NTIA Report 98-356

Personal Communications Services Technology Field Trials

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U.S. DEPARTMENT OF COMMERCE
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for Communications and Information

September 1998

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PERSONAL COMMUNICATIONS SERVICES TECHNOLOGY FIELD TRIALS AT THE BOULDER INDUSTRY TEST BED

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PERSONAL COMMUNICATIONS SERVICES TECHNOLOGY FIELD TRIALS AT THE BOULDER INDUSTRY TEST BED

Technology field trials for six personal communications services (PCS) common air-interface technologies (whose standards were developed by the Joint Technical Committee on Wireless Access) were performed at the US West Boulder Industry Test Bed (BITB). The BITB provided a common environment for the field testing of all of the technologies. The same configuration (cell site layout, antenna type, and antenna orientation) was used for all of the systems tested as high-tier systems. Similarly, another configuration was used for all systems tested as low-tier systems. Field testing of the technologies typically consisted of four general types: area coverage testing, handoff testing, interference testing, and voice quality testing. Results from these field trials, and descriptions of the measurement and data analysis procedures, are presented in this report.

Key words: adjacent channel interference; area coverage; bit error rate; co-channel interference; expert listener; frame error rate; handoff; Joint Technical Committee on Wireless Access; JTC; mean opinion score; MOS; PCS; personal communications services; received signal strength; Telecommunications Industry Association; TIA; voice quality; word error rate.

1. INTRODUCTION

In the United States, technical standards for the personal communications services (PCS) common air interface were developed in the Joint Technical Committee on Wireless Access (JTC). The JTC was a joint activity between committee T1 of the American National Standards Institute (ANSI) and the Telecommunications Industry Association (TIA). Within the JTC, draft standards for six air-interface technologies for licensed PCS were developed and forwarded to the ANSI. The six technologies are listed below:

1) IS-95-based code-division multiple access (CDMA)
2) IS-136-based time-division multiple access (TDMA)
3) personal access communication system (PACS)
4) PCS 1900
5) Wideband CDMA
6) Omnipoint TDMA/CDMA

Some of the specifications for these technologies are given in Table 1.1. Note that each technology is identified by the specific JTC Technology Ad Hoc Group (TAG) responsible for that technology.

Technology field trials for the six air-interface technologies were performed at the US West Boulder Industry Test Bed (BITB) in cooperation with the JTC. The purpose of the field trials was to (1) demonstrate the performance of the air interface for each technology and (2) to fulfill the JTC requirement that each technology undergo a technology field trial before being forwarded for ballot as a standard.

An individual JTC report was written for each of the six technology field trials. The reports describe the system and test configurations, the types of tests performed, and the results of the analyses of the measured data taken during the field trials. The intent of this report is to provide a consolidation of the six JTC reports. It is intended to be an easily accessible reference that describes the six technology field trials. In both the original JTC reports and in this report, no comparison of the different technologies and no comparison of the performance of the different technologies during the field trials is made.

The original JTC reports present both statistical analyses of the data and maps showing the data as a function of geographical location. In this report, to provide a more concise document, only the statistical analyses of the data are presented. More detailed information about each one of the field trials is available in the individual test reports submitted to the JTC for each air-interface technology [1, 2, and 4-7].

Table 1.1. PCS Technologies Tested During the JTC Field Trials*

	TAG Number					
	TAG 5	**TAG 2**	**TAG 4**	**TAG 7**	**TAG 3**	**TAG 1**
Base Technology	GSM/ PCS1900	IS-95	IS-136	W-CDMA (new)	PACS (new)	Omnipoint (new)
Dates of Field Trial	10/17 - 11/23/94	5/1 - 5/30/95	7/14 - 8/17/95	8/23 - 9/15/95	10/1 - 10/31/95	11/1 - 12/1/95
Access Method	TDMA	CDMA	TDMA	CDMA	TDMA	TDMA/ CDMA
RF Band-width	200 kHz	1.25 MHz	30 kHz	5 MHz	300 kHz	5 MHz
Bit Rate (no overhead)	13 kbps	Two rates available: 8 kbps or 13.3 kbps	7 kbps	32 kbps	32 kbps	32 kbps
System Type	High Tier	High Tier	High Tier	High and Low Tier	Low Tier	High and Low Tier
Error Control (voice)	FEC	FEC	FEC	FEC	None	None
System Capacity Relative to AMPS	2-3x	10x	3x	16x	0.8x	16x

* Courtesy of C.I. Cook, U S West Technologies, Inc. and J. Losh, Motorola, Inc.

The JTC technology field trials took place in a sequential, but not continuously ongoing, fashion over the course of about 14 months. The dates when each trial took place are listed in Table 1.1. The same configuration (cell site layout, antenna type, and antenna orientation) was used for all of the systems tested as high-tier systems. Similarly, another configuration was used for all systems tested as low-tier systems.[1] These configurations were fixed throughout the duration of the field trials and did not vary from one technology to another. This provided a common environment for testing. It did not, however, provide an opportunity for optimizing the performance of each technology. This should be kept in mind when examining the results of the trials.

Field testing for all six of the air-interface technologies typically consisted of four general types: area coverage testing, handoff testing, interference testing, and voice quality testing. The area coverage testing, performed for all of the technologies, included fundamental measurements of received signal strength (RSS) and error rate as a function of location. Handoff testing was performed for all of the technologies except the TAG 7 Wideband CDMA technology. Handoff testing for the TAG 2 CDMA technology included a determination of the percentage of time that the network was in a particular handoff state and the handoff state as a function of location. The types of parameters measured during handoff testing for the other technologies included the change in RSS before and after handoff, the change in error rates before and after handoff, the time between successive handoffs, and the cell site sector in use as a function of location.

Separate measurements for interference testing were also performed for all of the technologies except the TAG 2 CDMA and the TAG 7 Wideband CDMA technologies. No interference measurements were made during TAG 7 testing. All of the TAG 2 measurements were obtained in the presence of simulated interference; no separate interference testing was performed. For the rest of the technologies, both co-channel and adjacent channel interference measurements were made. The goal of the interference measurements was to determine the error rate performance as a function of co-channel and adjacent channel carrier to interference ratios.

Voice quality measurements were made for every technology. For the JTC PCS technology field trials in general, two types of voice quality measurements were made: quasi-stationary measurements and handoff measurements. The quasi-stationary measurements were made at fixed locations on a grid within each cell site. At each fixed location, voice recordings were made as the mobile unit traveled a specified distance. In addition to the voice recordings, various objective measures were recorded such as RSS and bit error rate (BER).

For the voice quality handoff measurements, continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. As in the quasi-stationary measurements, in addition to the voice recordings, various objective measures were recorded, such as RSS and BER. Note that voice quality handoff measurements were not made for the PCS 1900 (TAG 5) and the Wideband CDMA (TAG 7) technology field trials.

While, in general, the same fundamental types of measurements were made for each technology, some differences in the types of measurements are evident, due to the difference in each technology. Also, because each technology was different and the mechanisms for reporting data were different,

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[1] High-tier systems are characterized by large cell sizes, high-power handsets, and users traveling at high speeds (in vehicles). Low-tier systems are characterized by small cell sizes, low-power handsets, and stationary users or users traveling at slow speeds (pedestrians).

the reported data is sometimes given in different formats. As an example, one technology may report error rate performance in terms of BER while another technology may report the error rate performance in terms of frame error rate (FER). Differences also existed in what types of data were available at the uplink and downlink for the different technologies. For some technologies, the data for the objective measures (such as RSS and BER) were collected simultaneously at the uplink and downlink. For other technologies, this was not possible. Also, for some technologies, data for the objective measures were collected at the same time as the voice recordings for voice quality analysis. For other technologies, this was not possible. Additionally, as could be expected, since the trials took place sequentially for each technology, the experience gained from conducting one set of trials benefited the trials for the following technologies to be tested. Because of this, test procedures tended to become more refined after the first technology was tested.

Section 2 of this report describes the cell site configurations used during the JTC PCS technology field trials. Sections 3-8 then present the descriptions and results of the measurements and data analyses for each of the technologies tested during the field trials. At the end of each of the these sections, statements from the manufacturers that participated in the respective field trial are given. These statements are identical to those that were provided in the original JTC reports on the PCS technology field trials [1, 2, and 4-7] except for some minor editorial revisions. The manufacturers' comments represent the opinions of the individual corporations only and in no case imply recommendation or endorsement by the National Telecommunications and Information Administration (NTIA).

The Institute for Telecommunication Sciences (ITS) served as independent observers in all of the JTC PCS technology field trials. As independent observers, ITS reviewed test procedures, observed the execution of the tests, and directly participated in the data collection, storage, and analyses.

2. CELL SITE CONFIGURATION

Both high-tier and low-tier systems were tested in the JTC PCS technology field trials. The TAG 3 PACS technology was tested only in a low-tier configuration (in seven different microcells). The TAG 1 Omnipoint technology was tested in both a high-tier and low-tier configuration. Only one of the seven microcells used in testing the TAG 3 PACS technology was used in testing the TAG 1 Omnipoint technology in the low-tier configuration. The same antennas were used for all of the microcells in the low-tier configuration for both the TAG 1 and TAG 3 technologies. The remaining technologies were all tested as high-tier systems. The high-tier systems used the same cell sites and cell site antennas.

Three cells were used in the JTC PCS field trials for high-tier systems: the Walnut Street Central Office (WCO), the Green Mountain Mesa (GMM) site, and the Table Mesa Central Office (TMCO). All cells were located in Boulder, Colorado. The WCO is located in the bottom of a broad valley formed by Boulder Creek. The valley is oriented west to east with ridges rising up to the north and south. The Rocky Mountains rise rapidly, approximately one-half mile to the west. The elevation at 5,370 ft is lower than both the GMM site and the TMCO site. The antennas are located on top of the WCO building. The cell site is in an urban mid- to low-rise environment.

The TMCO is located on a plateau having a slight uphill slope to the south. This cell is located in a suburban residential environment. The Rocky Mountains rise dramatically 2 mi to the west. To the north lies an east-west directed valley. The north side of this valley rises up again after about 2 mi. This creates a coverage shadow down in the valley, but enhanced illumination on the north side.

The GMM site is located on a hilltop 400 ft above the Boulder Valley floor within a large open area in a suburban residential section of Boulder. This site is used both as a serving site to fill in coverage holes in the other sites and as an interfering site. A map of the Boulder area, including the high-tier cell site locations, is shown in Figure 2.1. The distance between the WCO and GMM, GMM and TMCO, and WCO and TMCO sites is 1.8 mi, 1.8 mi, and 3.2 mi, respectively. All high-tier cell sites were sectorized into three sectors: the line bisecting the north sector points true north, the line bisecting the southeast sector points 120° clockwise from true north, and the line bisecting the southwest sector points 240° clockwise from true north. Only the north and southeast facing sectors were used for the GMM site. In TAG 7 testing, the GMM site was not used at all. All three sectors were used for the WCO and TMCO sites except that in TAG 2 testing the TMCO site only used the north-facing sector.

A detailed description of the high-tier cell sites is given in Table 2.1. All high-tier cell sites used two receive antennas and one transmit antenna per sector except in TAG 7 and TAG 1 testing. In TAG 7 testing, one receive and one transmit antenna per sector were used. In TAG 1 testing, four antennas used both to transmit and receive were employed per sector for each cell. Therefore, all high-tier base stations used receive diversity except for TAG 7. TAG 1 used transmit diversity in addition to receive diversity.

For testing of the low-tier TAG 3 PACS technology used in the JTC PCS technology field trials, four microcell sites were used in the downtown Boulder area and three microcell sites were used in south Boulder. The three sites in south Boulder were used for high-speed

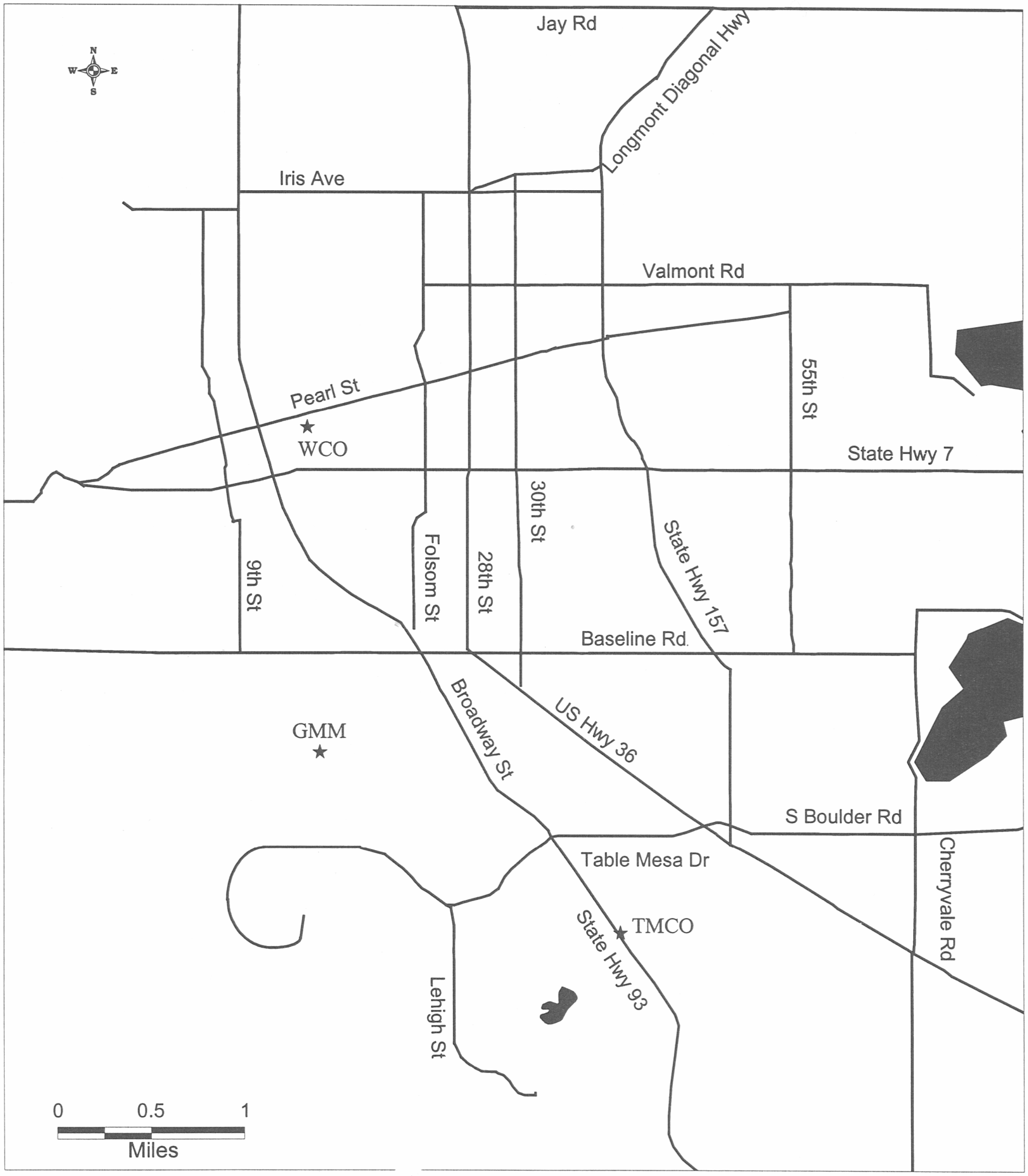


Figure 2.1. High-tier cell site locations in the Boulder, Colorado, area.

Table 2.1. High-Tier Cell Site Configuration Information

Cell Site Description	Location		
	Table Mesa CO	Walnut CO	Green Mountain Mesa[††]
Type of Coverage	Suburban	Light Urban	Suburban/Rural
Latitude	39□58'41.1"N	40□1'4.5"N	39□ 59' 32.4"N
Longitude	105□14'31.8"W	105□16'27.6"W	105□16'22.94"W
Height Above Valley Floor	29'	73'	400'
Ground Elevation at Site	5410'	5370'	5800'
Number of Sectors Used	3[*]	3	2
Number of Receive Antennas Per Sector	2[**,†]	2[**,†]	2[**,†]
Number of Transmit Antennas Per Sector	1[†]	1[†]	1[†]
Orientation of Sectors	N,SW,SE[*]	N,SW,SE	N,SE
Antenna Azimuth Beamwidth	120□	105□	120□
Antenna Elevation Beamwidth	7□	7□	12□
Antenna Gain (dBi)	15.6	16.6	13.5
Antenna Null Filling	No	No	Yes
Estimated Cable Loss (dB)	2.0	3.2	3.2

[*] Only the north-facing sector was used in TAG 2 testing and in TAG 1 high-tier testing.

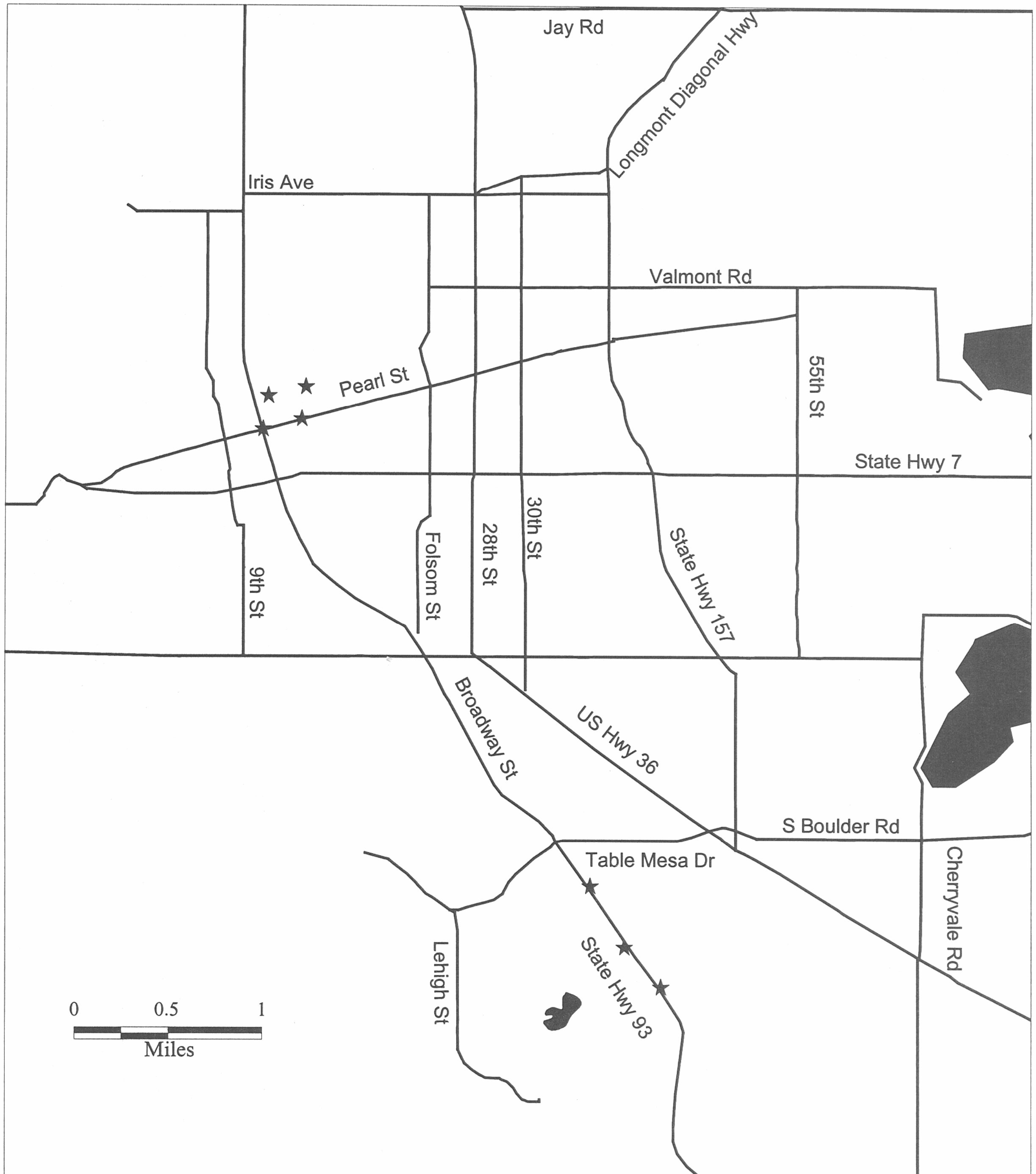
[**] One receive antenna was used per sector in TAG 7 testing.

[†] Four antennas used for both transmit and receive were employed per sector in each cell for TAG 1 high-tier testing.

[††]Not used in TAG 7 testing.

handoff testing. The TAG 1 Omnipoint technology only used one of the downtown Boulder microcells for testing in the low-tier configuration (Site 3). A map of the Boulder area including all the low-tier microcell site locations is given in Figure 2.2. These microcell sites are listed below:

Site 1 - Intersection of Pearl Street and Broadway
Site 3 - Intersection of Pearl Street and 15th Street
Site 9 - On 13th Street halfway between Pine Street and Mapleton Avenue
Site 11 - On 16th Street halfway between Pine Street and Mapleton Avenue
Site 17 - Hanover Street and Broadway
Site 18 - Chambers Street and Broadway
Site 19 - TMCO on Grinnell Street and Broadway



Maps made with MapInfo Professional ™

Figure 2.2. Low-tier microcell site locations in the Boulder, Colorado, area.

The downtown sites used 6-dBi omnidirectional (in azimuth) antennas and the high-speed sites used 9-dBi shaped pattern antennas. The antenna height for all of the microcell sites was 24 ft above street level. All low-tier base stations used receive diversity. In addition, TAG 1 low-tier base stations used transmit diversity. In TAG 1 low-tier testing, two antennas used both to transmit and receive were employed at the base station for Site 3 (the only microcell used in TAG 1 low-tier testing).

3. TAG 5 (PCS 1900) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 5. The PCS 1900 technology tested was the US PCS variant of the GSM and DCS 1800 Standards. The TAG 5 equipment was provided by Motorola, Inc. and Northern Telecom, Inc. The TAG 5 field tests examined area coverage, handoff, and voice quality, and the effects of co-channel and adjacent channel interference on system performance.

The information presented in this section is taken from [1]. This reference provides a more complete and detailed presentation of the TAG 5 technology field testing at the BITB.

3.1 TAG 5 Test System Configuration

The block diagram of the test system configuration is shown in Figure 3.1. The test system consisted of the three cell sites in Boulder (WCO, TMCO, and GMM), a mobile-switching

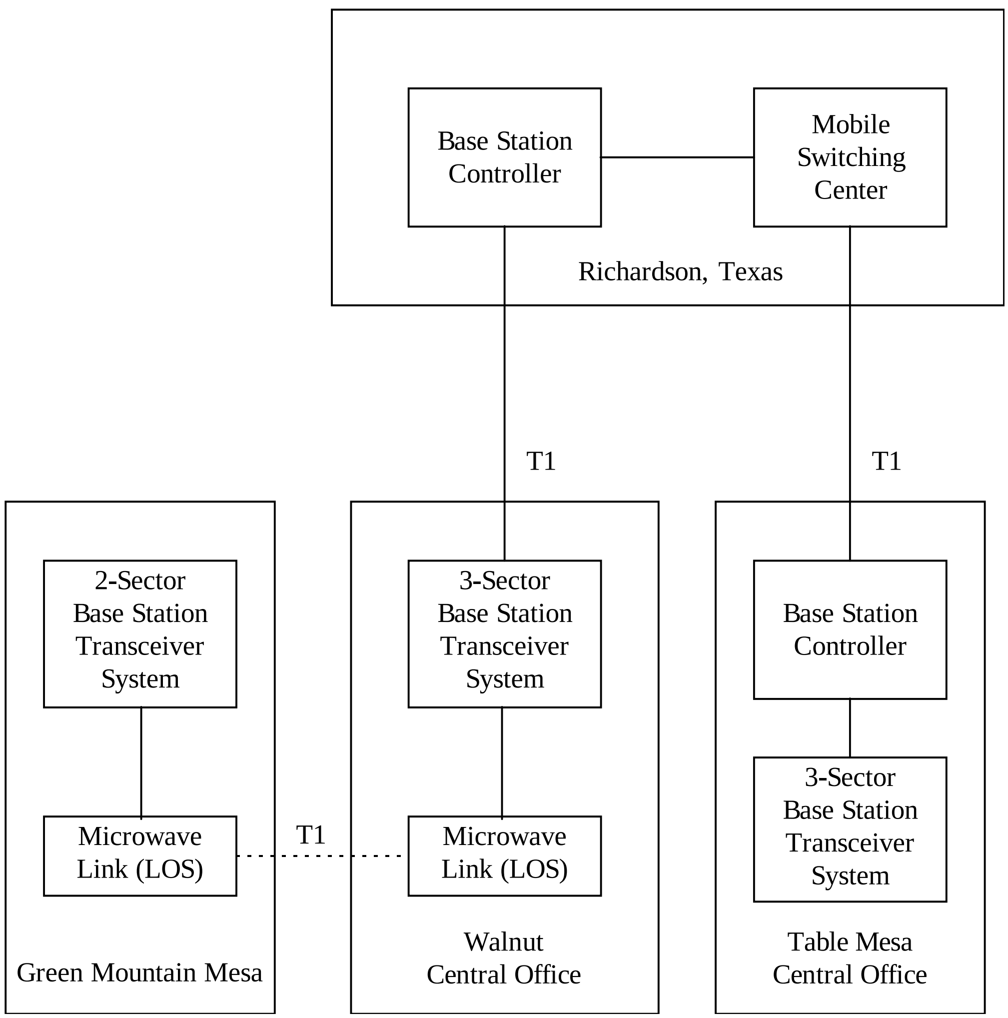


Figure 3.1. Block diagram of the TAG 5 test system configuration.

center (MSC) with a home location register (HLR) in Richardson, Texas, and a base station controller (BSC) in Richardson, Texas. The WCO three-sector base station transceiver system (BTS) was connected to the BSC in Richardson, Texas via a T1 line. A line-of-sight (LOS) microwave link was used to provide a partial T1 link between the GMM two-sector BTS and the WCO BTS. The BSC for the TMCO three-sector BTS was located at the TMCO site; in fact, the TMCO BSC and BTS were housed in the same cabinet. The TMCO BSC was connected to the MSC via a T1 line. The MSC, the BSC in Richardson, Texas, and the BTS's for the WCO and GMM were provided by Northern Telecom, Inc. The TMCO BSC and BTS were provided by Motorola, Inc. The base station receive and transmit frequencies used during the testing for each cell site and sector are given in Table 3.1.

Table 3.1. Base Station Transmit and Receive Frequencies

Cell Site	Sector	Channel #	Receive Frequency (MHz)	Transmit Frequency (MHz)
WCO	North	562	1860.2	1940.2
WCO	Southeast	574	1862.6	1942.6
WCO	Southwest	586	1865.0	1945.0
GMM	North	598	1867.4	1947.4
GMM	Southeast	610	1869.8	1949.8
TMCO	North	622	1872.2	1952.2
TMCO	Southeast	634	1874.6	1954.6
TMCO	Southwest	646	1877.0	1957.0

3.2 Calibration

A major part of the calibration consisted of determining the accuracy of the Rxlev values reported from both the BTS and the mobile unit. Rxlev is a measure of the received signal strength (RSS). Rxlev is related to the RSS by

$$\text{RSS (dBm)} = \text{Rxlev} - 110 \text{ dB.}$$

The accuracy of the Rxlev values reported from both the BTS and the mobile unit were calibrated by connecting the BTS and the mobile unit together via a coaxial cable, high-power and variable attenuators, and two directional couplers. The BTS served as the signal source for testing the accuracy of the Rxlev values reported from the mobile unit. Conversely, the mobile unit served as the signal source for testing the accuracy of the Rxlev values reported from the BTS. The mobile unit (handset) was then placed in a shielded enclosure to prevent coupling from the radiated fields in and around the BTS site.

The first step in the calibration procedure was to determine the losses through the calibration configuration from the transmitter to the receiver. This was accomplished using a signal generator and a spectrum analyzer. Then, a call was established using a fixed attenuation level and the transmitter power was measured. By knowing the losses through the calibration configuration, the RSS was calculated from the measured transmitter power. The calculated RSS was compared to the Rxlev value reported. This procedure was repeated for several different attenuation levels using both the TMCO and WCO BTS's and using two different mobile units manufactured by Motorola, Inc. and two different mobile units manufactured by Northern Telecom, Inc. The maximum difference between the calculated RSS and the corresponding Rxlev value reported was 5.5 dB.

Various transmitter parameters such as transmit power were also characterized as part of the calibration procedure. The results of this characterization are not presented here.

3.3 Area Coverage Testing

The BTS power was set so that the output power for all of the cells was 100-W equivalent radiated power (ERP). Measurements to show area coverage were made with the mobile unit[2] located in a mini-van. The mobile unit was a portable handheld unit that was mounted inside the van on a wooden structure. The structure was located between the two front captain's chairs, 2 ft back from the front window of the van and one foot below the roof. The measurements were taken by driving along routes (radials) away from the site and filling in-between the radials as time permitted. The mobile unit was allowed to handoff within the site to maintain the call as long as possible. Generally, calls were originated close to the cell site and the van was driven away until the lack of radio signal would cause the call to drop. The mobile unit was not able to re-establish the call at that location because the minimum access level was set higher than the sensitivity of the radio. The other sites in the system were turned off for the coverage testing, to determine the area coverage for each cell independently.

3.3.1 TMCO Area Coverage Data

The data were measured and collected at the mobile unit, the GPS receiver, and at the BTS. Data from all three sources were collated with respect to time and combined to provide a file with location, speed, and uplink and downlink Rxlev and Rxqual values in addition to other information about the radio link. Rxqual is a measure of the raw BER. It is related to the raw BER as shown in Table 3.2. All of the data on the uplink were collected (sampled) every 6 s. All of the data on the downlink were collected every 480 ms. In the collated file, the data are listed every second. Of course, data values from the uplink are only available every 6 s so a -1 value was used in the collated file when no data value was available from the uplink. The total number of data points, including both the downlink and uplink, is 6,583.

Downlink Rxlev as a function of distance is shown in Figure 3.2. Note the wide variation in Rxlev values at any given distance. A portion of this variation in the Rxlev data is due to the hilly terrain surrounding this site.

[2] Measurements were also made with an antenna mounted on the roof outside of the mini-van. For purposes of brevity and because it was not a formal part of the JTC PCS technology field trials, TAG 5 measurements performed with the antenna located out of the measurement van are not discussed in this report.

Table 3.2. Relationship Between Rxqual and the Raw BER

Rxqual Value	Raw BER (%)
0	<0.2
1	0.2 to 0.4
2	0.4 to 0.8
3	0.8 to 1.6
4	1.6 to 3.2
5	3.2 to 6.4
6	6.4 to 12.8
7	>12.8

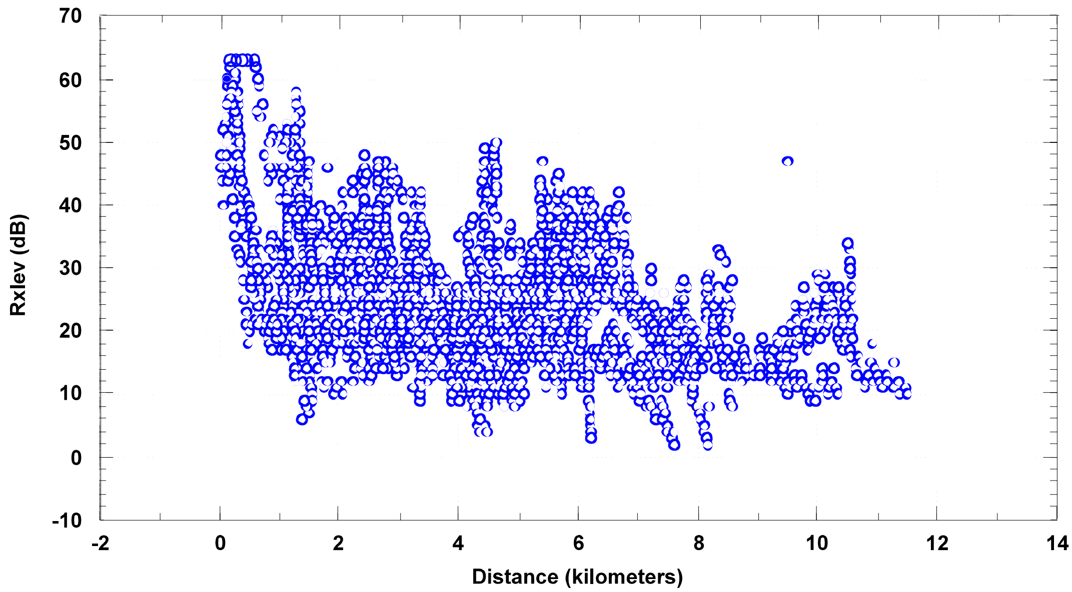


Figure 3.2. Downlink Rxlev vs. distance (TAG 5, TMCO cell).

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. The point along each route where the RSS first dropped below -100 dBm was used to define the coverage boundaries. By doing this, a coverage area of approximately 75 km^2 was obtained.

Figure 3.3 shows the probability density function of Rxlev for both the uplink and downlink. Note that the amount of data for the downlink was larger than the uplink because of the faster data collection rate.

Link balance between the uplink and the downlink was analyzed by generating a scatter plot of Rxlev for the uplink vs. the downlink. Linear regression was then performed to determine the best fit for the data. The best fit line through the data was then used to evaluate the link balance here. Figure 3.4 shows the scatter plot and the results of the linear regression for the case when the effects of uplink power control were not included. As can be observed in Figure 3.4, the links were nearly equivalent.

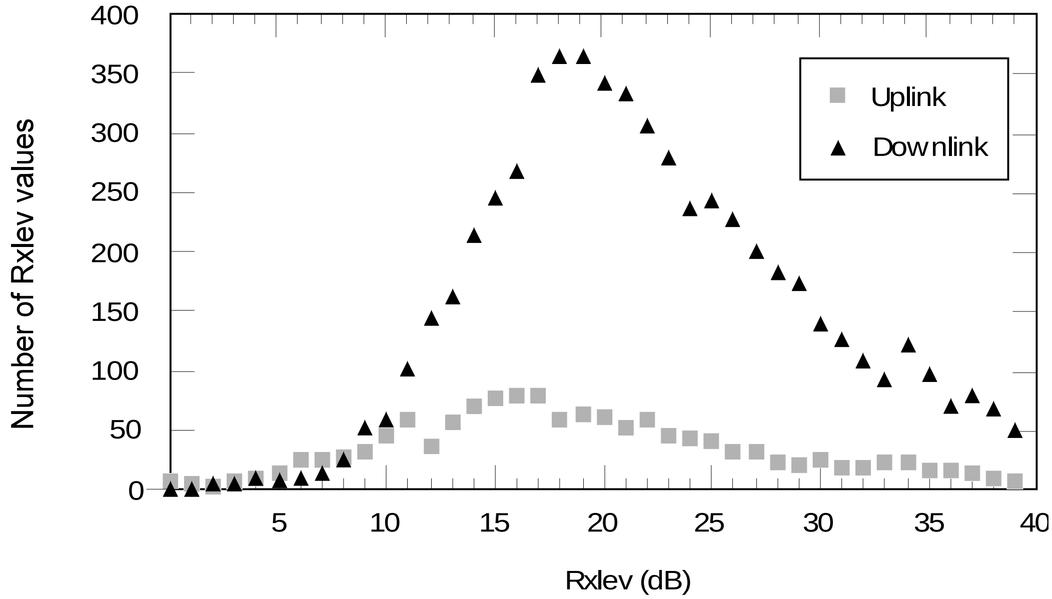


Figure 3.3. Probability density function for Rxlev (TAG 5, TMCO cell).

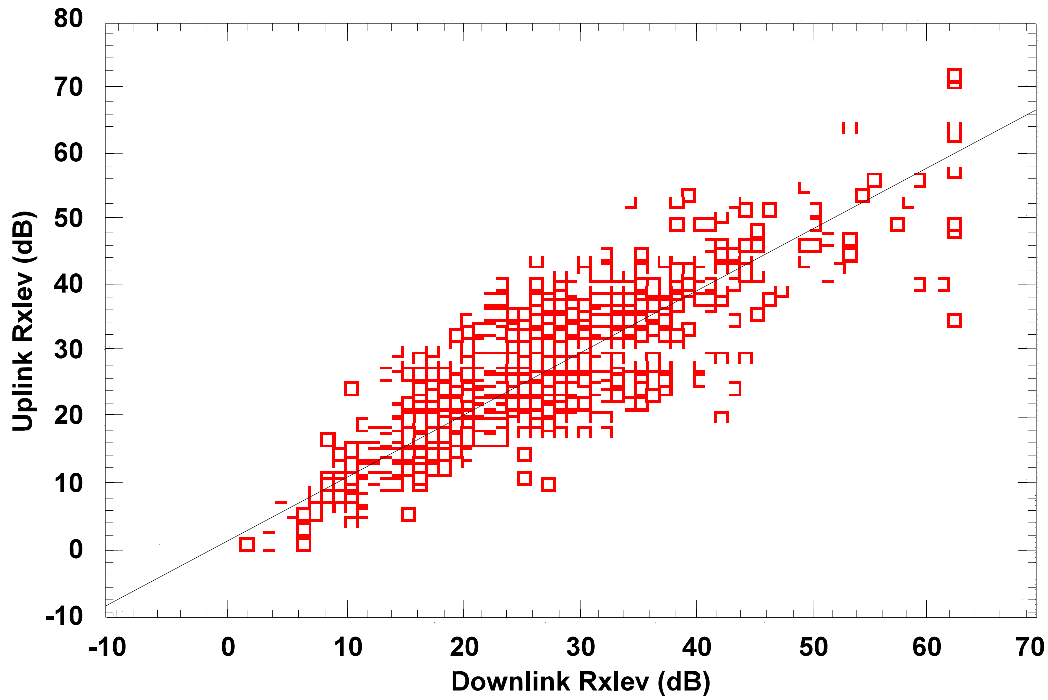


Figure 3.4. Uplink Rxlev vs. downlink Rxlev (TAG 5, TMCO cell).

Figure 3.5 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As expected, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink. Scatter plots of Rxqual vs. Rxlev were generated for both the uplink and downlink as shown in

Figures 3.6 and 3.7, respectively. The results showed that a wide range of Rxlev values (up to 50 dB) gave the same Rxqual value.

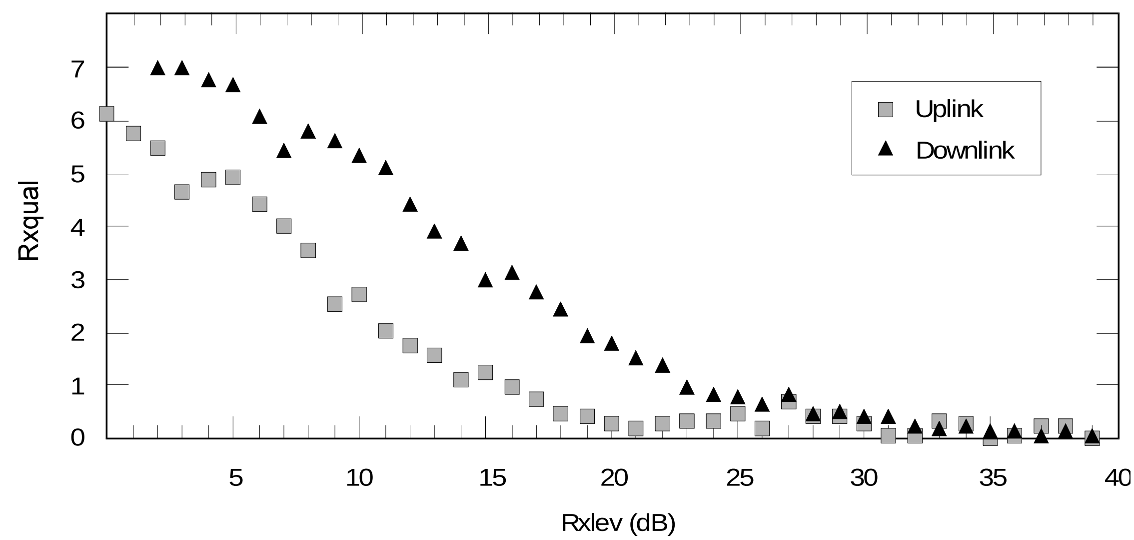


Figure 3.5. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, TMCO cell).

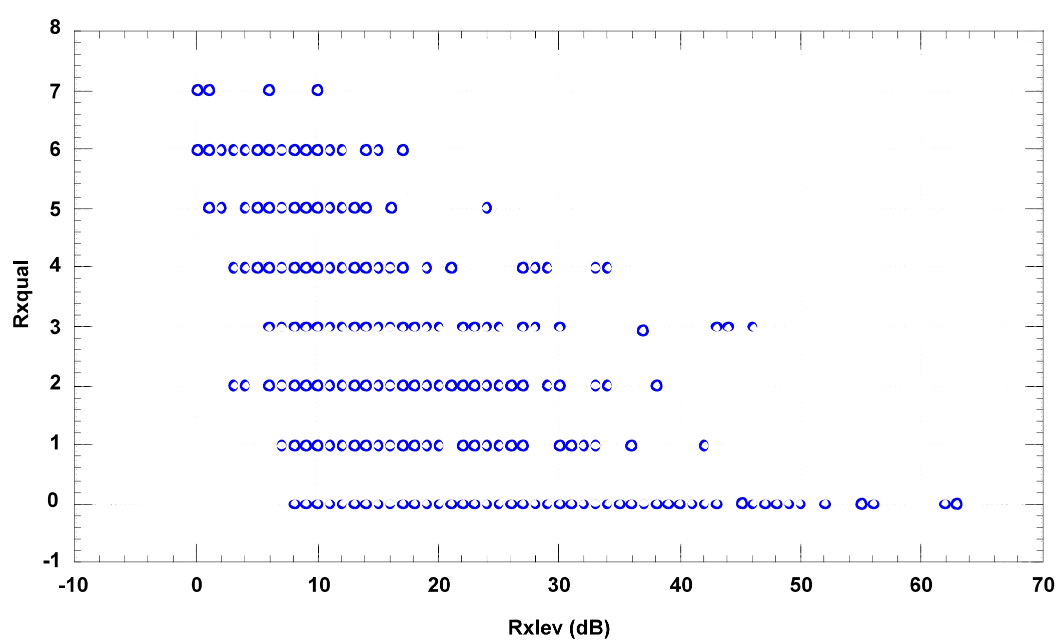


Figure 3.6. Uplink Rxqual vs. Rxlev (TAG 5, TMCO cell).

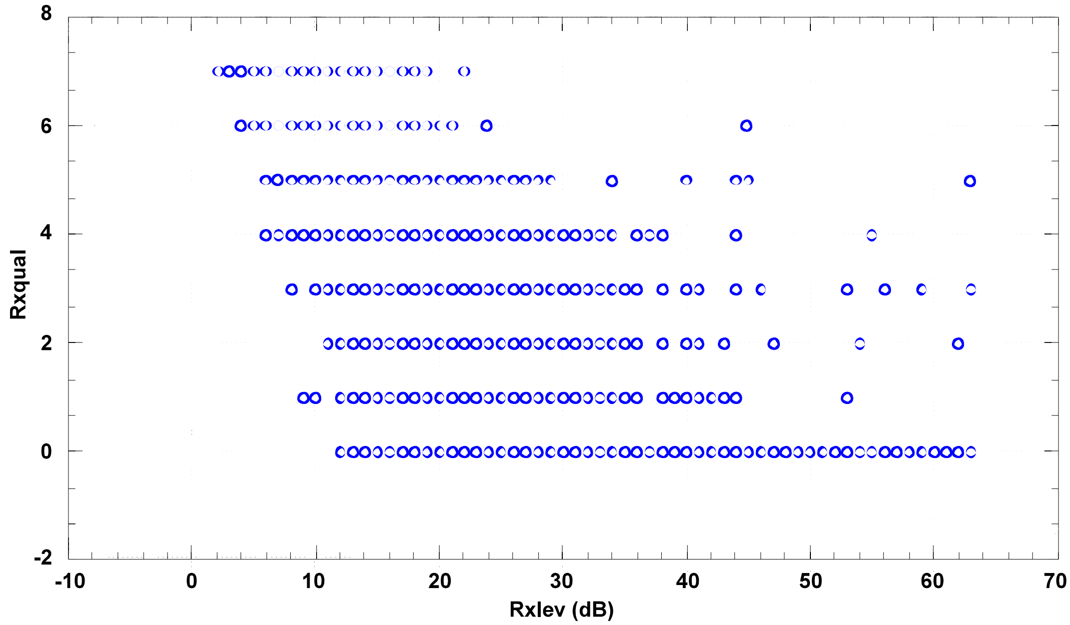


Figure 3.7. Downlink Rxqual vs. Rxlev (TAG 5, TMCO cell).

While no base station (downlink) power control was used, mobile power control was enabled and its effectiveness analyzed. The results showed that the mobile unit was transmitting at its highest power level (30 dBm) 90.4% of the time. Note that this result is dependent on the setting of the power control parameters. When the uplink RSS was greater than about -70 dBm, the mobile unit appeared to reduce its transmitted power level.

3.3.2 WCO Area Coverage Data

The uplink and downlink Rxlev and Rxqual values in addition to other information about the radio link were collected by a protocol analyzer from the T1 link between the WCO BTS and the BSC. Location and speed data were collected from the GPS receiver and dead-reckoning system located in the measurement van. The radio data were collected every 480 ms while the GPS data were collected every second. Data from the protocol analyzer and the GPS receiver were collated with respect to time and combined to provide a single data file. In the collated file, the data are listed every 480 ms. The previous GPS value is used for data records that have no new GPS value. The total number of data points, including both the uplink and downlink, is 16,384.

The location of the WCO cell site with a greater number of tall, closely spaced buildings than in the TMCO cell provided greater decorrelation between the two receive antennas than in the TMCO cell. This provided for greater diversity gain in the base station receiver over the 3-dB gain expected in order two diversity when the branches are correlated. It should be noted that the Northern Telecom BTS reports the Rxlev as the total combined power from the diversity branches.

