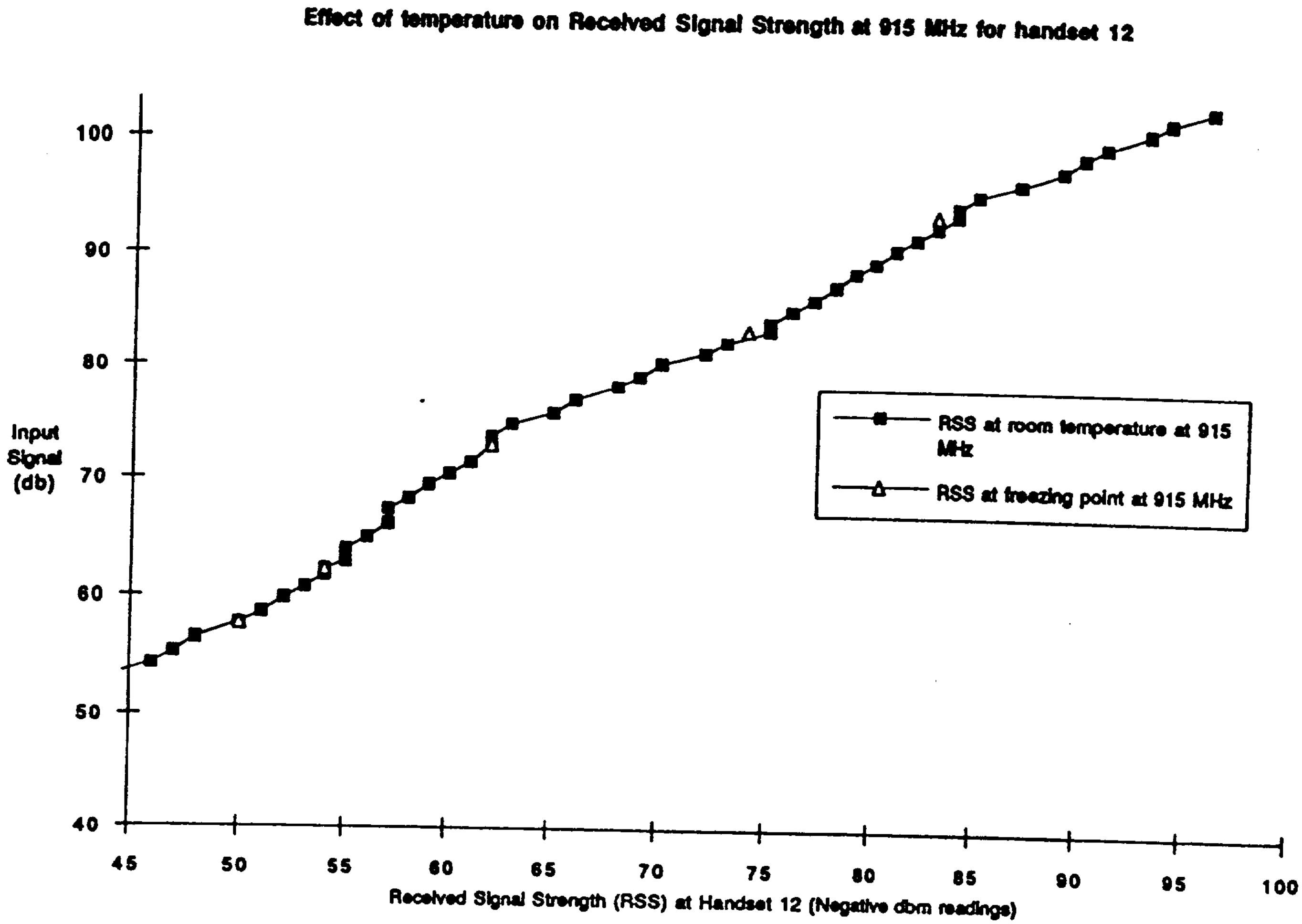

Figure 5. Effect of operating temperature on handset received signal strength (RSS) readings.