Downlink Rxlev as a function of distance is shown in Figure 3.8. As in the TMCO cell, there is a wide variation in Rxlev values at any given distance. Although the site was fairly high, it had surrounding buildings that limited its coverage area quite severely. Using the same method as described for the TMCO cell, a coverage area of approximately 50 km^2 was obtained.

Figure 3.9 shows the probability density function of Rxlev for both the uplink and downlink. In this case, the probability density function of Rxlev is nearly the same for the uplink and downlink.

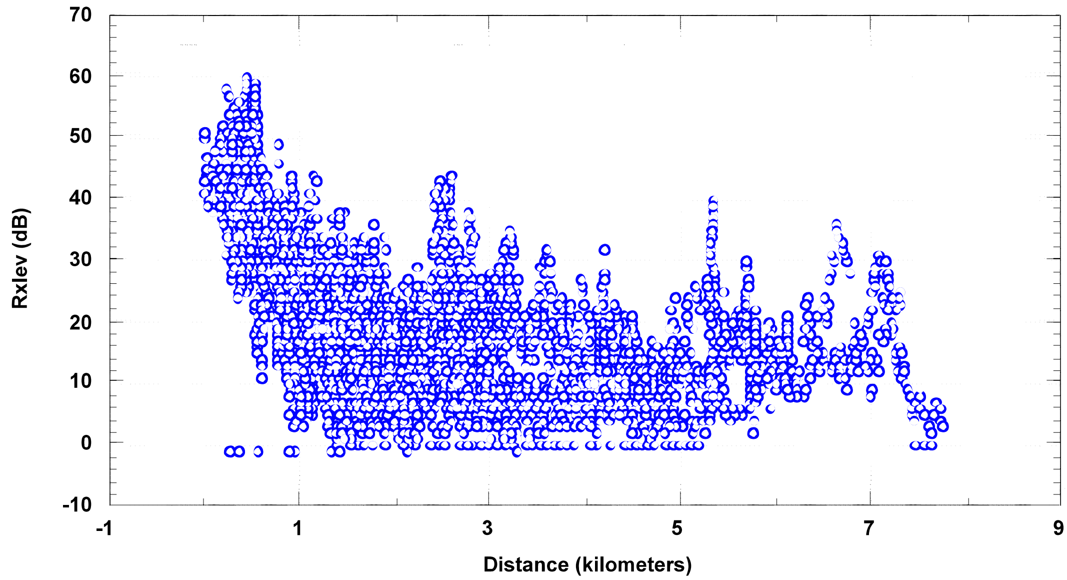


Figure 3.8. Downlink Rxlev vs. distance (TAG 5, WCO cell).

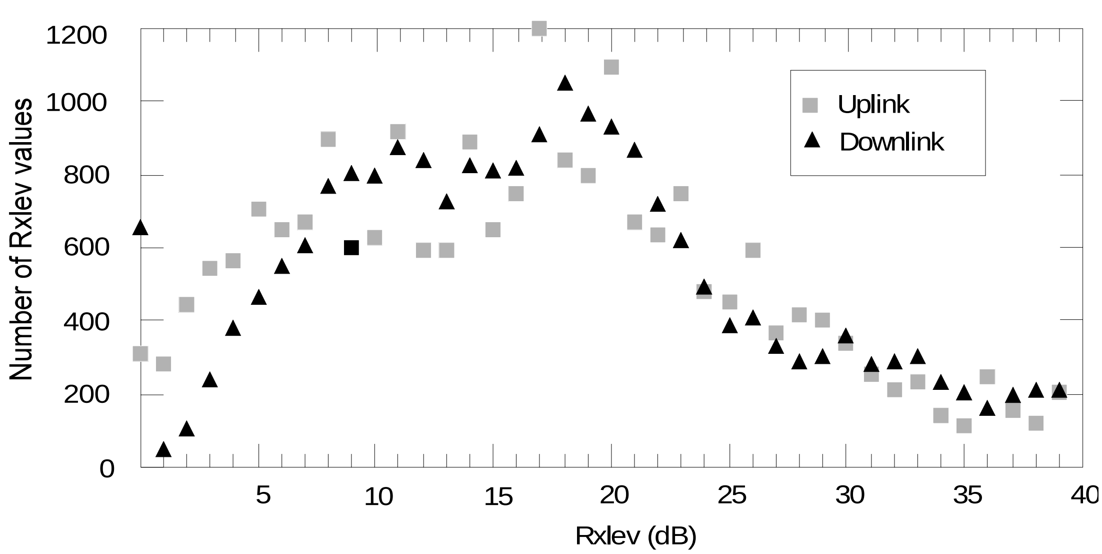


Figure 3.9. Probability density function for Rxlev (TAG 5, WCO cell).

Link balance between the uplink and the downlink was analyzed in the same way as for the TMCO cell by generating a scatter plot of Rxlev for the uplink vs. the downlink. Figure 3.10 shows the scatter plot and the results of the linear regression for the case when the effects of uplink power control were not included. Figure 3.10 shows that the uplink and downlink were roughly equivalent. Figure 3.11 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As in the data for the TMCO site, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink.

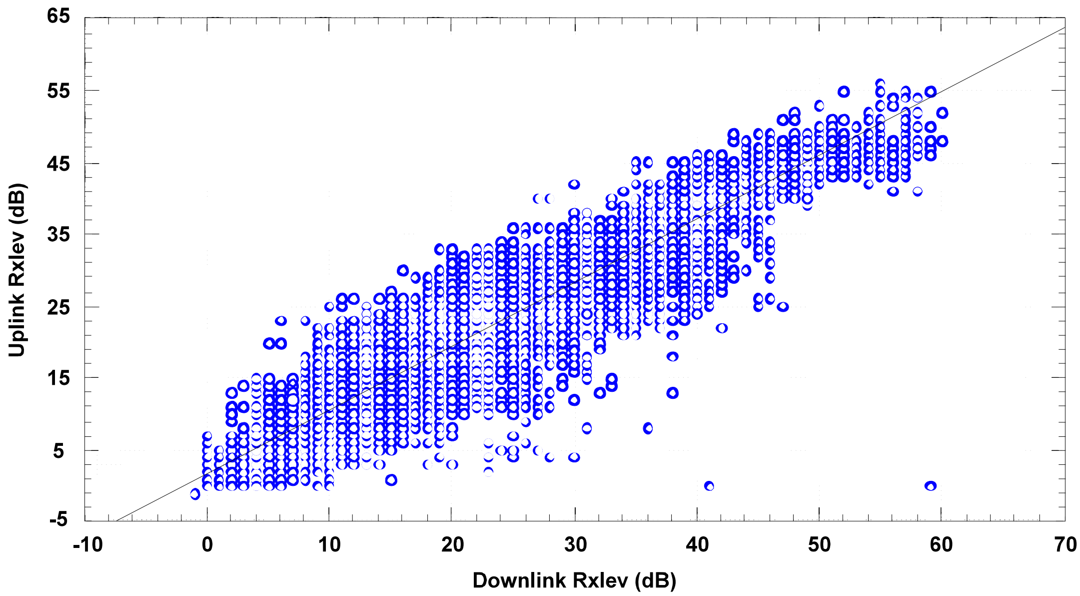


Figure 3.10. Uplink Rxlev vs. downlink Rxlev (TAG 5, WCO cell).

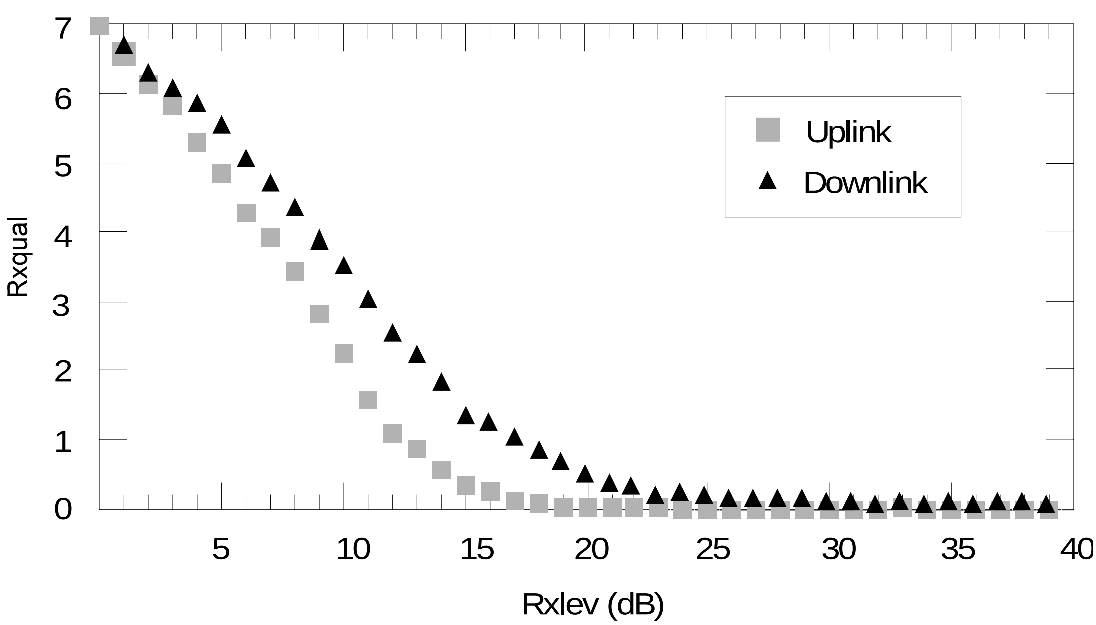


Figure 3.11. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, WCO cell).

Scatter plots of Rxqual vs. Rxlev were generated for both the uplink and downlink as shown in Figures 3.12 and 3.13, respectively. The results showed that a range of Rxlev values gave the same Rxqual value. However, this range of Rxlev values is, in general, smaller for the WCO cell than for the TMCO cell.

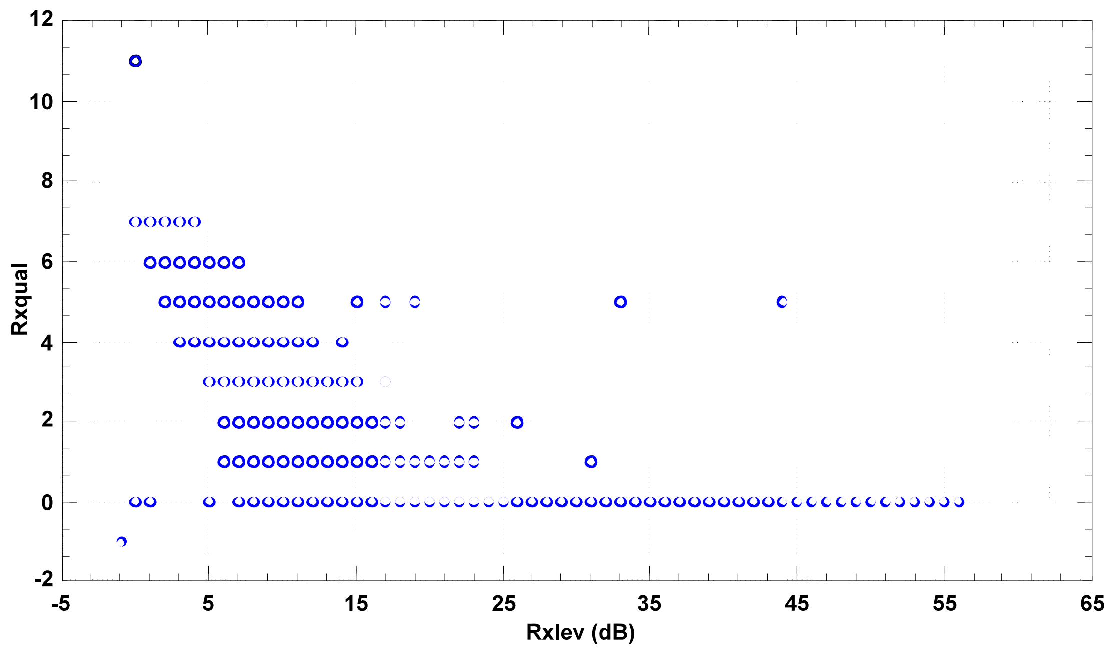


Figure 3.12. Uplink Rxqual vs. Rxlev (TAG 5, WCO cell).

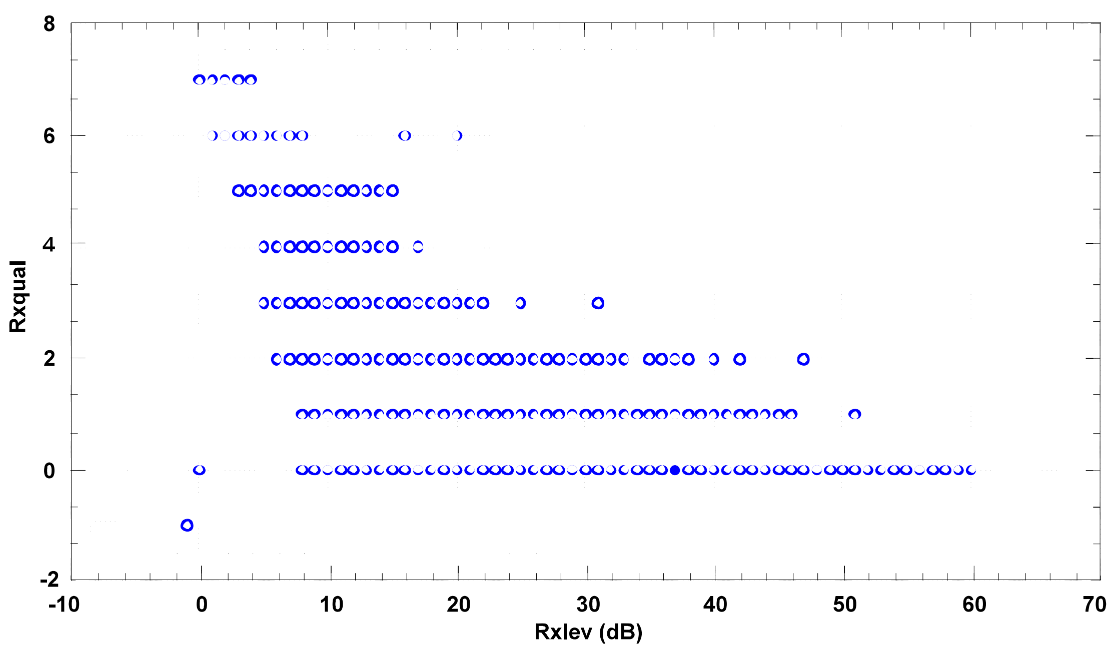


Figure 3.13. Downlink Rxqual vs. Rxlev (TAG 5, WCO cell).

3.3.3 GMM Area Coverage Data

The same data collection methods were used for this site as for the WCO site. However, the total number of data points, including both the downlink and uplink, is approximately 12,000.

Downlink Rxlev as a function of distance is shown in Figure 3.14. As in the TMCO and WCO cells, there was a wide variation in Rxlev values at any given distance. Because this site is located high above the surrounding terrain, line-of-sight propagation extends a long distance away from the BTS. Figure 3.14 shows Rxlev values farther away from the BTS than for either the TMCO or WCO cell sites. Using the same method as described for the TMCO cell, a coverage area of approximately 110 km^2 was obtained. Note that the coverage area is the largest for the GMM site and the smallest for the WCO site.

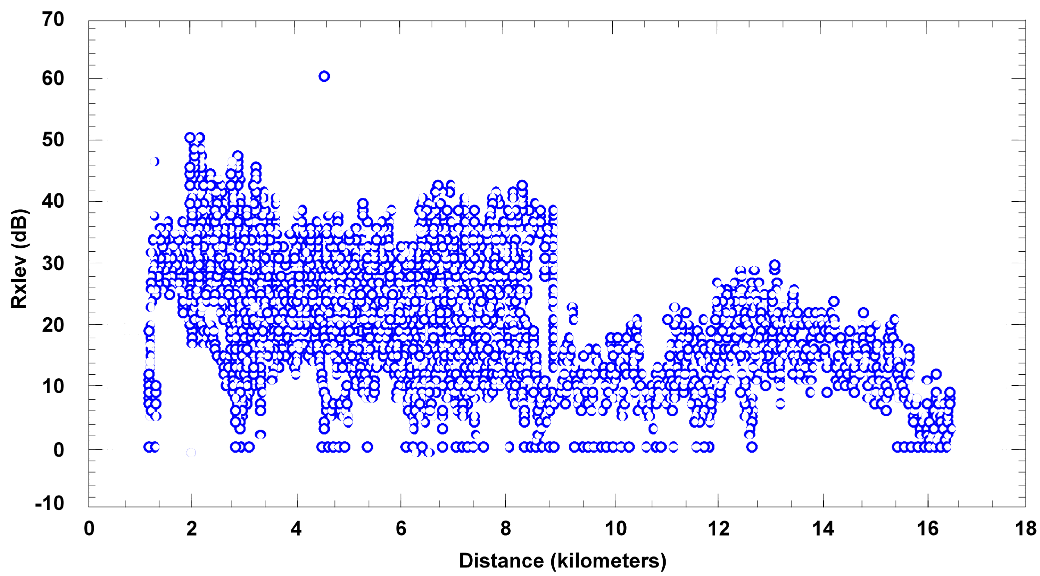


Figure 3.14. Downlink Rxlev vs. distance (TAG 5, GMM cell).

Figure 3.15 shows the probability density function of Rxlev for both the uplink and downlink. For this site, as for the WCO site, the probability density function of Rxlev is nearly the same for the uplink and downlink. Figure 3.16 shows a plot of average Rxqual vs. Rxlev for both the uplink and downlink. As in the data for the TMCO and WCO sites, the Rxqual values decrease with increasing Rxlev for both the uplink and downlink. In this case, the curves for the uplink and downlink are very similar.

3.4 Handoff Testing

Handoff testing was performed by driving the measurement van on routes that would pass through the coverage area of each cell site and each sector within a cell site. Handoff was barred to the GMM site, allowing only handoff between the TMCO and WCO sites.

Handoff testing was performed by establishing an uplink and a downlink simultaneously using two Motorola mobile units that were placed side by side in the handset carrier inside the

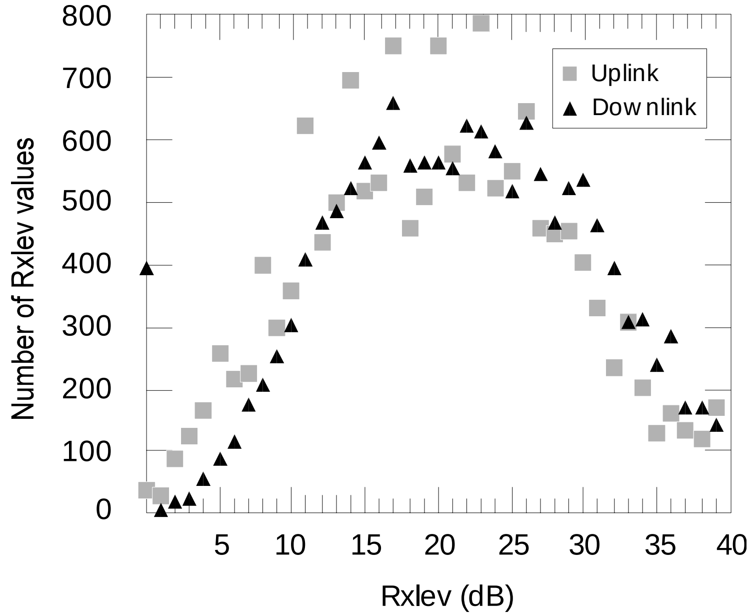


Figure 3.15. Probability density function for Rxlev (TAG 5, GMM cell).

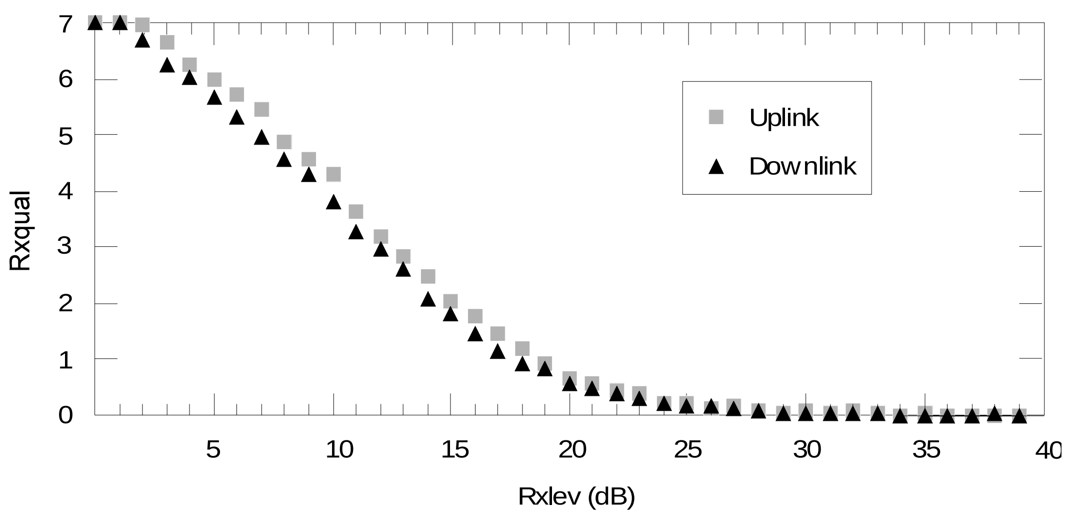


Figure 3.16. Average Rxqual vs. Rxlev for both the uplink and downlink (TAG 5, GMM cell).

measurement van. Data from each link were collected approximately every second. The data recorded included Rxlev, Rxqual, the difference between Rxlev and the access minimum, the handoff type (either between RF channels or between time slots), and the Rxlev of each neighboring cell or sector.

Manufacturers configured their respective sites with generic handoff parameters. As in all of the PCS JTC technology field trials, there was no practical opportunity to optimize any parameters that impacted inter-BSC performance, due to time constraints. Selection of cell site locations was greatly limited to facilities readily available to U S West. As such, the chosen locations were in no way optimal with respect to RF system planning.

The system handoff parameters for both the TMCO and WCO cell sites were set as follows:

Intercell handoff delta = 1 dB
Intracell handoff delta = 4 dB
Intercell access minimum = -105 dBm
Intracell access minimum = -100 dBm

Handoff delta is the difference in RSS levels measured at the mobile unit between the current carrier and a potential carrier for handoff. Access minimum is the minimum RSS that a potential carrier must meet for handoff to be allowed. Note that since the intercell handoff delta was set less than the intracell handoff delta, and the intercell access minimum was set lower than the intracell access minimum, handoff between cell sites was encouraged more than handoff between sectors within a cell. The handoff parameters were chosen to induce handoff between the TMCO and WCO cell sites since there was a lack of sufficient signal overlap between these sites.

Voice quality tapes were played/recorded continuously on the uplink and downlink while the testing was conducted. Each time a handoff occurred, the link, new channel, time, tape counter position, and geographic location were recorded.

Three types of handoff were observed. The first occurred between the sectors at a given cell site. The second occurred between two different cell sites. A third type of handoff was observed, only at the TMCO site, between time slots of a given RF channel.

Data collected from the handoff testing were analyzed to determine the change in the Rxlev and Rxqual values before and after handoff. The time between successive handoffs was also examined. This gives an indication of any “ping-ponging” occurring. Ping-ponging is a rapid sequence of handoffs between cell sites and/or sectors. A total of 63 RF channel-to-RF channel handoffs were examined in the analysis that follows.

The average Rxlev before and after handoff was calculated over six consecutive samples before and after handoff. This corresponds to an average over approximately 3 s. The first sample after handoff was discarded to allow the handset to stabilize. In cases where another handoff occurred before six samples were accumulated, the average was calculated on the number of samples available.

Figure 3.17 presents a histogram of the change in the average Rxlev value (in dB) before and after handoff. Negative values represent cases when the average Rxlev value was actually lower after handoff than before. The cause of this was not definitively determined. Figure 3.18 shows the histograms of change in Rxlev for both intercell and intracell handoffs. Note that the change in Rxlev tends to be greater for the intracell handoffs than for the intercell handoffs directly corresponding to the larger handoff deltas.

Analysis of the handoff data showed that the Rxlev before 22% of the intercell handoffs was fairly low (RSS below -100 dBm), meaning that the area coverage in the cells did not have enough overlap to always complete and ensure a silent transition during intercell handoff. The

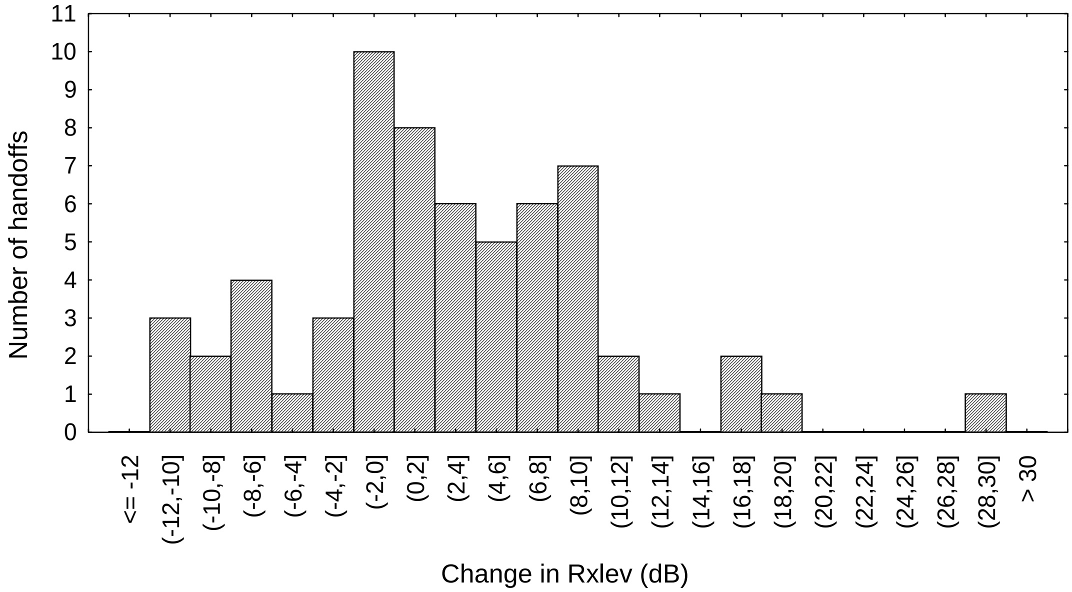


Figure 3.17. Histogram of change in Rxlev during handoff (TAG 5).

change in the average Rxqual before and after handoff was calculated in the same manner as the change in average Rxlev before and after handoff described earlier. Figure 3.19 shows a histogram of the change in the average Rxqual value before and after handoff. Negative values represent cases when the average Rxqual value was higher after handoff than before. Figure 3.20 shows the histograms of change in Rxqual for both intercell and intracell handoffs. Figure 3.21 shows a histogram of the time between successive handoffs. The histogram shows that a relatively large number of successive handoffs had less than 10 s between them. Handoffs occurred with times between successive handoffs up to about 290 s.

3.5 Interference Testing

Interference measurements were performed for the downlink only. These measurements were made as the mobile unit traveled along a square route that included areas with a range of good to poor carrier-to-interference (C/I) ratios. The route was chosen to provide RSS values above the noise floor. Most of the RSS values were above -100 dBm. The route was repeated for each test scenario: no interference, co-channel interference, and adjacent channel interference. Frequency hopping and discontinuous transmission (a transmission mode using a variable speech-coding bit rate) were not employed during these tests.

For the co-channel interference measurement, the WCO north sector was used as the intended source. The GMM north sector was used as the source for the co-channel interference. Both the GMM north sector and the WCO north sector were tuned to the same frequency. A second carrier, at a different frequency, was transmitted from the GMM north sector. This carrier was used to measure the RSS of the interfering signal from the GMM site at the mobile unit. Note that in this configuration, the channel used for monitoring the interference level fades independently of the actual interfering signal.

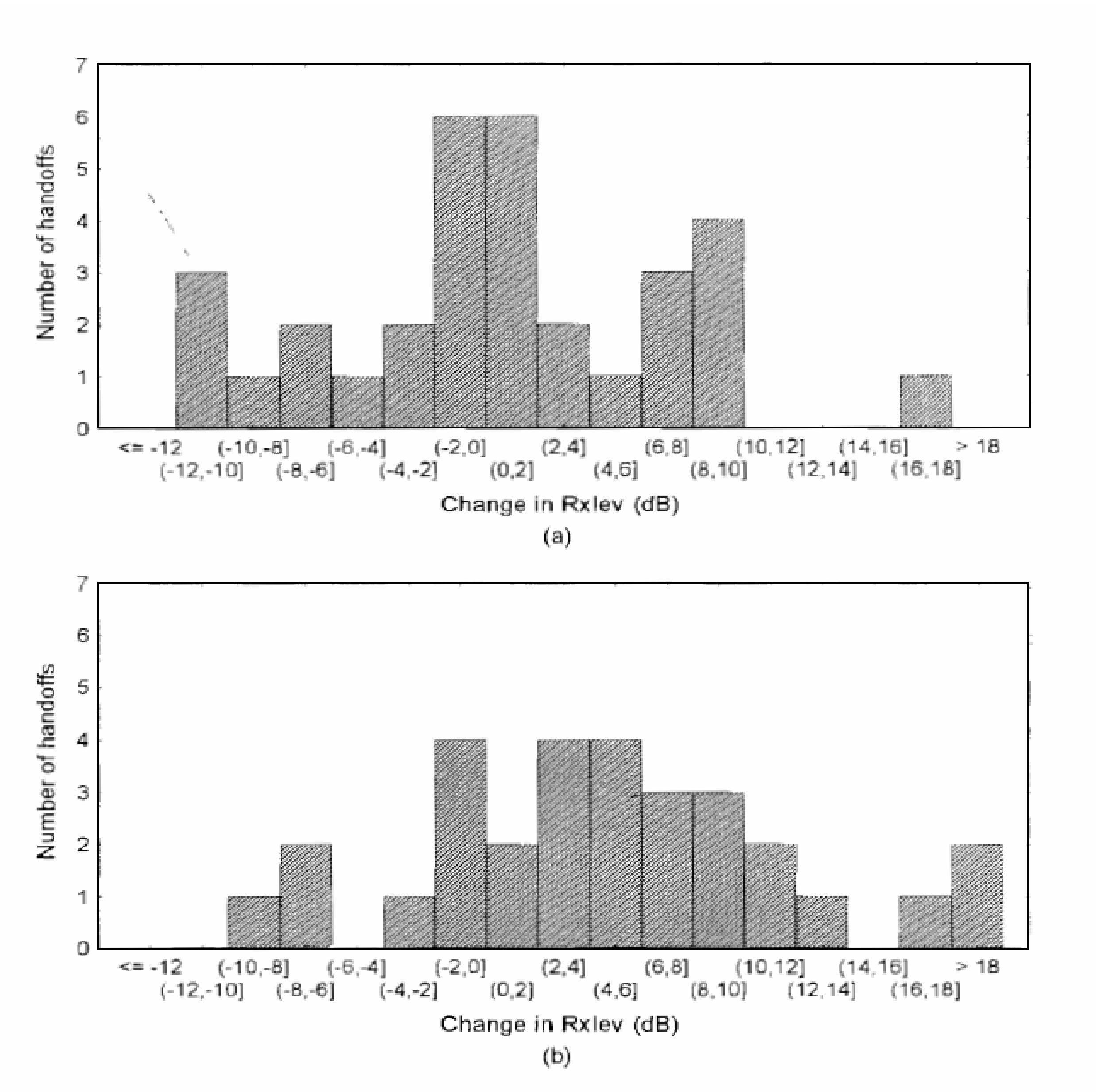


Figure 3.18. Histograms of change in Rxlev for (a) intercell and (b) intracell handoffs (TAG 5).

For the adjacent channel interference measurement, the WCO north sector was again used as the intended source. The GMM north sector was used as the source for the adjacent channel interference. The carrier for the adjacent channel interferer was set to a frequency 200 kHz away from the intended source's carrier.

Figure 3.22 shows average Rxqual as a function of the C/I for both the co-channel and adjacent channel cases. As expected, when the C/I is increased, lower values of Rxqual are seen; i.e., the bit error rate decreases. Also as expected, to achieve the same Rxqual value, a much lower C/I (approximately 20 dB lower) is required for the adjacent channel interference than the co-channel interference.

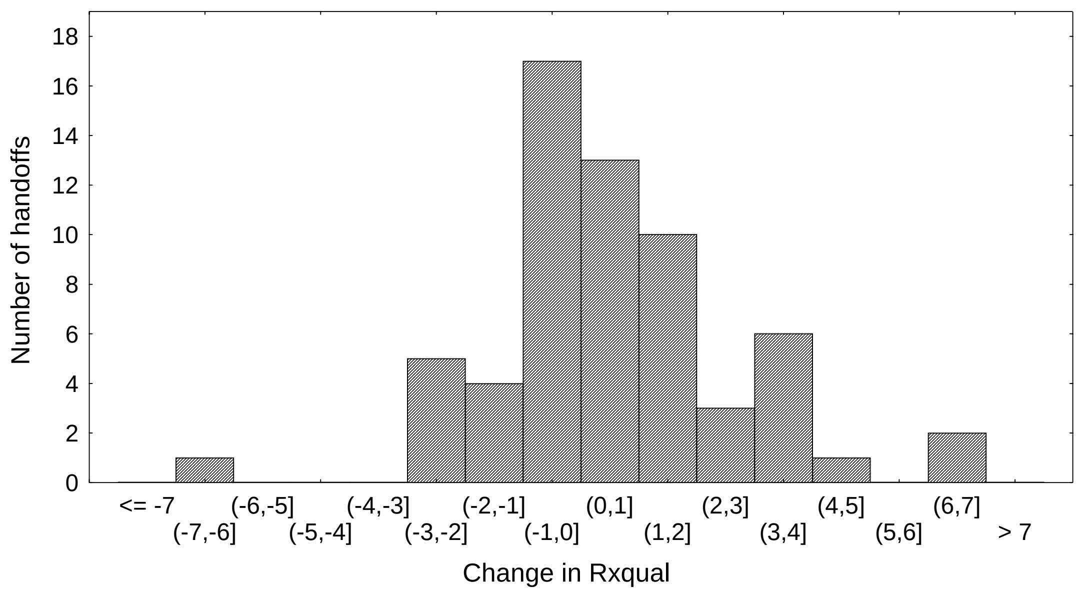


Figure 3.19. Histogram of change in Rxqual during handoff (TAG 5).

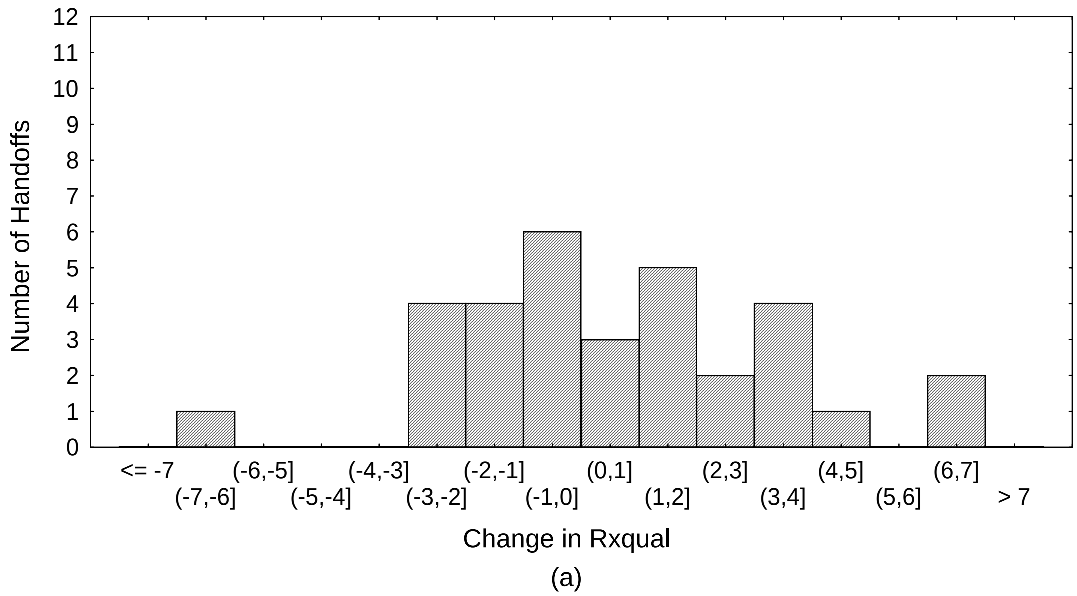
3.6 Voice Quality

For the JTC PCS technology field trials in general, two types of voice quality measurements were made: quasi-stationary measurements and handoff measurements. The quasi-stationary measurements were made at fixed locations on a grid within each cell site. At each fixed location, voice recordings of transmitted voice signals were made as the mobile unit traveled a specified distance. In addition to the voice recordings, various objective measures were recorded, such as RSS and BER.

For the voice quality handoff measurements, continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. As in the quasi-stationary measurements, in addition to the voice recordings, various objective measures were recorded such as RSS and BER. Note that voice quality handoff measurements were not made for the PCS 1900 (TAG 5) and the Wideband CDMA (TAG 7) technology field trials.

3.6.1 Quasi-stationary Measurements

Voice recordings and Rxlev and Rxqual data were collected at locations on a 0.5-mi grid that encompassed the expected coverage area for the TMCO and WCO sites. Eighty-two locations were identified as measurement sites for the quasi-stationary measurements: 40 centered around the TMCO site and 42 centered around the WCO site. Measurements were taken at 78 of these locations for the TAG 5 testing. Only one cell was activated at a time. Measurements were taken at the 40 locations around the TMCO cell site when the TMCO cell was active. Similarly, measurements were taken at 38 of the 42 locations around the WCO cell site when the WCO cell was active. At each location, data were collected as the measurement van traveled at one of two speeds. The vehicle traveled either 10 m or 100 m over the sample time. The sample time was the same for both cases. The particular vehicular speed used at each location (distance traveled



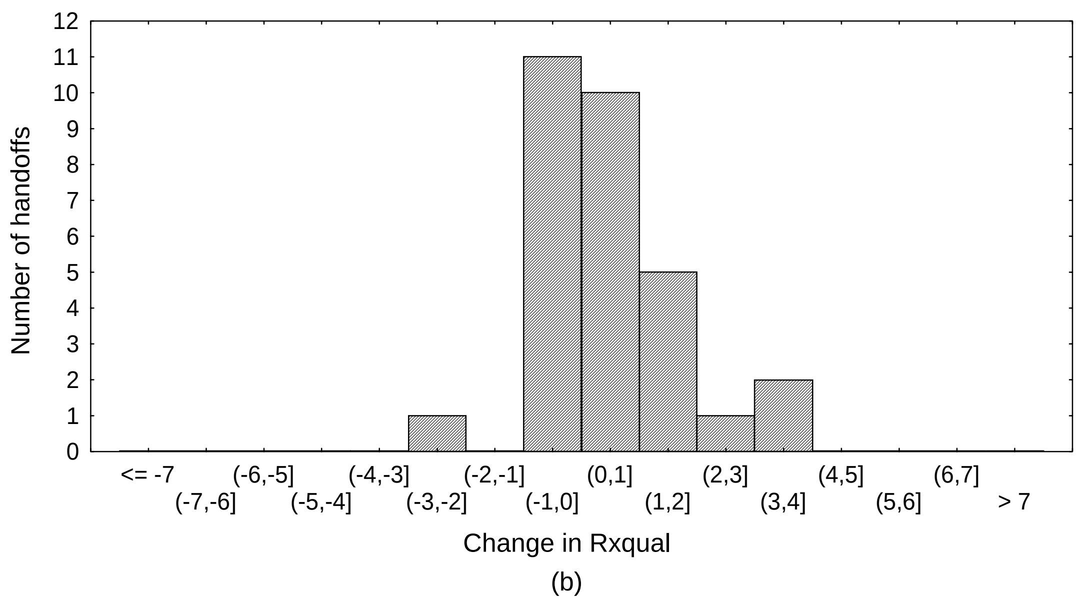


Figure 3.20. Histograms of change in Rxqual for (a) intercell and (b) intracell handoffs (TAG 5).

over a fixed sample time) used in the TAG 5 testing was predefined and is shown on the map in Figure 3.23.

The quasi-stationary voice quality measurements were made at various subsets of the 82 defined locations for all of the high-tier testing in the JTC PCS technology field trials, except for TAG 7. While the TAG 7 technology was tested in a high-tier configuration, the quasi-stationary voice quality measurements were made at different locations than the other

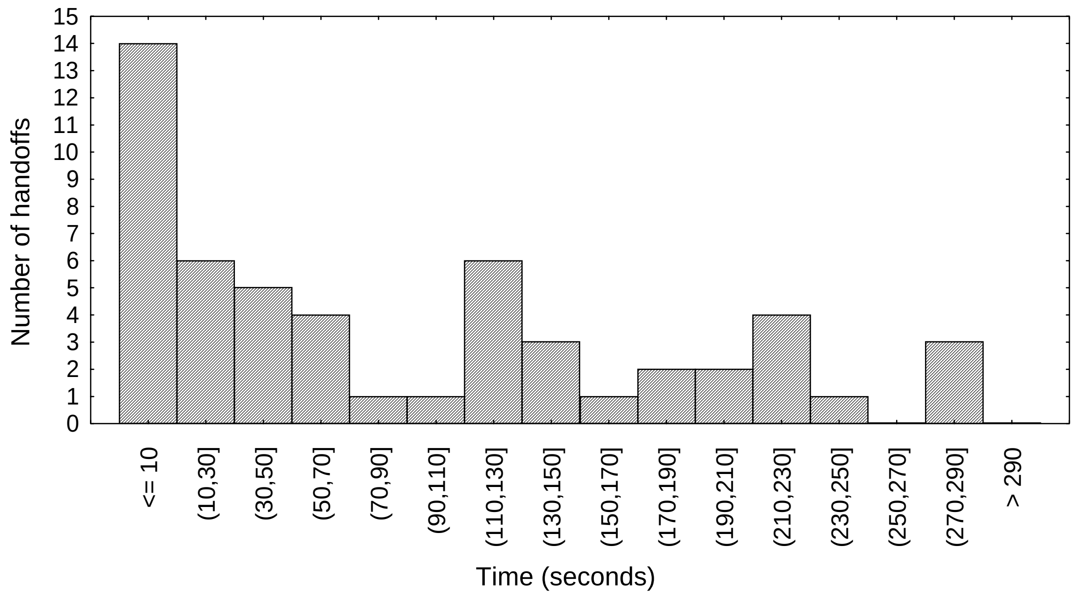


Figure 3.21. Histogram of time between successive handoffs (TAG 5).

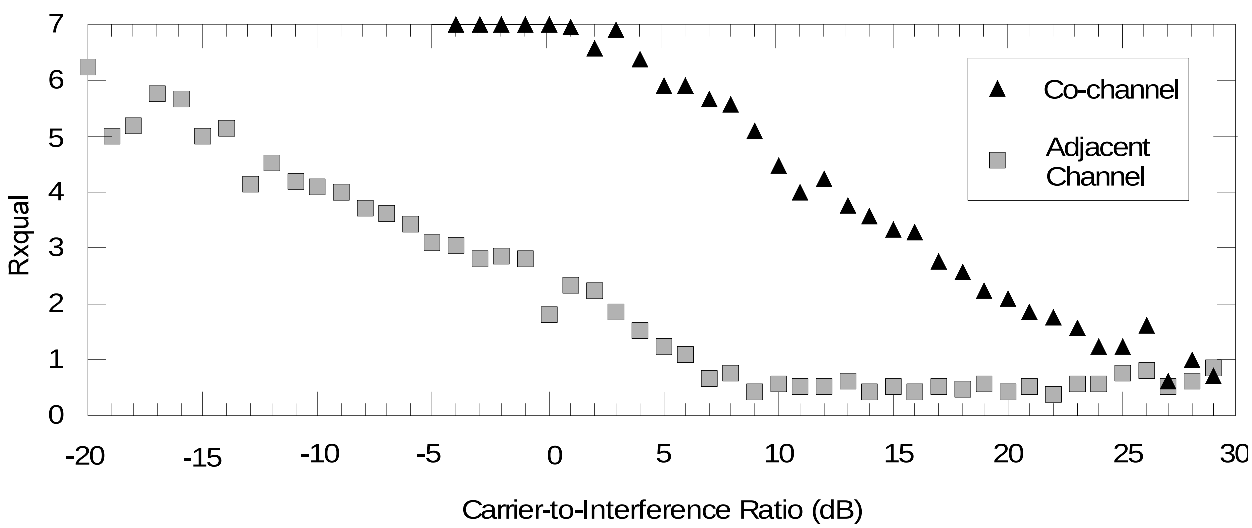


Figure 3.22. Average Rxqual vs. carrier-to-interference ratio (C/I) for co-channel and adjacent channel interference (TAG 5).

technologies that were tested in a high-tier configuration. All of the JTC PCS technologies were tested in a high-tier configuration except for the TAG 3 PACS technology. (The TAG 1 technology was tested in both a high-tier and low-tier configuration.) The TAG 3 PACS technology was tested only in a low-tier configuration.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the uplink and downlink simultaneously. The source tape transmitted over each link was identical and contained 75-80 s of spoken standard Harvard sentences; 10 spoken by a male and 10 spoken by a female. These sentences are phonetically balanced and include all the sounds in the American usage of the English language. The 10 male and 10 female sentences together as a group are referred to as a *voice segment* in the remainder of this report.

The received voice transmissions were recorded on analog audio tape at the receiver for the uplink and at the receiver for the downlink. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. Rxlev and Rxqual data were collected simultaneously with the recorded voice transmissions. During all data processing, the average Rxlev and Rxqual values were computed for each recorded voice segment.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

3.6.2 Mean Opinion Score Assessment

The MOS technique for determining voice quality entails a group of listeners (called subjects) rating the quality of voice segments subjectively. For each voice segment, the results from all subjects in the group are then averaged to form the MOS.