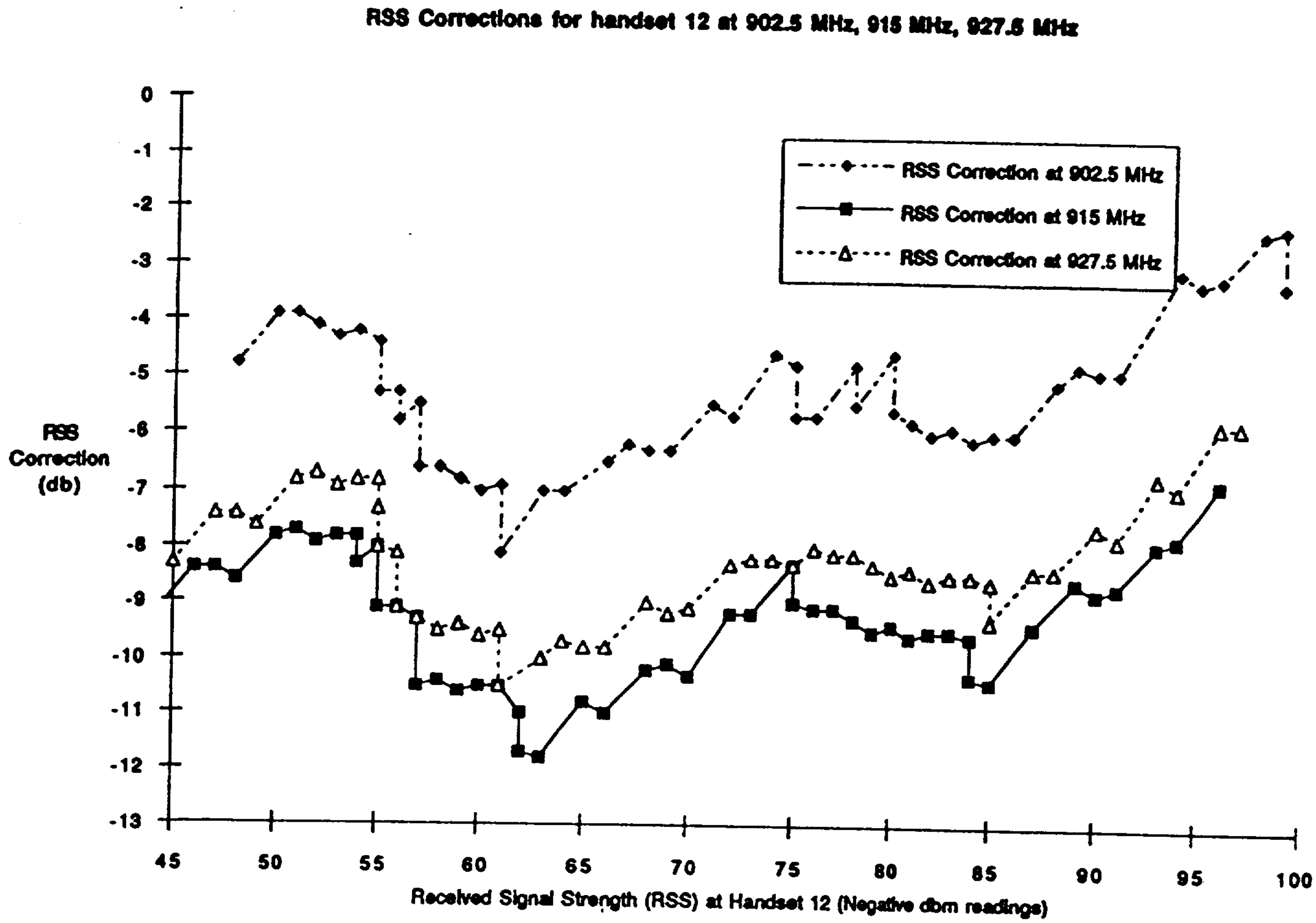

Figure 6. Effect of operating frequency on handset received signal strength (RSS) corrections.

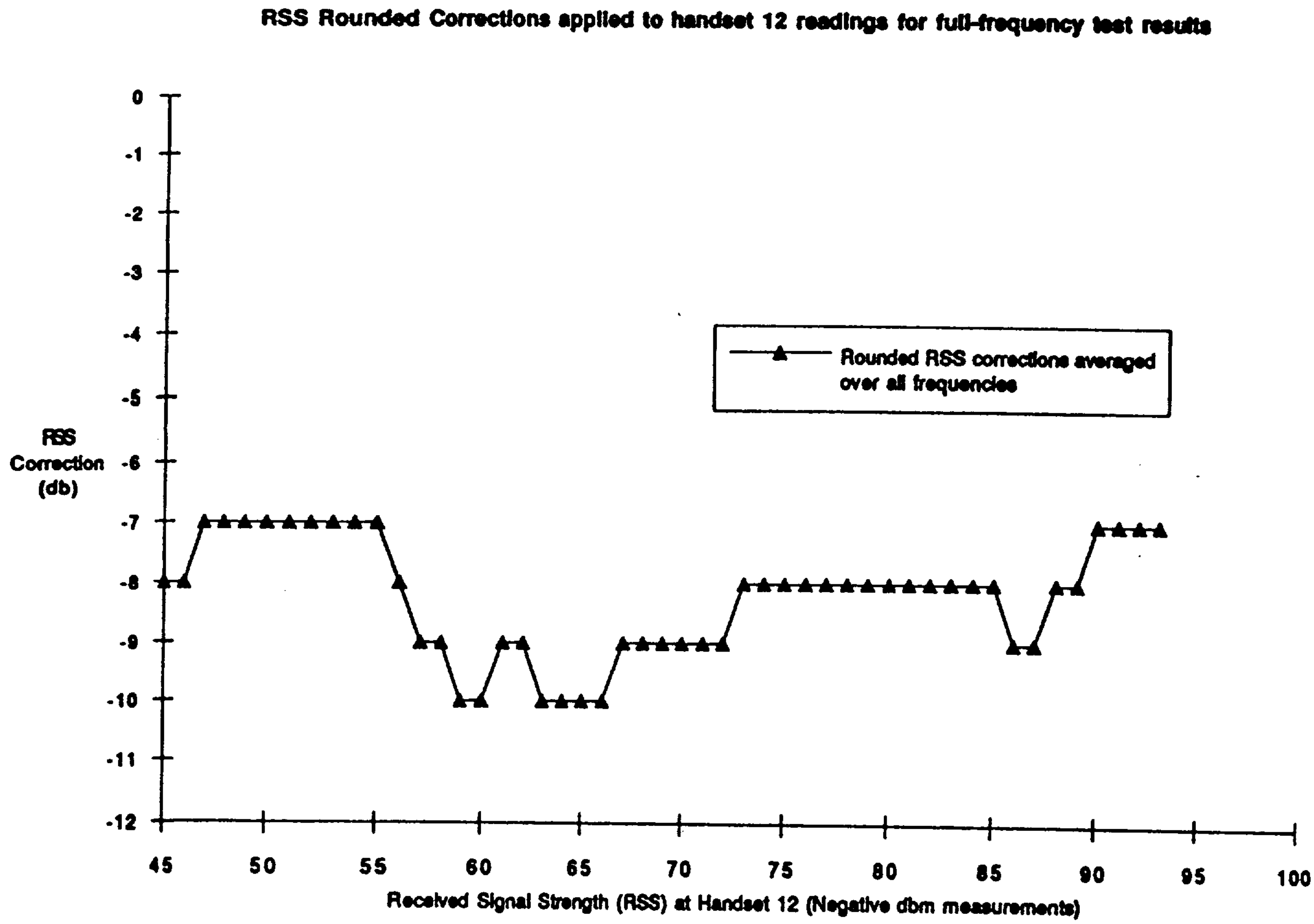

Figure 7. Received signal strength correction applied to handset number 12 for full-band frequency hopping tests. Correction is based on rounded weighted average over the full frequency band.

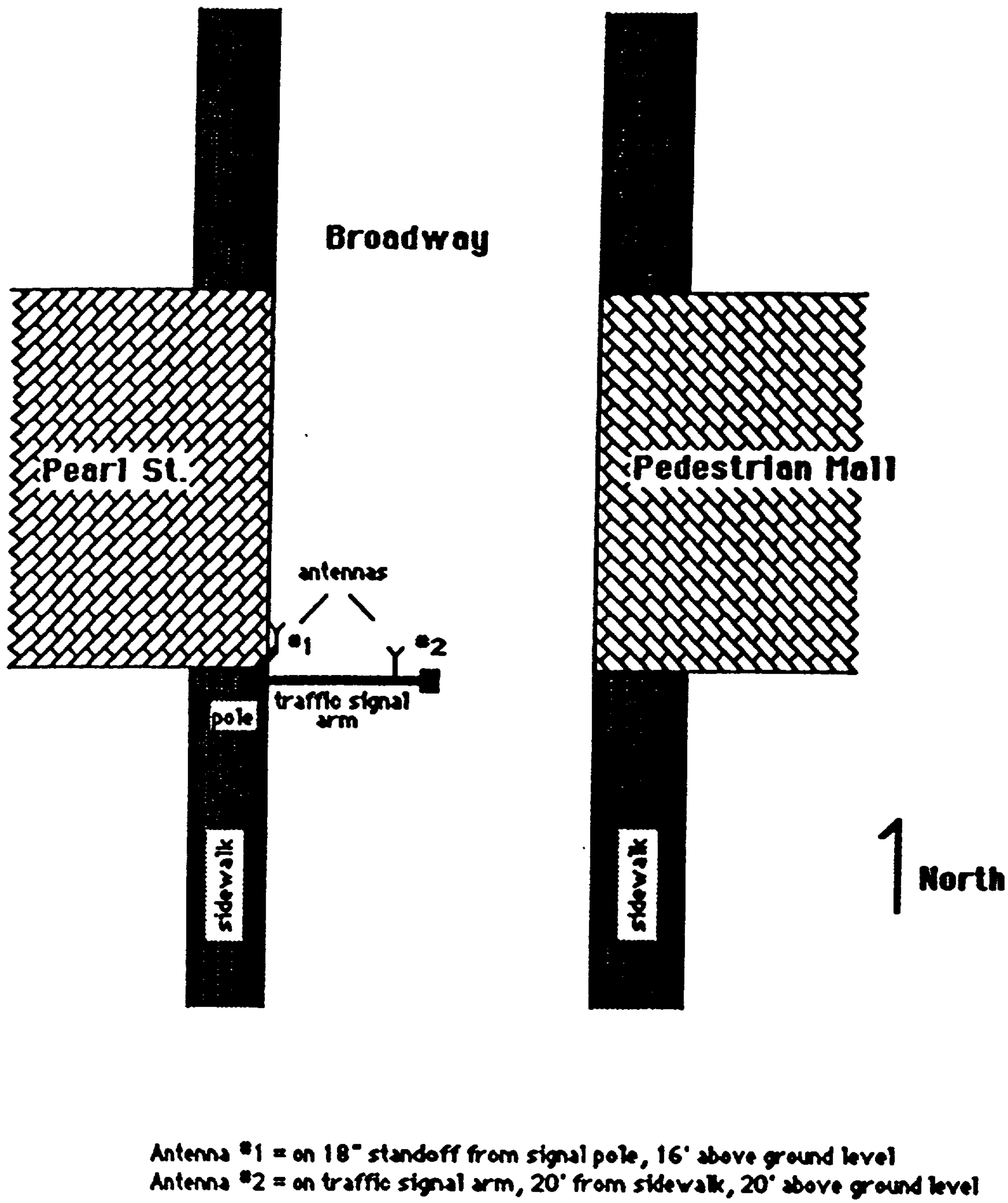

Figure 8. Aerial view of base station location number 1 showing placement of diversity antennas on traffic signal pole and arm.

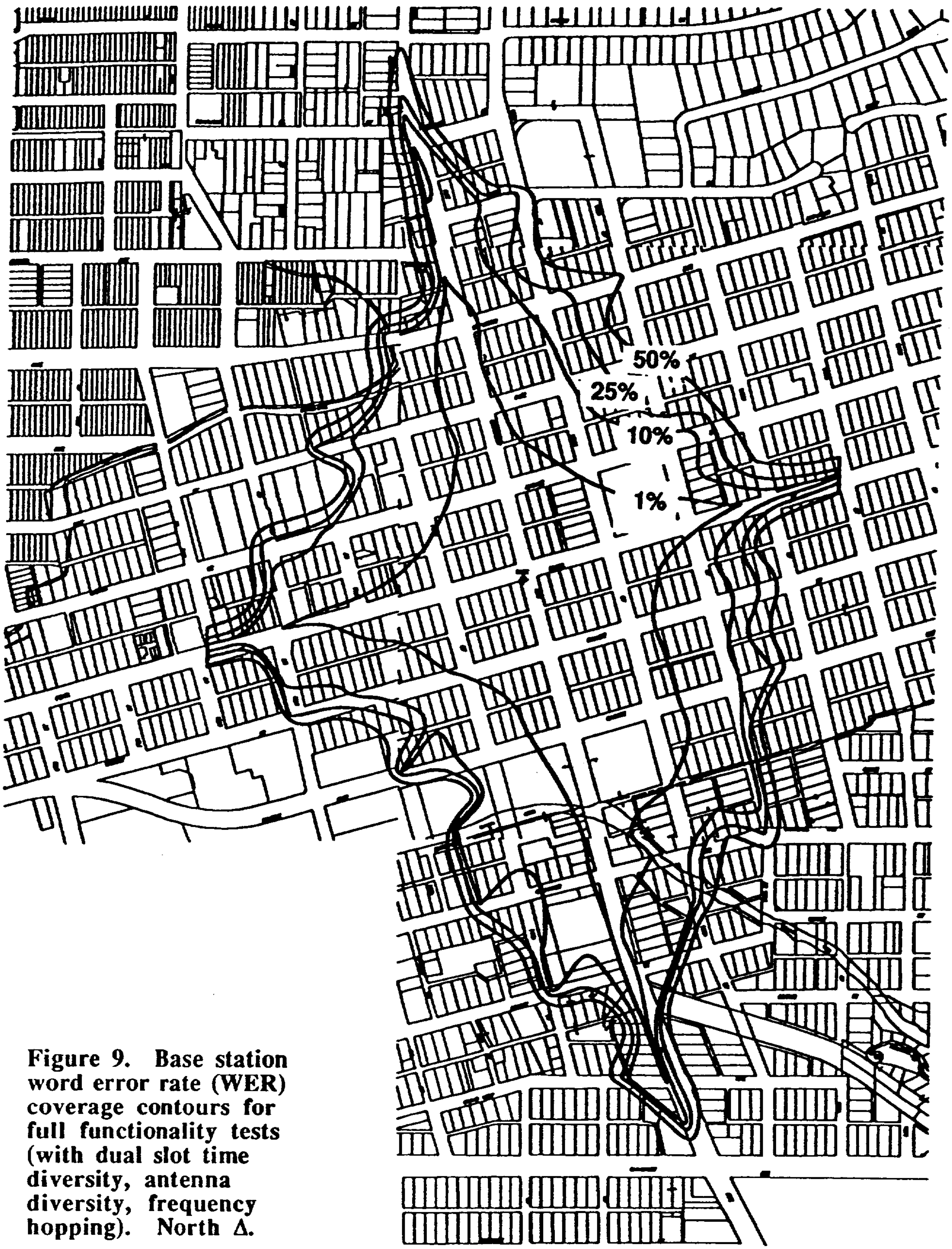

Figure 9. Base station word error rate (WER) coverage contours for full functionality tests (with dual slot time diversity, antenna diversity, frequency hopping). North Δ.