To accomplish the MOS testing, a pool of 30 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, and 35-50, and those over 50 years of age. There were an equal number of male and female subjects. The subjects were cordless, noncellular telephone users.

Four groups of subjects from the subject pool were formed: two groups of eight and two groups of seven. The subjects were asked to rate voice segments by answering the following questions after each segment was presented:

1) How would you rate the overall quality of the sound? (on a 5-point scale where 5=excellent, 4=good, 3=fair, 2=poor, and 1=bad);

2) How annoying are any additional sounds you might hear? (not at all annoying, slightly annoying, annoying, very annoying, or extremely annoying); and

3) Would this be acceptable as portable service? (acceptable or unacceptable).

First, the subjects in each of the four groups were presented with two practice voice segments to rate. Then the subjects in each of the four groups were asked to rate one quarter of all the voice segments taken from the measurements. In each voice segment the 10 male sentences were presented before the 10 female sentences half of the time. In addition, the order of presentation of the voice segments was randomized.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain

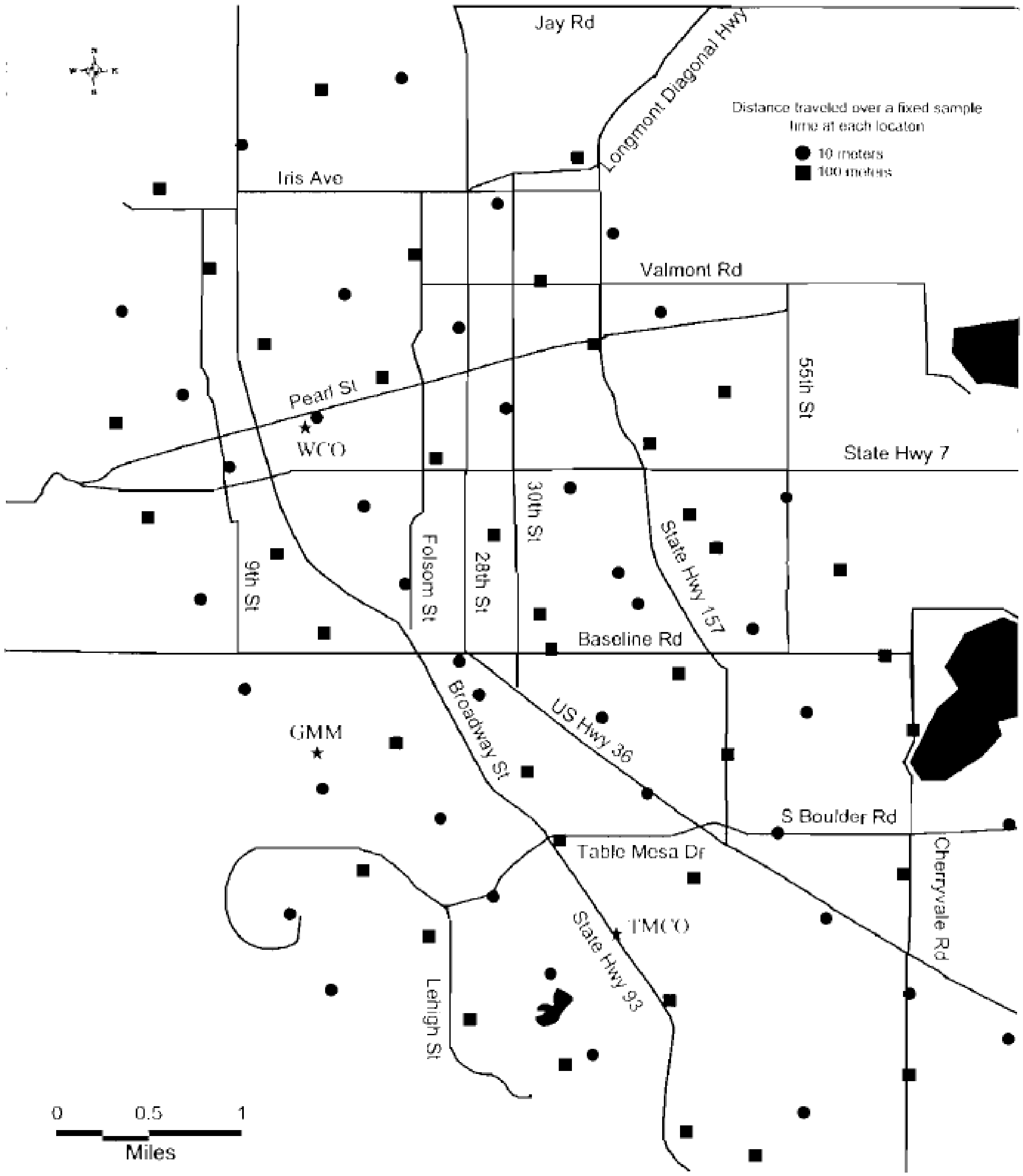


Figure 3.23. Quasi-stationary measurement locations and vehicular speed used at each location for TAG 5.

an MOS. The results from all four of the groups (for both the uplink and downlink for the WCO cell only) are shown in the histogram in Figure 3.24. Overall, the voice segments were marked favorably, with 80% of the segments rated between fair and excellent. The mean MOS was 3.09 and the standard deviation was 0.80.

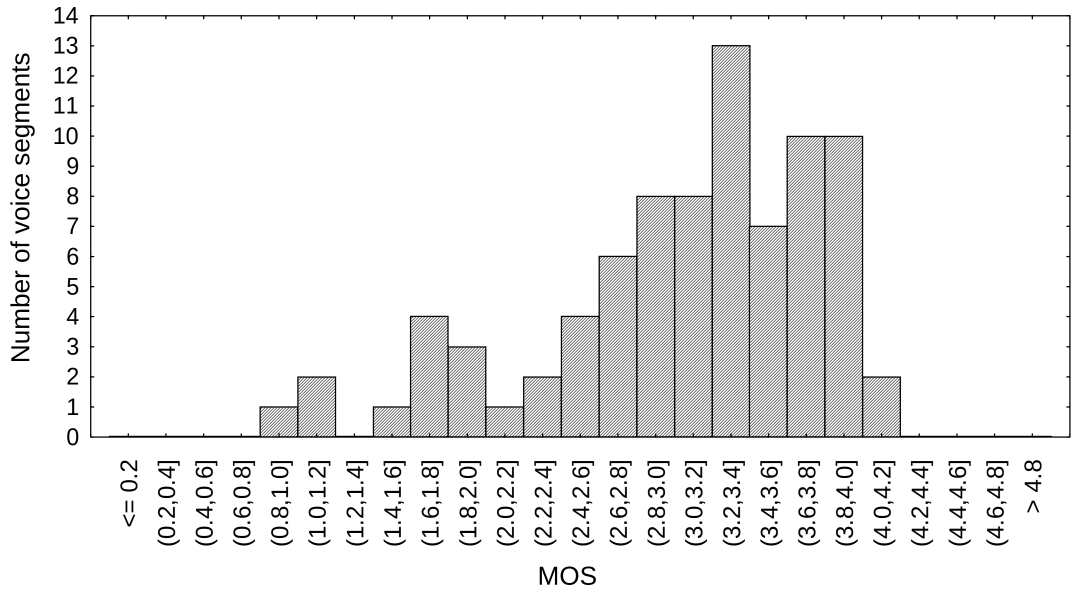


Figure 3.24. Histogram of mean opinion scores (MOS's; TAG 5, WCO cell).

Scatter plots of MOS vs. average Rxlev and MOS vs. average Rxqual, shown in Figures 3.25 and 3.26, respectively, were generated to help determine the relationship between MOS's and the objective measures. These plots show a large variation in MOS's at all values of Rxlev and Rxqual.

Pearson product-moment correlations were performed to determine the correlation between MOS and average Rxlev, between MOS and average Rxqual, and between average Rxlev and average Rxqual. The correlation coefficient between MOS and average Rxlev was 0.22 and that between MOS and average Rxqual was -0.34. The negative correlation coefficient occurs because increasing MOS's correspond to decreasing Rxqual values. The low correlation coefficients imply that a strong linear relationship does not exist between both MOS and average Rxlev and MOS and average Rxqual. The correlation coefficient between average Rxlev and average Rxqual was -0.67. While this shows a stronger correlation than between the MOS's and the objective measures, a strong linear relationship between the two objective measures still does not exist.

While there does not appear to be a strong linear relationship between MOS and the objective measures, there still may be a consistently increasing or decreasing relationship between them.

The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the

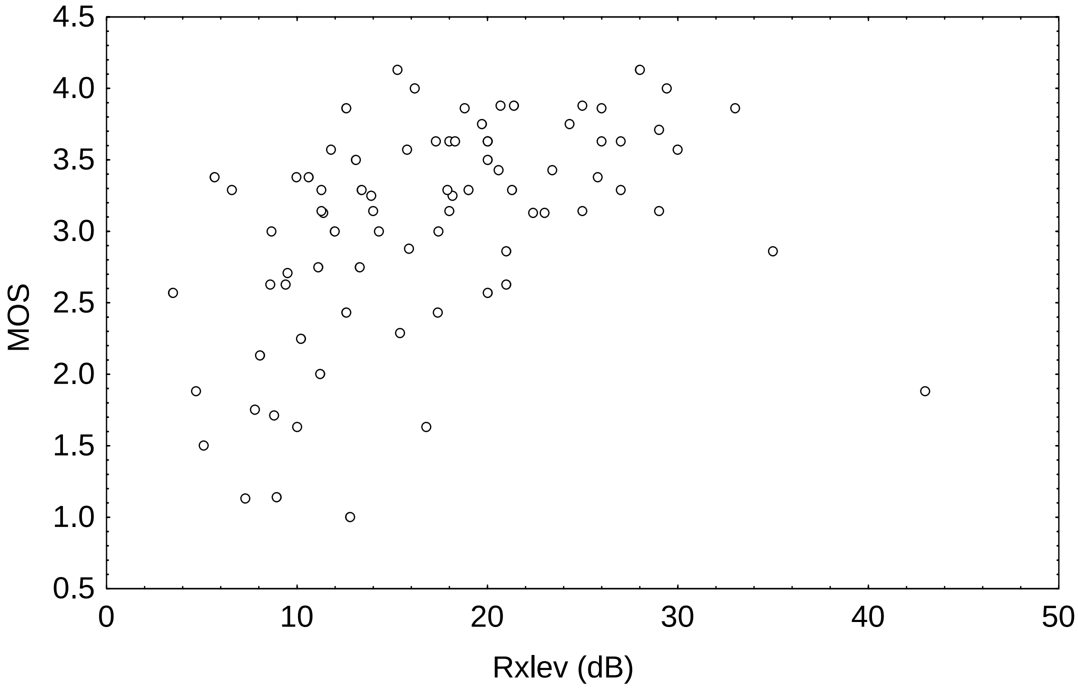


Figure 3.25. Mean opinion score (MOS) vs. Rxlev (TAG 5).

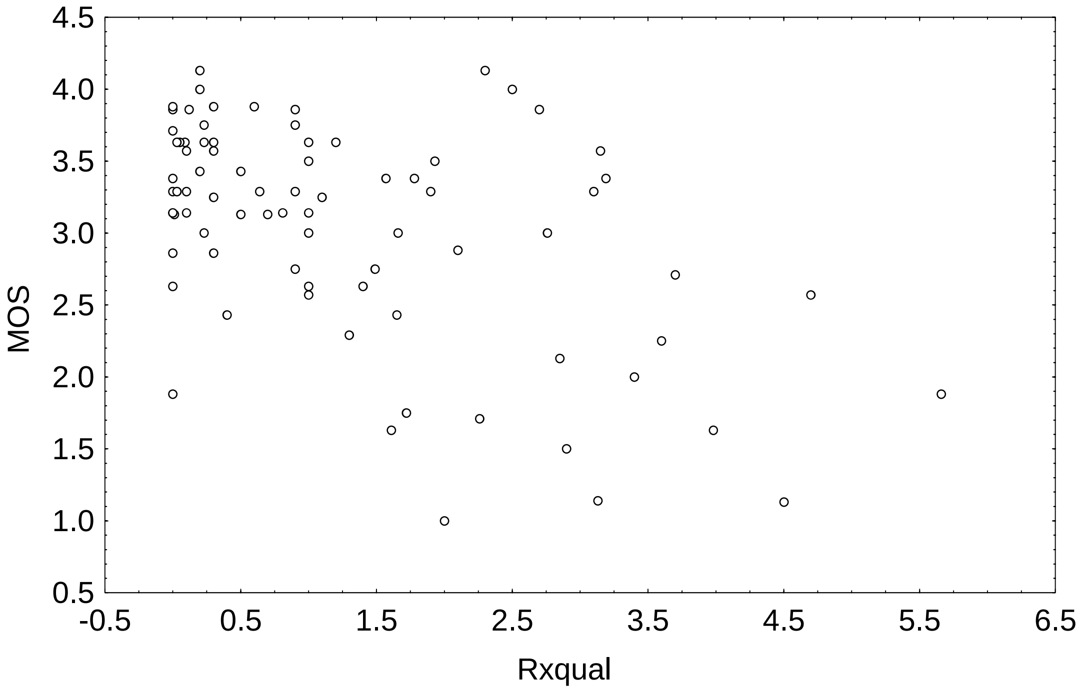


Figure 3.26. Mean opinion score (MOS) vs. Rxqual (TAG 5).

ranks of average Rxlev and between the ranks of MOS and the ranks of average Rxqual. The Spearman rank correlation coefficient between MOS and average Rxlev was 0.28 and that between MOS and average Rxqual was -0.27. These low rank correlations between MOS and averaged objective measures suggest that a consistently increasing or decreasing relationship between MOS and the objective measures does not exist.

Note, the values used for Rxlev and Rxqual above were averages over the entire length of the voice segments. The objective measures, averaged over the entire voice segment, do not appear to be accurate predictors of listener satisfaction. A small number of low instantaneous Rxlev values or high instantaneous Rxqual values can significantly influence the MOS's but not affect the average Rxlev or Rxqual value. By analyzing the instantaneous variation of these objective measures within each voice segment, further insight might be gained on the behavior of the MOS's. By considering minimum Rxlev or maximum Rxqual values, a better understanding of the nature of the MOS's might be obtained.

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the voice recordings of the PCS 1900 system according to listeners:

1) muting and synthesization of human voice (e.g. "mechanical voice," "blanks"),
2) fading within a voice sample ("voice signals becoming faint"),
3) background noise, especially "echo" (prevalent in most samples), and
4) distortions in higher frequencies ("ringing" or "shrill" sounds during higher frequencies, "inability to hear the letter 's' ").

Most importantly, the nature of the distortions are judged differently by different listeners. In other words, each of the above distortions are weighed on different scales by each listener. Some listeners judged distortions 1 and 2 more harshly than other listeners. Distortions 1 and 2 are most likely related to RSS. Distortions 3 and 4,[3] seemingly not affected by RSS, were also judged more harshly by some listeners than others. This caused voice segments with high Rxlev values to have lower MOS's than expected. Since distortions 1-4 were judged differently by different listeners, the MOS's were affected.

One listener mentioned a concern over his ability to "focus for 2 hours." It is possible that the experimental design was not the most ideal. By being asked to judge the overall quality of a voice segment (over 1 min in duration) a listener tends to average the score to include good parts and bad parts. Their ratings then might be affected more by how the latter part of a segment sounds. They are affected by what is fresh in their minds (recency effect). They may also have been overly influenced by how the beginning of a segment sounded (primacy effect). Because of the length of a given segment, it may have been difficult to concentrate and make an accurate judgment on the entire segment. Alternative experimental design considerations are necessary to ensure that this difficulty in concentrating and making an accurate judgment on the entire segment is not occurring in testing.

[3] Distortions 3 and 4 tended to be more obvious in voice segments where distortions 1 and 2 were not present.

3.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener. The expert listener was trained to emulate the responses of listener panels to the question "Would you consider this acceptable as portable service?" The expert listener rated voice segments according to a three-point scale of acceptability: definitely acceptable, marginally acceptable, and unacceptable. Listener panel responses to this question were used to categorize a voice segment according to this same three-point scale of acceptability. Voice segments were categorized from the listener panel responses as definitely acceptable if more than 70% of the subjects rated the segment as acceptable, marginally acceptable if 30-70% of the subjects rated the segment as acceptable, and unacceptable if less than 30% of the subjects rated the segment as acceptable.

A training software package was developed that outlined sample voice segments for each type of acceptability level determined by listener panel testing. The expert listener was trained using this software package until she could match listener panel ratings of acceptability well. The voice segments used in training were limited to those having listener panel data available. Numerous voice segments for technologies such as Digital European Cordless Telephone (DECT), Personal Handy Phone System (PHS), and Wireless Access Communication System (WACS) were available; however, it is unlikely that all types of digital noise and distortions were represented in the training material.

Figure 3.27 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data. A large variance in percent acceptability is seen for each expert listener rating. A rating of unacceptable, for instance, includes voice segments that were described as acceptable by 90% of the listeners. A rating of marginally acceptable includes voice segments rated as high as 100% acceptable and as low as 0% acceptable. A rating of definitely acceptable includes voice segments rated as low as 50% acceptable. The boxes are elongated, which also show the large spread in data. Based on the data presented in Figure 3.27, the expert listener ratings do not appear to be accurate predictors of listener responses to the question "Would you consider this acceptable as portable service?"

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.89. As would be expected, the relationship between these measures is highly correlated. We would then expect the relationship between MOS and expert listener rating to be similar to that between percent acceptability and expert listener rating. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.54, indicating that a strong linear relationship between these measures does not exist.

The expert listener's ratings were based on the distortion types 1 and 2 that were discussed in Section 3.6.2. This may help explain why the expert listener ratings were not better predictors of MOS's.

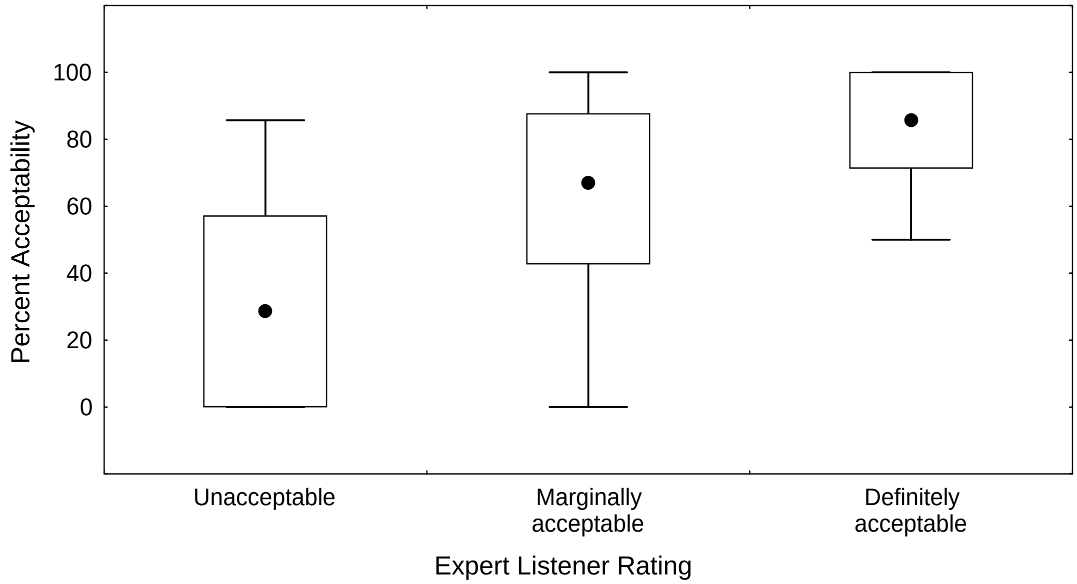


Figure 3.27. Percent acceptability vs. expert listener rating (TAG 5).

It is possible that the combination of expert listener rating, Rxlev, and Rxqual can predict MOS's. A multiple regression analysis was completed in order to determine if MOS is related to a combination of expert listener rating, Rxlev, and Rxqual. The analysis did not consider interactions among factors. The result showed that only 36.8% of the variance can be explained by expert listener rating, Rxlev, and Rxqual together and that these measures reliably account for the 36.8% of variance. From this analysis it appears that, at least at first glance, the combination of expert listener rating, Rxlev, and Rxqual does not offer any substantial predictive power over MOS's.

Expert listener ratings, average Rxlev, and average Rxqual have not offered much insight into the behavior of MOS's during this trial. One must wonder: how valid are the MOS's? Are MOS's really providing an accurate view of listener satisfaction to these voice segments?

3.6.4 Voice Quality Handoff Measurements

Voice quality handoff measurements were not made for the PCS 1900 (TAG 5) technology field trials.

3.7 Manufacturers' Statements

Statements provided by the manufacturers involved in the testing are included in this section. These statements are identical to those given in [1], except for some minor editorial changes.

3.7.1 Motorola, Inc.

Motorola extends its thanks to all participants in this very successful field test. Special thanks are extended to U S West for providing the Boulder Industry Test Bed (BITB) and their very capable technical staff. Additional thanks go to ITS and Northern Telecom for their contributions, as well as all other TAG 5 members who assisted with funding of the testing.

Motorola is pleased to have been part of the TAG 5 field test. As the first technology to complete field testing as required by the JTC, PCS 1900, based on the Groupe Speciale Mobile (GSM) technology, has laid much of the groundwork for other technologies to follow. At the same time, the efficiency and comprehensiveness of the tests have set a high standard by which others will be compared.

Motorola wishes to caution the reader from drawing conclusions about certain aspects of system performance described in this report. The emphasis of the testing was on air-interface aspects of PCS 1900. Fundamental aspects of radio system performance such as coverage, interference immunity, and voice quality were the focus of the test plan. This focused scope, combined with a limited time frame, did not permit any system parameter optimization to take place. As a consequence, inter-BSC functionality (such as handoff) did not perform with the efficiency and reliability that has become the norm in mature GSM systems worldwide.

Other advanced features available with PCS 1900, such as slow frequency hopping (SFH), and advanced frequency re-use schemes, were also outside the scope of the JTC test plan. These and other features are deserving of consideration when assessing the performance of the PCS 1900 air interface.

Certainly, one of the most significant results of this field test was an intrinsic test of inter-operability between multiple manufacturers. Only one month was required to assemble a system comprised of a switch and base stations from multiple vendors, providing seamless handoffs to mobile units from multiple vendors. The success of this venture is a testimony to the open architecture of PCS 1900.

The results of this field test will hopefully serve as a valuable source of information to the PCS industry. Motorola is happy to have been a part of this cooperative effort.

3.7.2 Northern Telecom, Inc.

Northern Telecom would like to acknowledge all the participants for their contributions towards the success of this PCS 1900 technology field trial, the first technology to be tested as required by the JTC. This includes the contributions from all TAG 5 members, Motorola, the staff and facilities of U S West for the use of the BITB, and ITS.

The robustness and maturity of the GSM-based technology is evidenced by two separate manufacturers, in a very short time frame, building a seamless operational network within a metropolitan area. PCS 1900 was the first technology to be tested, and as such encountered some nontechnology dependent testing difficulties. Future tests with other technologies will draw on this experience base with enhanced testing procedures providing more exacting outcomes.

With the time constraints, it was not possible to perform a thorough evaluation on many of the PCS 1900/GSM technology features (e.g., short message, quality control with DTX, frequency hopping, power stepping, and handoff deltas). Handoffs performed correctly for the environment they were set for, but to ensure inter-BSC handoffs in extremely weak areas where no overlap was predicted to occur, deltas and margins were set to values which are not representative of an optimized system.

One would expect that MOS scoring should have a direct correlation with Rxlev and/or Rxqual. Additional analysis must be performed to identify the cause of the low correlation, while recognizing that the system was not optimized for voice quality (e.g., no echo cancellers were deployed towards the public switched telephone network (PSTN) although the BTS/ BSC distance was over 700 mi).

Northern Telecom is pleased to have assisted in the demonstration of PCS 1900, towards the goal of rapid introduction of the technology into the industry. Furthermore, Northern Telecom trusts that these results will be found useful by others in the PCS industry.

4. TAG 2 (IS-95-BASED CDMA SYSTEM) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 2. The technology tested was the PCS variant of the IS-95 cellular CDMA standard. For this field trial, rate set 1 and the IS-96A codec were used. The three-chip base station technology was used. All TAG 2 equipment was provided by Qualcomm, Incorporated. The TAG 2 field tests examined area coverage, handoff, and voice quality of the system.

The information presented in this section is taken from [2]. The reader is referred to [2] for a more complete and detailed presentation of the TAG 2 technology field testing at the BITB.

4.1 TAG 2 Test System Configuration

The block diagram of the test system configuration is shown in Figure 4.1. The test system consisted of the three cell sites (WCO, TMCO, and GMM) and one Qualcomm Telecommunications Switching Office (QTSO) located in Boulder, Colorado. The system functioned as a closed system as calls to and from the public switched telephone network (PSTN) were not allowed during the trial. The QTSO was located at the BITB 28th Street laboratory. As shown in Figure 4.1, the T1 line from each of the TMCO and WCO base stations was connected to a digital cross-connect and fiber multiplexer to provide an OC3 optical link between the base stations and the QTSO. As in the TAG 5 test system configuration, an LOS microwave link was used to provide a partial T1 link between the GMM base station and the WCO base station. For all of the TAG 2 testing, the uplink (mobile transmit) center frequency was set to 1872.99 MHz and the downlink (base station transmit) center frequency was set to 1952.99 MHz.

4.1.1 Simulated Interference

All data were collected in the presence of simulated interference. The interference was simulated on the uplink by the other user noise simulator (OUNS) and on the downlink by the orthogonal channel noise simulator (OCNS).

Uplink capacity was simulated based on the effects of interference from users in the same cell and users in surrounding cells. The noise generated by these other users was modeled as a Gaussian random process simulated by a single "big fictitious" user. The resulting simulated noise of N simultaneous users was injected at the inputs of the IF amplifier. The N simulated users were assigned a desired E_b/N_o (energy per bit to noise density ratio) set point to be maintained (8.5 dB in this testing). This set point was normally set higher than the QTSO recorded E_b/N_o set point as a safety margin to ensure that the interference was at least that of the desired users.

The downlink capacity was simulated by modulating a random information stream on unused Walsh codes. The number of Walsh codes used was fewer than the number of simulated users. To obtain the equivalent power of the simulated number of users, the power in each Walsh code

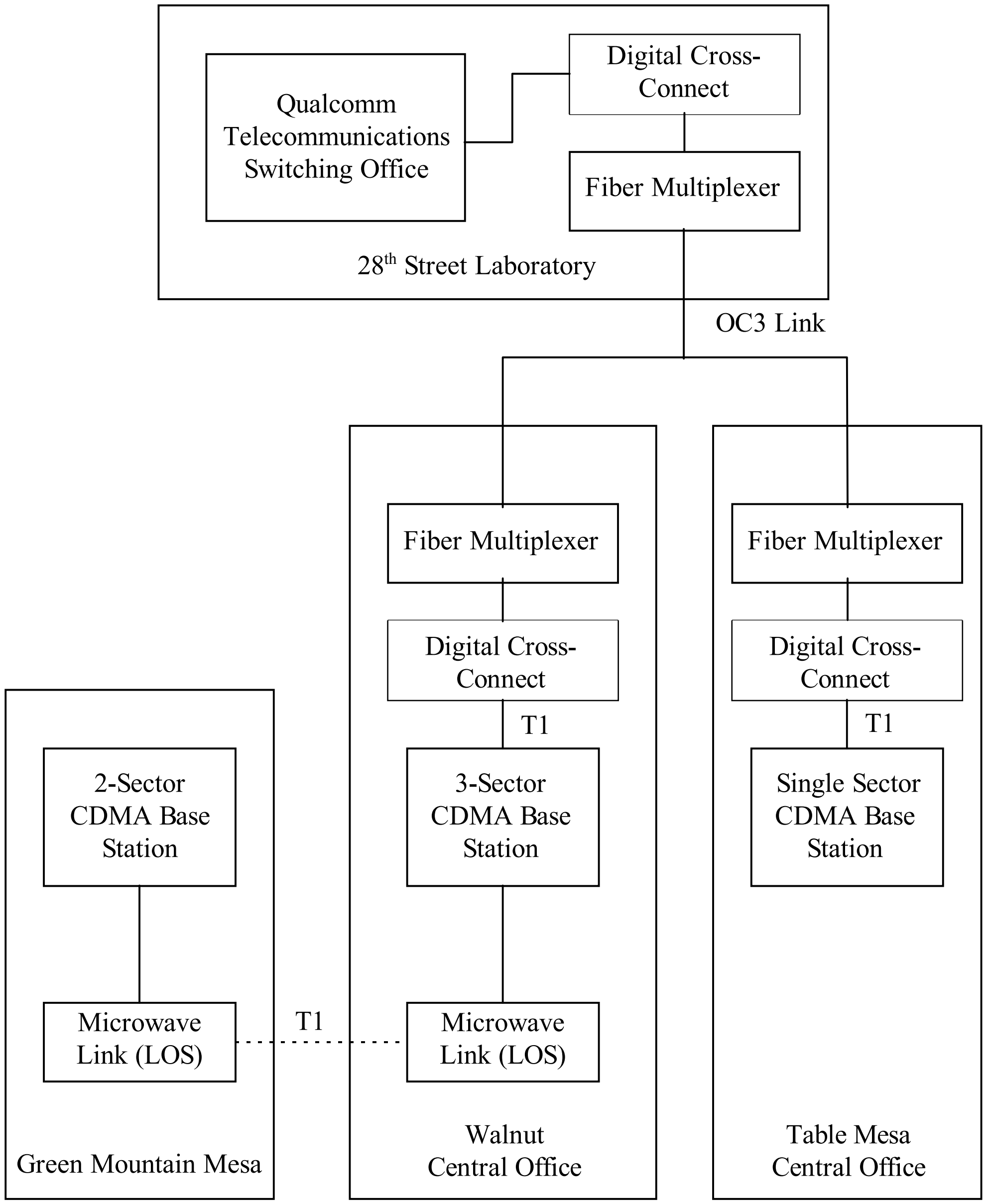


Figure 4.1. Block diagram of the TAG 2 test system configuration.

used for simulation was increased so that the total power was identical to that if a Walsh code was used for each user.

4.1.2 Markov Calls

During the testing of the TAG 2 technology, "Markov" test calls were used to collect link performance statistics. During a Markov test call, the mobile unit and the vocoder/selector (within the QTSO) use synchronized pseudorandom generators and statistical models to generate and verify the data rate and data bits over the air. The data rate of a Markov test call can be set to fixed or variable rates. For a fixed rate, the data rate is set to one of the following values for the duration of the call: full rate (9,600 bps), half rate (4,800 bps), quarter rate (2,400 bps), or eighth rate (1,200 bps). A variable rate Markov call uses a combination of the above rates according to the statistics of a typical voice conversation. The variable rate Markov call produces a voice activity of 40%.

4.2 Calibration

The calibration performed at the field trial for TAG 2 was not a formal calibration of the equipment but was instead a verification of the accuracy of the data measurement reports. Formal calibration of this equipment was carried out by the manufacturer at the factory.

The mobile unit, used for all mobile data logging, was checked for accuracy of the RSS values reported. The reported RSS is the total received signal power within the IF bandwidth and is detected prior to correlation (de-spreading). The base station was connected to the mobile unit via a coaxial cable for this calibration. A known signal level was injected into the mobile unit and compared (taking into consideration the transmission loss) to the RSS value reported on the mobile diagnostic monitor (an instrument that provides information about the operation of the mobile unit). The mobile unit RSS, as reported by the mobile diagnostic monitor, was always within 3 dB of the actual RSS.

The mobile diagnostic monitor gives only a coarse report of the RSS. A more accurate calibration curve for the mobile unit is stored in the data analysis tool (proprietary software from the manufacturer) used for final data processing. The independent observer was provided with a copy of the mobile station factory calibration curve.

A qualitative examination of the base station transmitter characteristics was also performed; however, the results of this examination are not presented here. The base station RSS, and other parameters such as the base station received E_b/N_o, were not examined during this calibration.

4.3 Area Coverage Testing

Measurements to show area coverage were taken with the mobile unit[4] located in a mini-van as in TAG 5 testing. The mobile unit was mounted inside the van on the same wooden structure as used in the TAG 5 testing. The measurements were taken by driving along routes (radials) away from the cell site and filling in-between the radials as time permitted. Markov calls with a 40% voice activity factor were used to generate link performance statistics. The OCNS and the OUNS were set to simulate 10 active users in an embedded cell (i.e., a cell surrounded by other operational cells).

[4] In the JTC test report on TAG 2 testing, a distinction was made between portable and mobile handsets. The mobile handset used an antenna mounted outside of the van while the portable handset used an antenna located in the measurement van. In this section of this NTIA Report, the term mobile unit implies a handset with an antenna located in the measurement van. For purposes of brevity and because it was not a formal part of the JTC PCS technology field trials, TAG 2 measurements performed with an antenna located out of the measurement van are not discussed in this NTIA Report.

Only one cell site was activated at a time during area coverage testing. During the area coverage testing for each cell, all other cell sites were shut down. Softer handoff was allowed between the sectors of the active cell. Softer handoff occurs when the mobile unit initiates communication with a new active serving sector of the same cell while maintaining communication with the currently active serving sector. For each drive route, a Markov call was initiated close to the cell site. Collection of mobile data and cell site data was initiated as the measurement van traveled away from the cell site along the drive route. (In some cases, shadowing or poor coverage caused the call to be dropped on the route; in those cases, the call was reinitiated if the pilot carrier signal[5]-to-interference ratio (E_c/I_o) improved in a short distance.) At the end of the route, the data collection was stopped and the data were saved to disk. The data were collected at the mobile unit and at the QTSO. The data from the different sources were then collated with respect to time and combined to provide a file that included GPS location, velocity, and time; downlink RSS; mobile transmit power; uplink and downlink frame error rate (FER); QTSO target E_b/N_o; uplink E_b/N_o; received pilot E_c/I_o at the mobile unit; and other system parameters. All data were recorded once each second except for the FER statistics. The FER statistics were calculated on a 500-frame basis that corresponds to a minimum 10-s sample time.

In addition to driving from the cell site outward, some routes were also driven in the opposite direction, i.e., driving towards the cell site. These routes were excluded from the analysis in this section for consistency. However, the outbound routes show a lower RSS (by approximately 6 dB) than the inbound routes due to shadowing effects from passengers inside the vehicle and the tinting of all windows in the measurement van except the windshield.

4.3.1 TMCO Area Coverage Data

The data were collected as explained in Section 4.3. Only the north-facing sector was active for this cell site.

Downlink RSS as a function of distance is shown in Figure 4.2. This figure includes the overall data for this cell, excluding RSS values less than -104 dBm. Those values were excluded because -104 dBm is the threshold level for normal system operation. The large variation in RSS is partially due to the fact that the data were taken outside of the north sector coverage area. On the other hand, relatively strong signals (approximately -76 to -82 dBm) exist far away from the cell (approximately 13.5 mi). Those signals were recorded in an area where LOS propagation existed between the base station and mobile unit.

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. Due to the irregularity of the terrain, the RSS varied significantly along the TMCO routes, crossing the -100-dBm level several times before finally staying below -100 dBm. The point along each route where the RSS first dropped below -100 dBm was used to define the coverage boundaries. For this case, the coverage boundaries were approximately 5.7 mi due north-northeast, 3.75 mi due northeast, and 4.44 mi due east. Since the TMCO cell is at a higher elevation than the WCO cell, the TMCO cell had greater coverage in the northern-northeastern direction than the WCO cell.

[5] The pilot carrier signal is an unmodulated spread spectrum signal that is transmitted from a CDMA base station.

Figure 4.3 shows the histogram of downlink RSS values. Again, RSS values less than -104 dBm were excluded. The mean RSS is -91.8 dBm with a standard deviation of 10.0 dB.

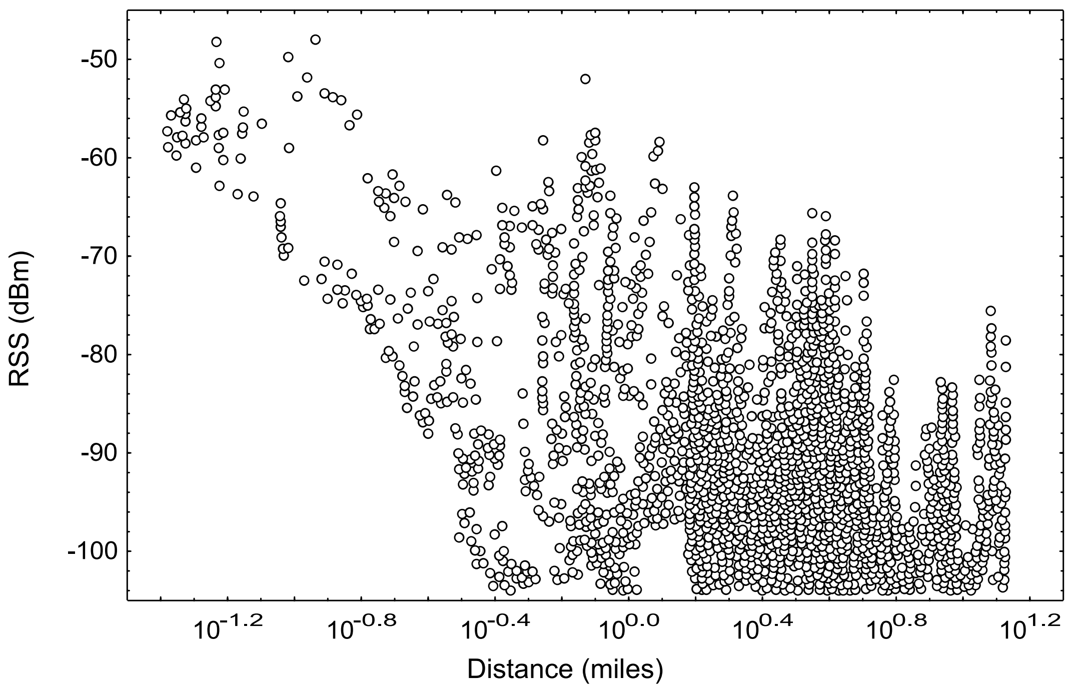


Figure 4.2. Downlink received signal strength (RSS) vs. distance (TAG 2, TMCO cell).

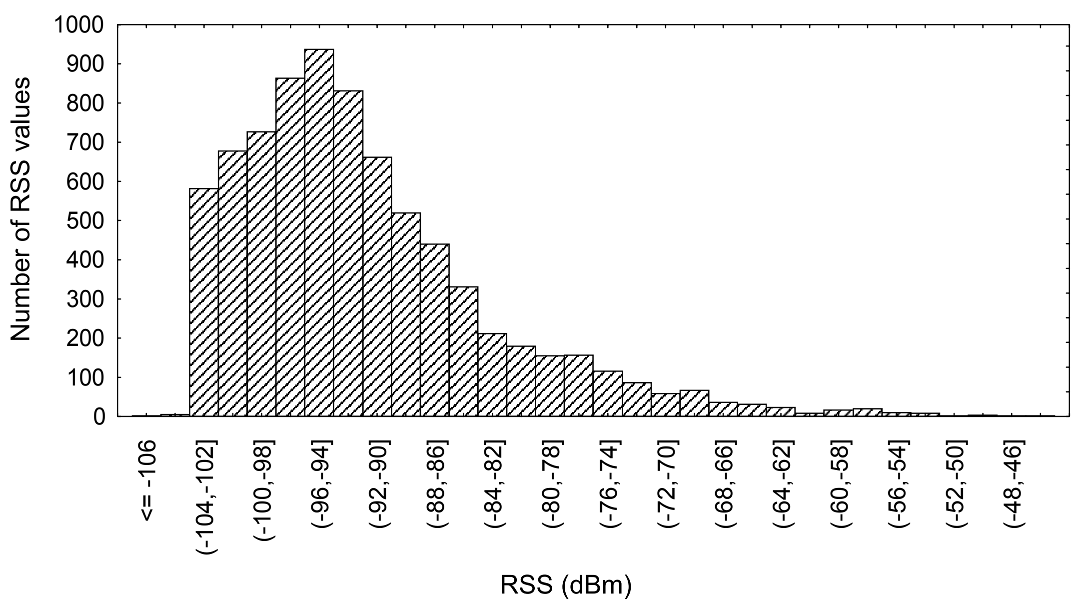


Figure 4.3. Histogram of downlink received signal strength (RSS; TAG 2, TMCO cell).

Figure 4.4 shows the histogram of uplink transmit power. The maximum transmitted power is +26 dBm. Approximately 1.6% of the data points had a transmit power greater than +25 dBm. That indicates that 1.6% of the time, the mobile unit was transmitting at or near its full power capacity. The mobile unit's transmit power increases when its corresponding RSS decreases. The RSS decreases as the mobile unit moves farther away from the cell site or if there is signal loss due to shadowing. The areas where the mobile unit was transmitting at its full power capacity were generally the areas close to the edge of coverage for this cell.

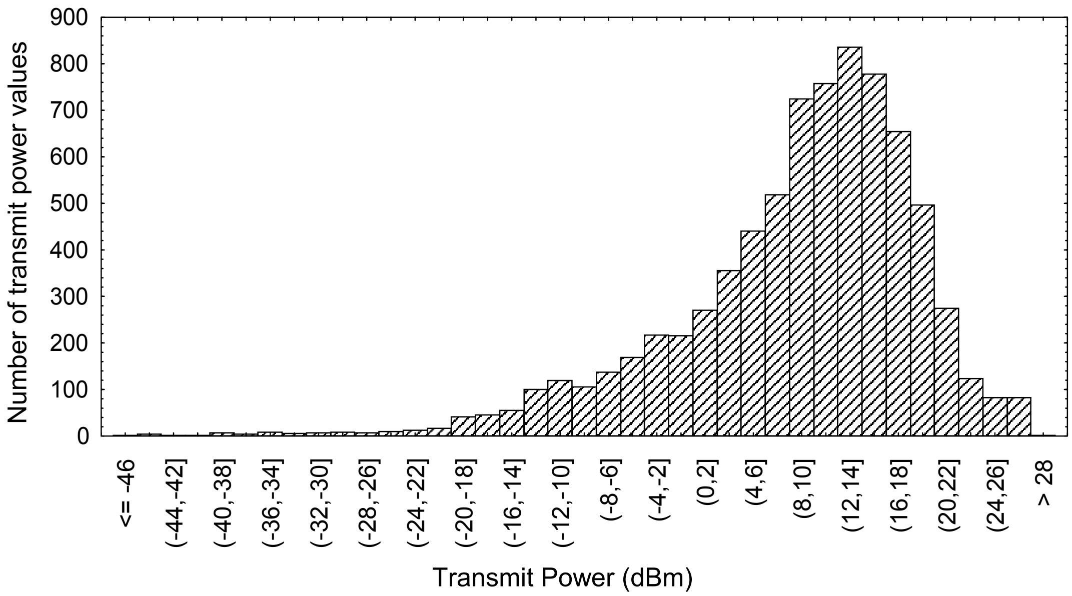


Figure 4.4. Histogram of uplink transmit power (TAG 2, TMCO cell).

The QTSO target E_b/N_o was set by the open loop power control to provide an uplink FER of 1%. When the mobile unit moves outside of the coverage area and can transmit no more power than its maximum rating, the QTSO target E_b/N_o reaches its maximum value (set to 8 dB for this test). When the mobile unit cannot transmit enough power to meet the target E_b/N_o the uplink FER increases above the 1% target. This is clearly seen in Figure 4.5 (a plot of uplink FER vs. QTSO target E_b/N_o). The target E_b/N_o varies between its minimum and maximum values (set to 5 and 8 dB, respectively in this test) in order to keep FER at or below 1%. As the mobile unit moves outside of the region of good coverage, the QTSO target E_b/N_o reaches its maximum and the uplink FER increases until the call is dropped. (Note that the actual uplink E_b/N_o decreases.)

Figures 4.6 and 4.7 show the histograms of the uplink and downlink FER, respectively. These histograms show that most of the FER's for both the uplink and downlink were less than or equal to 1%.

One way to estimate the link balance is to compare the uplink FER and downlink FER. However, the uplink FER and downlink FER were sampled at different times. The time difference varied from one to several seconds. The measurements at the mobile unit

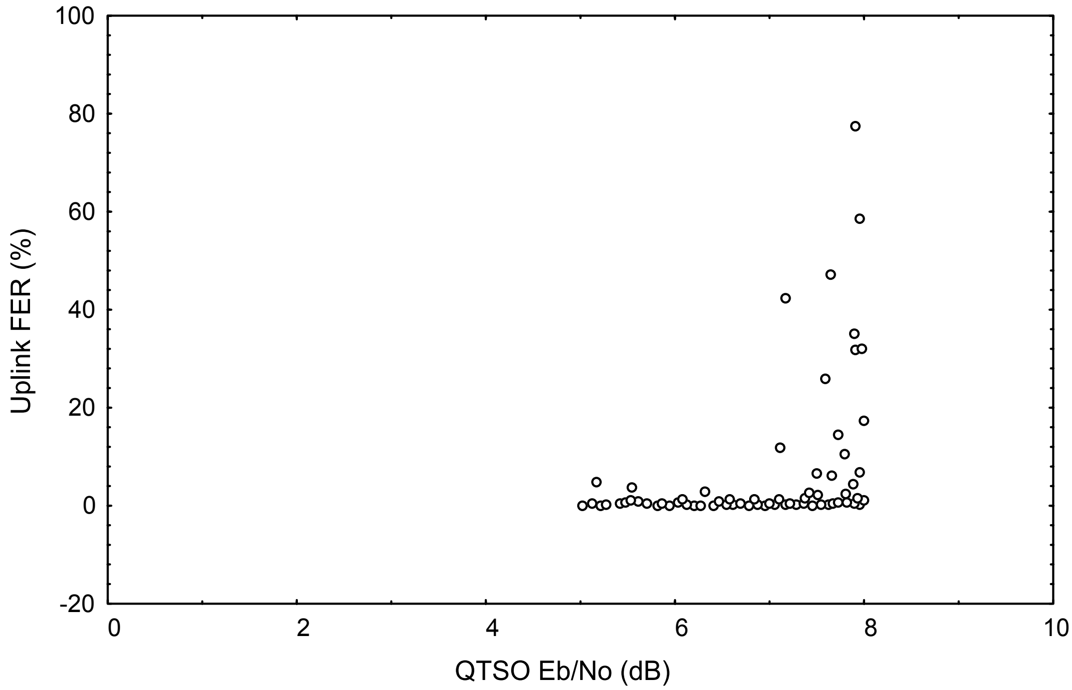


Figure 4.5. Uplink frame error rate (FER) vs. Qualcomm Telecommunications Switching Office (QTSO) target E_b/N_o (TAG 2, TMCO cell).