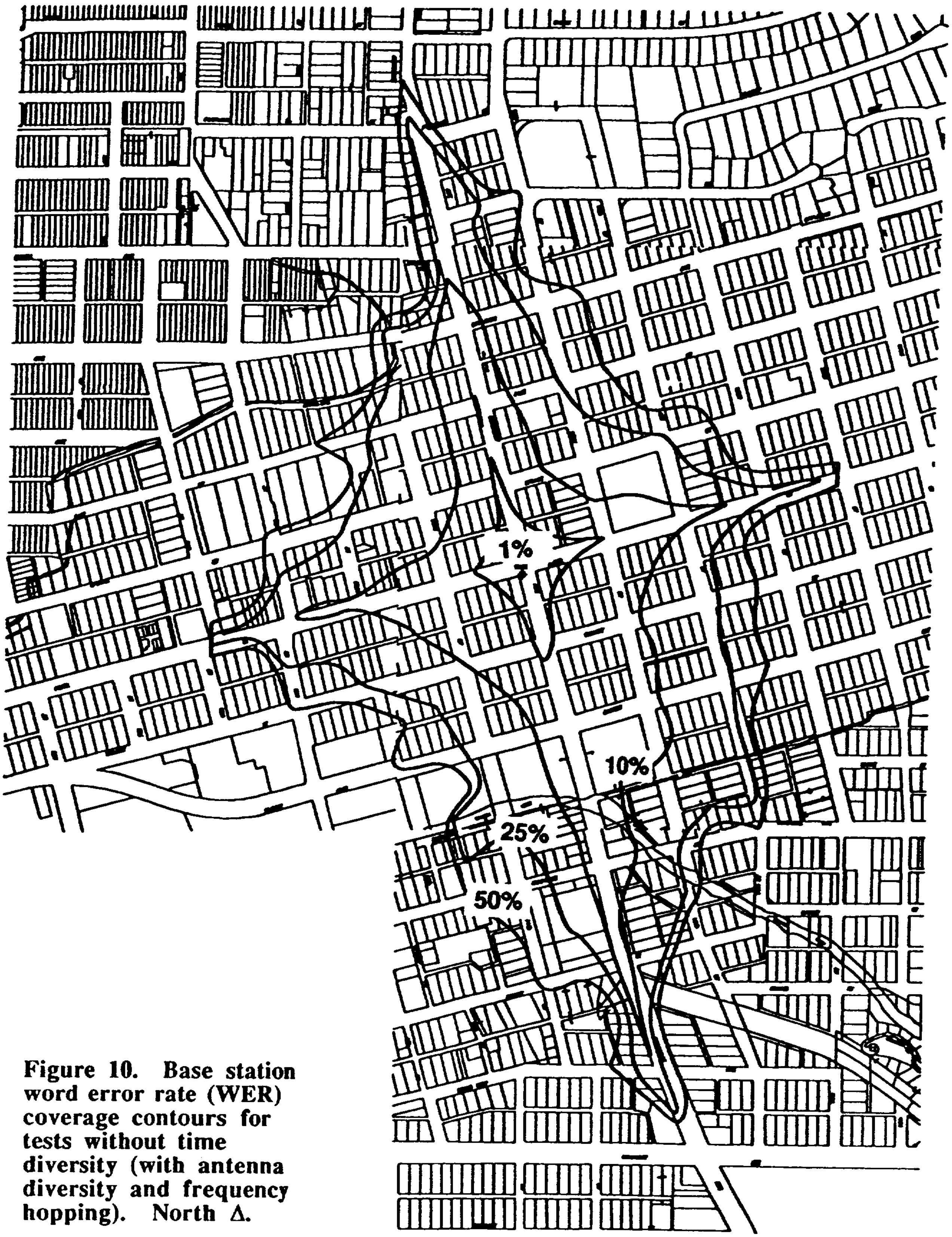

Figure 10. Base station word error rate (WER) coverage contours for tests without time diversity (with antenna diversity and frequency hopping). North Δ.