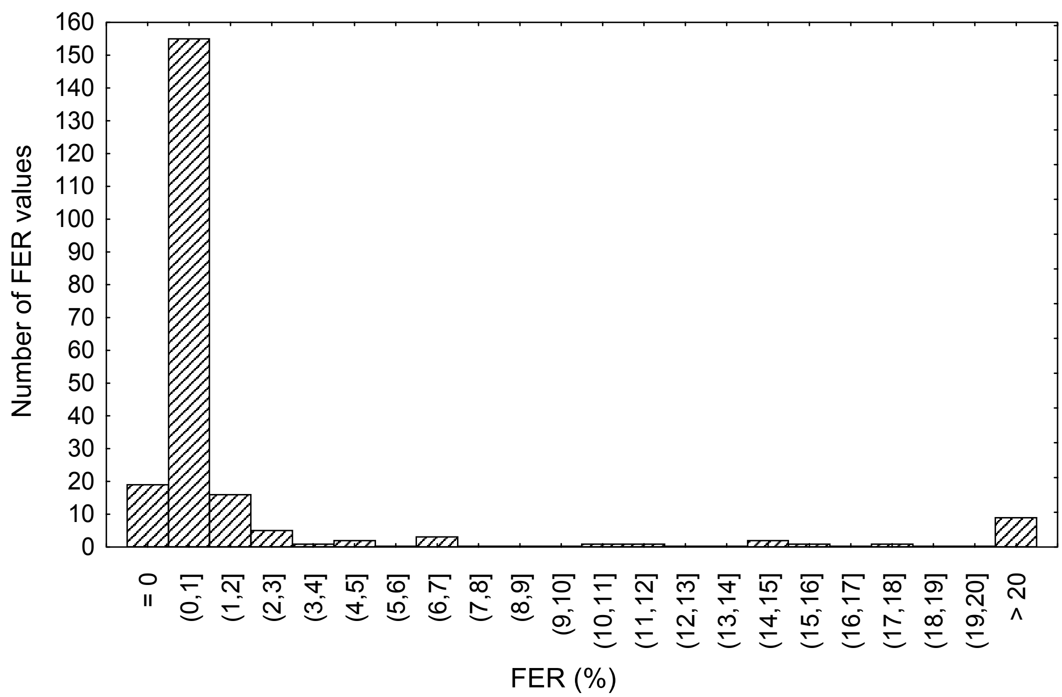


Figure 4.6. Histogram of uplink frame error rate (FER; TAG 2, TMCO cell).

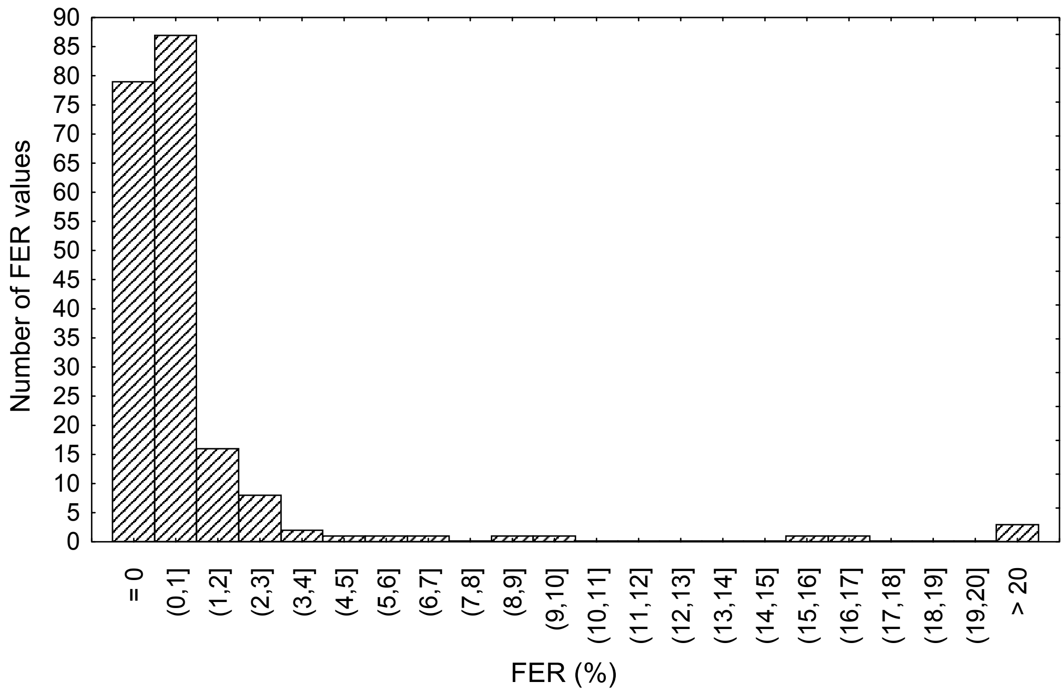


Figure 4.7. Histogram of downlink frame error rate (FER; TAG 2, TMCO cell).

correspond to speeds varying from a full stop (at the traffic lights) to 55 mph. Due to the difference in sample times, the uplink and downlink FER measurements were taken at different physical points — up to 400 ft apart. In order to make a fair analysis of the link balance, it is essential to collect uplink and downlink data at the exact same spot (within a few feet). Therefore, while it is possible to analyze the link balance on an averaged basis, the link balance analysis was not performed for the JTC TAG 2 technology field trial.

4.3.2 WCO Area Coverage Data

The data were collected in the WCO cell in the same manner as in the TMCO cell. This procedure is explained in Section 4.3. All three sectors were active for the WCO cell.

Downlink RSS as a function of distance is shown in Figure 4.8. The data included in this figure are the overall data for this cell, excluding RSS values less than -104 dBm. Those values were excluded because -104 dBm is the threshold level for normal system operation. As with the TMCO area coverage, there is a large variation in the RSS for a given distance. This is due to shadowing in the light urban environment and the choice of routes. Note that there exists a single RSS value of approximately -100 dBm 8 mi away from the WCO cell site. This maximum coverage distance for the WCO cell is significantly less than the maximum coverage distance for the TMCO cell (13.5 mi).

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. The point along each route where the RSS first dropped below -100 dBm was used to define the coverage boundaries. For this case, the coverage boundaries were 1.4 mi due north, 4.5 mi due east, and 1.6 mi due southeast and due west. Once the RSS dropped below -100 dBm in these directions, it generally stayed below that value. Due to the lower elevation of the WCO cell (relative to the TMCO cell) and the terrain profile, this cell had a smaller total coverage area than the TMCO cell.

Figure 4.9 shows the histogram of downlink RSS values. Again, RSS values less than -104 dBm were excluded. The mean RSS is -89 dBm with a standard deviation of 13.5 dB. Figure 4.10 shows the histogram of uplink transmit power. The maximum transmitted power is +26 dBm. Approximately 2.8% of the data points had a transmit power greater than +25 dBm. That indicates that 2.8% of the time the mobile unit was transmitting at or near its full power capacity. The areas where the mobile unit was transmitting at its full power capacity were the areas close to the edge of coverage for this cell or where significant shadowing occurred.

Figure 4.11 shows a plot of the uplink FER vs. the QTSO target E_b/N_o. The target E_b/N_o varies between 5 and 8 dB in order to keep FER at or below 1%. As the mobile unit moves outside of the region of good coverage, the QTSO target E_b/N_o reaches its maximum and the uplink FER increases until the call is dropped.

Figures 4.12 and 4.13 show the histograms of the uplink and downlink FER, respectively. As seen for the TMCO cell, these histograms show that most of the FER's for both the uplink and downlink were less than or equal to 1%.

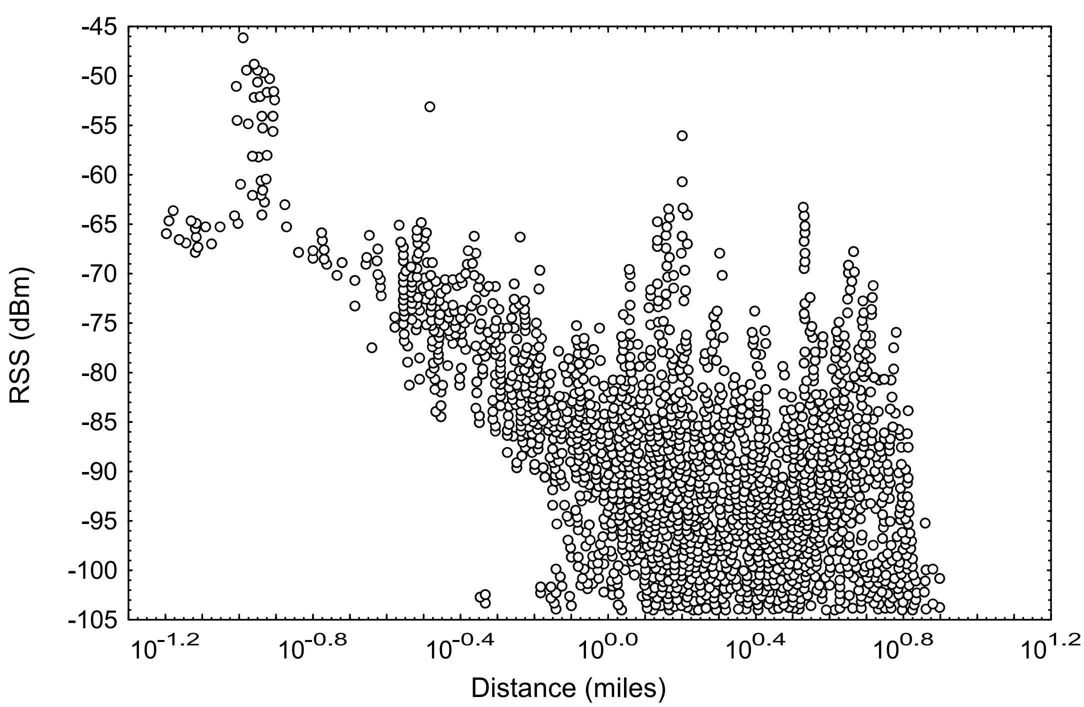


Figure 4.8. Downlink received signal strength (RSS) vs. distance (TAG 2, WCO cell).

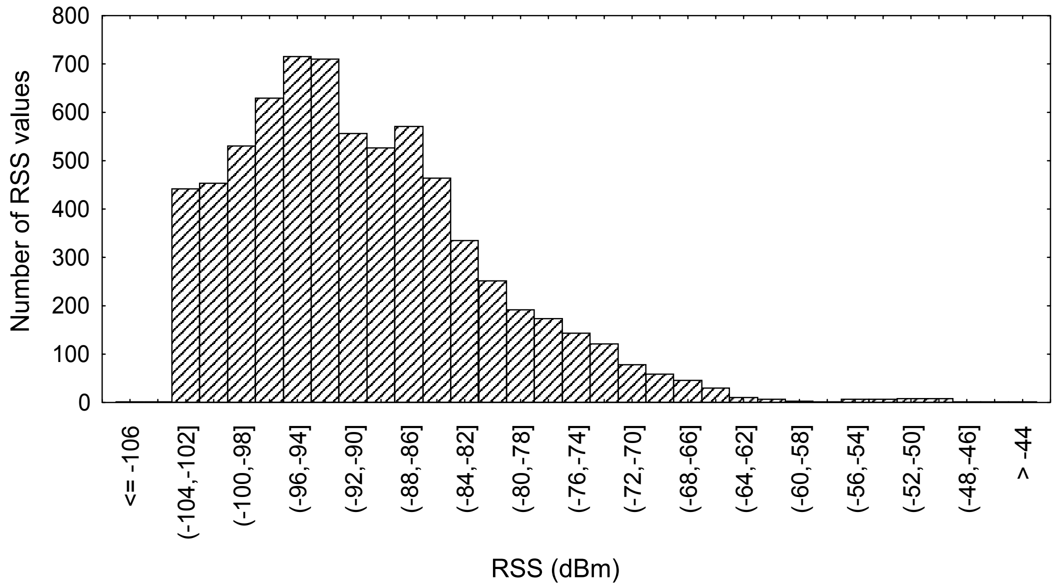


Figure 4.9. Histogram of downlink received signal strength (RSS; TAG 2, WCO cell).

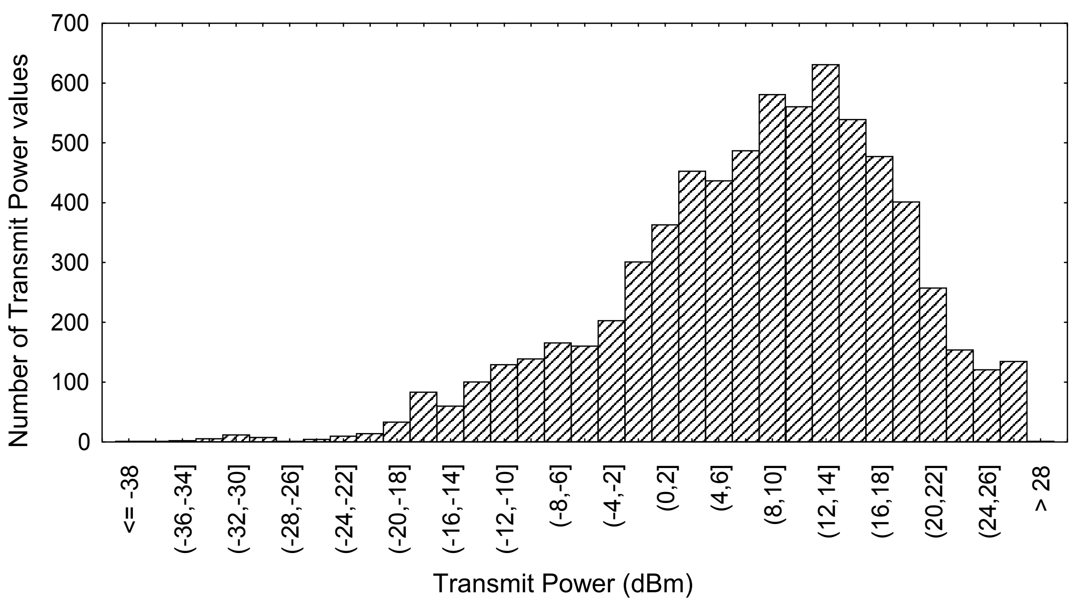


Figure 4.10. Histogram of uplink transmit power (TAG 2, WCO cell).

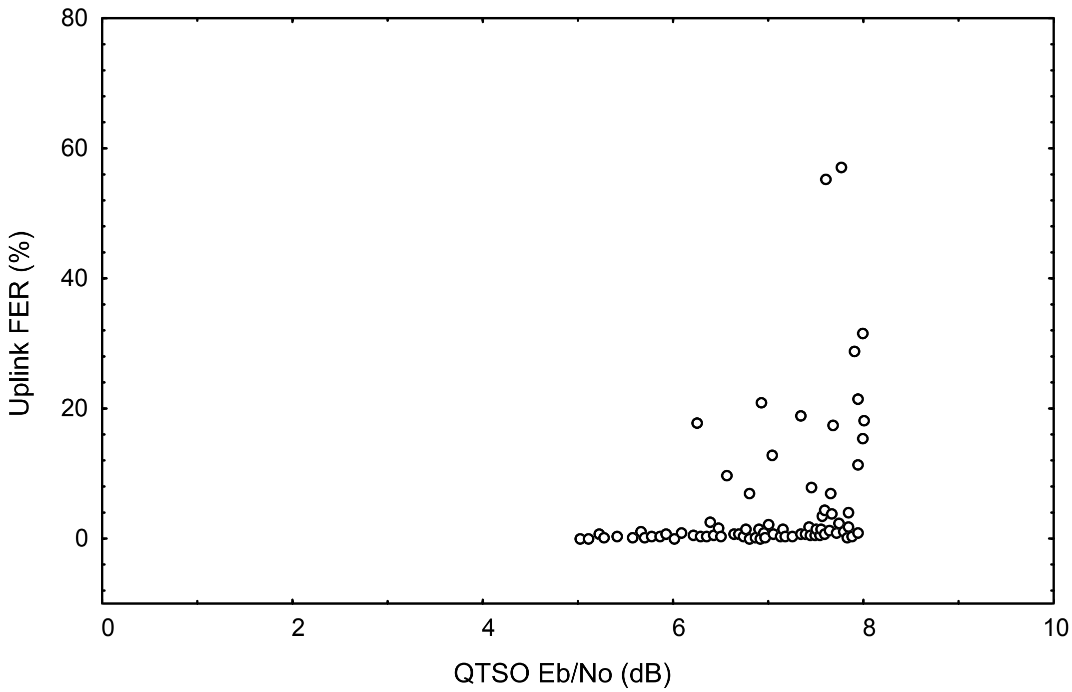


Figure 4.11. Uplink frame error rate (FER) vs. Qualcomm Telecommunications Switching Office (QTSO) target E_b/N_o (TAG 2, WCO cell).

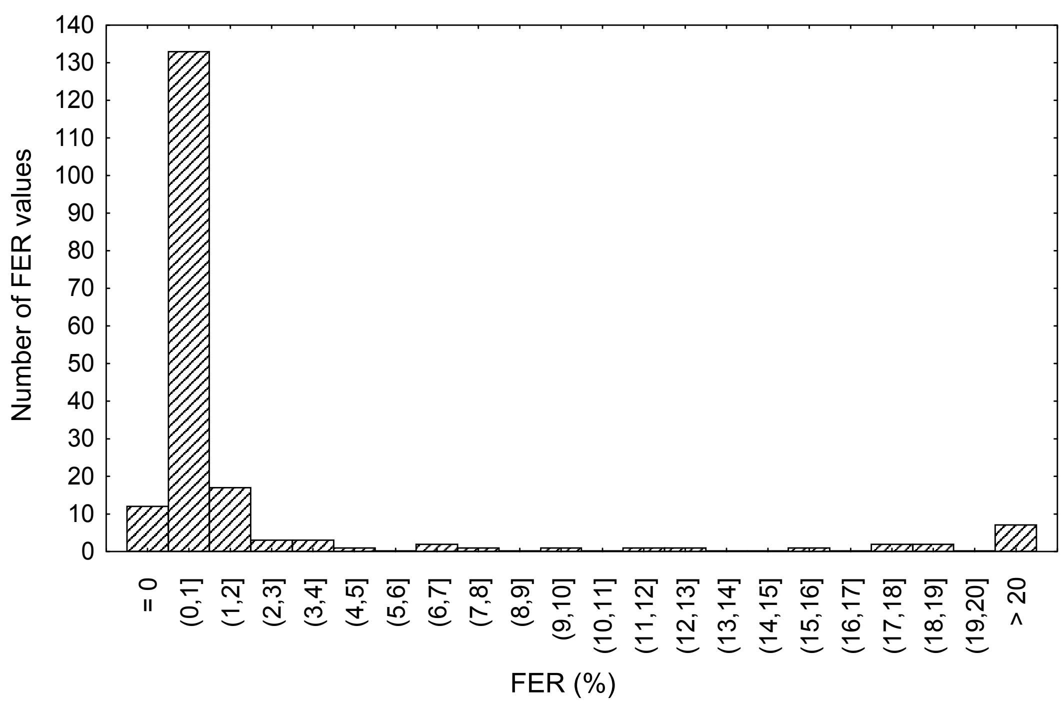


Figure 4.12. Histogram of uplink frame error rate (FER; TAG 2, WCO cell).

4.4 Handoff Testing

The north sector for the TMCO cell site and all three sectors of the WCO cell site were activated for the handoff testing. Soft handoff was employed. Soft handoff[6] occurs when the mobile station initiates communication with a new serving cell or sector while maintaining communication with the currently active serving cell or sector. Handoff testing was performed by driving the measurement van and collecting data along routes that would pass through the coverage area of both the TMCO and WCO cell sites and each active sector within the WCO cell site. Markov calls were used for the handoff testing. The system handoff parameters were set as follows:

Add Pilot Threshold (T_ADD) = -14 dB
Drop Pilot Threshold (T_DROP) = -16 dB
Active Set vs. Candidate Set Threshold (T_COMP) = 5 dB
Drop Pilot Timer Value (T_TDROP) = 6 s.

An explanation of how these parameters affect handoff is quite detailed and can be found in [3]. Data analysis for handoff testing for the TAG 2 technology consisted of determining the handoff state as a function of geographic location and the percentage of time the network was in a particular handoff state (no handoff, soft handoff, softer handoff, etc.).

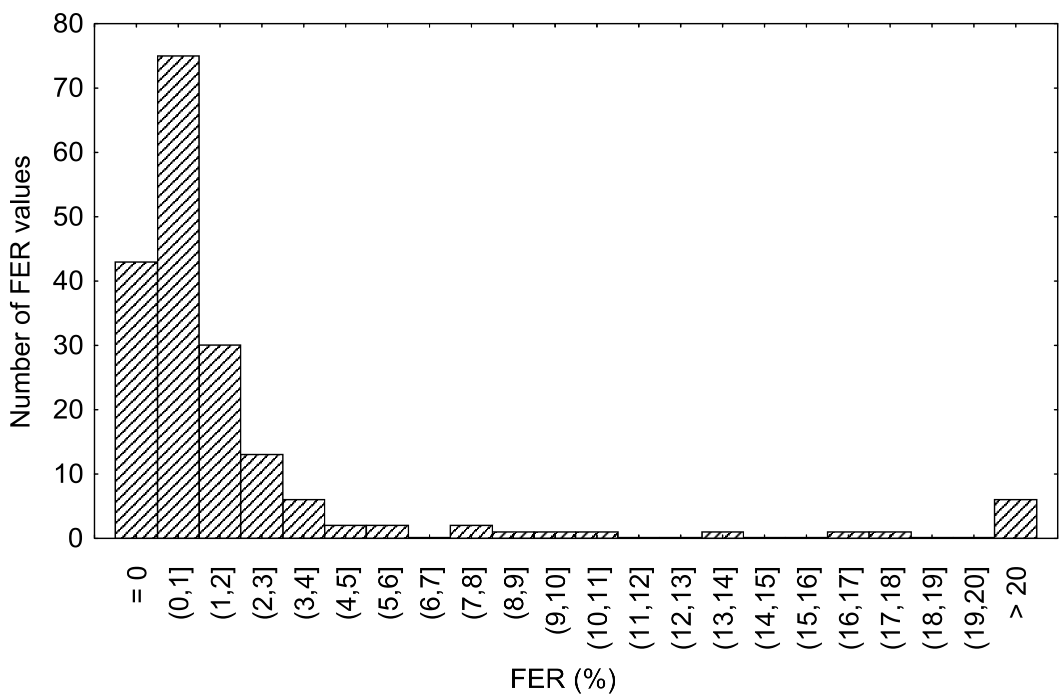


Figure 4.13. Histogram of downlink frame error rate (FER; TAG 2, WCO cell).

[6] More formally, soft handoff occurs between two active cells, softer handoff occurs between two active sectors of the same cell, soft-softer handoff occurs between two active sectors of the same cell and another active cell, and softer-softer handoff occurs between three active sectors of a given cell.

The results of the analysis of handoff state as a function of geographic location showed that no handoff was observed in the immediate vicinity of both the TMCO and WCO cells. Soft handoff was present in the open areas east of Boulder, where both the TMCO and WCO cells had overlapping coverage. Softer handoff was pronounced in areas where the signal from neighboring sectors in the WCO cell were overlapping. Soft-softer handoff occurred in the open areas along Foothills Parkway, east-northeast of Boulder. In this area, two sectors from the WCO cell overlap and there is LOS propagation to the TMCO cell. There are a few other isolated areas where soft-softer handoff occurred, but in a less consistent manner than along Foothills Parkway.

The percentage of time during the handoff testing that the system was in a particular handoff state was then determined. No handoff occurred 37% of the time, soft handoff occurred 40% of the time, softer handoff occurred 9% of the time, and soft-softer handoff occurred 14% of the time.

The percentage of locations in soft handoff is quite high. This occurred because the coverage area for the WCO cell was contained within the coverage area for the TMCO cell (i.e., the WCO cell was an embedded cell in this configuration). Soft handoff occurred frequently because the pilot carrier signals from both the TMCO and WCO cells had a high E_c/I_o. Due to the light load of the system, the pilot carrier signals have a high E_c/I_o. With increasing load, the E_c/I_o of each of the pilot carrier signals decreases. The E_c/I_o of the pilot carrier signal for the original cell sector decreases along with the E_c/I_o of the pilot carrier signals from cell sectors other than the original cell sector. Because the E_c/I_o of the pilot carrier signals from cell sectors other than the original cell sector decreases, there is less potential for handoff to occur and the percentage of measurement locations with no handoff increases. (The manufacturer stated that the system was not optimized for the given test configuration and cell spacing. Instead, the system used the same settings used in other Qualcomm CDMA tests.)

4.5 Interference Testing

Separate interference testing was not performed during the TAG 2 testing because all measurements were made with simulated interference as described in Section 4.1.1.

4.6 Voice Quality

As discussed in Section 3.6, two types of voice quality measurements were made for the PCS JTC technology field trials in general: quasi-stationary measurements and handoff measurements. Both types of measurements were performed for the IS-95-based CDMA (TAG 2) technology.

4.6.1 Quasi-stationary Measurements

Voice recordings and various objective measures including RSS, uplink and downlink FER, and QTSO target E_b/N_o were collected at locations on a 0.5-mi grid that encompassed the expected coverage area for the TMCO and WCO sites. Measurements were taken at 69 of the 82 locations that were identified for the quasi-stationary measurements as discussed in Section 3.6.1. The specific locations used are shown on the map in Figure 4.14. Both the TMCO and WCO cells were activated for these measurements. (In the TAG 5 testing, recall that only one cell was activated at a time.) At each location data were collected as the measurement van traveled at one of two speeds. The vehicle traveled either 10 m or 100 m over the sample time. The particular vehicular speed used at each location (distance traveled over a fixed sample time) is shown on the map in Figure 4.14.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the uplink and downlink simultaneously. The source tape transmitted over each link was the same as that used for TAG 5 testing (see Section 3.6.1).

The received voice transmissions were recorded on digital audio tape simultaneously at the receiver for the uplink and at the receiver for the downlink. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. At each location, the objective measures including downlink RSS; uplink and downlink FER; QTSO target E_b/N_o; and GPS location, velocity, and time were collected during a separate measurement performed after the voice transmissions were recorded. The separate measurements used full-rate Markov calls to approximate the 75% voice activity of the source tape.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

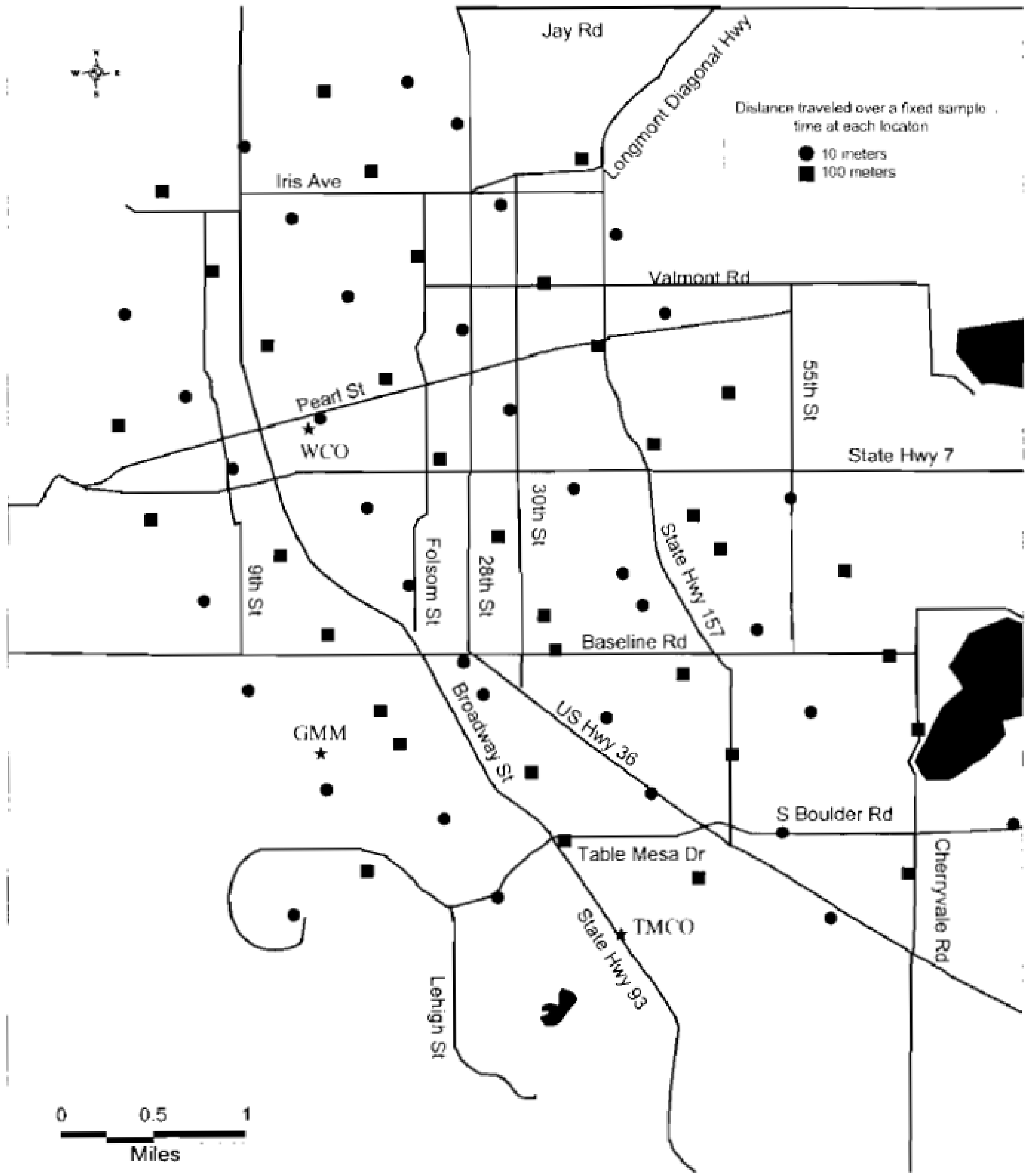
4.6.2 Mean Opinion Score Assessment

To accomplish the MOS testing, a pool of 31 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, 35-45, 45-55, and those over 55 years of age. There were an equal number of male and female subjects. The subjects were cordless, noncellular telephone users.

Four groups consisting of seven or eight subjects from the subject pool were formed. The subjects were asked to rate voice segments by answering the three questions listed in Section 3.6.2 after each segment was presented.

First the subjects in each of the four groups were presented 10 practice voice segments[7] to rate. The practice segments included two 64-kbps wireline voice segments and six segments recorded over a speech codec in Qualcomm's lab. The 64-kbps wireline voice segments consisted of one good quality voice segment from a field measurement and one poor quality

[7] The quantity and type of practice segments presented to the listener panels for the IS-95-based CDMA (TAG 2) testing (as well as the other subsequent JTC PCS technologies) was different from that presented to the listener panels for the PCS 1900 (TAG 5) testing. More practice segments were used and the use of more 64-kbps wireline voice segments was initiated.



Maps made with Mapinfo Professional TM

Figure 4.14. Quasi-stationary measurement locations and vehicular speed used at each location for TAG 2.

voice segment from a field measurement. Each of these wireline segments was presented twice. The codec segments used in training were either full-rate or half-rate segments, with an average FER of either 0%, 1%, 3%, or 5%. The goal was to demonstrate a wide range of quality in the practice segments presented to listeners. It was felt that the voice segments collected during the quasi-stationary measurements did not represent the full range of quality needed, therefore the codec segments were recorded in the lab. The practice segments allowed inexperienced listeners to gain exposure to the full range of possible voice quality, from excellent to poor, and ensured proper scaling of the MOS's.

After the practice segments were presented, the subjects in each of the four groups were asked to rate 33 voice segments: 3 reference voice segments and 30 voice segments from the field trial measurements. Every listener within a group listened to the same voice segments. The reference voice segments were either 64-kbps wireline segments or poor quality voice segments collected from the field measurements. The 30 voice segments from the field trial measurements came from the uplink or downlink measurements at 60 out of the 69 measurement locations. Only 60 of these locations were used in the MOS testing to limit the number of voice segments each listener had to rate. As stated earlier, each of the voice segments from the field trial measurements consisted of 10 male and 10 female sentences. For the MOS testing, the first sentence and the last sentence of each recorded voice segment were not used. This was done to avoid the possible inclusion of sentences that had been cut short due to starting a recording too late or stopping a recording too soon. Therefore, during MOS testing, a total of 18 sentences (out of the original 20 sentences) were presented to listeners for each segment. For each segment, nine male sentences and nine female sentences were presented. The nine male sentences were presented before the nine female sentences half of the time. In addition, the order of presentation of the voice segments was randomized. Subjects were given a 15- to 20-min break half way through the session. After all segments were presented, subjects filled out a post-trial questionnaire.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain an MOS. The results from all four of the groups (a total of 120 voice segments) are shown in the histogram in Figure 4.15. Overall, the voice segments were rated favorably, with 88% of the segments rated between fair and excellent. The average MOS was 3.56 and the standard deviation was 0.50.

Figures 4.16 and 4.17, show histograms of MOS's for the uplink and downlink, respectively. The average MOS for the uplink was 3.65 and for the downlink was 3.47. A t-test revealed that there was a statistically significant difference in the average MOS's between the uplink and downlink.

The relationship between the MOS's and some of the objective measures was initially investigated by generating some scatter plots. Figure 4.18 shows the relationship between the MOS's and the average downlink RSS. For each MOS, the average RSS is the average of the measured RSS values computed over the duration of the voice segment. In Figure 4.18, a large variation in MOS's is seen for all values of average RSS. Figures 4.19 and 4.20 show the relationship between the MOS's and the average FER for both the uplink and downlink,

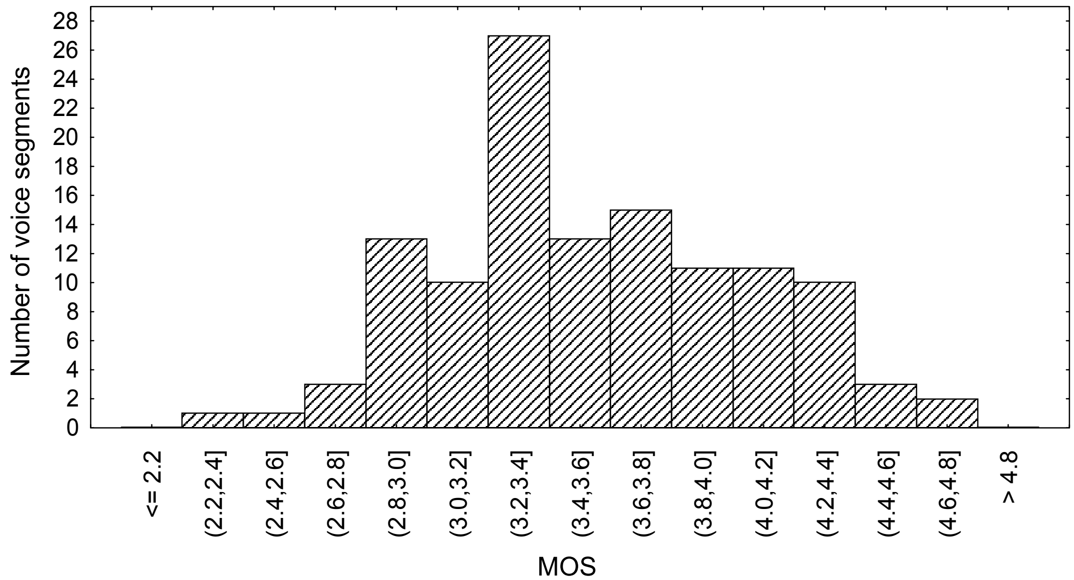


Figure 4.15. Histogram of mean opinion scores (MOS's) for all voice segments (TAG 2).

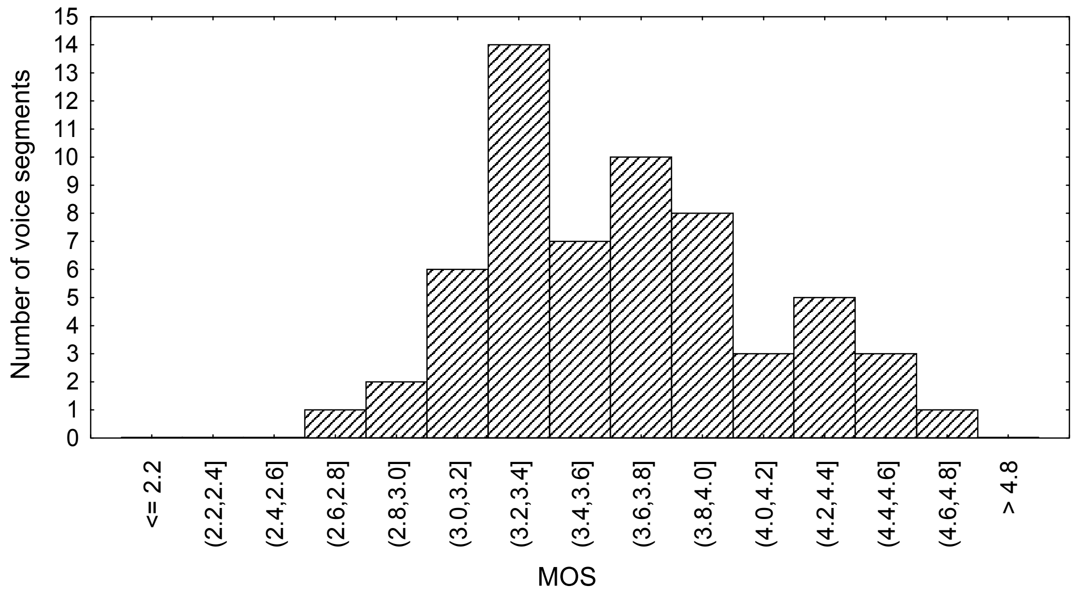


Figure 4.16. Histogram of mean opinion scores (MOS's) for the uplink (TAG 2).

respectively. As with the average RSS, for each MOS, the average FER is the average of the measured FER values computed over the duration of the voice segment. A large variation in MOS's for all average FER's on both the uplink and downlink is seen in Figures 4.19 and 4.20. The RSS and the FER, when averaged over the entire voice segment, do not appear to be accurate predictors of listener satisfaction.

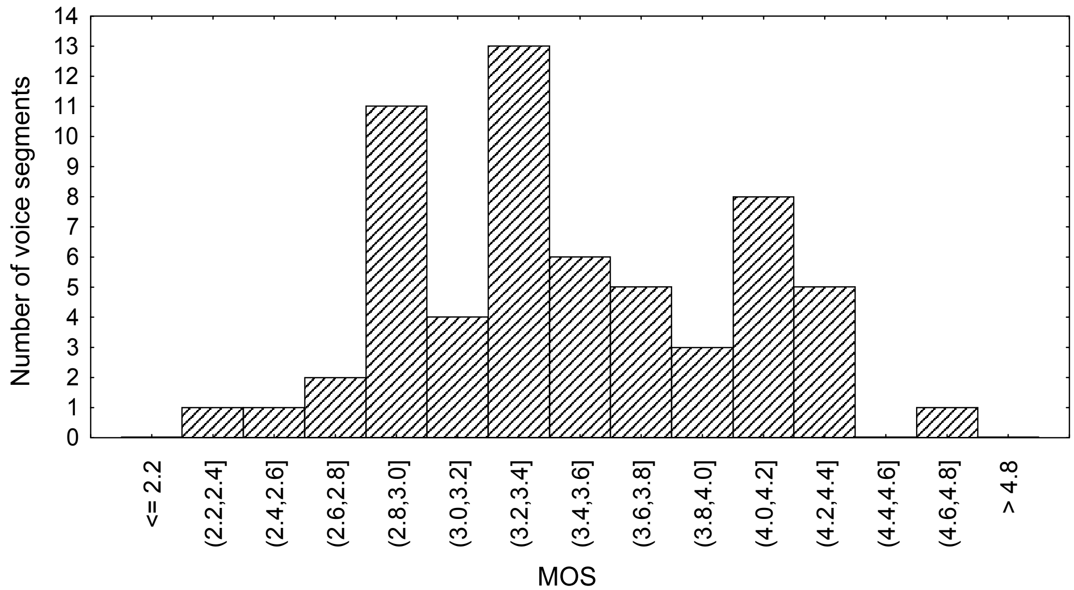


Figure 4.17. Histogram of mean opinion scores (MOS's) for the downlink (TAG 2).

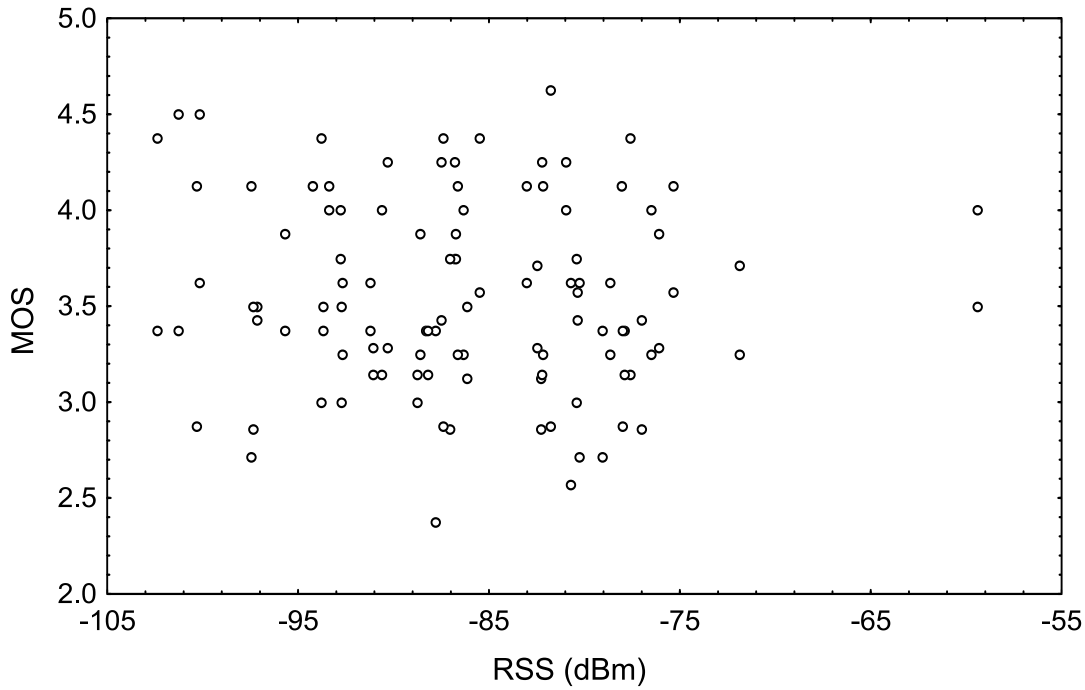


Figure 4.18. Mean opinion score (MOS) vs. average downlink received signal strength (RSS; TAG 2).

Pearson product-moment correlations were performed to determine the correlation between MOS's and average RSS, MOS's and average FER, and MOS's and other objective measures. The correlation coefficient between MOS and average RSS was -0.08 and that between MOS and average FER was 0.01. The highest correlation coefficient between MOS and any objective measure, that between MOS and average mobile transmit gain adjust, was only 0.15. These very low correlations between MOS and averaged objective measures suggest that a linear relationship between MOS and the objective measures does not exist.

While there does not appear to be linear relationship between MOS and the objective measures, there still may be a consistently increasing or decreasing relationship between them. The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average downlink RSS, between the ranks of MOS and the ranks of average FER, and between the ranks of MOS and the ranks of other objective measures. The Spearman rank correlation coefficient between MOS and average downlink RSS was -0.08 and that between MOS and average FER was 0.05. The highest Spearman rank correlation coefficient between MOS and any objective measure, that between MOS and average QTSO target E_b/N_o, was only 0.16. These very low rank correlations between MOS and averaged objective measures suggest that a consistently increasing or decreasing relationship between MOS and the objective measures does not exist.

Note that the objective measures were averaged over the entire length of the voice segment. By analyzing the instantaneous variation or possibly minimum and maximum values of the objective measures within the voice segment, further insight may be gained on the behavior of MOS's.

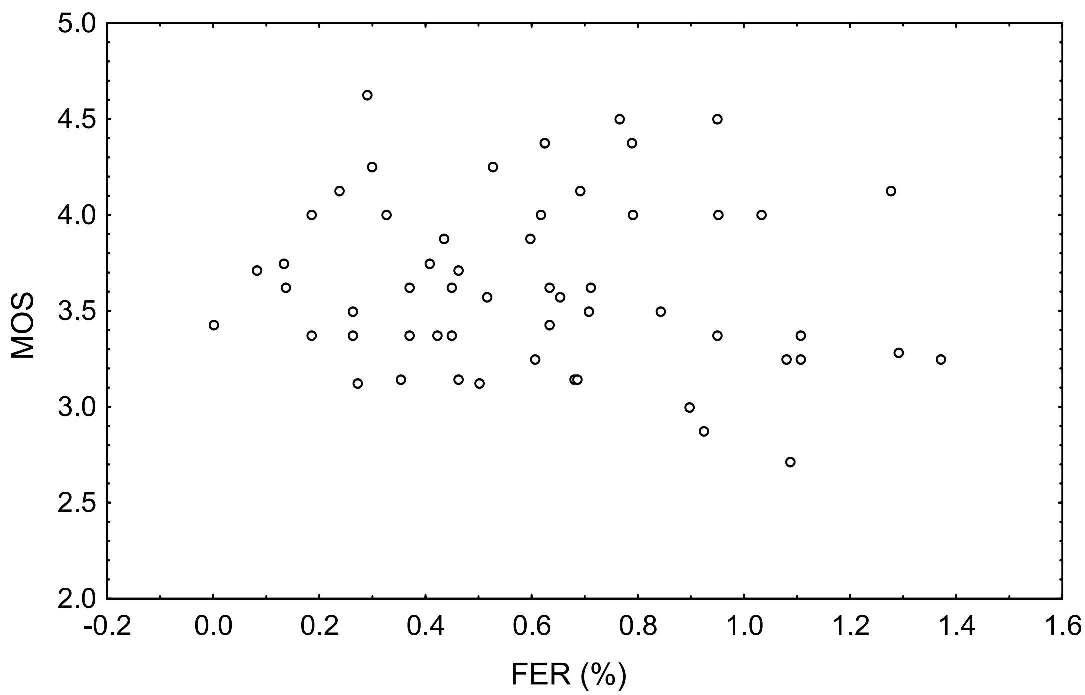


Figure 4.19. Mean opinion score (MOS) vs. uplink frame error rate (FER; TAG 2).

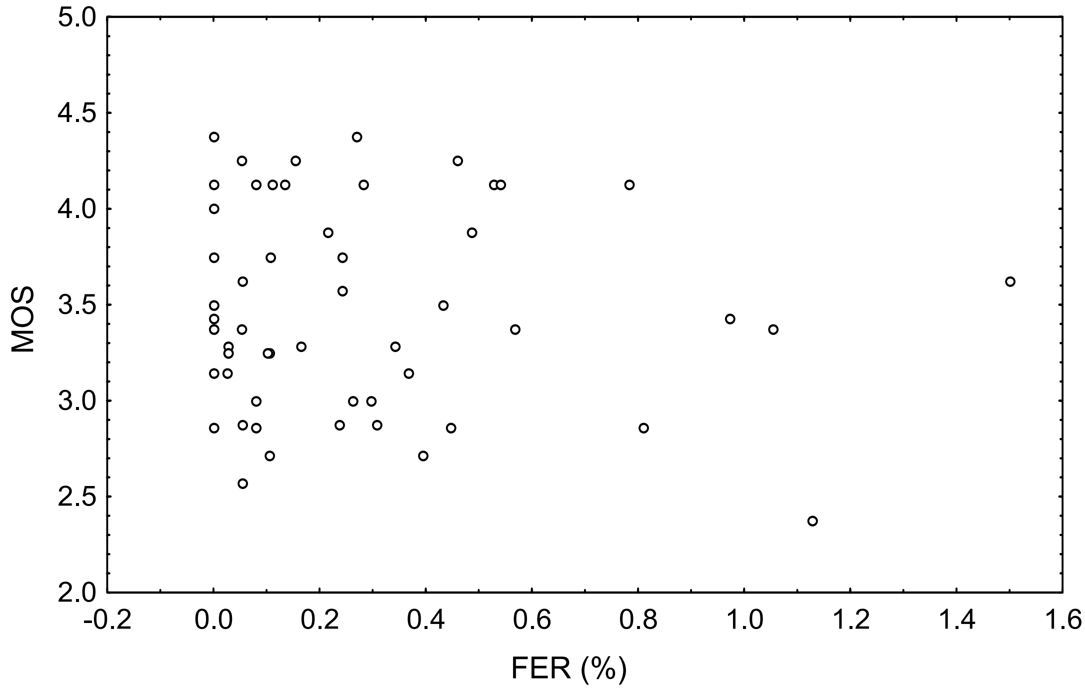


Figure 4.20. Mean opinion score (MOS) vs. downlink frame error rate (FER; TAG 2).

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the voice recordings of the IS-95-based CDMA system according to listeners:

1) echo;
2) fading/muting;
3) synthesized voice;
4) "chirping," or "squeaking" background noise; and
5) a clearer male (vs. female) voice.

The nature of these distortions are likely judged differently by different listeners. Intelligibility and speaker recognition are two main aspects of perceived quality. In the case of most of the voice segments for the IS-95-based system, intelligibility remained high. The above-mentioned types of distortions seem to affect a listener's ability to recognize the speaker more than their ability to understand the speech. As a result, overall MOS's were high. However, it is of interest to note that the MOS's were significantly lower in one particular group of listeners with average MOS's of 2.95 vs. the average of 3.56 over all MOS's.

There were more women aged 35 and above in this group than any other. Compared to other age/gender groups, marked differences in MOS's for this demographic group were seen. Two of the women in this group stated in their post-test questionnaires that the female voice was more degraded than the male voice in many of the voice segments. When asked whether their ratings of acceptability would have changed if told to consider them as wireline samples vs. portable, the answer was no for all four women over 35 in this group. One hypothesis for explaining the differences in MOS's for this demographic group is that female listeners are harder "graders" of quality than others. Another hypothesis is that female listeners are more sensitive to distortions in higher frequencies, and the voice segments reflected such a distortion. Further research is necessary to pinpoint whether there is a significant difference between ratings given by females over the age of 35 and those given by others, and to pinpoint potential reasons for this. It is still unclear at this stage why some listeners were harder "graders" than others.

The variability in scoring may indicate subjects graded voice segments with unrealistic criteria. Many of the voice segments were nearly identical in quality, and yet judged quite differently by the same subject. This might indicate randomness in scoring among listeners. Further analysis may pinpoint the likelihood of random or unrealistic scoring.

4.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener. The expert listener ratings followed the identical procedure as in the PCS 1900 (TAG 5) testing. This procedure is described in Section 3.6.3.

Figure 4.21 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data.

For the most part, the definitely acceptable ratings of the expert listener were relatively good indicators of percent acceptability. In the definitely acceptable category, most of the voice segments were rated as acceptable by 70-100% of the subjects; a few voice segments were rated as acceptable by less than 70% of the subjects. The mean percent acceptability in the definitely acceptable category was 90.2%, well within the target range of 70-100%. The marginally acceptable and unacceptable expert listener categories show more variance. For the voice segments rated as marginally acceptable by the expert listener, the mean percent acceptability was 71.9%, slightly above the target range of 30-70%. The mean percent acceptability associated with voice segments rated as unacceptable by the expert listener was 59.5%, well above the target 30% and below.

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.67. This indicates some correlation between these quantities as would be expected. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.40, indicating that a strong linear relationship between these measures does not exist.

It is possible that expert listener rating, downlink RSS, FER, and the other objective measures including transmit gain adjust, mobile transmit power, mobile received pilot E_c/I_o, QTSO target E_b/N_o, and QTSO forward power control gain can be predictors of MOS when all are taken together. A multiple regression analysis was completed in order to determine if MOS is

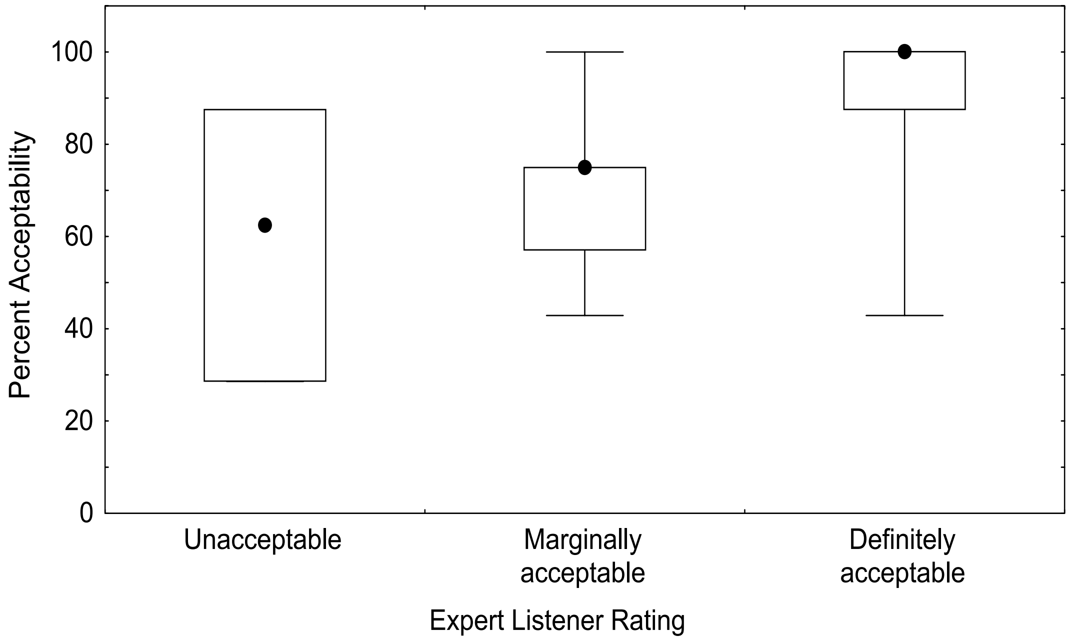


Figure 4.21. Percent acceptability vs. expert listener rating (TAG 2).

related to a combination of all the above factors. Interactions among the various factors were not considered in the analysis.

The result showed that only 21% of the variance can be explained by expert listener rating, downlink RSS, FER, and the other objective measures listed above. The result of the multiple regression analysis also showed that all these factors reliably account for the 21% of variance. From this analysis, it appears that at least at first glance, the expert listener rating, downlink RSS, FER, and the other objective measures listed above taken together do not offer any substantial predictive power over MOS's.

4.6.4 Voice Quality Handoff Measurements

Continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. While the measurement van was in motion, an audio source tape was transmitted over the uplink and downlink simultaneously. The source tape consisted of Harvard sentences and was played continuously as the measurement van traveled along each route. The received voice transmissions were recorded on digital audio tape at the receiver for the uplink and at the receiver for the downlink. Continuous voice recordings were made along the route until the call was finally dropped. The routes were selected according to previous tests at the BITB. One route was driven along Broadway, at a vehicular speed of 25-30 mph. The second route was driven along Foothills Parkway, at a vehicular speed of 55-60 mph. The beginning of a route was selected within the coverage area. Two runs were conducted along each route, one traveling from the north to the south, and the other in the opposite direction. Voice quality was assessed using the expert listener methodology described in Section 3.6.3.

For the voice quality handoff testing, an expert listener rating was made for each 4-s period of the continuous voice recordings taken along a measurement route. This equates to roughly one rating per sentence.

Handoffs were indistinguishable to the expert listener, including soft, softer, and soft-softer handoffs. In general, voice quality remained good until the coverage boundaries were approached. Then, voice quality dropped quickly, most likely due to dramatic changes in terrain.

4.7 Manufacturer's Statement

The statement provided by Qualcomm Incorporated is included in this section. This statement is identical to that given in [2], except for some minor editorial changes.

Qualcomm Incorporated would like to thank U S West and ITS for their support during the demonstration of the performance of the U S CDMA PCS radio air interface at 1.9 GHz at the BITB in Colorado. The test bed is operated by U S West. In particular, the support provided by M. Laflin of ITS and the technical staff of U S West is acknowledged and very much appreciated. Qualcomm would further like to thank all TAG 2 participants for their hard work in completing the ANSI J-STD-008, personal station-base station compatibility requirements for 1.8- to 2.0-GHz CDMA PCS, and for their support of this test. Funding for the test was provided by Qualcomm, AT&T, Motorola, Nokia, and Nortel.

Qualcomm was pleased to supply equipment to demonstrate the CDMA PCS air interface in the BITB as part of the standardization requirements of the JTC. TAG 2 of the JTC developed the PCS standard which is based on TIA/EIA dual mode cellular CDMA standard IS-95-A. The resulting ANSI PCS standard has been approved for publication by both T1P1 and TR46.

The CDMA system performed quite well as the results of the testing show. The results are consistent with trials of the CDMA PCS technology in other locations. CDMA provided consistently high voice quality and excellent coverage. The test was conducted with a loading equivalent to 10 calls in every sector of each cell using a single CDMA radio channel.

Because of time constraints, there was no attempt to tune or optimize the system used in Boulder, Colorado. As a result, the percentage of soft handoff is higher than would be targeted in an operational deployment. An interesting test would have been to investigate the influence of the handoff parameters and higher load on the percentage of soft handoffs and overall system performance.

The roving test system (RTS) used for the JTC tests is a noncommercial test system that employs older 3-chip CDMA technology in the base station. The more recently available single chip cell-site modem (CSM) that is being employed in operational CDMA systems requires about 2 dB less E_b/N_o on the reverse traffic channel (uplink) — the exact amount depends upon the multipath environment. In addition, in the BITB tests, the 8-kbps IS-96-A speech codec was used. Higher voice quality is provided in deployed CDMA systems tests that use the more recently available 13-kbps speech codec.

5. TAG 4 (IS-136-BASED SYSTEM) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 4. The technology tested was the PCS variant of the IS-136 cellular TDMA standard. The base station equipment was provided by AT&T Network Wireless Systems and the mobile units were provided by Ericsson and Nokia. The TAG 4 field tests examined area coverage, handoff, and voice quality; and the effects of co-channel and adjacent channel interference on system performance.

The information presented in this section is taken from [4]. The reader is referred to [4] for a more complete and detailed presentation of the TAG 4 technology field testing at the BITB.

5.1 TAG 4 Test System Configuration

The block diagram of the test system configuration is shown in Figure 5.1. The test system consisted of the three cell sites in Boulder, Colorado (WCO, TMCO, and GMM) and one mobile switching center (MSC) supplied by AT&T. Plain old telephone service (POTS) was provided remotely by an AT&T switch located in Whippany, New Jersey. The MSC was also located in Whippany, New Jersey. The MSC was connected to the WCO cell site via a T1 circuit. The T1 circuit connects to the MSC by using a digital automatic cross connect system (DACS) and two T1 circuits. Connection was made to the WCO base station by using a micro DACS (μDACS). Another T1 circuit connects the MSC to the TMCO base station.

The TAG 4 system that was tested during the field trials was based on an IS-136 cellular A-band system upbanded to PCS D-band frequencies. An analog control channel was used in accordance with the IS-136 specification. The base station and mobile unit transmit frequencies in the PCS-D band are shown in Table 5.1.

5.2 Calibration

A calibration of the base station RSS was performed by injecting a digitally modulated signal of known level into the receiver and then generating a table of scale factors used by the logging software to provide accurate RSS reports during the field trial. This was done for all active sectors at each cell site.

The input signal into the base station receiver was provided by a digital modulation signal generator. Losses in the cabling between the signal generator and the input of the base station receiver were measured and a correction, or offset, was added to the signal generator output-level reading. The level of the input signal was varied over the dynamic range of the receiver to generate the table of scale factors. Note that for this calibration procedure, the diversity branch of the receiver was terminated with a 50 Ω load.

The mobile units (provided by Ericsson and Nokia) were checked for accuracy of the reported RSS values. This was done by injecting a digitally modulated signal of known strength directly

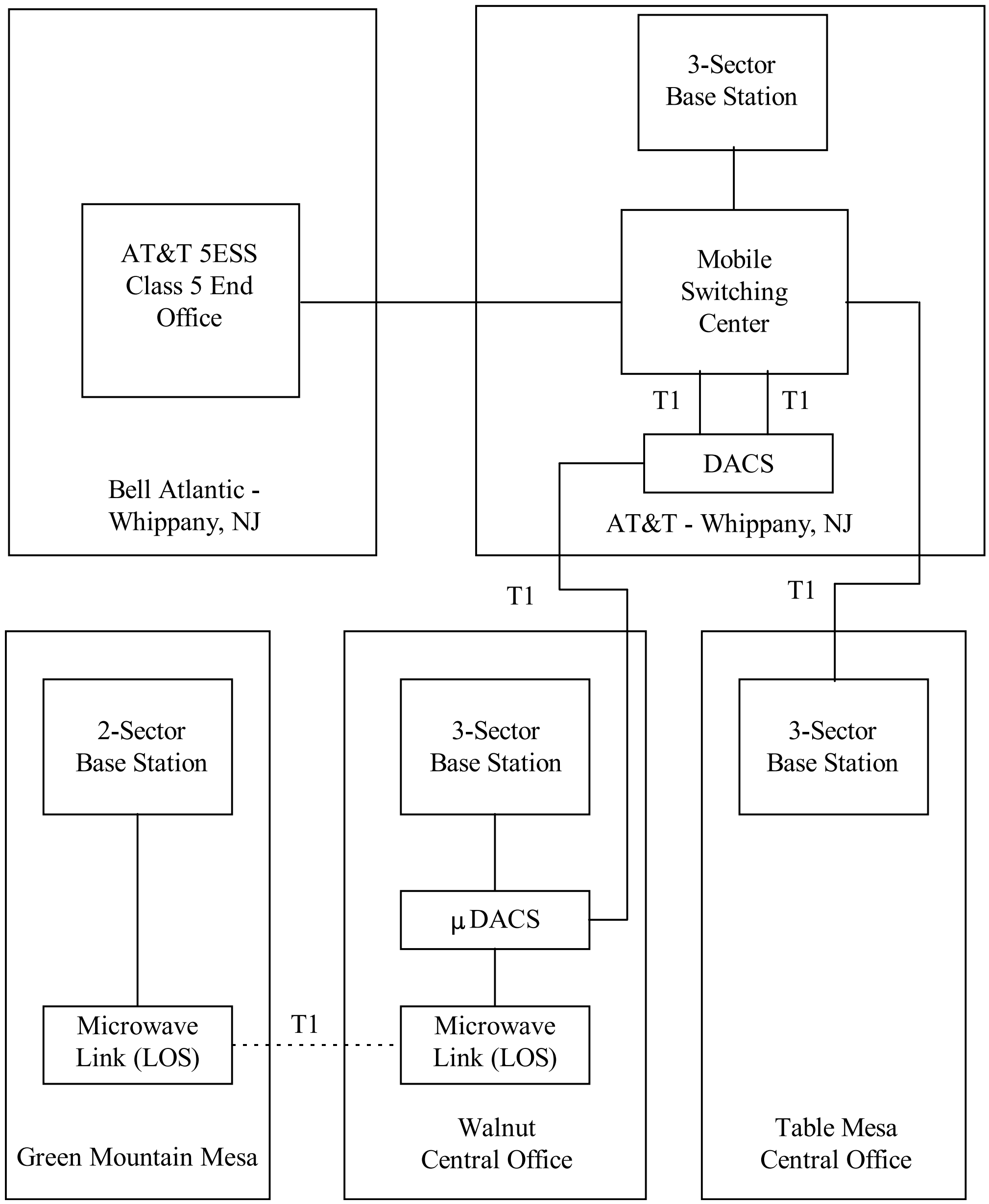


Figure 5.1. Block diagram of the TAG 4 test system configuration.

into the antenna port of the mobile unit. The level of the input signal was then compared to the RSS value reported by the mobile unit. All of the mobile units had reported values of RSS within 4 dB of the actual input signal level. Note that both the Ericsson and Nokia mobile units report RSS in 2-dB steps.

5.3 Area Coverage Testing

To provide maximum coverage area, both the base station and the mobile unit used full power outputs. The base station power for each cell site was set so that the output power was approximately 50 W ERP. Measurements to show area coverage were taken with the mobile

Table 5.1. TAG 4 Base Station And Mobile Unit Transmit Frequencies

Cell Site	Sector	Type of Channel	PCS Channel #	Mobile Unit Transmit Frequency (MHz)	Base Station Transmit Frequency (MHz)
WCO	North	Control	632	1868.94	1948.98
WCO	North	Traffic	532	1865.94	1945.98
WCO	Southeast	Control	635	1869.03	1949.07
WCO	Southeast	Traffic	535	1866.03	1946.07
WCO	Southwest	Control	628	1868.82	1948.86
WCO	Southwest	Traffic	528	1865.82	1945.86
GMM	North	Control	644	1869.30	1949.34
GMM	North	Traffic	544	1866.30	1946.34
GMM	Southeast	Control	637	1869.09	1949.13
GMM	Southeast	Traffic	537	1866.09	1946.13
TMCO	North	Control	625	1868.73	1948.77
TMCO	North	Traffic	525	1865.73	1945.77
TMCO	Southeast	Control	639	1869.15	1949.19
TMCO	Southeast	Traffic	539	1866.15	1946.19
TMCO	Southwest	Control	642	1869.24	1949.28
TMCO	Southwest	Traffic	542	1866.24	1946.28

unit[8] located in a mini-van as in both the TAG 5 and TAG 2 testing. The mobile unit was mounted inside the van on the same wooden structure used in all of the JTC PCS technology field trials. This structure is described in Section 3.3. The measurements were taken by driving along routes (radials) away from the cell site. When time permitted, measurements along additional routes in between the radials were taken.

Only one cell site was activated at a time during area coverage testing; all other cell sites were powered down. Handoff was allowed between the sectors of the active cell. The data were collected both at the mobile unit and at the base station. The data collected at the mobile unit included GPS location, velocity, and time; downlink RSS; downlink BER class; and downlink FER (or number of frame errors); in addition to other system parameters. BER class is a measure of the average BER and is related to the average BER as shown in Table 5.2. The data collected at the base station included GPS time, uplink RSS, uplink FER (actually number of frame errors), uplink number of bits in error per second, and downlink RSS and BER class (as reported by the mobile unit), in addition to other system parameters.

Calls were originated from the mobile unit prior to the start of data collection. Collection of mobile data and base station data was initiated as the measurement van began traveling away from the cell site along the drive route. In some cases, shadowing or poor coverage would cause the call to be dropped along the route; in those cases, the call was reinstated if the RSS improved in a short distance. At the end of the route, the data collection was stopped and the data were saved to disk. All data collected were averaged over 1 s. Because of mobile unit sampling rate problems, the data reported by the mobile unit to the base station (and recorded at the base station) were used in the data analysis instead of the data recorded at the mobile unit. Therefore, the downlink FER was not available for the data analysis; downlink BER class was used instead.

[8] Measurements were also taken with an antenna mounted on the roof outside of the mini-van. For purposes of brevity and because it was not a formal part of the JTC PCS technology field trials, TAG 4 measurements performed with the antenna located out of the measurement van are not discussed in this NTIA report.

Table 5.2. Relationship Between Bit Error Rate (BER) Class and Average BER

BER Class	Average BER
0	less than 0.01%
1	0.01% to less than 0.1%
2	0.1% to less than 0.5%
3	0.5% to less than 1.0%
4	1.0% to less than 2.0%
5	2.0% to less than 4.0%
6	4.0% to less than 8.0%
7	greater than 8.0%

5.3.1 TMCO Area Coverage Data

The test procedure followed and data collection methodology used are explained in Section 5.3. All three sectors were active for this cell site. The mobile units used for the TMCO cell were manufactured by Ericsson.

Downlink RSS as a function of distance is shown in Figure 5.2. The data included in this figure are the overall data for this cell, excluding RSS values less than -109 dBm. RSS values less than -109 dBm were excluded because -109 dBm is the threshold level for normal system operation of the mobile unit receiver. The large variation in RSS seen in Figure 5.2 is due to the irregularity of the terrain. Note that relatively strong signals (approximately -72 to -80 dBm) exist far away from the cell (approximately 12.5 mi). Those signals were recorded in areas having LOS propagation between the mobile unit and the base station.

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. Due to the irregularity of the terrain, the RSS varied significantly along the TMCO routes, crossing the -100 dBm level several times before finally staying below -100 dBm. The point along each route where the RSS first dropped below -100 dBm was used to define the coverage boundaries. For this case, the coverage boundaries were approximately 8.6 mi north-northeast, 3.2 mi to the northeast, 4.8 mi due east, and 2.71 mi due south. Due to the higher elevation of this site (relative to the WCO cell), this cell had greater coverage in the northern-northeastern direction than did the WCO cell.

Figure 5.3 shows the histogram of downlink RSS values. Again, RSS values less than -109 dBm were excluded. The mean RSS is -88.2 dBm with a standard deviation of 10.0 dB. Figure 5.4 shows a histogram of the uplink RSS values for the TMCO site.

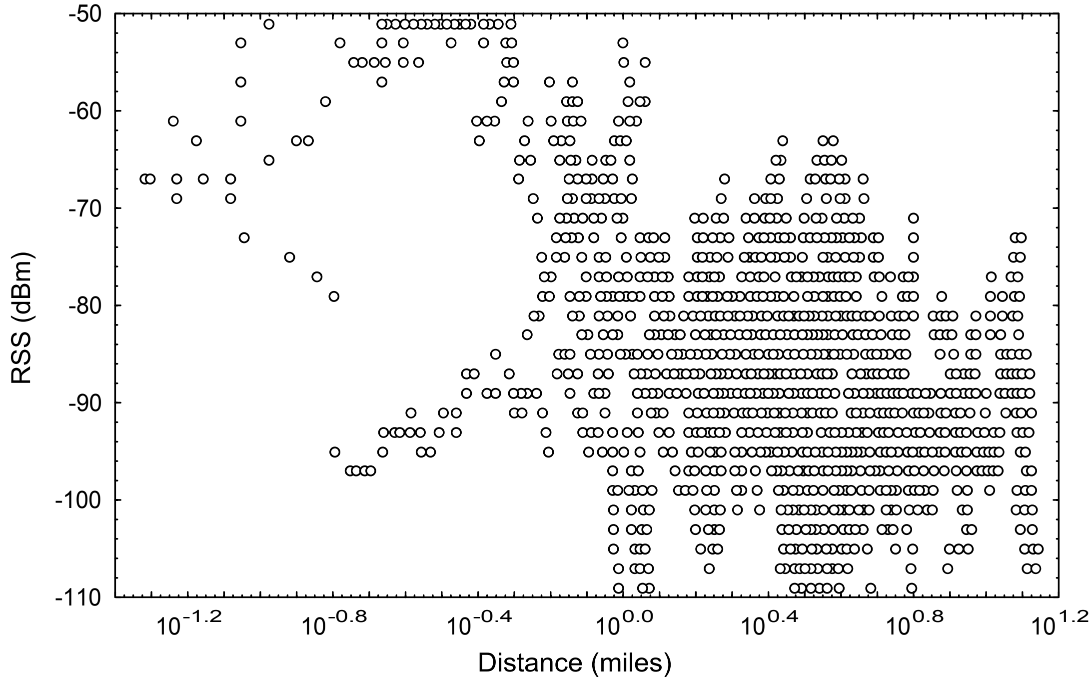


Figure 5.2. Downlink received signal strength (RSS) vs. distance (TAG 4, TMCO cell).

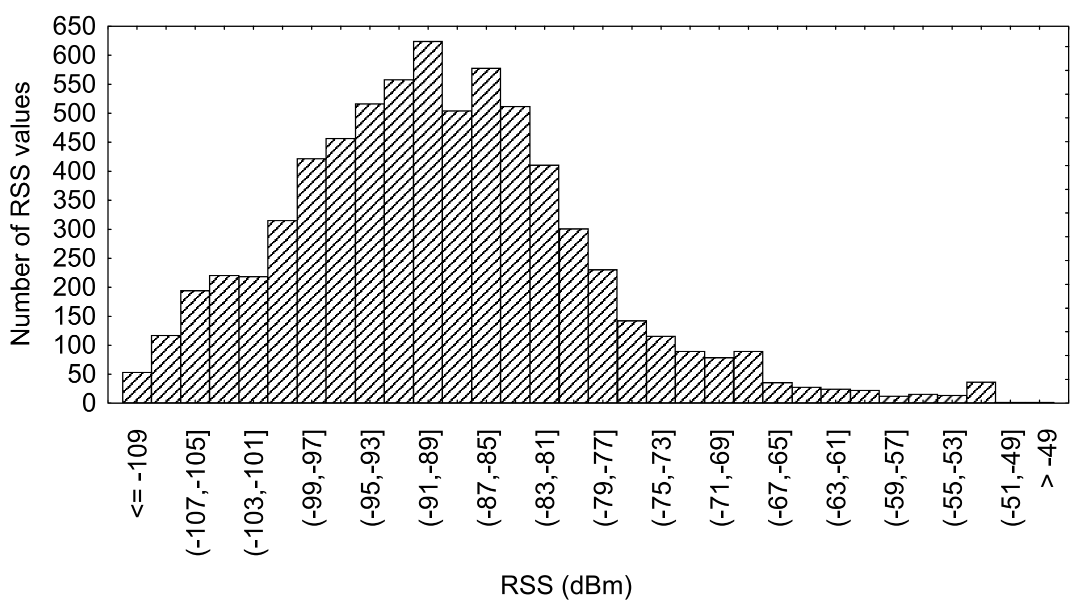


Figure 5.3. Histogram of downlink received signal strength (RSS) values (TAG 4, TMCO cell).

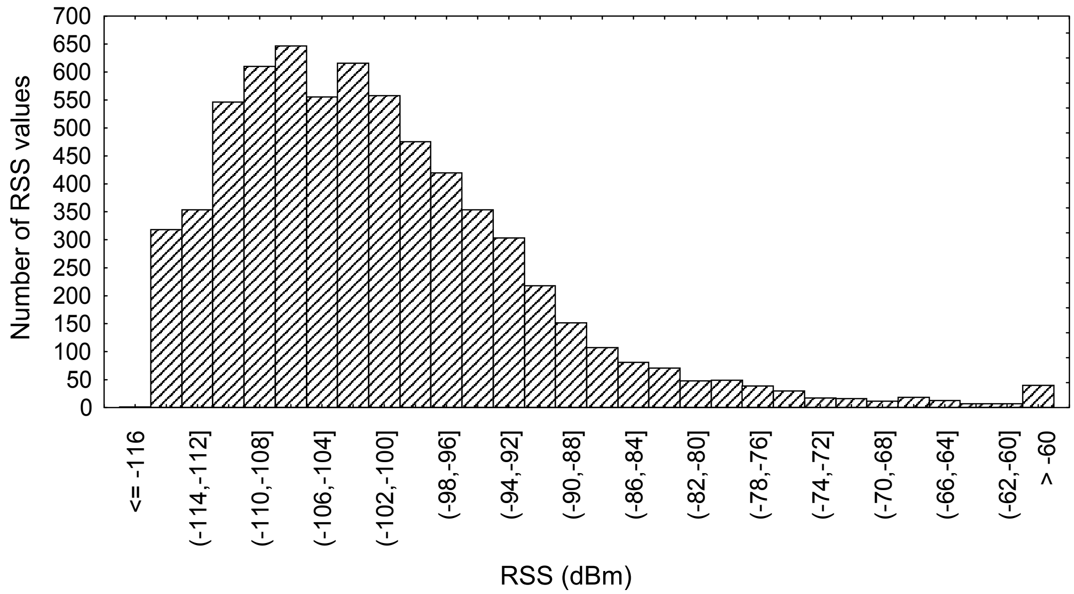


Figure 5.4. Histogram of uplink received signal strength (RSS) values (TAG 4, TMCO cell).

Link balance between the uplink and the downlink was analyzed by generating a scatter plot of downlink RSS vs. uplink RSS. Linear regression was then performed to determine the best fit for the data. Figure 5.5 shows the scatter plot and the results of the linear regression. Both the scatter plot and the linear regression indicate that the link was unbalanced.

To estimate the amount of link imbalance, a histogram of the difference between the downlink and uplink RSS was generated. This histogram is shown in Figure 5.6. The mean difference between downlink and uplink RSS was 13.3 dB with a standard deviation of 4.36 dB. The histogram indicates that the system was uplink-limited (i.e., RSS at the base station was typically weaker than RSS at the mobile unit). This is probably the result of operating at full power to provide wide area coverage.

The uplink FER as a function of uplink RSS is shown in Figure 5.7. As expected, the FER decreased as the RSS increased. The FER was below 1% for RSS values of -106 dBm and higher.

5.3.2 WCO Area Coverage Data

As for the TMCO cell, the test procedure followed and data collection methodology used are explained in Section 5.3. All three sectors were active for this cell site with handoff allowed between the sectors. About half of the measurement routes in the WCO cell used mobile units manufactured by Ericsson; the other half used mobile units manufactured by Nokia. Since there were some regions of overlapping of the different measurement routes, data were collected in some areas by both the Nokia and Ericsson mobile units.

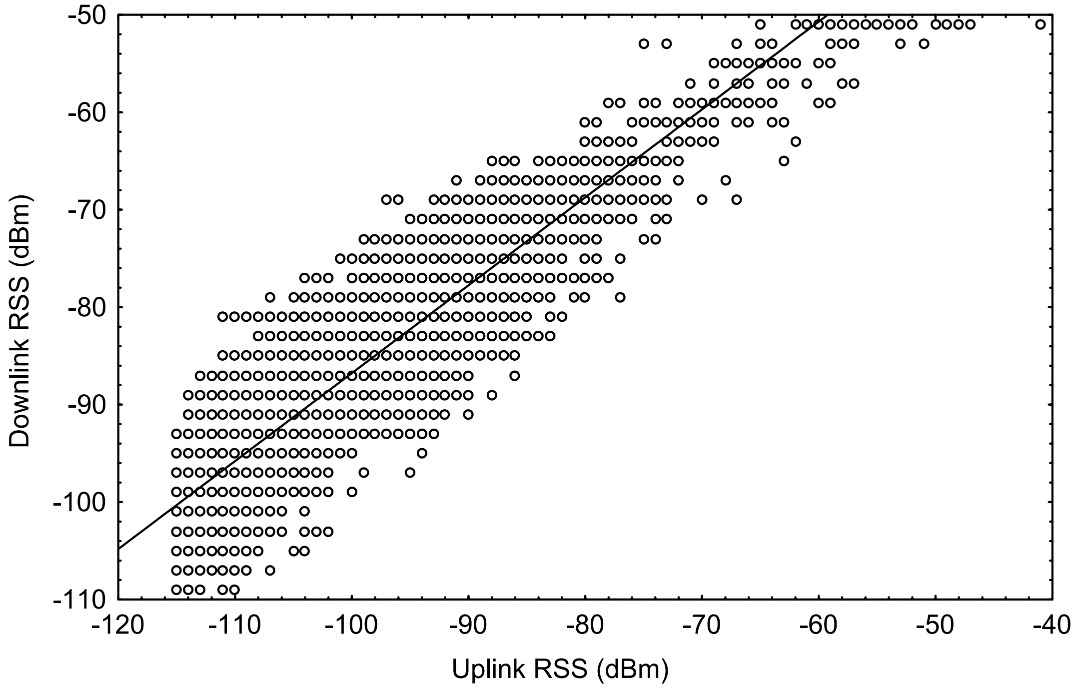


Figure 5.5. Downlink received signal strength (RSS) vs. uplink RSS (TAG 4, TMCO cell).

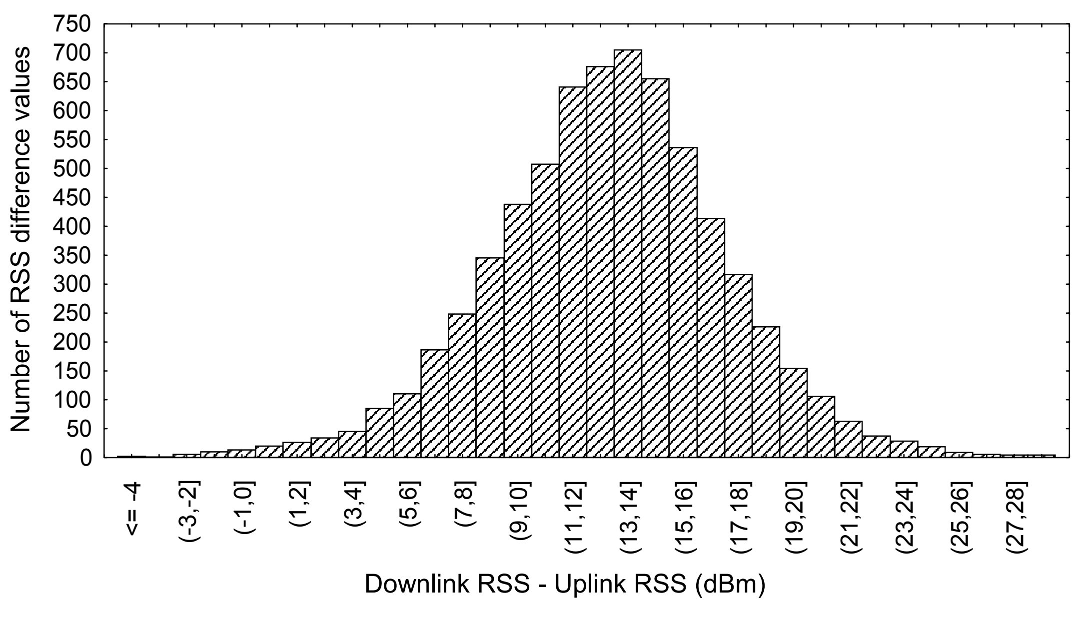


Figure 5.6. Histogram of difference between downlink and uplink received signal strength (RSS; TAG 4, TMCO cell).

Plots of downlink RSS as a function of distance for the Ericsson and Nokia mobile units are shown in Figures 5.8 and 5.9, respectively. The data included in these figures are the overall

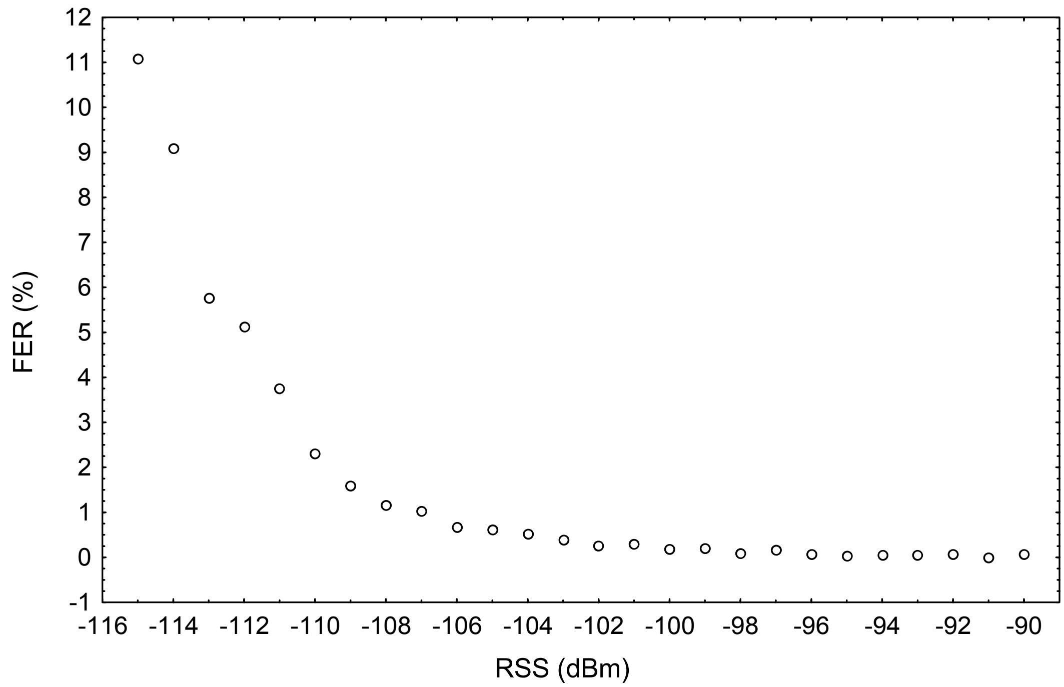


Figure 5.7. Uplink frame error rate (FER) vs. received signal strength (RSS; TAG 4, TMCO cell).

data for this cell, excluding RSS values less than -109 dBm. RSS values less than -109 dBm were excluded because -109 dBm is the threshold level for normal system operation of the mobile unit receiver. As in the TMCO cell, there is a large variation in the RSS for a given distance. The large variation in RSS seen in Figures 5.8 and 5.9 is due to shadowing and the particular choice of routes. Note that some signals with an RSS greater than -100 dBm exist 9 mi away from the center of the cell. Comparing this maximum distance with the maximum distance obtained for the TMCO cell (approximately 12.5 mi) suggests that the WCO cell has a smaller coverage area than the TMCO cell.

A rough estimate of the coverage area was determined by assuming that an RSS of -100 dBm or greater is desired. The measured RSS data using both the Ericsson and Nokia mobile units along all of the routes driven within the cell were used to determine the coverage area. The coverage boundaries were approximately 1.26 mi due north, 3.2 mi due east, 2.0 mi to the southeast, and 2.0 mi to the west. Once the RSS dropped below -100 dBm in these directions, it generally stayed below that value. Due to the lower elevation of this site (relative to the TMCO cell) and the terrain profile, this cell had a smaller coverage area than did the TMCO cell.

Figure 5.10 shows a histogram of the uplink RSS values for the WCO site. The mean uplink RSS was -99.49 dBm with a standard deviation of 9.94 dB.

Link balance between the uplink and the downlink was analyzed by generating histograms of the difference between the downlink and uplink RSS for both the Ericsson and Nokia mobile units. These histograms are shown in Figures 5.11 and 5.12. The mean difference between

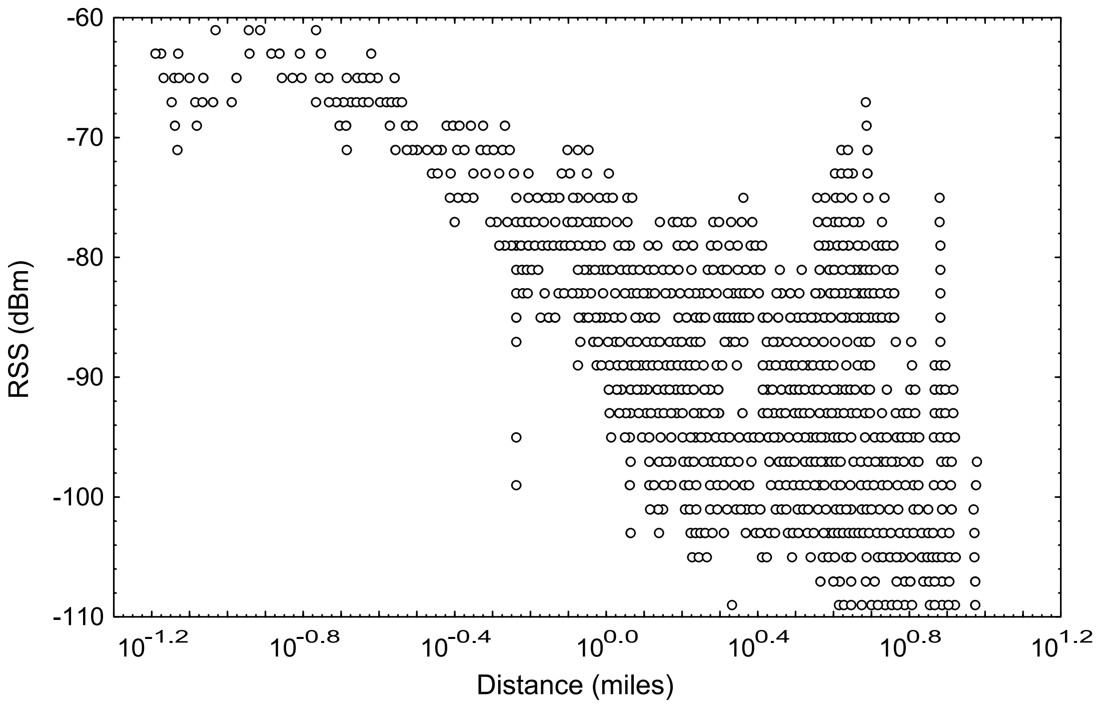


Figure 5.8. Downlink received signal strength (RSS) vs. distance (TAG 4, WCO cell, Ericsson mobile unit).

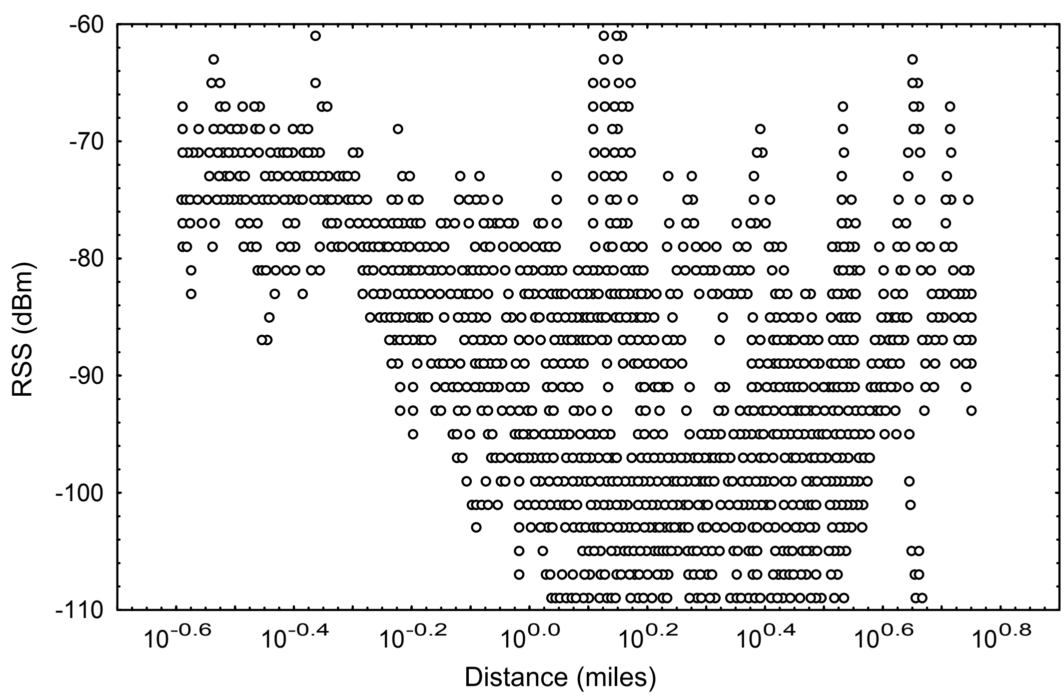


Figure 5.9. Downlink received signal strength (RSS) vs. distance (TAG 4, WCO cell, Nokia mobile unit).