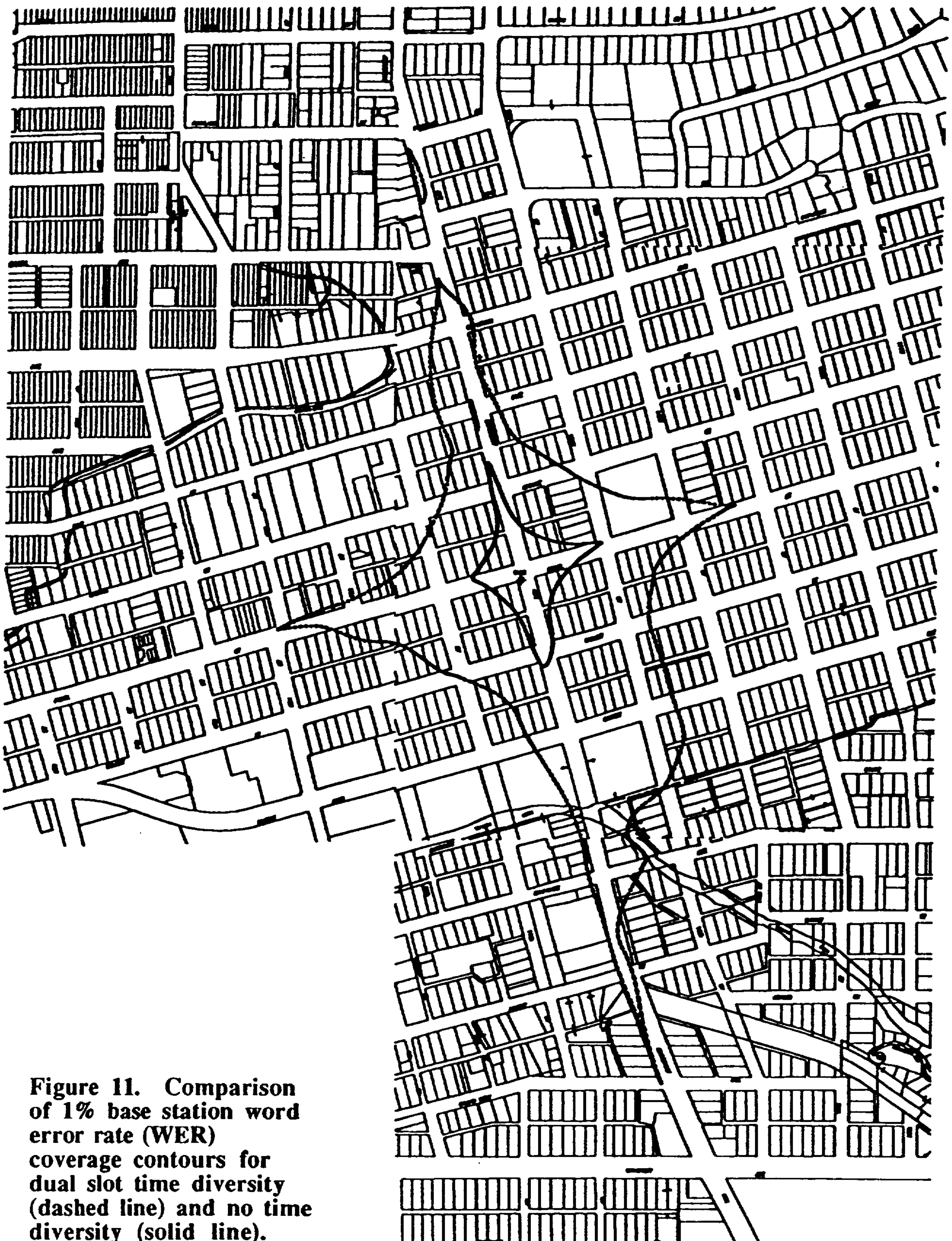

Figure 11. Comparison of 1% base station word error rate (WER) coverage contours for dual slot time diversity (dashed line) and no time diversity (solid line). North Δ.

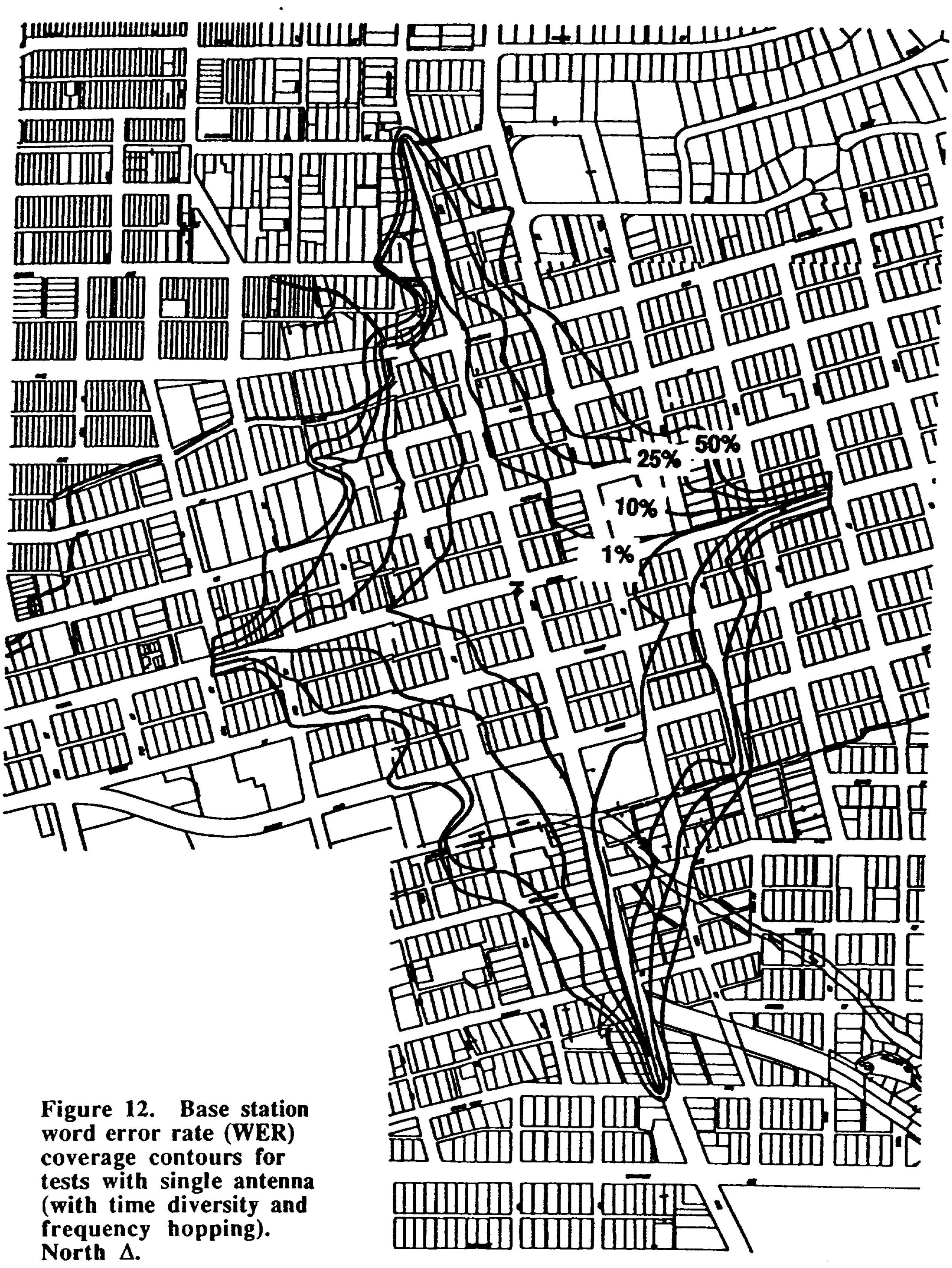

Figure 12. Base station word error rate (WER) coverage contours for tests with single antenna (with time diversity and frequency hopping). North Δ.