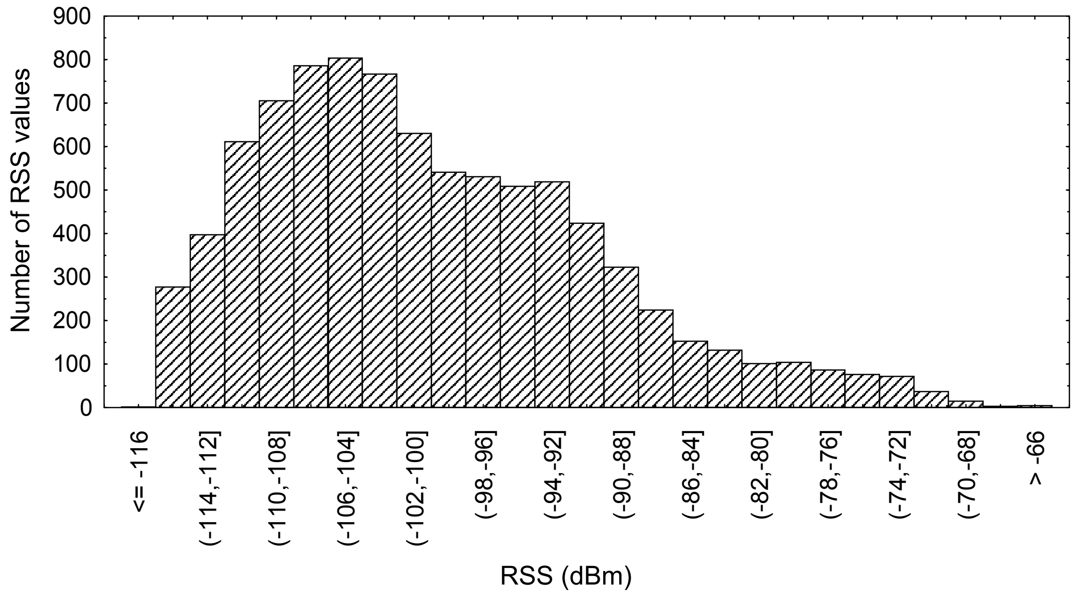


Figure 5.10. Histogram of uplink received signal strength (RSS) values (TAG 4, WCO cell).

downlink and uplink RSS for the Ericsson mobile unit was 13.09 dB with a standard deviation of 4.38 dB. The mean difference between downlink and uplink RSS for the Nokia mobile unit was 6.77 dB with a standard deviation of 3.98 dB. These histograms indicate that the link was unbalanced and that the system was uplink limited (i.e., RSS at the base station was typically weaker than RSS at the mobile unit). This is probably the result of operating at full power to provide wide area coverage.

The difference in link imbalance between the Ericsson and Nokia mobile units may have been caused by differences in the RSS reporting accuracy (discussed in Section 5.2), the antenna frequency response of the Nokia handset antenna (higher gain at the mobile transmit frequency than at the mobile receive frequency), and the higher transmit power of the Nokia mobile unit (approximately 0.5 dB).

The uplink FER as a function of uplink RSS is shown in Figure 5.13. As expected, the FER decreases as the RSS increases. The FER was below 1% for RSS values of -108 dBm and higher.

5.4 Handoff Testing

Handoff testing was performed by driving the measurement van on routes that would pass through the coverage area of each cell site and each sector within a cell site. Three routes were chosen for the handoff testing; two on Broadway, and one on Foothills Parkway. The first Broadway route was from 27th Way & Broadway north to US 36 (28th Street). The second Broadway route was from 27th Way and Broadway to Marshall Road. The third route went from 63rd Street and the Diagonal Highway south along the Foothills Parkway then onto US 36 to the Louisville exit. All routes were driven in northbound and southbound directions. Only the Ericsson mobile unit was used for handoff testing.

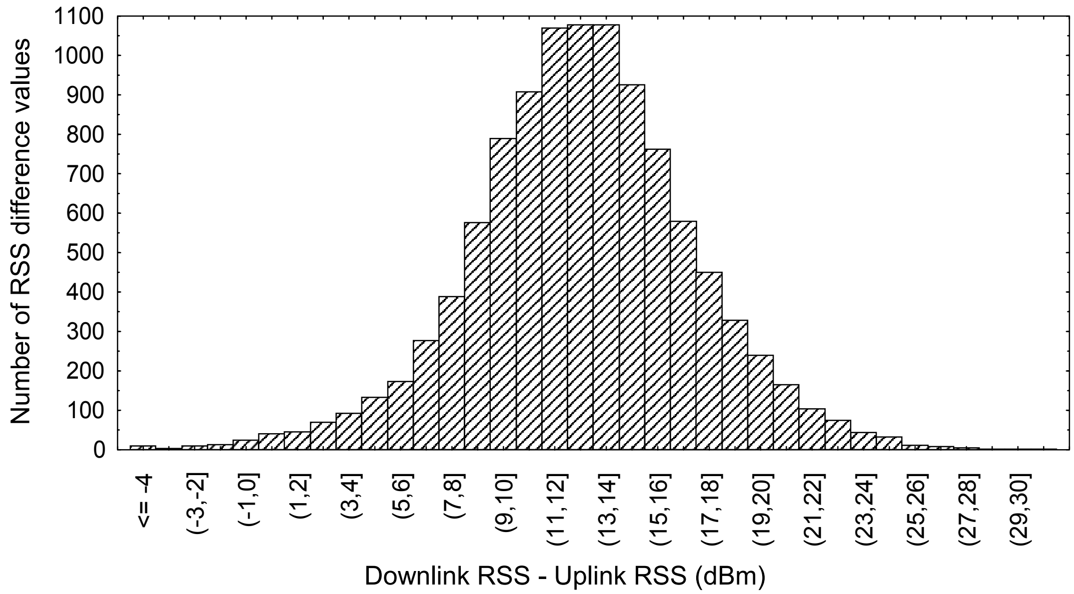


Figure 5.11. Histogram of difference between downlink and uplink received signal strength (RSS; TAG 4, WCO cell, Ericsson mobile unit).

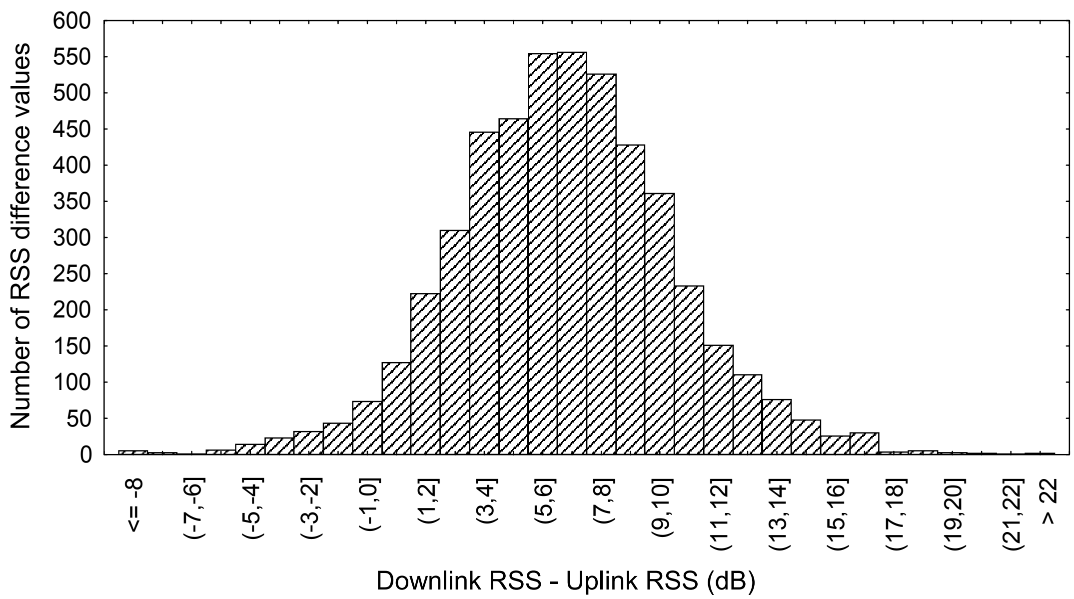


Figure 5.12. Histogram of difference between downlink and uplink received signal strength (RSS; TAG 4, WCO cell, Nokia mobile unit).

For the Broadway routes, the north sector of the TMCO cell, the north and southeast sectors of the GMM cell, and the southeast and southwest sectors of the WCO cell were active. For the Foothills Parkway route, the north and southwest sectors of the TMCO cell, the north and southeast sectors of the GMM cell, and the southeast sector of the WCO cell were active.

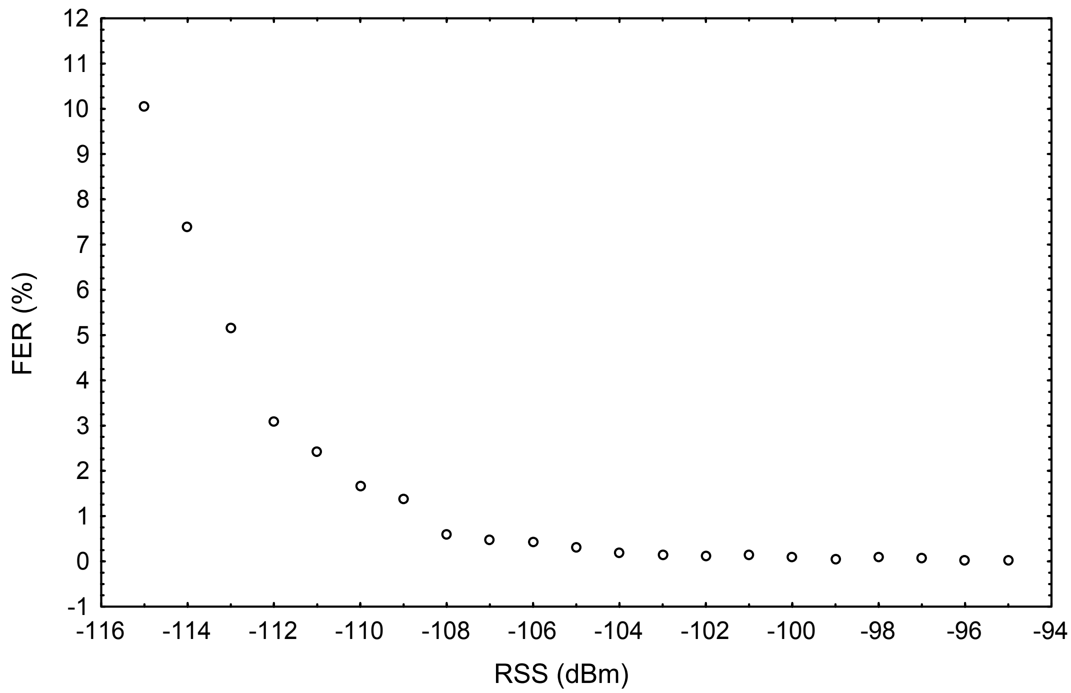


Figure 5.13. Uplink frame error rate (FER) vs. received signal strength (RSS; TAG 4, WCO cell).

Data collected from the handoff testing were analyzed to determine the change in the RSS values before and after handover. The time between successive handoffs was also examined. This gives an indication of the occurrence of any ping-ponging. Recall that ping-ponging was defined as a rapid switching of handoffs back and forth between cell sites and/or sectors. A total of 62 handoffs were examined in the analysis that follows.

Figure 5.14 shows the histogram of the change in RSS value before and after handoff. As in the handoff testing for TAG 5, some negative values of the change in RSS value before and after handoff occurred. Negative values represent cases when the average RSS value was actually lower after handoff than before handoff. In these cases, while the average RSS value in the current cell (or cell sector) was expected to be less than the average RSS value in the candidate cell (or cell sector) when handoff was initiated, by the time handoff was completed the average RSS in the new cell was less than the average RSS in the original cell.

Figure 5.15 shows the histogram of time between successive handoffs. The time between the handoffs is a function of speed, terrain configuration, route chosen, and cell planning. The occurrence of ping-ponging is indicated when the time between successive handoffs is too short (less than 10 s). Figure 5.15 shows that the time between successive handoffs was less than 10 s for 10 out of the 62 handoff cases. These were generally recorded on the uplink, on the Foothills Parkway route, directly east of the WCO.

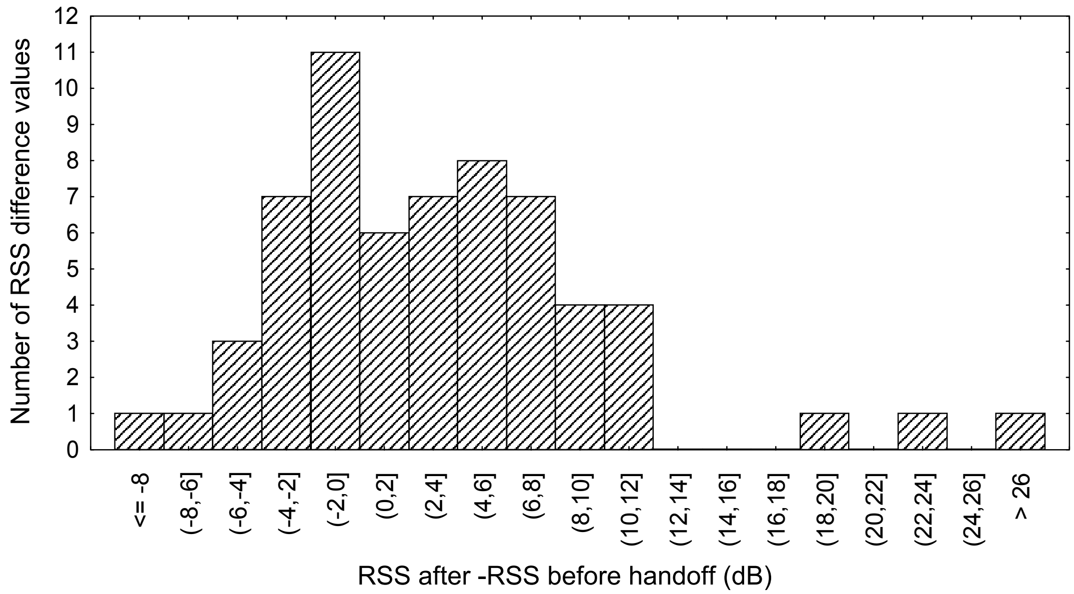


Figure 5.14. Histogram of change in received signal strength (RSS) during handoff (TAG 4).

5.5 Interference Testing

Both co-channel and adjacent channel interference measurements were performed for the downlink only. This provided C/I performance characterization for the mobile unit only. No interference measurements were taken for the base station receiver. The downlink measurements were made as the mobile unit traveled along routes that included areas with a range of good to poor C/I levels. The Ericsson mobile unit was used for all interference measurements.

For the co-channel interference measurement, the WCO north sector was used as the intended source. The GMM north sector was used as the source for the co-channel interference. Both the GMM north sector and the WCO north sector were tuned to the same frequency. A second carrier, at a different frequency, was transmitted from the GMM north sector. This carrier was used to measure the RSS of the interfering signal from the GMM site at the mobile unit. Note that in this configuration, the channel used for monitoring the interference level fades independently of the actual interfering signal.

For the adjacent channel interference measurement, the WCO north sector was again used as the intended source. The GMM north sector was used as the source for the adjacent channel interference. The carrier for the adjacent channel interferer was set 30 kHz away from the intended source.

Figures 5.16 and 5.17 show average BER class as a function of the C/I for both the co-channel and adjacent channel cases, respectively. Average BER class is computed by converting all the BER class values for a given C/I to BER values, averaging the BER values, and then finally converting the averaged BER value back to BER class. As expected for both the co-channel

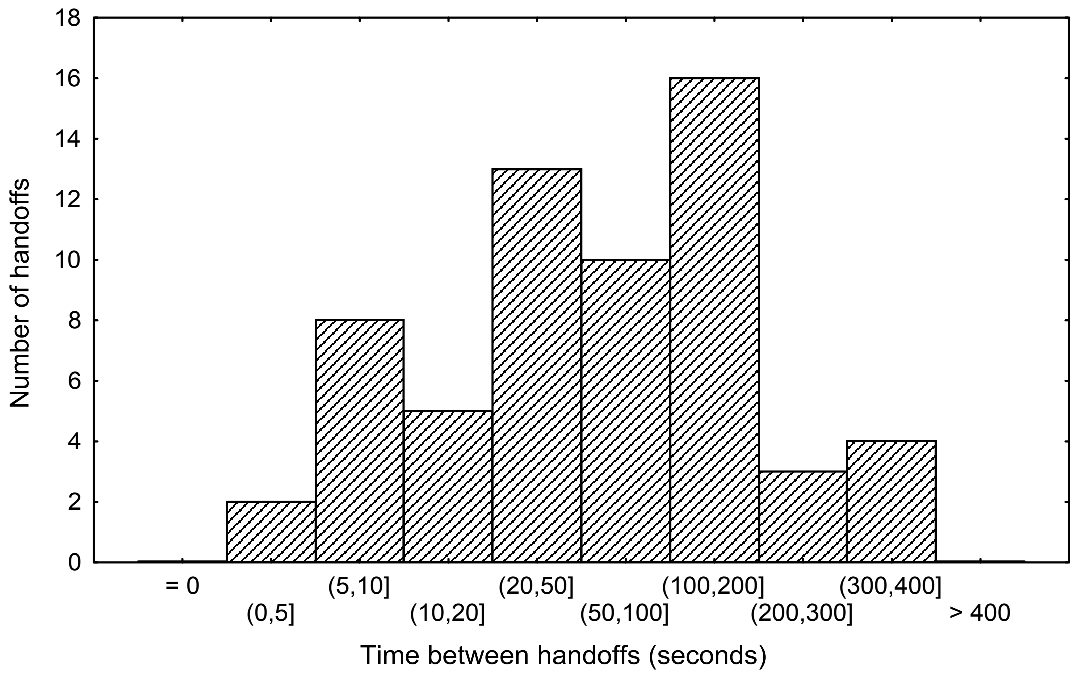


Figure 5.15. Histogram of time between successive handoffs (TAG 4).

and adjacent channel interference cases, when the C/I was increased, lower values of the BER class were seen, i.e., the BER decreases. Also as expected, to achieve the same BER class value, a much lower C/I was required for the adjacent channel interference than for the co-channel interference. As an example, for a BER class of 4, the co-channel C/I was 32 dB greater than the adjacent channel C/I.

5.6 Voice Quality

As discussed in Section 3.6, two types of voice quality measurements were made for the PCS JTC technology field trials in general: quasi-stationary measurements and handoff measurements. Both types of measurements were performed for the IS-136-based TDMA (TAG 4) technology.

5.6.1 Quasi-stationary Measurements

Voice recordings and various objective measures including uplink and downlink RSS, uplink number of bits in error per second, and downlink BER class were collected at locations on a 0.5-mi grid that encompassed the expected coverage area for the TMCO and WCO sites. Measurements were taken at 60 of the 82 locations that were identified for the quasi-stationary measurements as discussed in Section 3.6.1. The specific locations used are shown on the map in Figure 5.18. When making measurements at locations centered around the WCO cell site (the northern locations shown on the map in Figure 5.18), all sectors of the WCO cell were activated along with the north sector of the GMM cell site. When making measurements at locations centered around the TMCO cell site (the southern locations shown on the map in

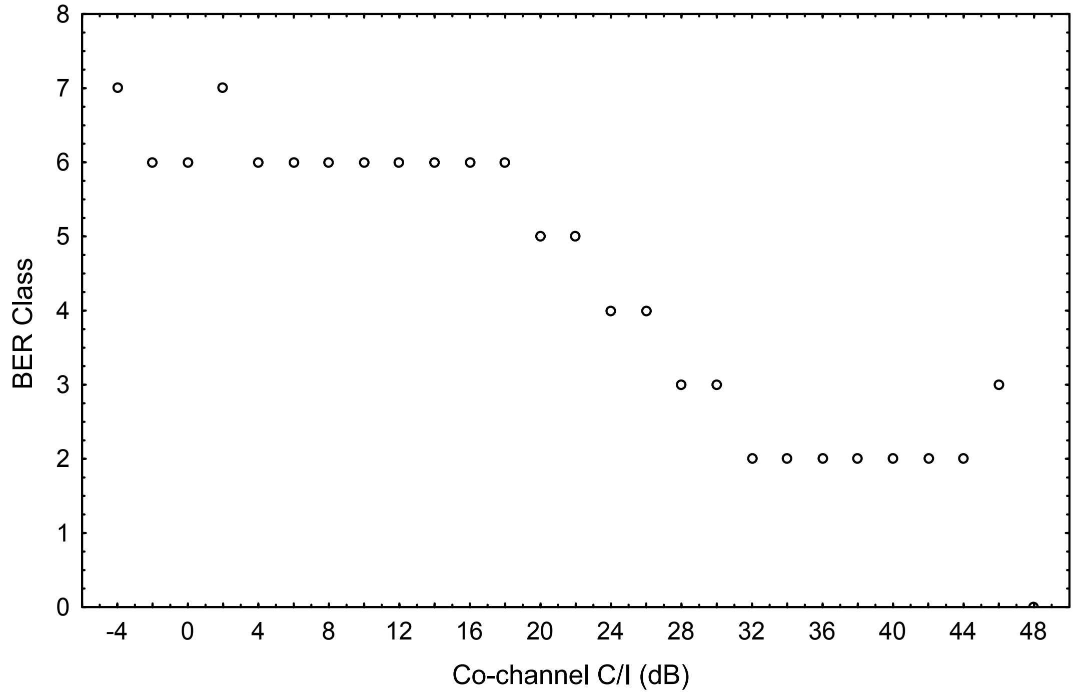


Figure 5.16. Average bit error rate (BER) class vs. carrier-to-interference ratio (C/I) for the co-channel interference case (TAG 4).

Figure 5.18), all sectors of the TMCO cell were activated along with the southeast sector of the GMM cell site.[9] At each location, data were collected as the measurement van traveled at one of two speeds. The vehicle traveled either 10 m or 100 m over the sample time. The particular vehicular speed used at each location (distance traveled over a fixed sample time) is shown on the map in Figure 5.18. At each location the sector that offered the highest signal strength was determined. This sector was used for the entire duration of the measurement at that location, i.e., handoff was not allowed during the measurement at a given location.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the radio link in either the uplink or downlink direction. The source tape transmitted over each link was the same as that used for TAG 5 testing (see Section 3.6.1).

The received voice transmissions were recorded on digital audio tape at the receiver for the uplink and at the receiver for the downlink. (Note that these recordings were not taken simultaneously.) The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. At each location, the objective measures including uplink and downlink RSS, uplink number of bits in error per second, and downlink BER class were also collected. The objective measures were collected at the same time as the voice recordings.

[9] The activation of cells and cell sectors for the quasi-stationary measurements in TAG 4 testing was slightly different from the testing in the previous JTC PCS field trials. In the TAG 2 testing, both the TMCO and WCO cells were activated. In the TAG 5 testing, only one cell was activated at a time.

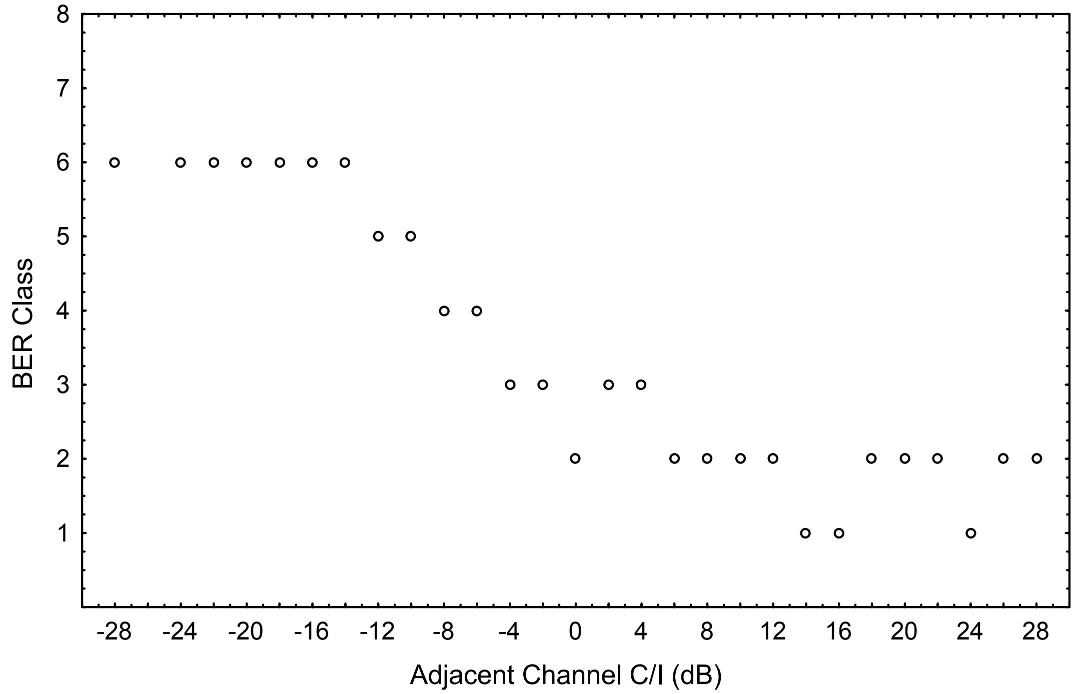


Figure 5.17. Average bit error rate (BER) class vs. carrier-to-interference ratio (C/I) for the adjacent channel interference case (TAG 4).

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

5.6.2 Mean Opinion Score Assessment

To accomplish the MOS testing, a pool of 32 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, 35-45, 45-55, and those over 55 years of age. There were an equal number of male and female subjects. The subjects were cordless, noncellular telephone users.

Four groups consisting of eight subjects each from the subject pool were formed The subjects were asked to rate voice segments by answering the three questions listed in Section 3.6.2 after each segment was presented.

First, the subjects in each of the four groups were presented 10 practice voice segments to rate. The practice segments included two 64-kbps wireline voice segments (actually one 64-kbps wireline segment presented twice) and eight voice segments of varying degrees of quality collected from field measurements. It was also important to allow listeners to be exposed to the types of distortions inherent in the TAG 4 voice coding performance at varying levels. The goal was to demonstrate a wide range of quality in the practice segments presented

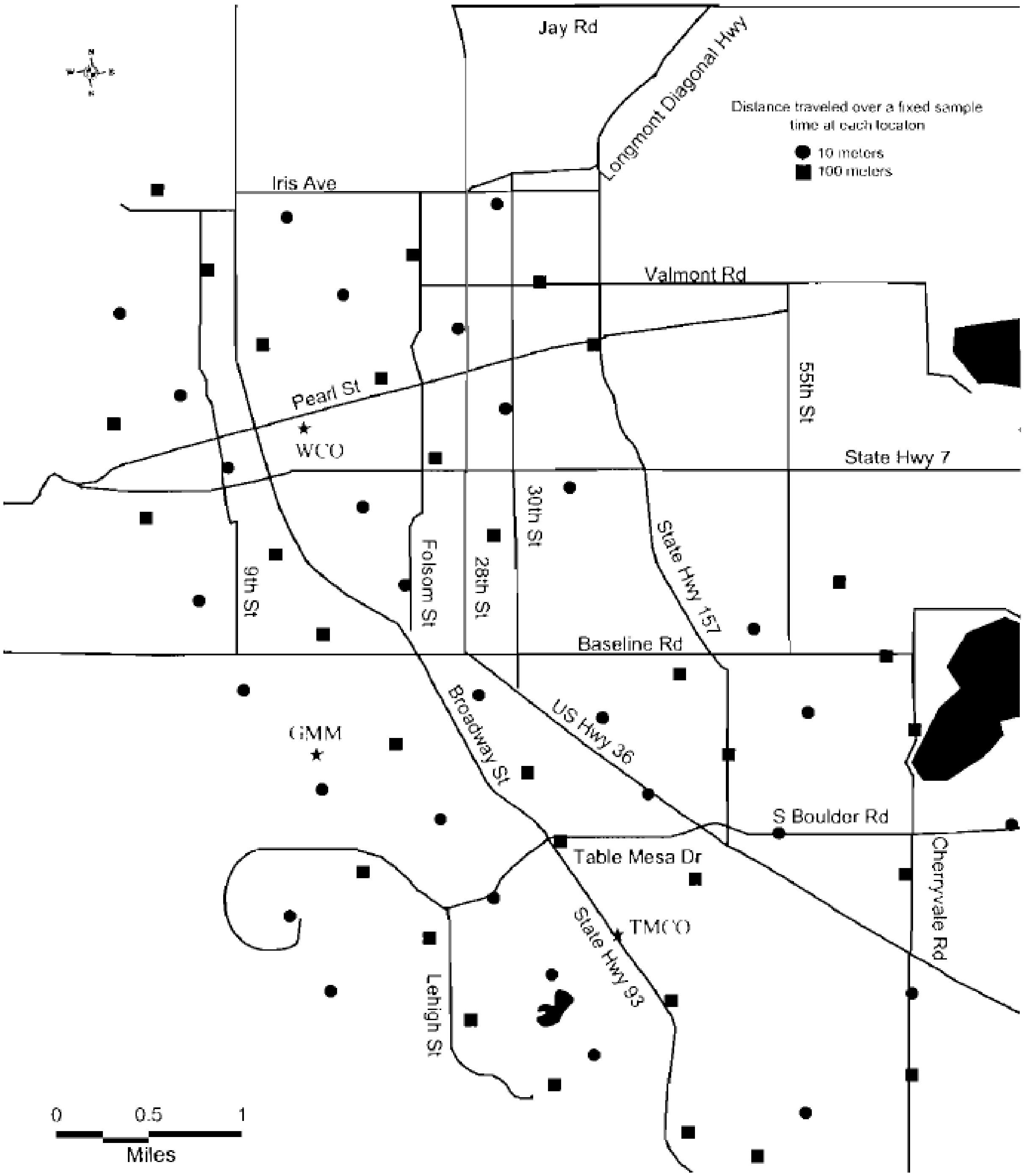


Figure 5.18. Quasi-stationary measurement locations and vehicular speed used at each location for TAG 4.

to listeners. It was felt that the voice segments collected during the quasi-stationary measurements did not represent the full range of quality needed, therefore during field testing, extra voice segments were collected while adjusting the transmit power within a cell. The practice segments allowed inexperienced listeners to gain exposure to the full range of possible voice quality, from excellent to poor, and ensured proper scaling of the MOS's.

After the practice segments were presented, the subjects in each of the four groups were asked to rate 33 voice segments: 3 reference voice segments and 30 voice segments from the field trial measurements. Every listener within a group listened to the same voice segments. The reference voice segments were either 64-kbps wireline segments or poor quality voice segments collected from the field. The 30 voice segments from the field trial measurements came from the uplink or downlink measurements at a portion of the 60 measurement locations.

A total of 120 voice segments were collected from the field measurements, representing the uplink and downlink measurements at all 60 measurement locations. Out of the 120 voice segments, nine of the voice segments recorded during the downlink measurements suffered from an unrealistically poor voice quality (possibly due to electrical interference being coupled in at the input to the digital audio tape recorder). Therefore, these voice segments were not included in the data analysis that follows. The number and type (male or female) of sentences that were used and the order in which they were used to form a voice segment are the same as that described in Section 4.6.2. Subjects were given two 10-min breaks half way through the session. After all segments were presented, subjects filled out a post-trial questionnaire.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain an MOS. The results from all four of the groups, from a total of 111 voice segments (because 9 out of the 120 voice segments were not used as explained earlier), are shown in the histogram in Figure 5.19. Overall, the voice segments were marked favorably, with 90% of the segments rated between fair and excellent. The average MOS was 3.53 and the standard deviation was 0.49. The one very low MOS occurred at a location where no LOS propagation existed between the mobile unit and the base station at either the TMCO or GMM cell sites. This location is in a small valley behind both cell sites.

Figures 5.20 and 5.21, show histograms of MOS's for the uplink and downlink, respectively. The data shown in these histograms are from the uplink and downlink voice segments at 51 out of the 60 locations. Both the uplink and downlink voice segments from the remaining nine locations were not used in these histograms. The average MOS for the uplink was 3.41 and for the downlink was 3.68. A t-test revealed that there is a statistically significant difference in the average MOS's between the uplink and downlink. The downlink MOS's were noticeably better than the uplink MOS's as expected because of the large link imbalance as discussed in Sections 5.3.1 and 5.3.2.

The relationship between the MOS's and some of the objective measures was initially investigated by generating some scatter plots. Figure 5.22 shows the relationship between the MOS's and average RSS for both the uplink and downlink combined (111 voice segments). In Figure 5.22, some variation in MOS's is seen for all values of average RSS. Figures 5.23 and

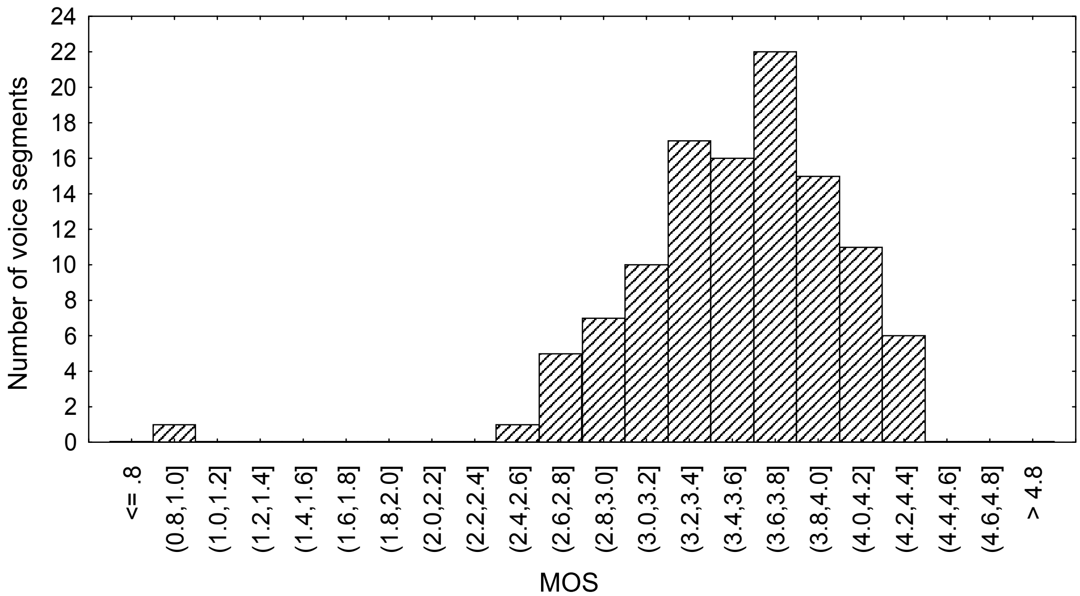


Figure 5.19. Histogram of mean opinion scores (MOS's) for all voice segments (TAG 4).

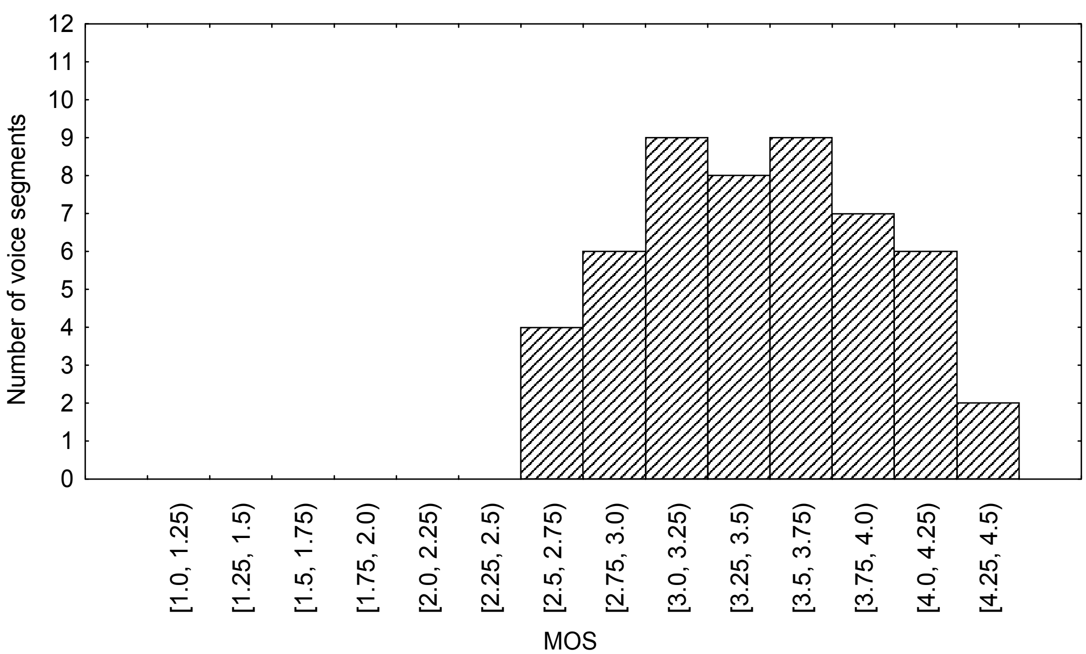


Figure 5.20. Histogram of mean opinion scores (MOS's) for the uplink (TAG 4).

5.24 show the relationship between the MOS's and the average BER for both the uplink (all 60 voice segments) and downlink (51 voice segments), respectively. Note that only one voice segment on the uplink had an average BER greater than 0.3%. The average BER never exceeded 0.4% on the downlink. While both the uplink and downlink show some variation in MOS's for all values of average BER, more variation is seen on the uplink. The variation in

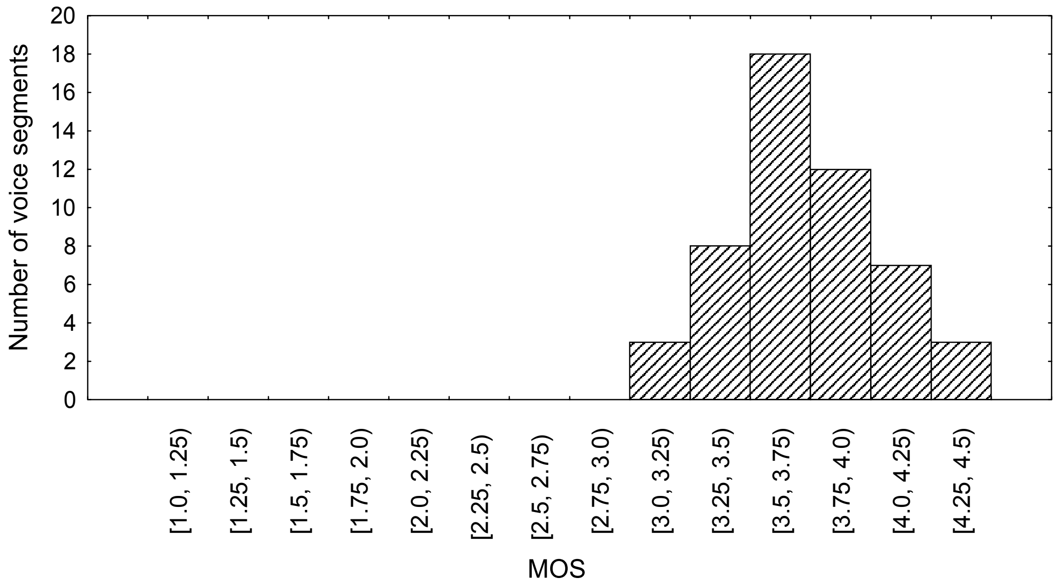


Figure 5.21. Histogram of mean opinion scores (MOS's) for the downlink (TAG 4).

MOS's for voice segments with average BER's on the uplink between 0 and 0.3% ranged from 2.50-4.38. The variation in MOS's for voice segments with average BER's on the downlink between 0 and 0.4% was relatively constant; MOS's ranged from 3.00-4.25.

Pearson product-moment correlations were performed to determine the correlation between MOS's and average RSS and MOS's and average BER (for the uplink and downlink data combined). The correlation coefficient between MOS and average RSS was 0.30 and that between MOS and average BER was -0.50. These correlation coefficients between MOS and averaged objective measures suggest that a strong linear relationship between MOS and the objective measures does not exist. The correlation between the average RSS and the average BER was -0.33. A higher correlation between these measures was expected.

While there does not appear to be a strong linear relationship between MOS and the objective measures, there still may be a consistently increasing or decreasing relationship between them. The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average RSS and between the ranks of MOS and the ranks of average BER. The Spearman rank correlation coefficient (for the uplink and downlink data combined) between MOS and average RSS was 0.16 and that between MOS and average BER was -0.05. These very low rank correlations between MOS and averaged objective measures suggest that a consistently increasing or decreasing relationship between MOS and the objective measures does not exist.

Note that as in the TAG 5 and TAG 2 data analysis, the objective measures were averaged over the entire length of the voice segment. By analyzing the instantaneous variation or possibly minimum and maximum values of the objective measures within the voice segment, further insight may be gained on the behavior of MOS's.

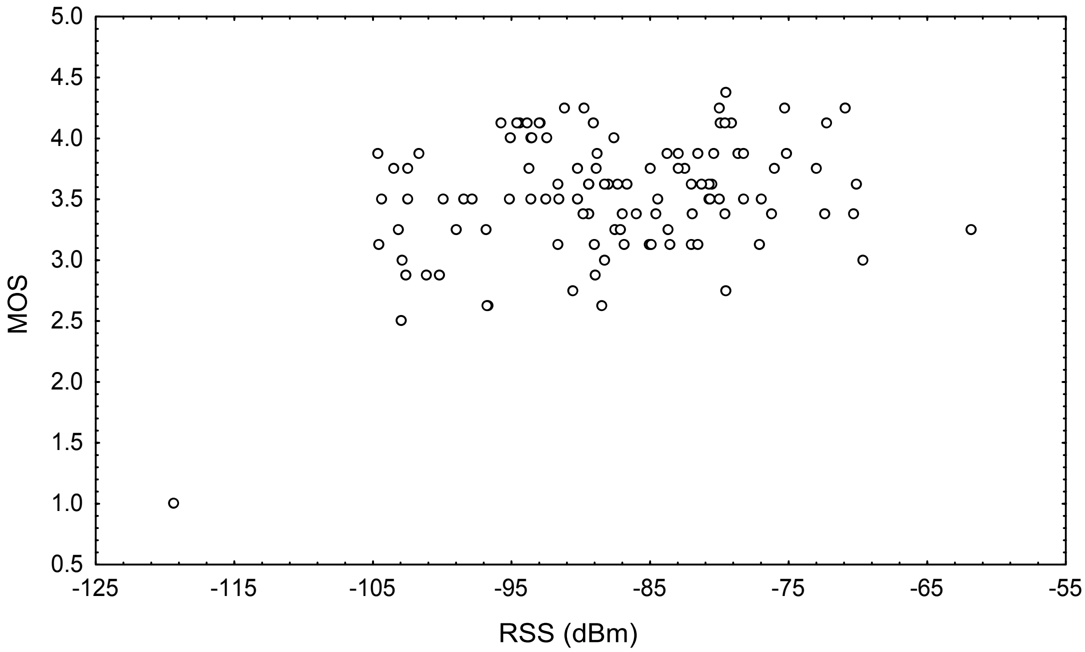


Figure 5.22. Mean opinion score (MOS) vs. average received signal strength (RSS; TAG 4).

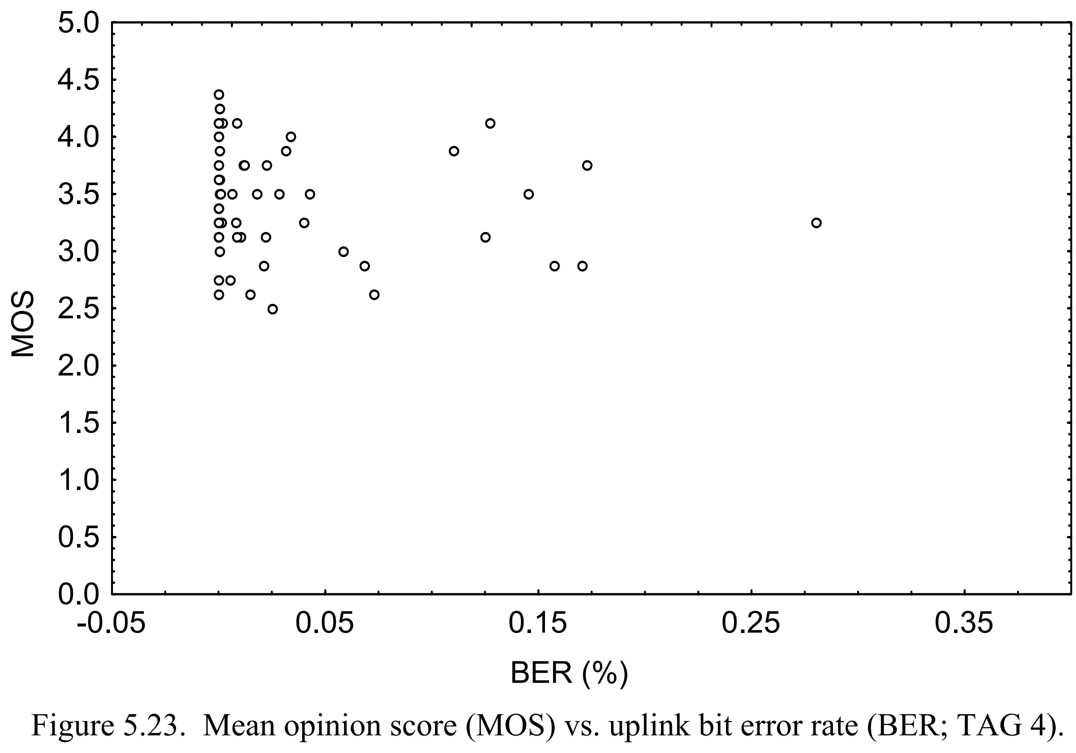


Figure 5.23. Mean opinion score (MOS) vs. uplink bit error rate (BER; TAG 4).