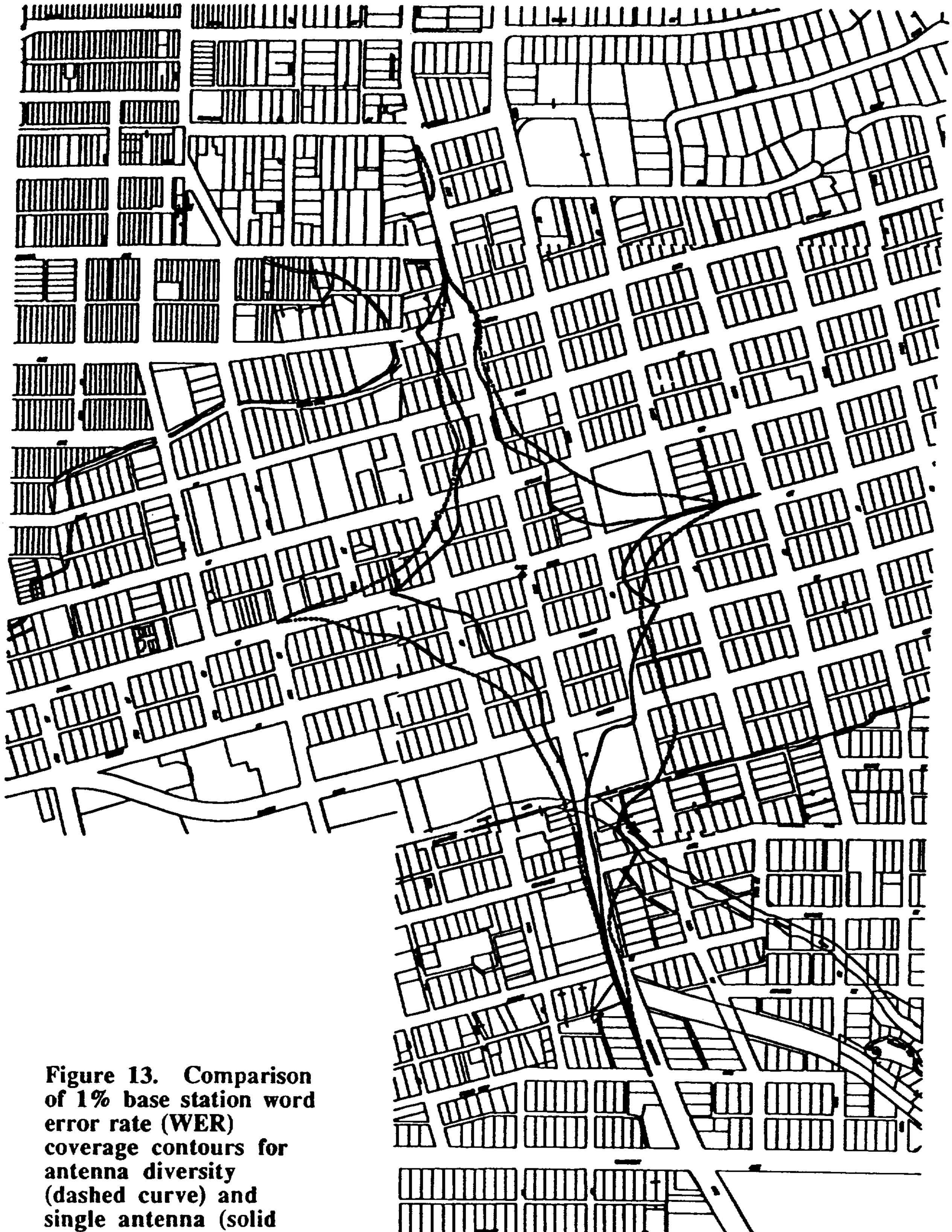

Figure 13. Comparison of 1% base station word error rate (WER) coverage contours for antenna diversity (dashed curve) and single antenna (solid curve). North Δ.

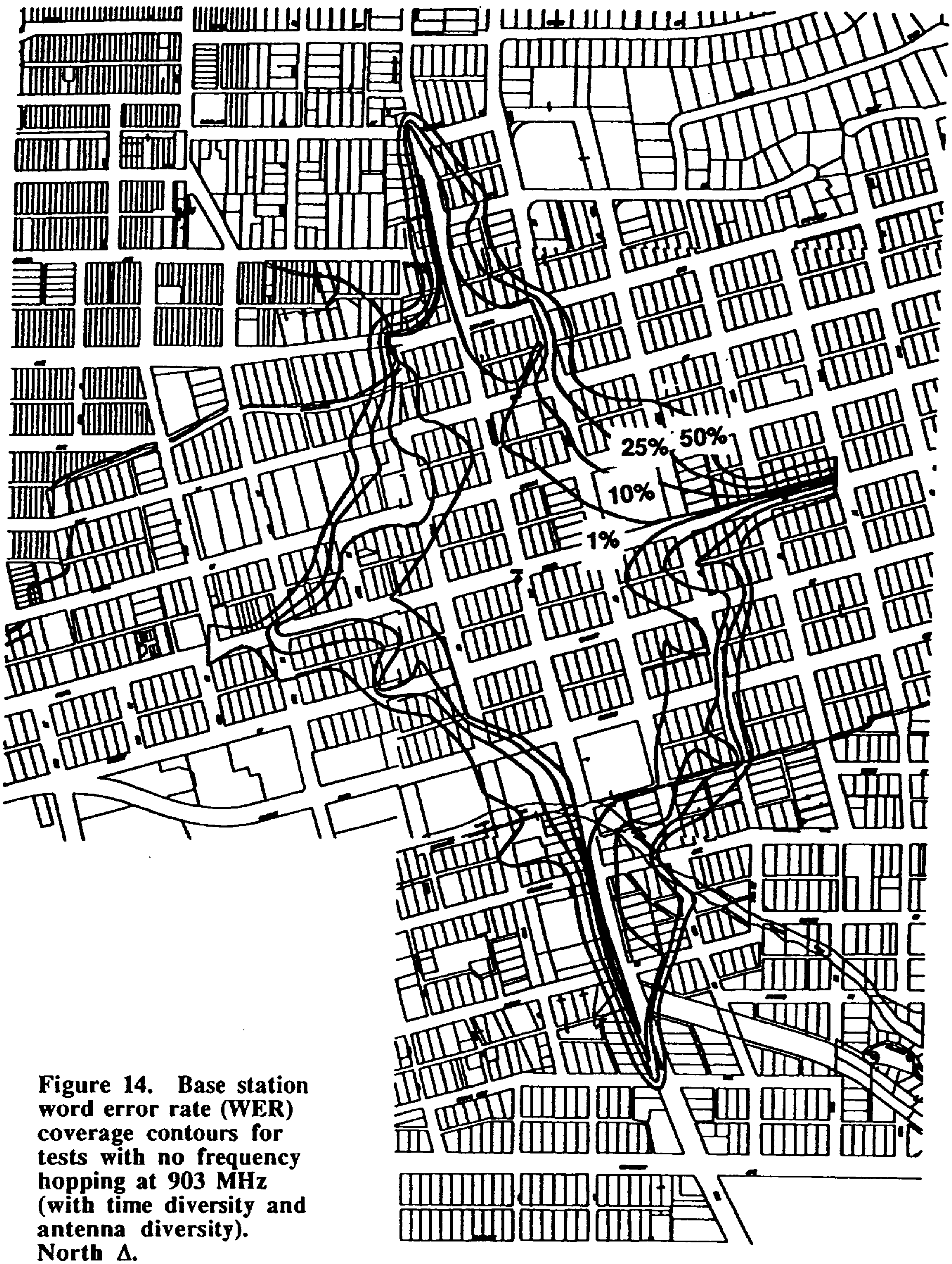

Figure 14. Base station word error rate (WER) coverage contours for tests with no frequency hopping at 903 MHz (with time diversity and antenna diversity). North Δ.

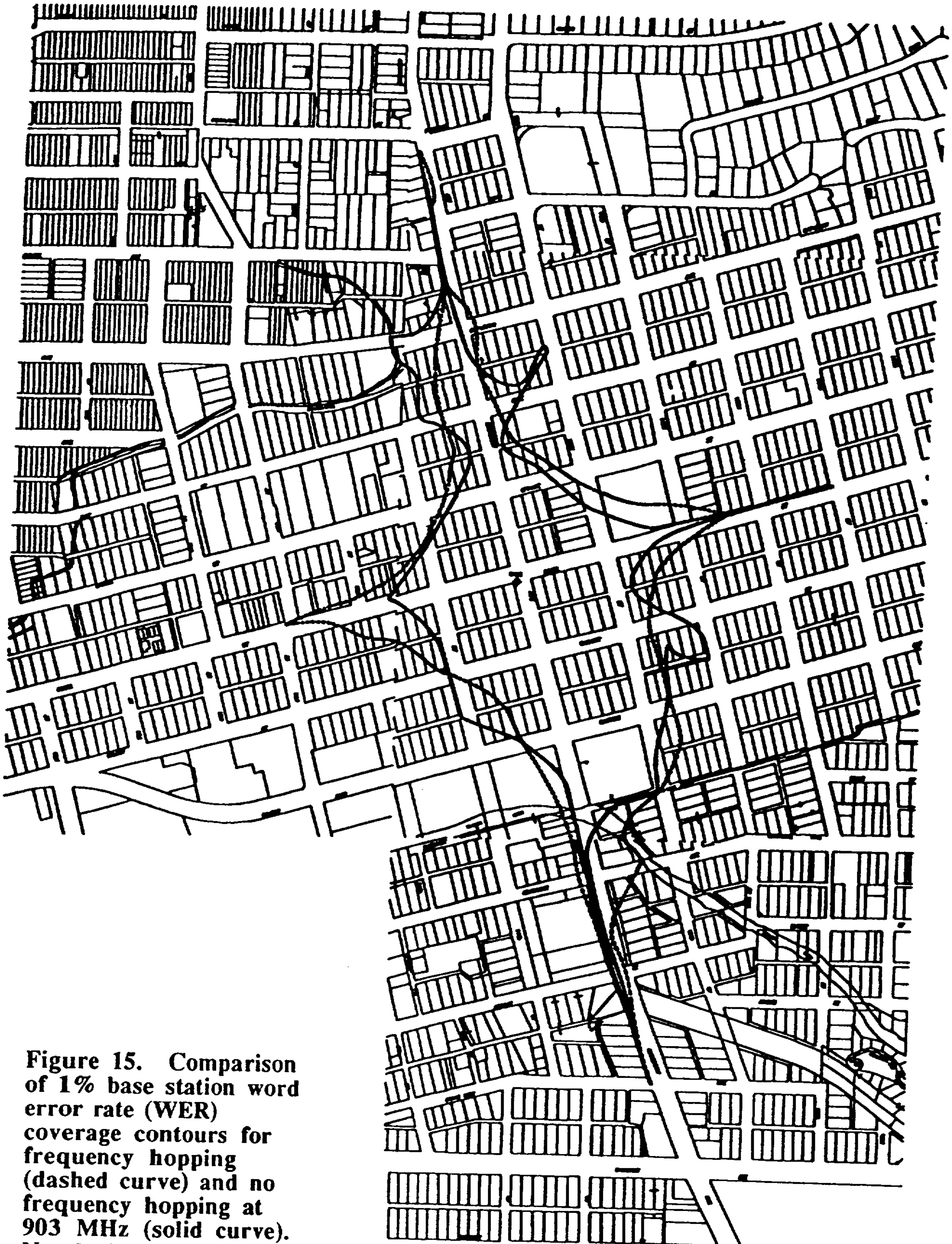

Figure 15. Comparison of 1% base station word error rate (WER) coverage contours for frequency hopping (dashed curve) and no frequency hopping at 903 MHz (solid curve). North Δ.

Figure 16. Handset received signal strength (RSS) coverage contours for full functionality test with antenna diversity and frequency hopping. North Δ.