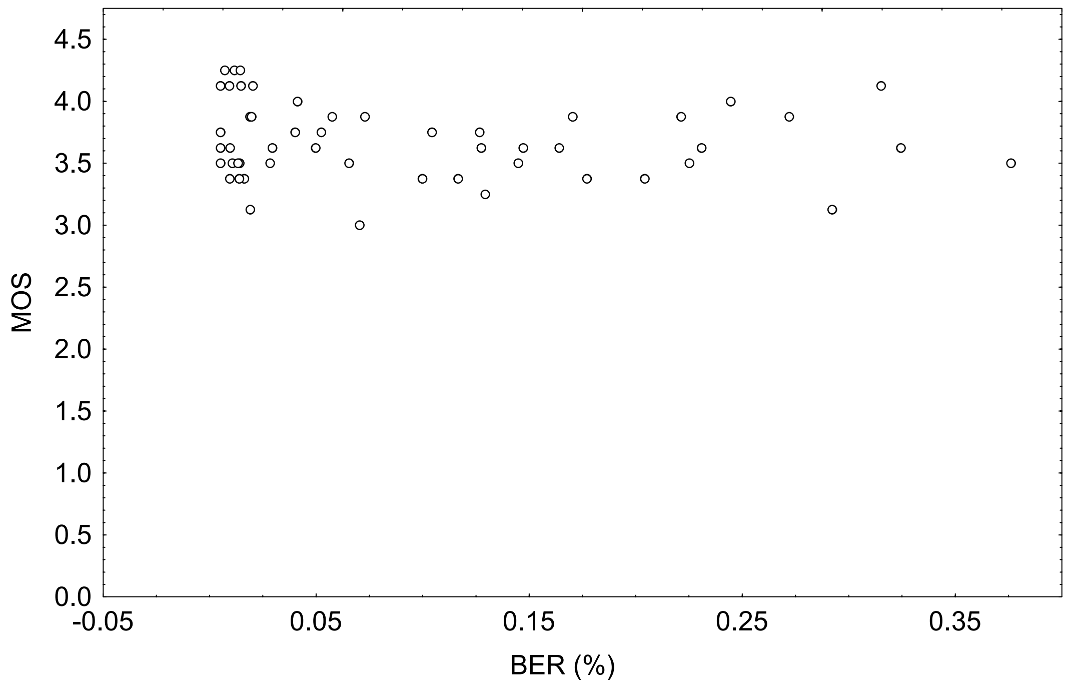


Figure 5.24. Mean opinion score (MOS) vs. downlink bit error rate (BER; TAG 4).

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the voice segments according to listeners:

1) echo;
2) "chirping," or "squeaking" noise; and
3) muting.

The nature of these distortions are likely judged differently by different listeners. Intelligibility and speaker recognition are two main aspects of perceived quality. In the case of most of the voice segments, intelligibility remained high. As a result, overall MOS's were high.

5.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener. The expert listener ratings followed the identical procedure as in the PCS 1900 (TAG 5) testing. This procedure is described in Section 3.6.3.

Figure 5.25 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data.

For the most part, the definitely acceptable ratings of the expert listener were relatively good indicators of percent acceptability. In the definitely acceptable category, most of the voice segments were rated as acceptable by 70-100% of the subjects; a few voice segments were rated as acceptable by less than 70% of the subjects. The marginally acceptable and unacceptable expert listener categories show more variance. In the marginally acceptable category, few voice segments were rated as acceptable by 30-70% of the subjects. Similarly, in the unacceptable category, few voice segments were rated as acceptable by less than 30% of the subjects.

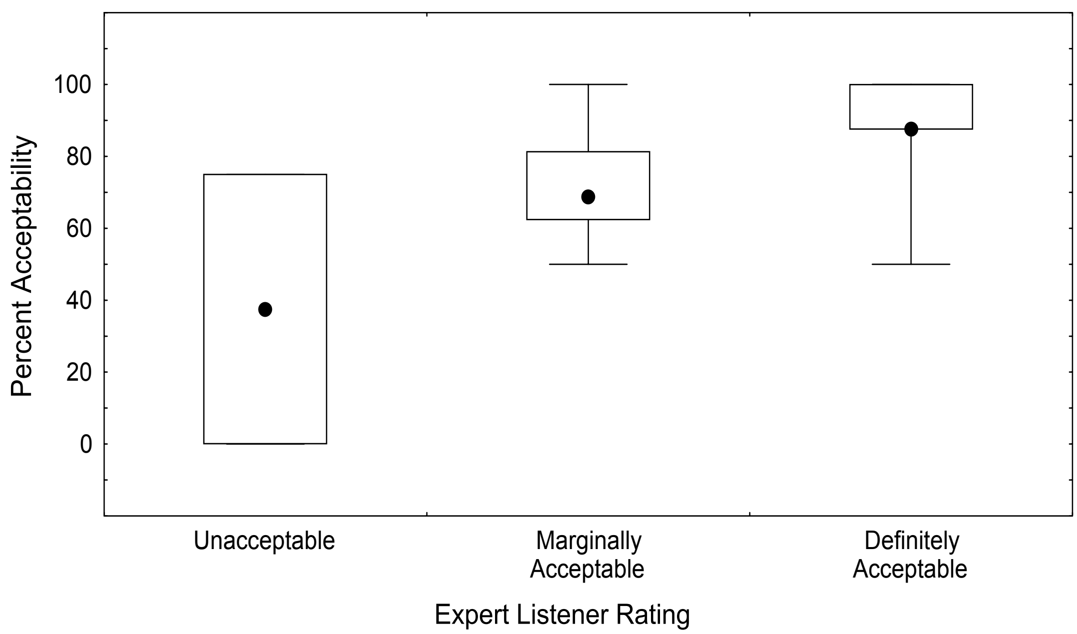


Figure 5.25. Percent acceptability vs. expert listener rating (TAG 4).

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.80, showing a strong correlation between these measures, as would be expected. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.53 and that between percent acceptability and expert listener rating was 0.53, indicating some correlation between these measures. However, a strong linear relationship between these measures does not exist.

It is possible that expert listener rating, average RSS, and average BER can be predictors of MOS when all are taken together. A multiple regression analysis was completed in order to determine if MOS is related to a combination of all the above factors. Interactions among the various factors were not considered in the analysis.

The result showed that only 36% of the variance can be explained by expert listener rating, average RSS, and average BER. The result of the multiple regression analysis also showed that all these factors reliably account for the 36% of variance. From this analysis, it appears that expert listener rating, average RSS, and average BER taken together do not offer any substantial predictive power over MOS's.

5.6.4 Voice Quality Handoff Measurements

Continuous voice recordings of transmitted voice signals were made as the mobile unit traveled along routes through handoff areas. While the measurement van was in motion, an audio source tape was transmitted over either the uplink or downlink. (Uplink and downlink voice recordings were made during separate runs.) The source tape consisted of Harvard sentences and was played continuously as the measurement van traveled along each route. The received voice transmissions were recorded on digital audio tape at the receiver for either the uplink or downlink. Continuous voice recordings were made along the route until the call was finally dropped. The routes were selected according to previous tests at the BITB. One route was driven along Broadway, at a vehicular speed of 25-30 mph from US 36 south to 27th Way. The second route was driven along Broadway from 27th Way south to Chambers Road or in some cases further south to Marshall Road. A third route was driven along Foothills Parkway, at a vehicular speed of 55-60 mph. The beginning of a route was selected within the coverage area. Four runs were conducted along each route: an uplink run traveling southward, an uplink run traveling northward, a downlink run traveling southward, and a downlink run traveling northward. Only the Ericsson mobile unit was used for the voice quality handoff testing. Voice quality was assessed using the expert listener methodology described in Section 3.6.3.

For the voice quality handoff testing, an expert listener rating was made for each 4-s period of the continuous voice recordings taken along a measurement route. In general, voice quality was good throughout most of the handoff testing. Voice quality did appear to degrade briefly during handoffs; the expert listener was able to identify when a handoff occurred. During handoff, a 200- to 400-ms period of muting was evident.

5.7. Manufacturers' Statements

Statements provided by the manufacturers involved in the testing are included in this section. These statements are identical to those given in [4], except for some minor editorial changes.

5.7.1 AT&T Network Wireless Systems

AT&T Network Wireless Systems would like to thank U S West, NTIA, Ericsson, Nokia, and McCaw (now AT&T Wireless) for their hard work and support during the testing of PCS TDMA. Special thanks is extended to U S West and NTIA for their contributions during the field trial, and for providing the BITB. AT&T Network Wireless Systems would also like to thank Nokia and Ericsson for providing mobile equipment to demonstrate the performance of PCS TDMA. Individuals from all of the above organizations put in many long hours cooperating together to meet the tight test schedules.

AT&T was pleased to supply the wireless infrastructure to demonstrate the PCS TDMA air interface as part of the JTC standardization process for PCS band air interfaces.

As can be seen from this section of the report and the Visitors' Day presentations and demonstrations, the PCS TDMA system performed beyond expectations. The PCS TDMA field tests consistently demonstrated high voice quality and excellent coverage.

Due to the nature of this technology demonstration, and the time constraints in the planning and execution of this event, external upbanders were utilized both on the base station infrastructure, and the mobile equipment. Time constraints, as well as the nature of the testing resulted in minimal time to tune the system after installation, and run proper interoperability, calibration, and integration tests prior to our arrival in Boulder. As a result, the links were not balanced, power control was not implemented and optimized, and the system was not tuned optimally as would have occurred had this been production equipment in a service provider environment.

Due to the JTC's legitimate need to standardize the testing for all of the PCS technologies as much as possible, cell site selection was predetermined by the BITB, and was not at TAG 4's discretion. As a result, the cell site selection was not optimized to cover the test area for TDMA.

As with all high technology, new products and ideas such as PCS TDMA production minicells and improved speech codecs are in development and hitting the marketplace as this is written.

5.7.2 Ericsson, Inc.

Ericsson Incorporated would like to thank U S West and ITS for their support during the demonstration of the performance of the US TDMA PCS radio air interfaces at 1.9-GHz at the BITB in Colorado. In particular, the support of M. Laflin of ITS and the technical staff of U S West is acknowledged and very much appreciated. Ericsson would further like to thank all of the AT&T Wireless Network Systems participants for their hard work in completing the compatibility requirements for the 1.9 GHz TDMA PCS system. In particular we wish to thank J. Siskind for his hard work in support of the system test.

Ericsson was pleased to provide equipment to demonstrate the TDMA PCS system in the BITB, and we feel that the TDMA system performed quite well as the report shows. The results were in agreement with the previous TDMA field demonstrations in other locations.

Because of the site location constraints and the time constraints, there was no attempt to optimize the system used in Boulder; however, the TDMA test system provided consistently high voice quality.

The BITB test system mobile units provided consisted of noncommercial engineering equipment based on the IS-54B standard. Work is underway to provide hand-held terminals for the commercial deployment of the TDMA PCS standard.

5.7.3 Nokia Mobile Phones

Nokia Mobile Phones, Inc. would like to thank AT&T Wireless Network Systems, U S West, and ITS for their support during the demonstration of the performance of the 1900-MHz US TDMA radio air interface at the BITB in Colorado. We found the atmosphere and attitude during the tests extremely positive and co-operative.

The cell sites were not completely tuned and balanced; that would have required more time than was allowed by the schedule. However, the purpose of this test was to prove the basic system functionality and to define the coverage area, and this was successfully done.

Noncommercial equipment was used for the testing. However, Nokia Mobile Phones is doing development work to provide handportable phones for IS-136-based PCS systems.

This test proves that the IS-136-based PCS system is a very competitive solution for the PCS operators, especially when the new vocoder becomes available for the system.

6. TAG 7 (WIDEBAND CDMA) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 7. The technology tested was the Wideband CDMA PCS standard. The base station and mobile equipment were provided by OKI America and Berkeley Varitronics Systems, Inc. The TAG 7 field tests examined area coverage and voice quality under quasi-stationary conditions. No handoff testing or interference testing was performed.

The information presented in this section is taken from [5]. The reader is referred to [5] for a more complete and detailed presentation of the TAG 7 technology field testing at the BITB.

6.1 TAG 7 Test System Configuration

The test system for TAG 7 was different from the previously tested JTC PCS systems (TAG 5, TAG 2, and TAG 4) because it consisted of a single base station and a single mobile unit. The base station was set up to operate on one sector of one cell at a time while testing proceeded for that particular sector. All three sectors of both the TMCO and WCO cell sites were tested one at a time. Because only one base station was used for the TAG 7 testing, no network configuration to connect base stations was needed. The voice signal interface was provided directly into the base station without access to any network switching or transmission components. No antenna diversity was used for any of the TAG 7 testing.

6.2 Calibration

A calibration of the base station RSS was performed by injecting a digitally modulated signal of known level into the receiver and then generating a table of scale factors that were used by the logging software to provide accurate RSS reports during the field trial.

The input signal into the base station receiver was provided by the mobile unit through a coaxial cable and high-power and variable attenuators. Losses through the coaxial cable and attenuators were measured and a correction, or offset, was added to the signal power output by the mobile unit. The level of the injected signal was varied over the dynamic range of the base station receiver to generate the table of scale factors. The maximum difference between the actual RSS and the RSS reported at the base station receiver was found to be 1.5 dB.

The OKI mobile units that were used in the TAG 7 field trial were checked for accuracy of the RSS values reported. This was done by injecting a digitally modulated signal of known level directly into the antenna port of the mobile unit and comparing this signal level with the RSS value reported by the mobile unit. The input signal into the mobile unit receiver was provided by the base station through a coaxial cable and high-power and variable attenuators. Losses through the coaxial cable and attenuators were measured and a correction, or offset, was added to the signal power output by the base station. The level of the injected signal was varied over the dynamic range of the mobile unit's receiver to find the maximum difference between the actual RSS and the RSS reported by the mobile unit's receiver. The maximum difference was found to be 2.5 dB. (Note that the OKI mobile units report RSS in 0.5 dB steps.)

Other parameters such as base station transmitter characteristics were not examined during this calibration.

6.3 Area Coverage Testing

The base station and mobile unit power were set so that the output power was approximately 5.6 W and 0.25 W ERP, respectively. Measurements to show area coverage were taken with the mobile unit located in a mini-van as in the previous JTC PCS field technology trials (TAG 5, TAG 2, and TAG 4). The mobile unit was mounted inside the van on the same wooden structure used in all of the JTC PCS technology field trials. This structure is described in Section 3.3. The measurements were taken by driving along routes (radials) away from the cell site. When time permitted, measurements along additional routes in between the radials were taken.

Since only one base station and mobile unit were used in the testing, only one sector of one cell site was activated at a time during area coverage testing. The data were collected both at the mobile unit and at the base station. The data collected at the mobile unit included GPS location, velocity, and time; downlink RSS; downlink BER; and other system parameters. The data collected at the base station included time, uplink RSS, uplink BER, and other system parameters.

Calls were originated prior to the start of data collection. Collection of mobile unit data and base station data was initiated as the measurement van began traveling away from the cell site along the drive route. The vehicle speed was approximately 5 mph. At the end of the route, the data collection was stopped and the data were saved to disk. All data collected were averaged over one second. The mobile unit was capable of open loop power control; however, the open loop power control was not used in this testing.

6.3.1 TMCO Area Coverage Data

The test procedure followed and data collection methodology used are explained in Section 6.3. Downlink RSS as a function of distance is shown in Figure 6.1. The large variation in RSS seen in Figure 6.1 is mostly due to shadowing. Note that signals up to approximately -87 dBm exist out to approximately 0.83 mi from the cell site.

A rough estimate of the coverage area was determined by assuming that an RSS of -83 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. Due to the irregularity of the terrain, the RSS varied significantly along the TMCO routes, crossing the -83-dBm level several times before finally staying below -83 dBm. The point along each route where the RSS first dropped below -83 dBm was used to define the coverage boundaries. For this case, the coverage boundaries were approximately 0.55 mi due north, 0.3 mi due southeast and southwest, and 0.6 mi due south.

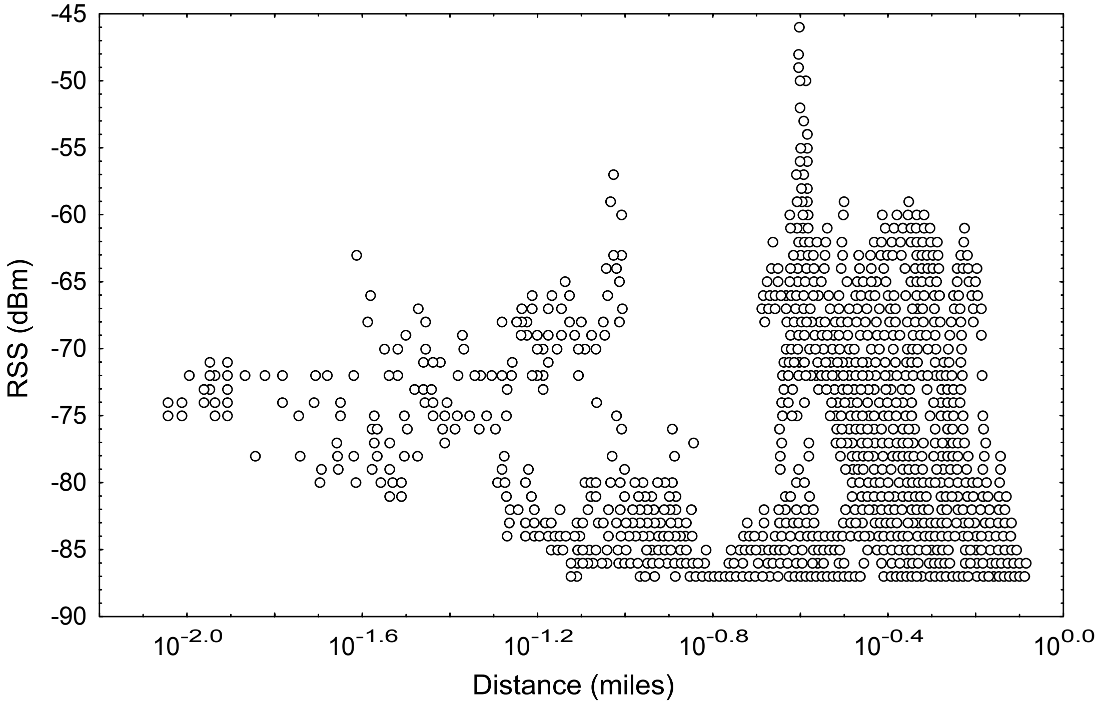


Figure 6.1. Downlink received signal strength (RSS) vs. distance (TAG 7, TMCO cell).

Figures 6.2 and 6.3 show the histograms of uplink and downlink RSS values, respectively. The direct comparison between uplink and downlink (link balance) was not possible, due to misalignment of the time stamps in the uplink and downlink data files. However, as seen in Figures 6.2 and 6.3, the histograms of RSS data are similar for both links. For both links, the majority of RSS values were less than -80 dBm. Also, for both links, RSS values greater than -80 dBm were fairly evenly distributed. The lowest recorded RSS was -87 dBm for the downlink and -85 dBm for the uplink.

Figures 6.4 and 6.5 show the uplink and downlink BER histograms, respectively. For the uplink, the vast majority of BER values were less than or equal to 0.001%. For the downlink, while a large number of BER values were less than or equal to 0.001%, there were more BER values in the 0.01 - 0.1% and 0.1 - 1.0% ranges than for the uplink.

6.3.2 WCO Area Coverage Data

As for the TMCO cell, the test procedure followed and data collection methodology used are explained in Section 6.3.

Downlink RSS as a function of distance is shown in Figure 6.6. As seen in the TMCO cell, there is a large variation in RSS for a given distance. This is due to shadowing and the choice of routes. Note that signals up to approximately -87 dBm exist approximately 0.89 mi from the cell site.

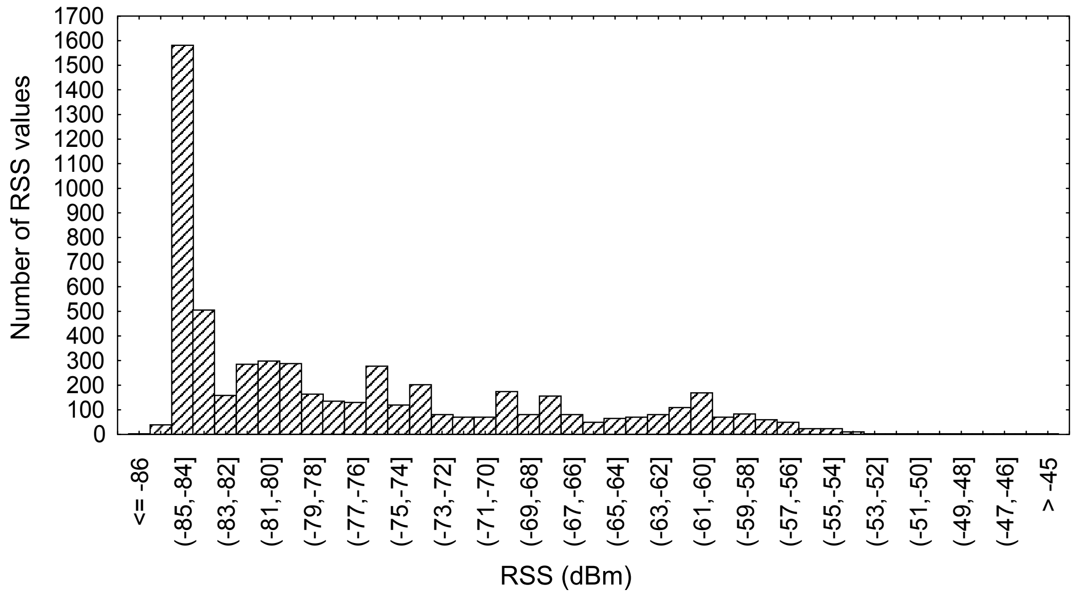


Figure 6.2. Histogram of uplink received signal strength (RSS) values (TAG 7, TMCO cell).

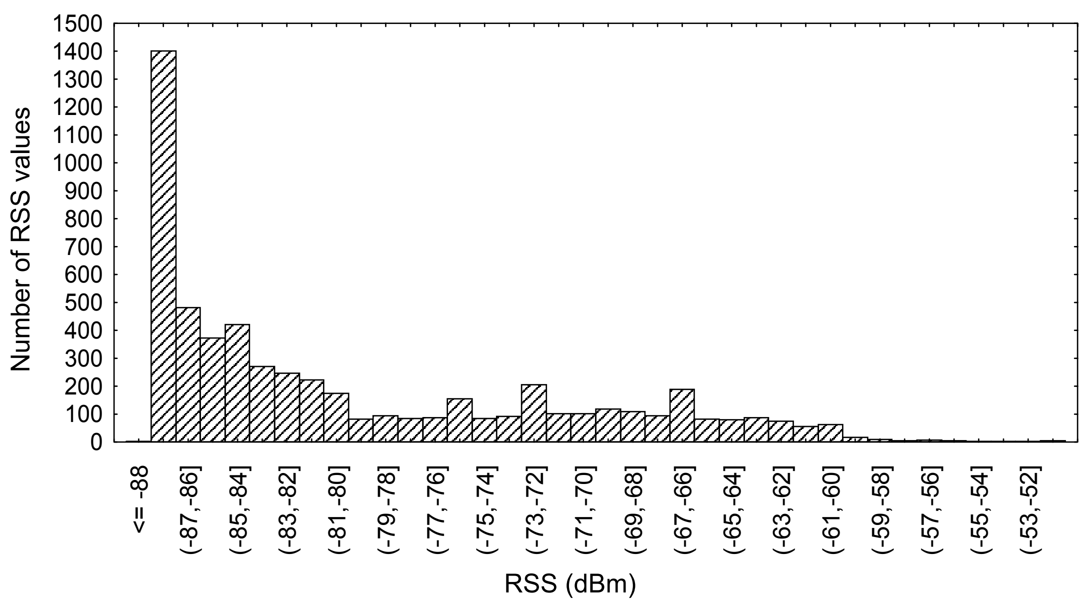


Figure 6.3. Histogram of downlink received signal strength (RSS) values (TAG 7, TMCO cell).

The coverage boundaries were determined in the same manner as for the TMCO cell. The coverage boundaries for the WCO cell were approximately 0.36 mi due north, 0.5 mi due east, and 0.42 mi due south. The WCO cell had a smaller total coverage area than the TMCO cell. The differences in area coverage between the two cells are due to different types of environments and different terrain profiles.

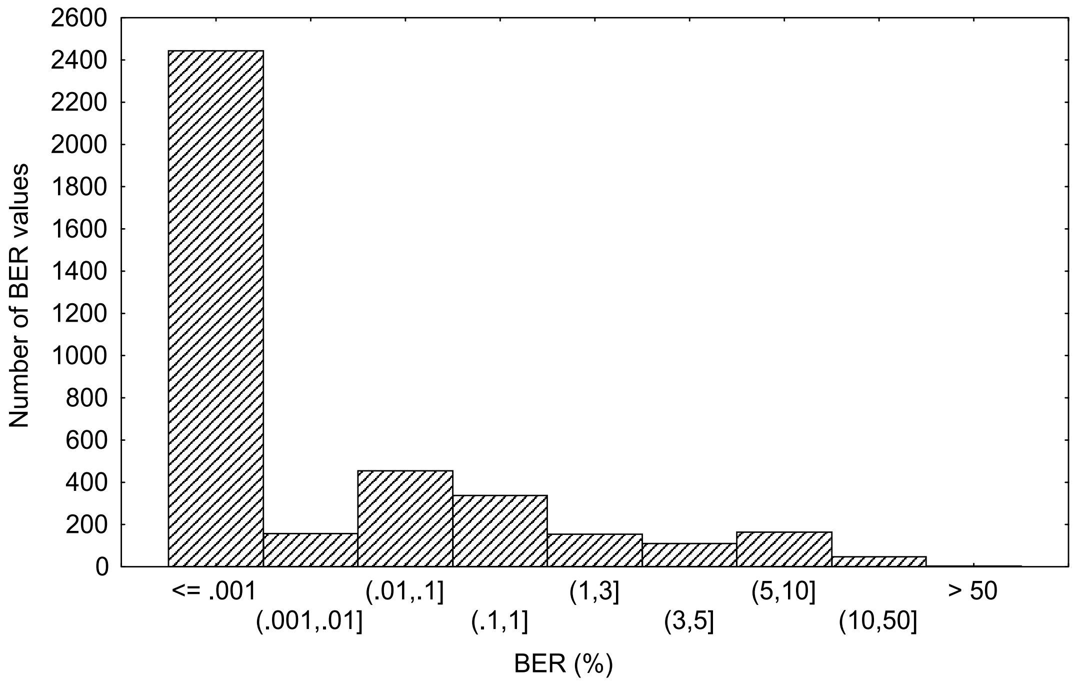


Figure 6.4. Histogram of uplink bit error rate (BER; TAG 7, TMCO cell).

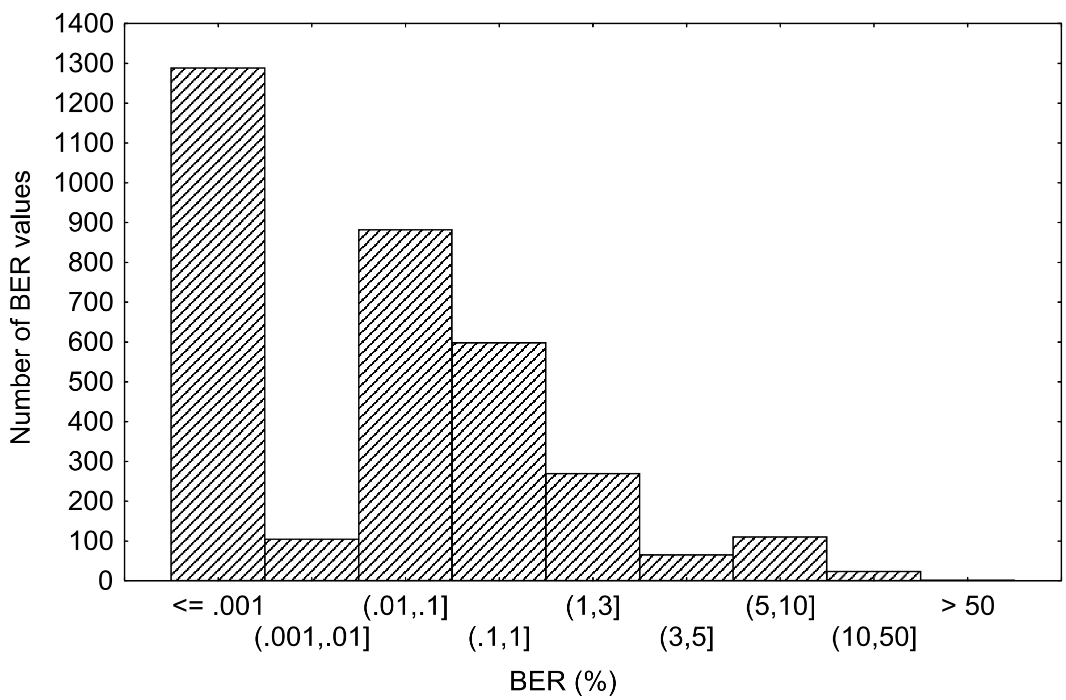


Figure 6.5. Histogram of downlink bit error rate (BER; TAG 7, TMCO cell).

Figures 6.7 and 6.8 show the histograms of uplink and downlink RSS values, respectively. As in the TMCO data, the direct comparison between uplink and downlink (link balance) was not possible, due to misalignment of the time stamps in the uplink and downlink data files. For both links, the majority of RSS values were less than -78 dBm. The distributions of RSS

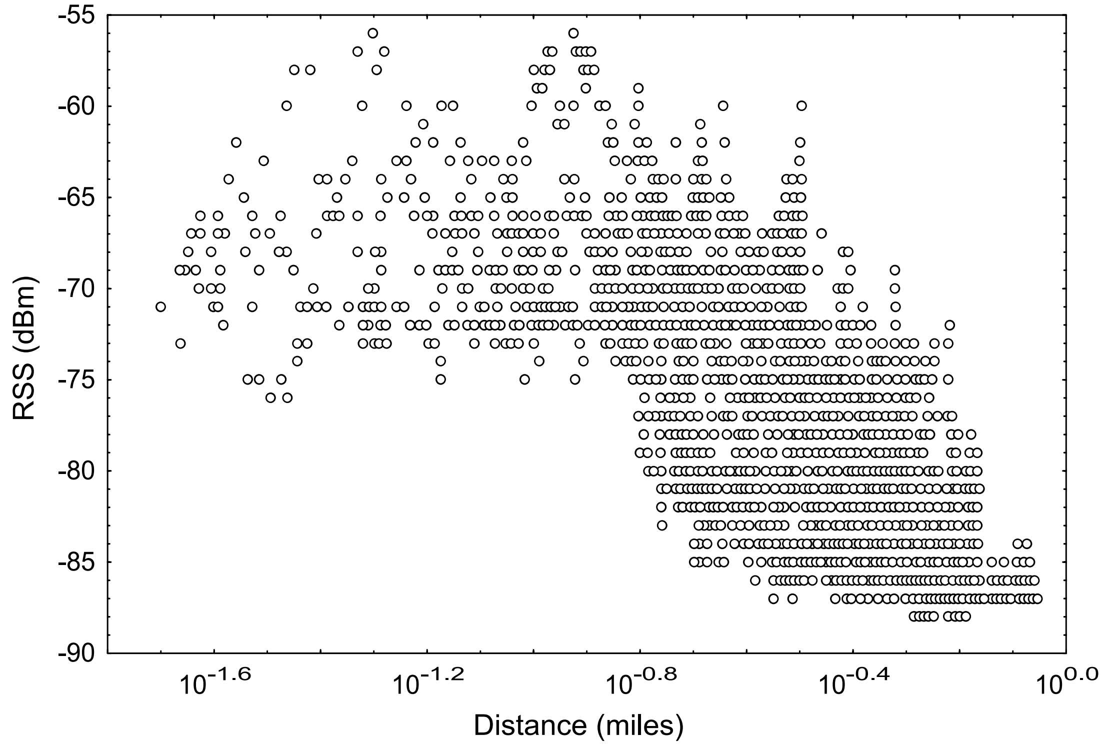


Figure 6.6. Downlink received signal strength (RSS) vs. distance (TAG 7, WCO cell).

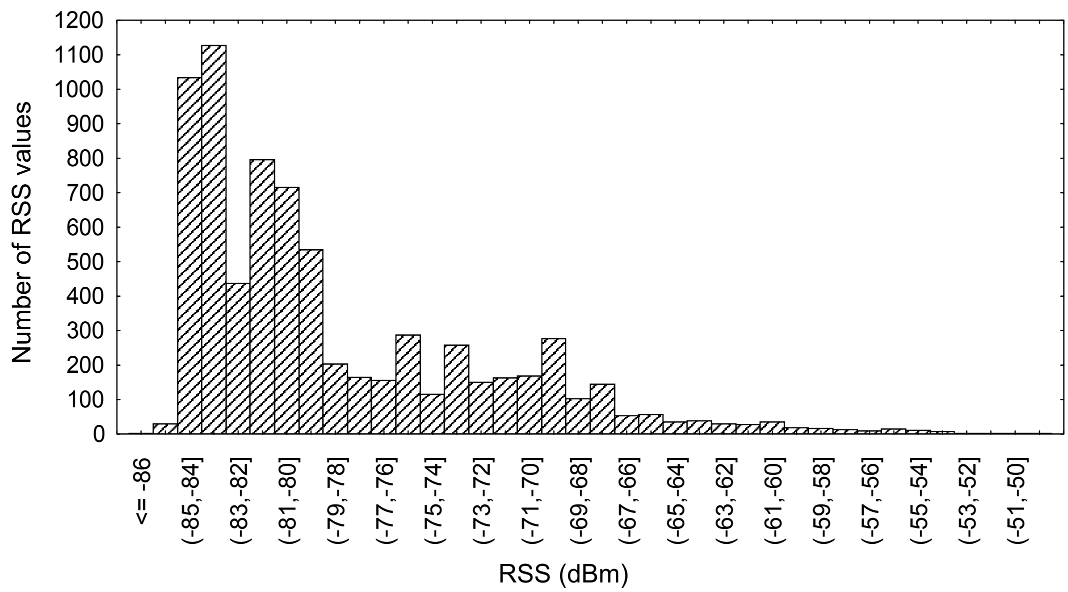


Figure 6.7. Histogram of uplink received signal strength (RSS; TAG 7, WCO cell).

values for the uplink and downlink are similar for RSS values of -78 dBm or greater. The lowest recorded RSS was -88 dBm for the downlink and -85 dBm for the uplink.

Figures 6.9 and 6.10 show the uplink and downlink BER histograms, respectively. The uplink BER histogram for the WCO cell is very similar to the one for the TMCO cell.

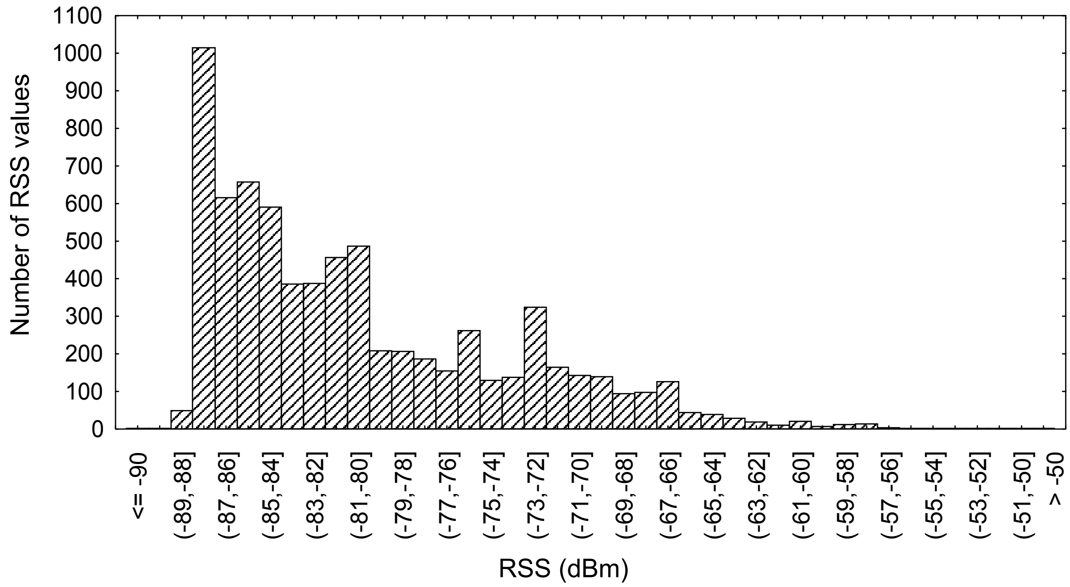


Figure 6.8. Histogram of downlink received signal strength (RSS; TAG 7, WCO cell).

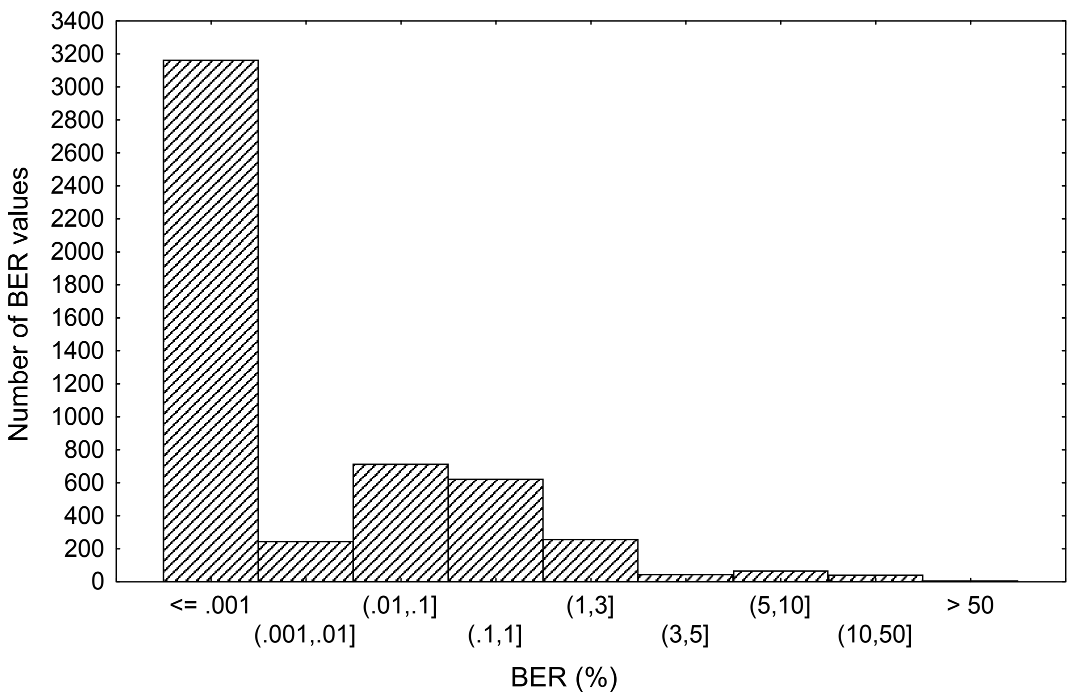


Figure 6.9. Histogram of uplink bit error rate (BER; TAG 7, WCO cell).

Likewise, the downlink BER histogram for the WCO cell is very similar to the one for the TMCO cell. For the uplink, the vast majority of BER values were less than or equal to 0.001%. For the downlink, while a large number of BER values were less than or equal to 0.001%, there were more BER values in the 0.01 - 0.1% and 0.1 - 1.0% ranges than for the uplink.

Figure 6.11 shows a plot of BER as a function of RSS for both the uplink and downlink cases. This plot includes data from both the WCO and TMCO cells. Note that as expected, the BER decreases as the RSS increases. There is a difference between the uplink and downlink curves that is particularly noticeable for BER values of 1% or greater. For a given BER of 1% or greater, the RSS is several dB lower for the uplink case than the downlink case.

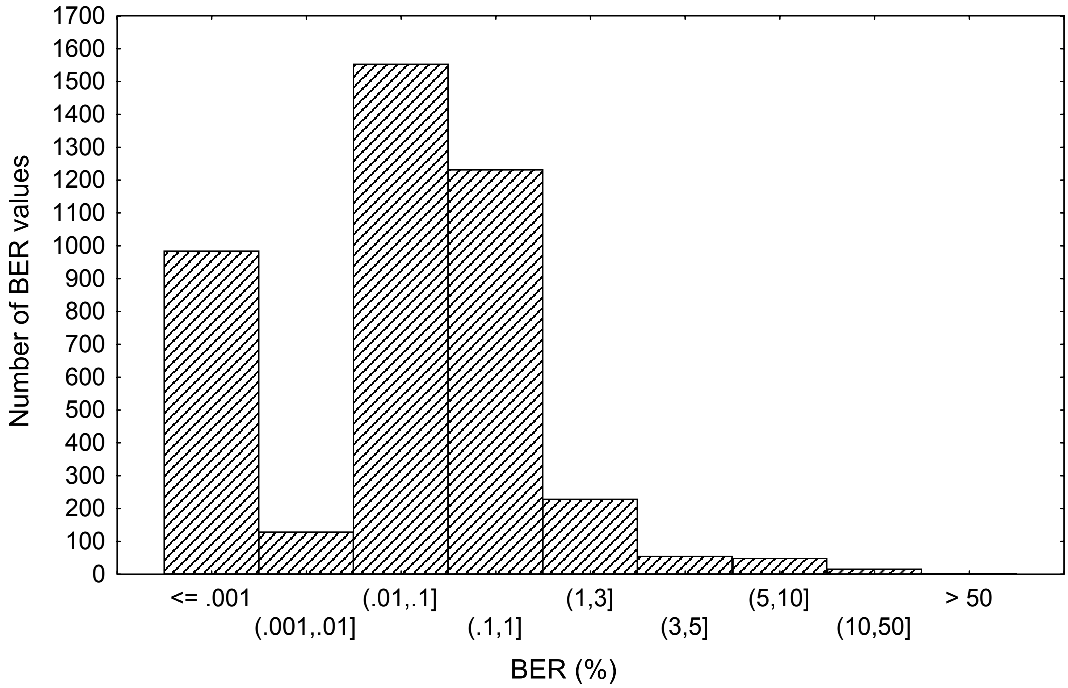


Figure 6.10. Histogram of downlink bit error rate (BER; TAG 7, WCO cell).

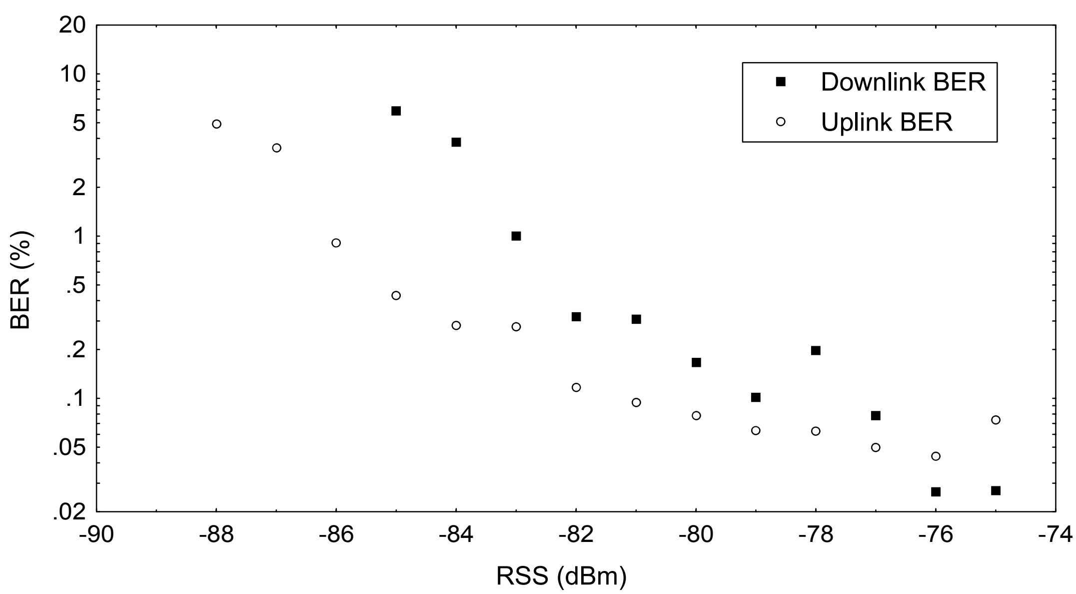


Figure 6.11. Bit error rate (BER) vs. uplink and downlink received signal strength (RSS) for the TMCO and WCO cells (TAG 7).

6.4 Handoff Testing

No handoff testing was performed because only one base station and one mobile unit were used for the TAG 7 testing. This allowed only one sector of one cell to be active at any time during the TAG 7 testing.

6.5 Interference Testing

No interference testing was performed during the TAG 7 testing.

6.6 Voice Quality

As discussed in Section 3.6, two types of voice quality measurements were made for the PCS JTC technology field trials in general: quasi-stationary measurements and handoff measurements. Only the quasi-stationary measurements were performed for the Wideband CDMA (TAG 7) technology; handoff was not possible because only one base station and one mobile unit were used for the TAG 7 testing.

6.6.1 Quasi-stationary Measurements

Voice recordings and various objective measures including uplink and downlink RSS and uplink and downlink BER were collected at locations on a 200-m grid that encompassed the expected coverage area for the TMCO and WCO sites. Note that this grid is smaller than the 0.5-mi grid used in the previous JTC PCS technology field trials. Measurements were taken at the 61 locations shown on the map in Figure 6.12. At each location, data were collected as the measurement van traveled at a given speed. The same vehicle speed and sample time for making the voice recordings was used at each location. The measurement van traveled 10 m over the sample time.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the radio link for both the uplink and downlink simultaneously. The source tape transmitted over each link was the same as that used for TAG 5 testing (see Section 3.6.1).

The received voice transmissions were recorded on digital audio tape simultaneously at the receiver for the uplink and at the receiver for the downlink. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. At each location, after the test run was made to make the voice recordings, another test run was made to collect uplink and downlink RSS and uplink and downlink BER data.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both MOS and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

6.6.2 Mean Opinion Score Assessment

To accomplish the MOS testing, a pool of 31 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, 35-45, 45-55, and those over 55 years of age. There were 17 male and 14 female subjects. The subjects were cordless, noncellular telephone users.

Three groups consisting of eight subjects each and one group consisting of seven subjects were formed from the subject pool. The subjects were asked to rate voice segments by answering the three questions listed in Section 3.6.2 after each segment was presented.