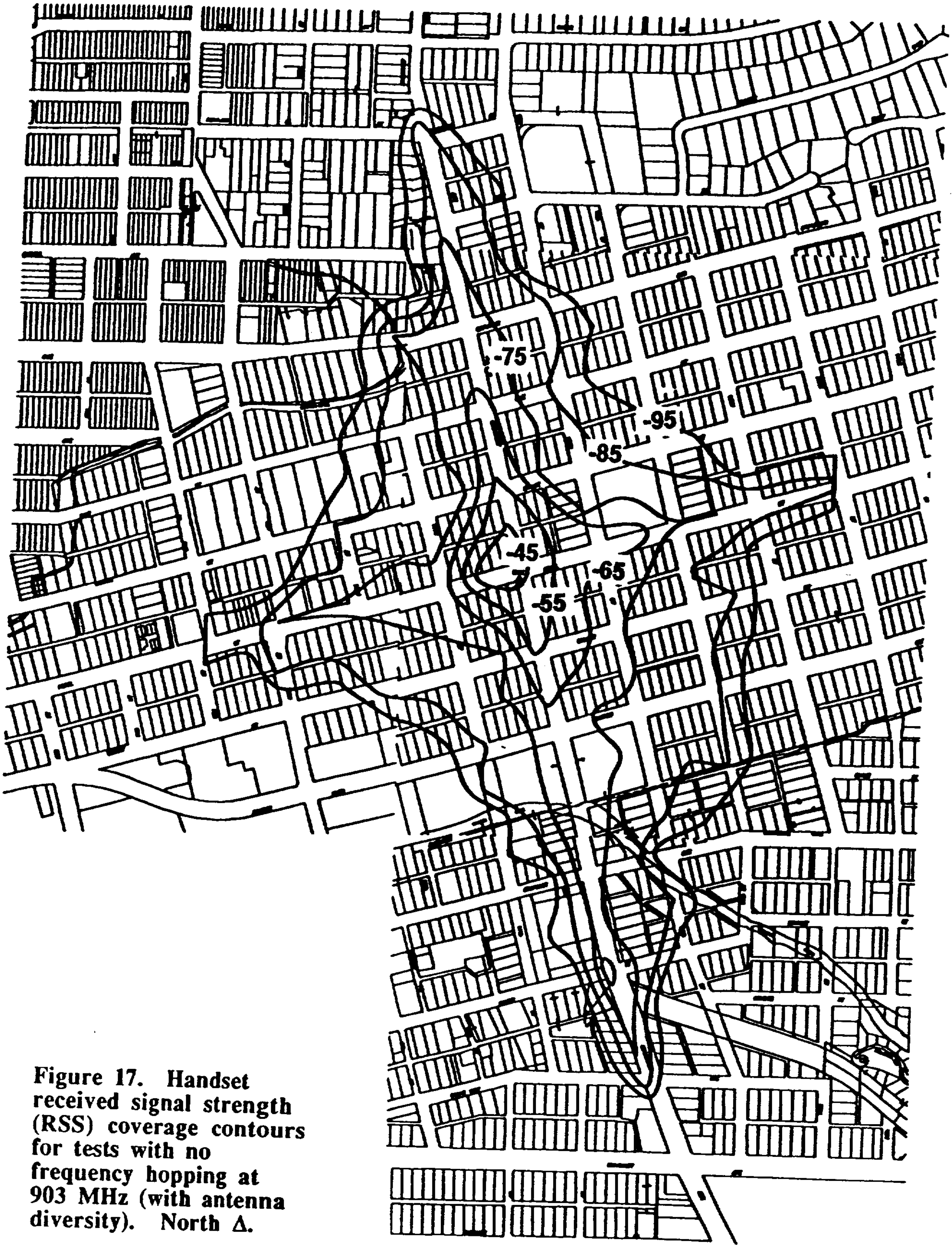

Figure 17. Handset received signal strength (RSS) coverage contours for tests with no frequency hopping at 903 MHz (with antenna diversity). North Δ.

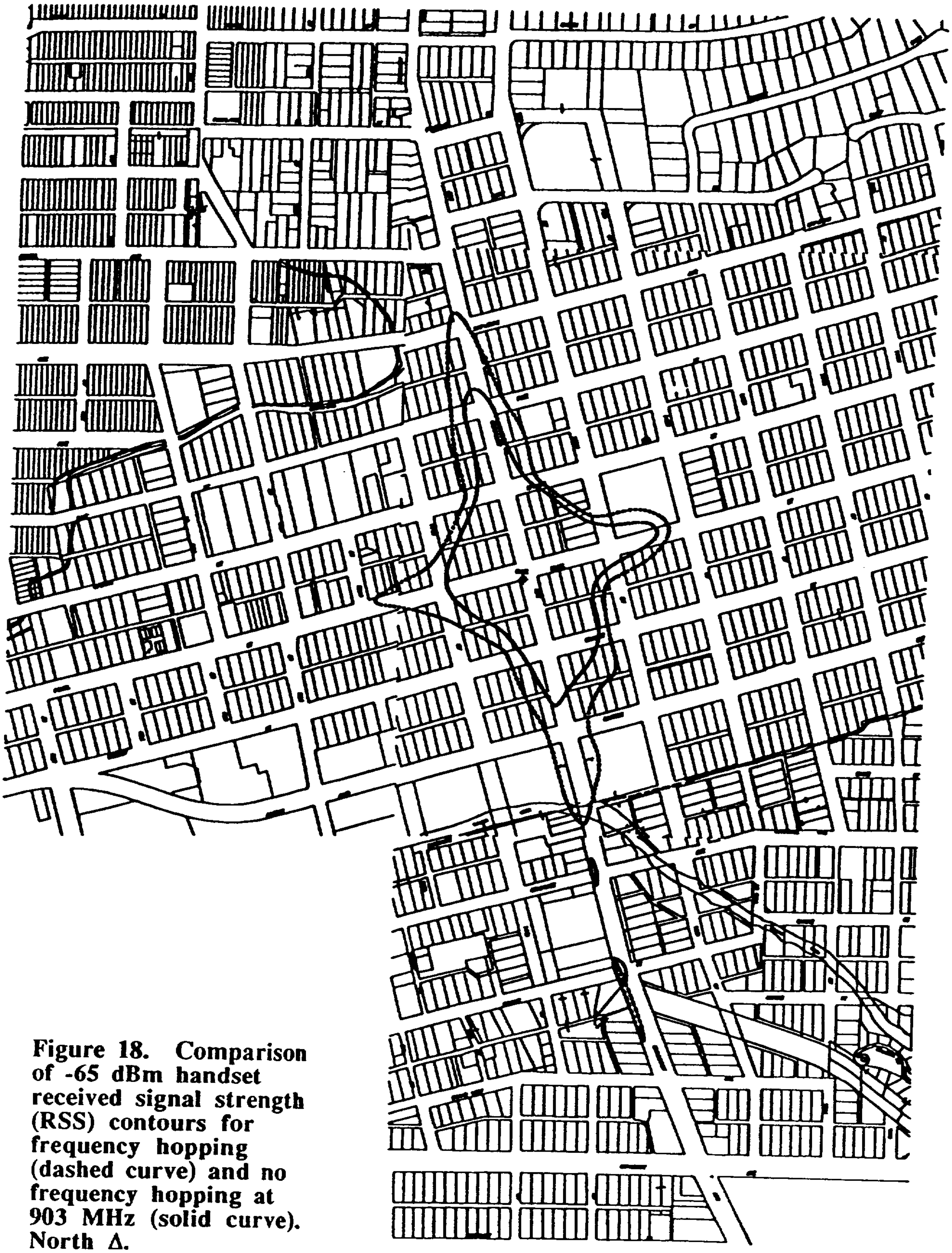

Figure 18. Comparison of -65 dBm handset received signal strength (RSS) contours for frequency hopping (dashed curve) and no frequency hopping at 903 MHz (solid curve). North Δ.

Figure 19. Handset received signal strength (RSS) coverage contours for tests with no antenna diversity (with frequency hopping). North Δ.

Figure 20. Comparison of -65 dBm handset received signal strength (RSS) contours for tests with antenna diversity (dashed curve) and single antenna (solid curve). North Δ.