First, the subjects in each of the 4 groups were presented 10 practice voice segments to rate. The practice segments included one 64-kbps wireline voice segment, two voice segments collected from field measurements (one with a definitely acceptable expert listener rating and one with an unacceptable expert listener rating), and seven modulated noise reference unit (MNRU) segments. The MNRU segments were used at the request of the TAG 7 vendor. MNRU's have been used in subjective tests as a reference condition with impairment that sounds similar to the impairment in the coders being tested. The impairment produced by the MNRU segments is defined as the ratio in dB of speech power to speech correlated noise power. For the TAG 7 testing, the MNRU's were produced by artificially adding Gaussian noise of varying levels to the 64-kbps wireline voice segment. The seven MNRU voice segments used during the rating of the practice voice segments included those with a signal-to-noise ratio (SNR) of 5, 10, 15, 20, 25, 30, and 40 dB.

After the practice segments were presented, the subjects in each of the four groups were asked to rate 3 reference voice segments and one quarter of the voice segments taken from the field trial measurements. Every listener within a group listened to the same voice segments. The reference voice segments consisted of one 64-kbps wireline voice segment and two MNRU voice segments with a 15-dB and 25-dB SNR. The voice segments from the field trial measurements came from the uplink or downlink measurements at a portion of the 61 measurement locations.[10] The number and type (male or female) of sentences that were used and the order in which they were used to form a voice segment are the same as that described in Section 4.6.2. Subjects were given two breaks during each session. After all segments were presented, subjects filled out a post-trial questionnaire.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain an MOS. The results from all four of the groups, from a total of 120 voice segments are shown in the histogram in Figure 6.13. Overall, the voice segments were rated favorably, with 70% of the segments rated between fair and excellent. The average MOS was 3.55 and the standard deviation was 1.05.

Figures 6.14 and 6.15 show histograms of MOS's for the uplink and downlink, respectively. The average MOS for the uplink was 3.58 and for the downlink was 3.51. A t-test revealed that there is no statistically significant difference in the average MOS's between the uplink and downlink.

[10] Note that both an uplink and a downlink measurement were made at most, but not all, of the measurement locations.

The relationship between the MOS's and some of the objective measures was initially investigated by generating some scatter plots. Figure 6.16 shows the relationship between the MOS's and average RSS for both the uplink and downlink combined. For RSS values above approximately -80 dBm, some variation in MOS's is seen but most of the MOS's are consistently 3.0 or higher. Note that the MOS's tend to degrade rapidly for values of RSS less than about -80 dBm.

Figures 6.17 and 6.18 show the relationship between the MOS's and the average BER for both the uplink and downlink, respectively. The average BER never exceeded 0.8% on the downlink and 0.45% on the uplink.

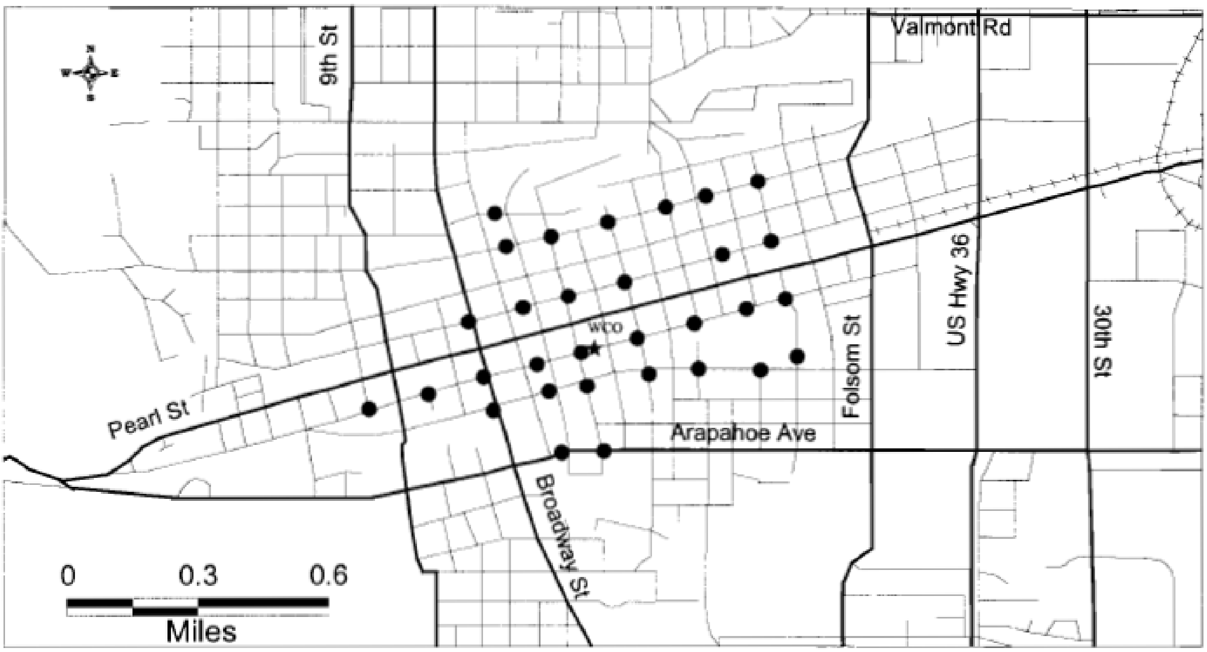
Pearson product-moment correlations were performed to determine the correlation between MOS's and average RSS and MOS's and average BER for the data on the uplink and downlink combined. The correlation coefficient between MOS and average RSS was 0.49 and that between MOS and average BER was -0.46. These correlation coefficients between MOS and averaged objective measures suggest that a strong linear relationship between MOS and the objective measures does not exist. The correlation between the average RSS and the average BER was -0.25. A higher correlation between these measures was expected.

While there does not appear to be a strong linear relationship between MOS and the objective measures, there still may be a strong consistently increasing or decreasing relationship between them. The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average RSS and between the ranks of MOS and the ranks of average BER. The Spearman rank correlation coefficient between MOS and average RSS was 0.45 and that between MOS and average BER was -0.54. These rank correlations between MOS and averaged objective measures suggest that a strong consistently increasing or decreasing relationship between MOS and the objective measures does not exist.

Note that as in the data analysis of the previous JTC PCS technologies (TAG 5, TAG 2, and TAG 4), the objective measures were averaged over the entire length of the voice segment. By analyzing the instantaneous variation or possibly minimum and maximum values of the objective measures within the voice segment, further insight may be gained on the behavior of MOS's.

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the TAG 7 voice samples according to listeners:

1) bursts of loud static,
2) "whine" or "feedback noises," and
3) "background hiss."



Maps made with MapInfo Professional™

Figure 6.12. Quasi-stationary measurement locations for TAG 7.

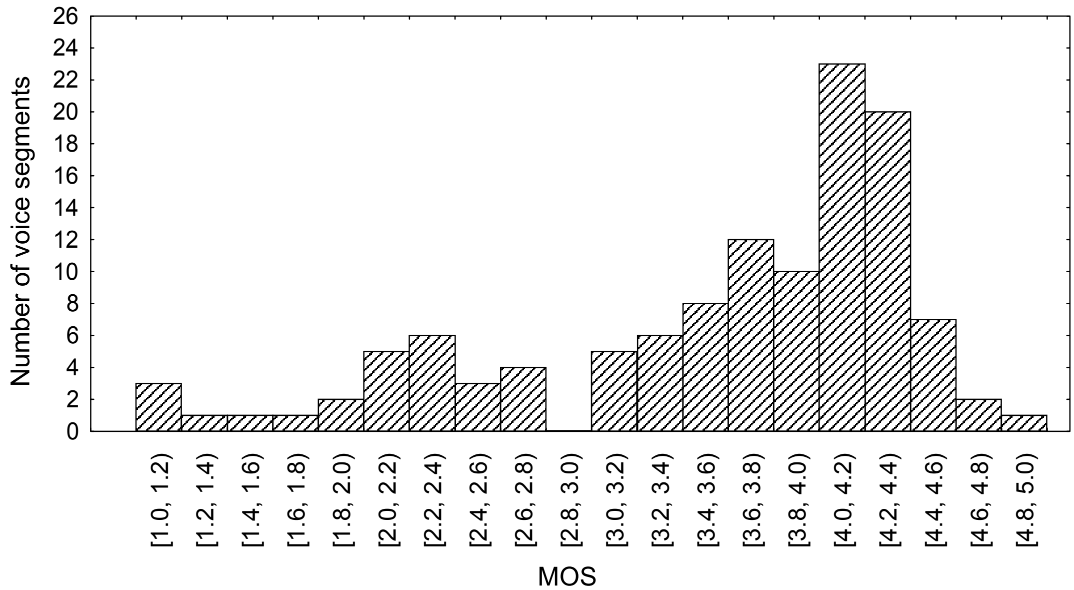


Figure 6.13. Histogram of mean opinion scores (MOS's; TAG 7).

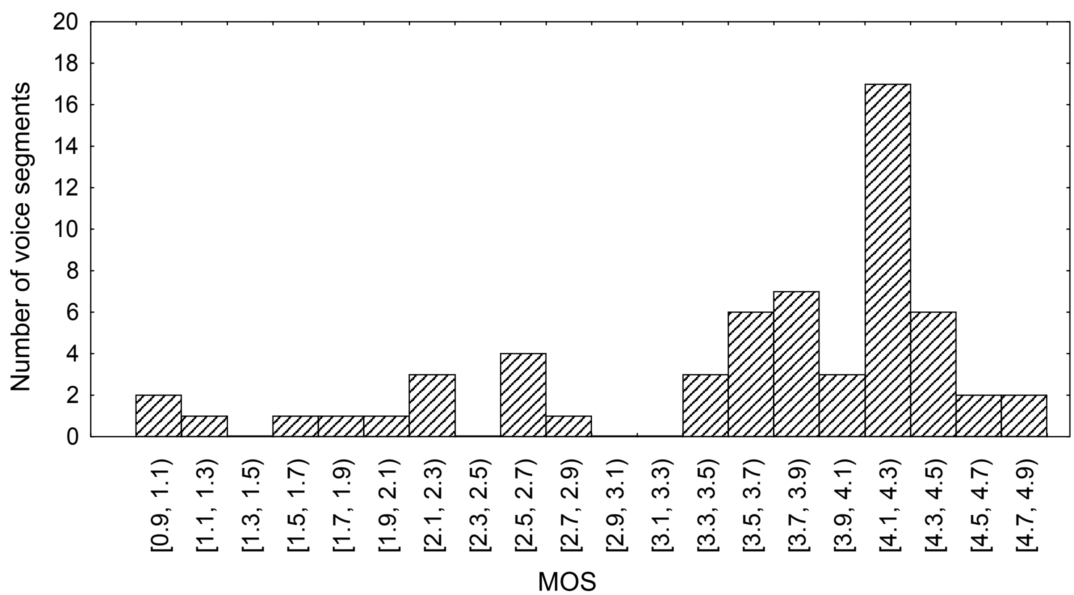


Figure 6.14. Histogram of uplink mean opinion scores (MOS's; TAG 7).

The nature of these distortions are likely judged differently by different listeners. Intelligibility and speaker recognition are two main aspects of perceived quality. For most of the voice samples, intelligibility remained high. As a result, overall MOS's were high.

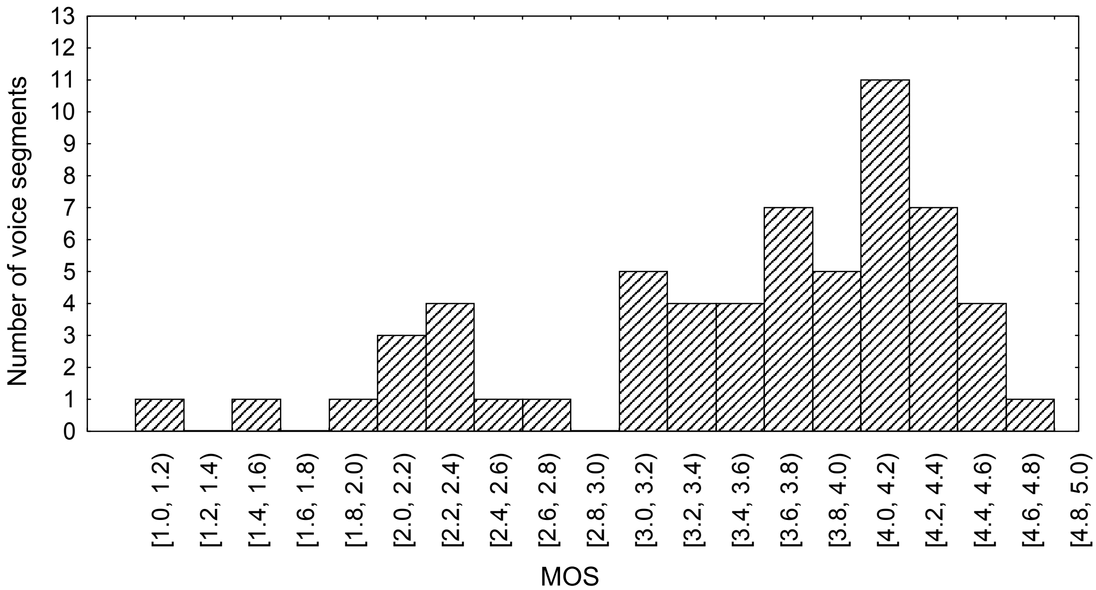


Figure 6.15. Histogram of downlink mean opinion scores (MOS's; TAG 7).

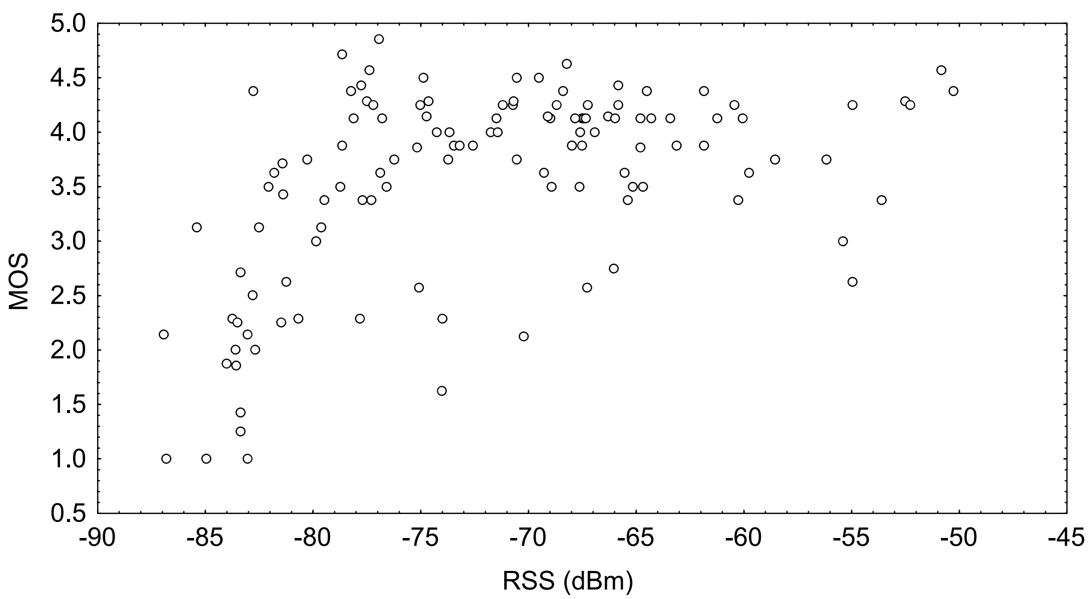


Figure 6.16. Mean opinion score (MOS) vs. average received signal strength (RSS; TAG 7).

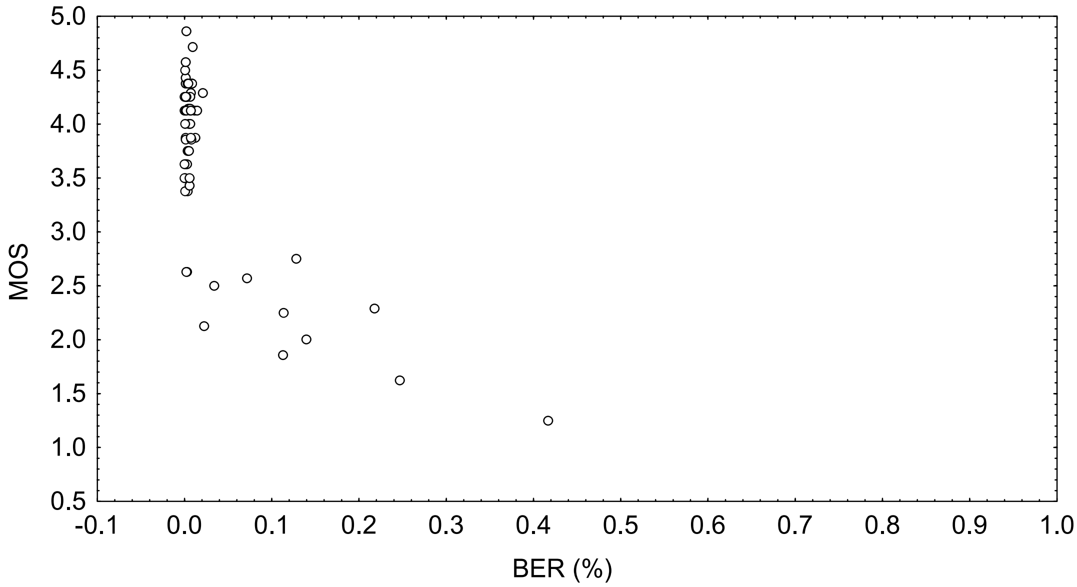


Figure 6.17. Mean opinion score (MOS) vs. average uplink bit error rate (BER; TAG 7).

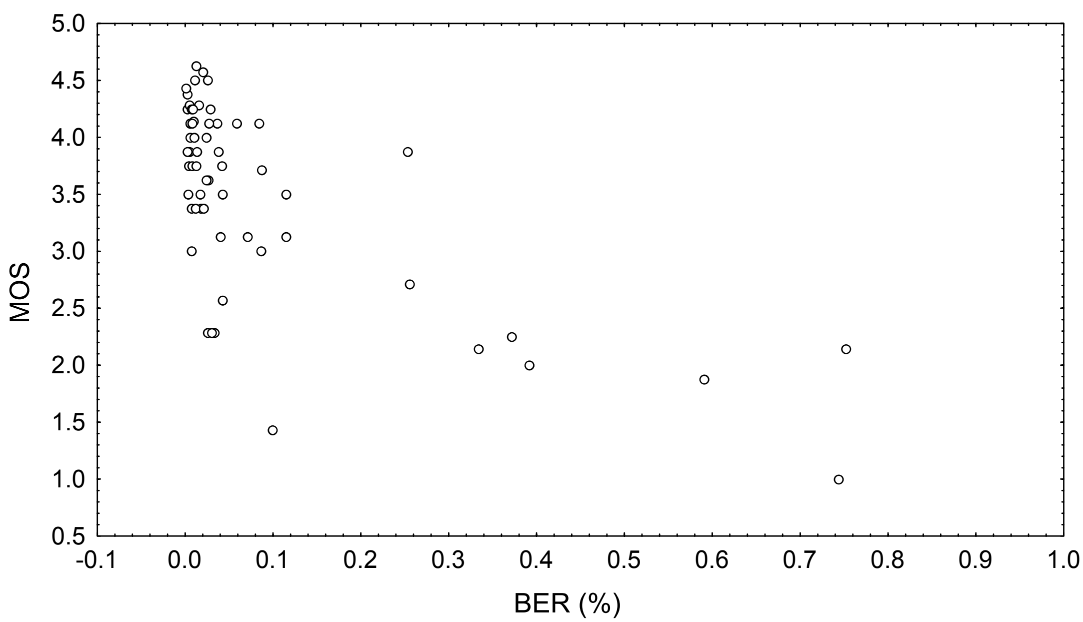


Figure 6.18. Mean opinion score (MOS) vs. average downlink bit error rate (BER; TAG 7).

6.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener.[11] The expert listener ratings followed the identical procedure as in the PCS 1900 (TAG 5) testing. This procedure is described in Section 3.6.3.

Figure 6.19 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data.

The expert listener ratings were very good indicators of percent acceptability for the voice segments in the TAG 7 testing. The expert listener ratings accurately predicted the percent acceptability for all of the 120 voice segments recorded.

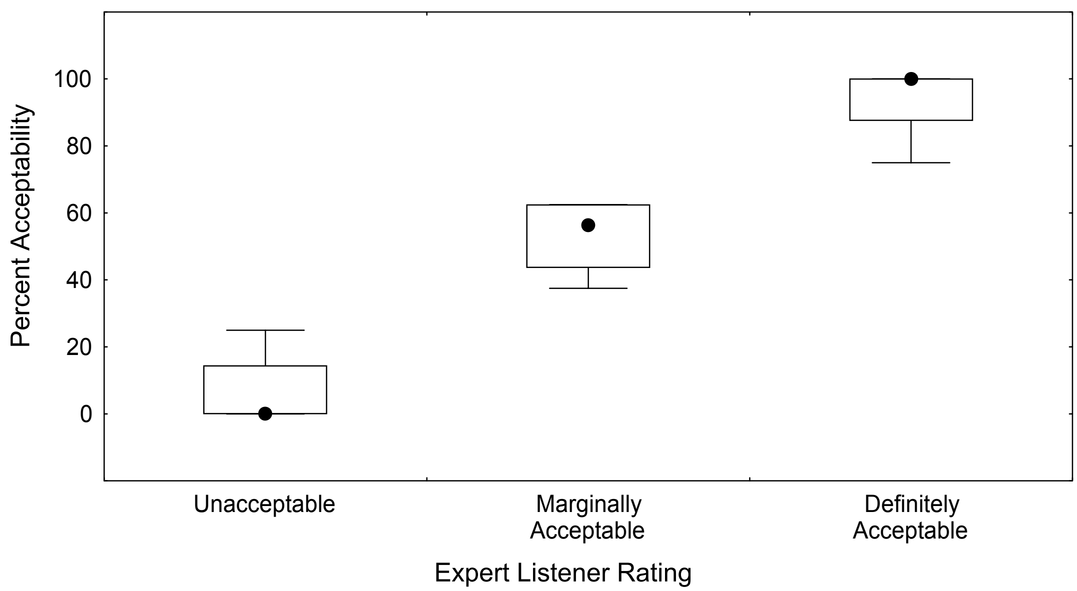


Figure 6.19. Percent acceptability vs. expert listener rating (TAG 7).

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.91; this indicates a strong correlation between these measures, as would be expected. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.89 and that between percent acceptability and expert listener rating was 0.98; this indicates strong correlation between these measures.

[11] A new expert listener was trained and rated voice segments for the TAG 7 and subsequent JTC PCS technology field trials (TAG 3 and TAG 1). The original expert listener rated voice segments for all of the previous JTC PCS technology field trials (TAG 5, TAG 2, and TAG 4).

6.6.4 Voice Quality Handoff Measurements

Voice quality handoff measurements were not made for the Wideband CDMA (TAG 7) technology field trials.

6.7 Manufacturer's Statement

The statement provided by OKI Electric Industry Co. Ltd. is included in this section. This statement is identical to that given in [5], except for some minor editorial changes.

OKI Electric Industry Co. Ltd. would like to thank U S West, NTIA, and ITS for their support during the demonstration of the performance of the Wideband CDMA radio air interface at the BITB in Colorado. We found the atmosphere and attitude during the tests positive and cooperative.

The purpose of this test was to prove the air-interface functionality and to ascertain coverage area and speech quality. These tasks were successfully accomplished.

Noncommercial hardware was used for the testing. The base station and portable station (mobile unit) transmitter output power was 200 mW, which met the specification. The adaptive pulse code modulation (ADPCM) speech quality was excellent when the portable station (mobile unit) was inside the coverage area. The Wideband CDMA coverage area was smaller than the specification because of the following hardware imperfection:

The RF shielding was imperfect. The resulting 1.9-GHz leakage produced a 2-kHz beat frequency signal which reduced the tracking capability of the RAKE[12] receiver. The degraded receiver sensitivity reduced the coverage radius to less than half of that expected. The Wideband CDMA MOS value was also lower than the specification because of the same hardware imperfection.

[12] The RAKE receiver uses multiple receivers to receive the strongest multipath components of a signal. The receiver then combines these multipath components to provide an improved received signal.

7. TAG 3 (PACS) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 3. The technology tested was the PACS PCS standard. The base station (called radio port or RP in this technology) and base station controller (called radio port control unit or RPCU in this technology) equipment was provided by NEC. The mobile units (called subscriber units in this technology) were supplied by Motorola and Panasonic. The TAG 3 field tests examined area coverage, handoff, and voice quality; and the effects of co-channel and adjacent channel interference on system performance.

The information presented in this section is taken from [6]. The reader is referred to [6] for a more complete and detailed presentation of the TAG 3 technology field testing at the BITB.

7.1 TAG 3 Test System Configuration

The block diagram of the test system configuration is shown in Figure 7.1. As discussed in Section 2.0, the TAG 3 PACS technology was tested only in a low-tier configuration in seven different microcells. The previous technologies tested in the JTC PCS technology field trials were tested in a high-tier configuration only.

The test system consisted of a base station (RP) at each of four microcell sites in downtown Boulder, Colorado and three microcell sites in south Boulder. The base stations at each microcell site used receive antenna diversity. The base station controllers (RPCU's) were located in the WCO. The base stations were connected to the base station controllers by high-speed digital subscriber loop circuits providing T1 connectivity between the base station controllers and the base stations. Fiber optic transport was used between the high-speed digital subscriber loop terminals at the TMCO and the base station controller located at the WCO.

7.2 Calibration

A calibration of the base station RSS was performed by injecting a digitally modulated signal of known level into the receiver and comparing this level to the RSS value reported by the receiver.

The input signal into the base station receiver was provided by a digital modulation signal generator. Losses in the cabling between the signal generator and the input of the base station receiver were measured and a correction, or offset, was added to the signal generator output level reading. The level of the input signal was varied over the dynamic range of the receiver to generate a table of actual input RSS values and their corresponding reported RSS values. Note that although the base station provides diversity reception, it does not allow the intentional selection of a diversity branch. Since the base station normally operates on diversity branch 1, all calibrations were conducted on this branch; calibrations were not conducted on diversity branch 2. The maximum difference between the actual input RSS values and their corresponding reported RSS values was 3 dB over the operating range of -60 to -108 dBm for all 7 base stations tested.

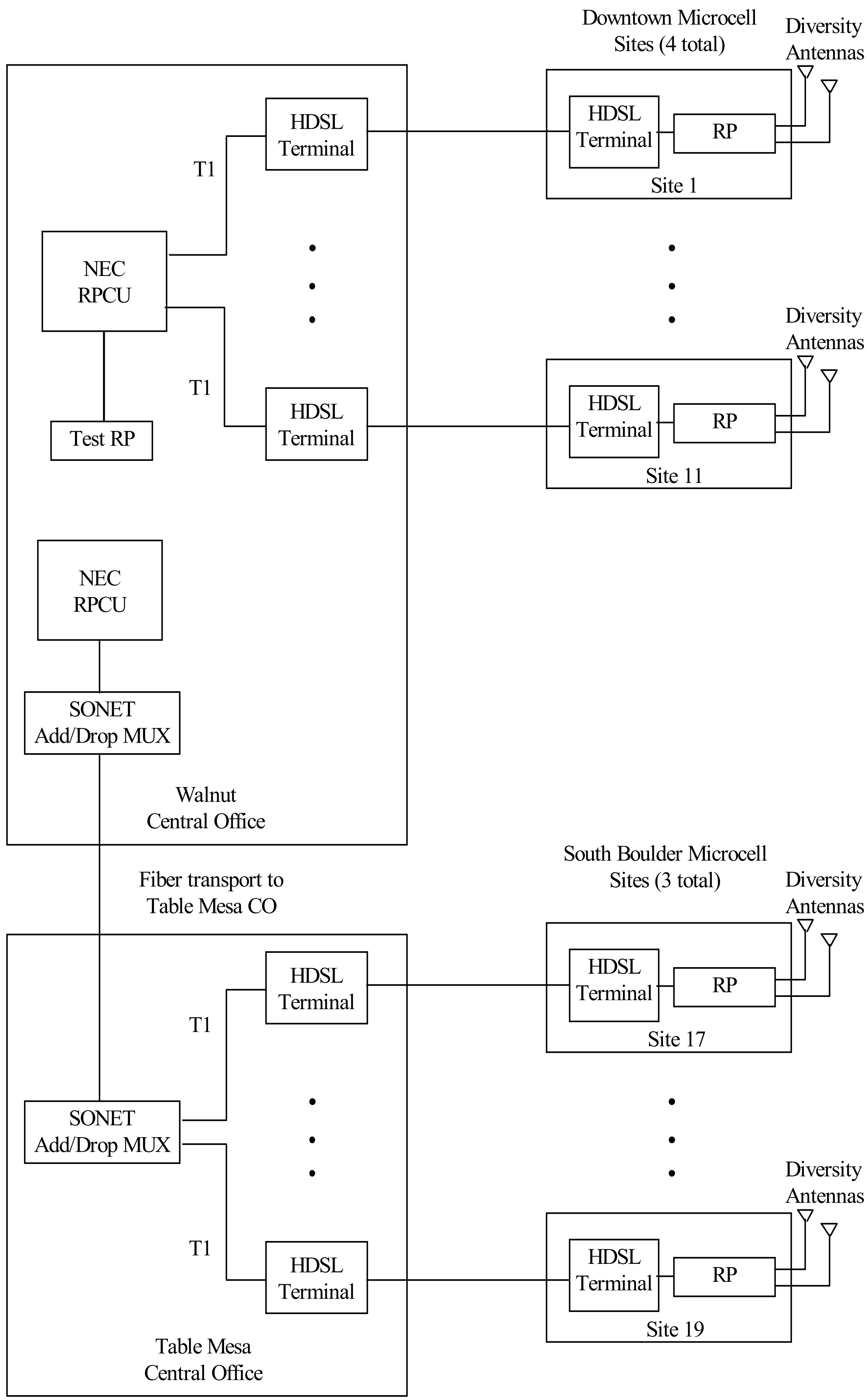


Figure 7.1. Block diagram of the TAG 3 test system configuration.

The mobile units (provided by Motorola and Panasonic) were checked for accuracy of the RSS reports. This was done by injecting a digitally modulated signal of known strength into the receiver of the mobile unit. The level of the input signal was then compared to the RSS value reported by the mobile unit. All of the mobile units had reported values of RSS within 4 dB of the actual input signal level for input signals from -45 to -100 dBm. Note that during the calibration procedure for the mobile units, receive diversity was enabled. With the receive diversity enabled, the mobile units report RSS from the strongest diversity branch.

An examination of the base station and mobile unit transmitter characteristics, including transmit power, frequency accuracy, modulation accuracy, and occupied bandwidth, was also performed; however, the results of this examination are not presented here.

7.3 Area Coverage Testing

Area coverage testing was performed in the four microcells located in downtown Boulder. These microcells, as described in Section 2.0 are:

Site 1 - Intersection of Pearl Street and Broadway
Site 3 - Intersection of Pearl Street and 15th Street
Site 9 - On 13th Street halfway between Pine Street and Mapleton Avenue
Site 11 - On 16th Street halfway between Pine Street and Mapleton Avenue

The base station power for each microcell site was set so that the output power was approximately 3.2 W equivalent isotropically radiated power (EIRP). Each base station used omnidirectional antennas. Measurements to show area coverage were taken with the mobile unit placed on a cart and with the antenna mounted on a wooden pole attached to the side of the cart. A Motorola mobile unit was used for all of the area coverage testing. A GPS receiver was mounted on the side of the cart next to the antenna mounting structure. The measurements were taken by pushing the cart at a pedestrian speed along routes (radials) away from the microcell site. When time permitted, measurements along additional routes in between the radials were taken.

Only one microcell site was activated at a time during area coverage testing; all other microcell sites were powered down. Calls were originated prior to the start of the route, approximately one half block away from the microcell site and data collection was initiated. The data were collected both at the mobile unit and at the base station as the measurement cart was pushed along the route. At the end of the route, the data collection was stopped and the data were saved to disk. If the call was dropped before the end of the route was reached, data collection was terminated and the data were saved to disk. The data collected at the mobile unit included GPS location and time, downlink RSS, downlink word error rate[13] (WER), and other system parameters. The data collected at the base station included GPS time, uplink RSS, uplink WER[13], and other system parameters. All data were averaged over 1 s.

[13] Actually, the number of errored frames per second (WERI) was recorded. The WER was computed from the following equation: WER = (WERI/400) • 100% since there are 400 frames per second.

7.3.1 Low-Tier Microcell Site 1 Area Coverage Data

Downlink RSS as a function of distance is shown in Figure 7.2. The data included in this figure are the overall data for this cell, excluding RSS values less than -101 dBm. RSS values less than -101 dBm were excluded because -101 dBm is the threshold level for normal system operation of the mobile unit receiver. The large variation in RSS seen in Figure 7.2 is mostly due to different propagation environments along Broadway and Pearl Street (foliage was heavier along Pearl Street) and shadowing. Note that signals up to approximately -88 dBm existed out to approximately 0.65 mi. Those signals were recorded along Broadway in areas having LOS propagation between the mobile unit and the base station.

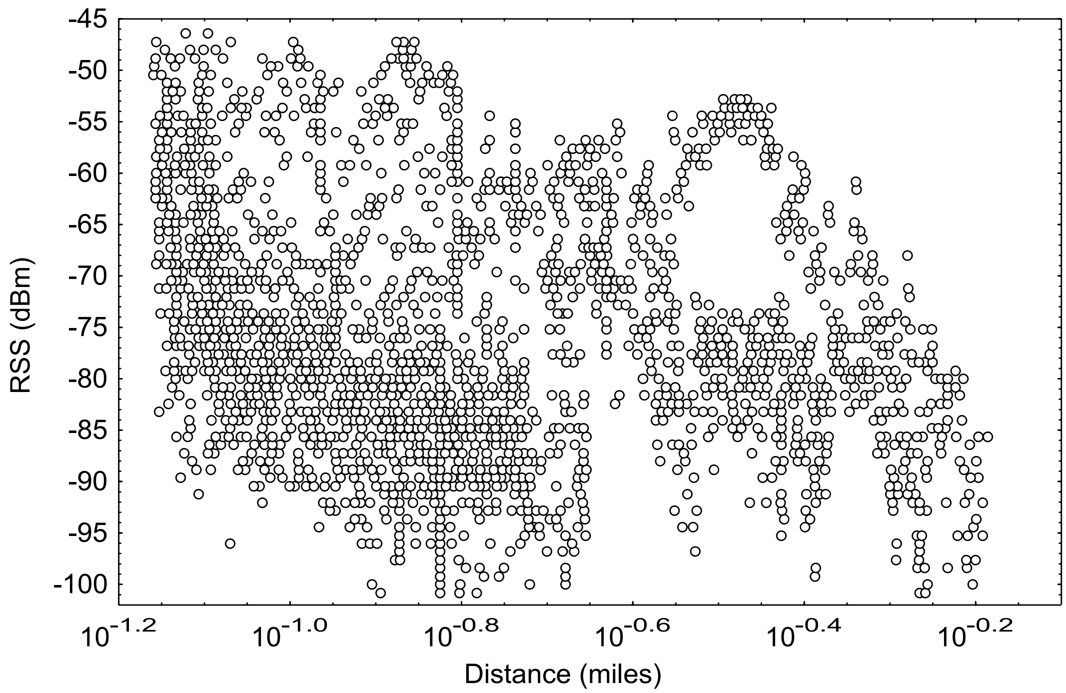


Figure 7.2. Downlink received signal strength (RSS) vs. distance (TAG 3, microcell site 1).

A rough estimate of the coverage area was determined by assuming that a downlink RSS of -90 dBm or greater is desired. The measured RSS data along all of the routes traversed within the microcell were used to determine the coverage area. Due to shadowing, the RSS varied significantly along the Site 1 routes, crossing the -90 dBm level several times before finally staying below -90 dBm. The point along each route where the RSS first dropped below -90 dBm was used to define the coverage boundaries. Under these conditions, the coverage boundaries were approximately 0.41 mi to the north-northwest, 0.35 mi to the west-southwest, and 0.57 mi to the south-southeast.

Figure 7.3 shows the histogram of downlink RSS values. Again, RSS values less than -101 dBm were excluded. The mean RSS was -75.9 dBm and the standard deviation was 12.95 dB. Figure 7.4 shows the histogram of downlink WER values. From this histogram it is seen that most of the data points had a WER less than or equal to 1%. One influencing factor on the WER is that the WER increases rapidly as the RSS approaches the -101-dBm threshold level (such as at the edge of the coverage area).

The histogram of uplink RSS values is shown in Figure 7.5. In this histogram, RSS values less than -118 dBm were excluded. The mean RSS was -91.24 dBm and the standard deviation was 11.28 dB for this case. Figure 7.6 shows the uplink WER histogram. Here, most of the data points had a WER less than or equal to 3%. A relatively large number of data points had a WER greater than 10%.

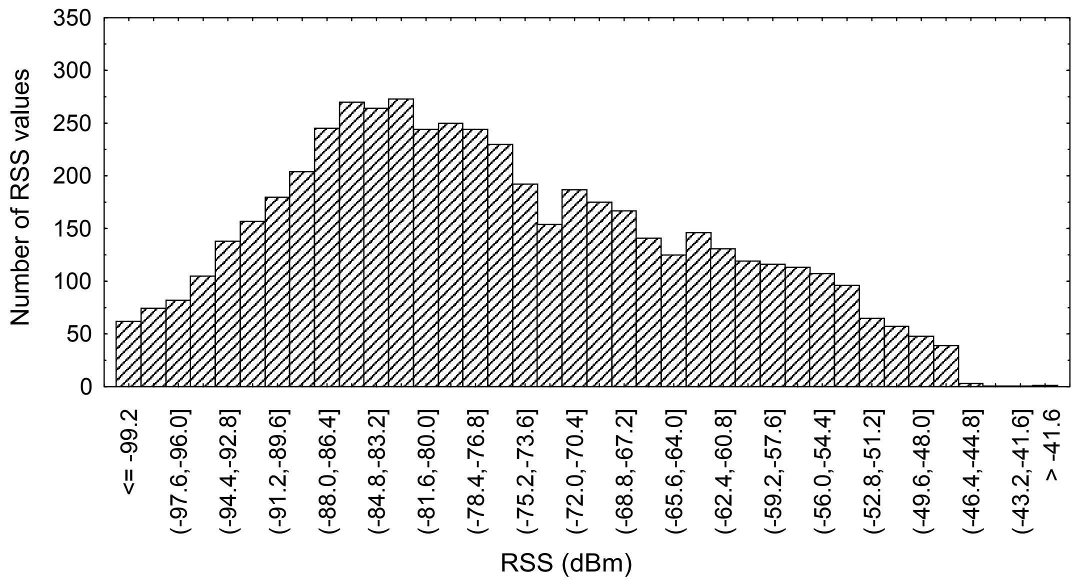


Figure 7.3. Histogram of downlink received signal strength (RSS; TAG 3, microcell site 1).

7.3.2 Low-Tier Microcell Site 3 Area Coverage Data

Downlink RSS as a function of distance is shown in Figure 7.7. The data included in this figure are the overall data for this cell, excluding RSS values less than -101 dBm. The large variation in RSS seen in Figure 7.7 occurs mostly because the base station was mounted on a light pole in the middle of the street which made shadowing more pronounced. Note that signals up to approximately -65 dBm existed out to approximately 1.35 mi. Those signals were recorded along 15th Street where a clear LOS propagation path existed between the mobile unit and the base station.

The estimate of the coverage area for Site 3 was determined in the same way as that for Site 1. The coverage boundaries were approximately 0.14 mi to the north-northwest, 0.26 mi to the west-southwest, and 0.36 mi to the south-southeast.

Figure 7.8 shows the histogram of downlink RSS values. Again, RSS values less than -101 dBm were excluded. The mean RSS was -74 dBm and the standard deviation was 15.81 dB. Figure 7.9 shows the histogram of downlink WER values. From this histogram it

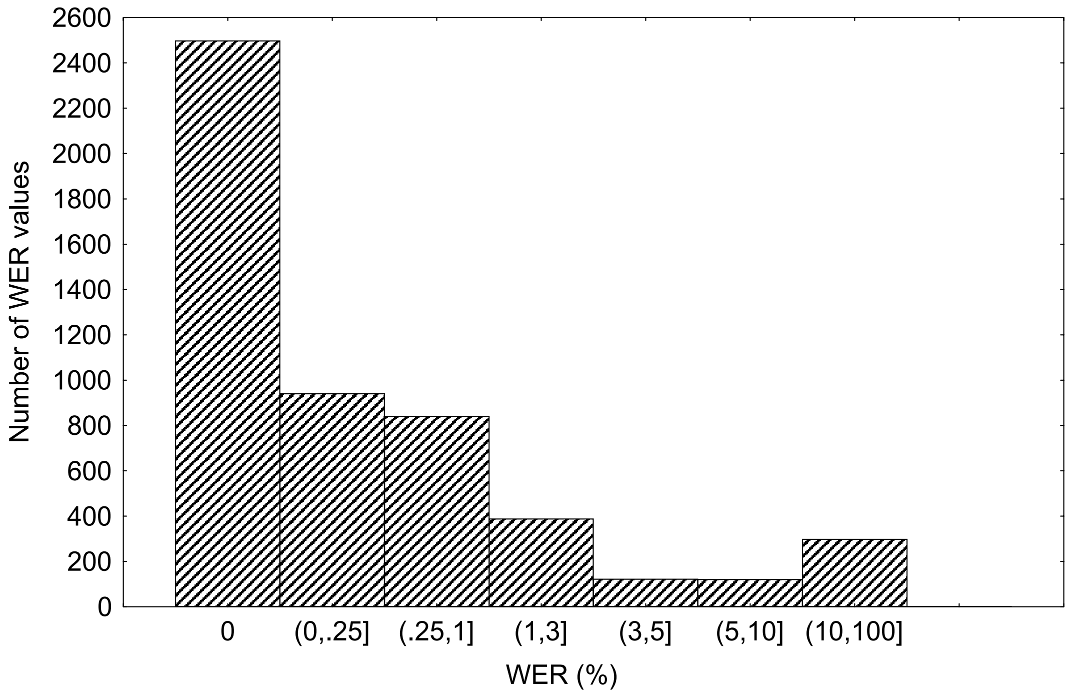


Figure 7.4. Histogram of downlink word error rate (WER; TAG 3, microcell site 1).

is seen that most of the data points had a WER less than or equal to 1%. The uplink RSS histogram is given in Figure 7.10. As in the uplink RSS histogram for Site 1, RSS values less than -118 dBm were excluded. The histogram shows a different distribution than for the downlink case in this microcell; RSS values around -70 dBm occur much more frequently than any other RSS values. The mean uplink RSS was -86 dBm and the standard deviation was 11.31 dB. Figure 7.11 shows the uplink WER histogram. Here, most of the data points had a WER less than or equal to 3%. A relatively large number of data points had a WER greater than 10%.

7.3.3 Low-Tier Microcell Site 9 Area Coverage Data

Downlink RSS as a function of distance is shown in Figure 7.12. The data included in this figure are the overall data for this cell, excluding RSS values less than -101 dBm. The large variation in RSS seen in Figure 7.12 occurs mostly because of shadowing in the environment and because the base station was mounted on a light pole in the middle of the street which made shadowing more pronounced. Note that signals up to approximately -83 dBm existed out to approximately 0.45 mi. Those signals were recorded in areas where a clear LOS propagation path existed between the mobile unit and the base station.

The estimate of the coverage area for Site 9 was determined in the same way as that for Site 1. The coverage boundaries were approximately 0.24 mi to the north-northwest, 0.42 mi to the west-southwest, and 0.24 mi to the west-northwest.

Figure 7.13 shows the histogram of downlink RSS values. Again, RSS values less than -101 dBm were excluded. The mean downlink RSS was -73.4 dBm and the standard deviation

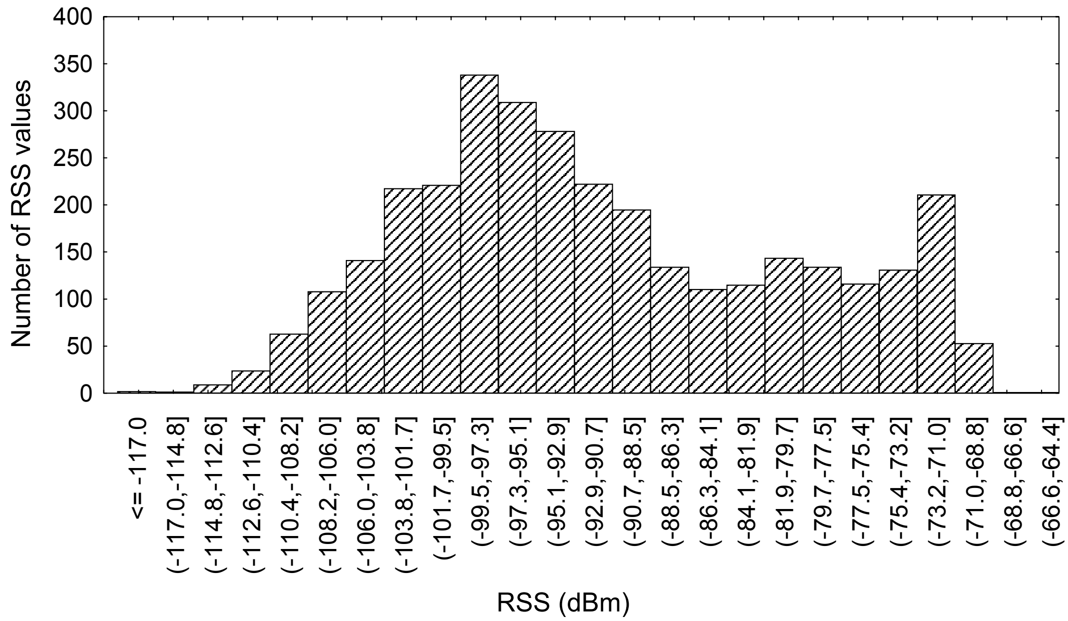


Figure 7.5. Histogram of uplink received signal strength (RSS; TAG 3, microcell site 1).

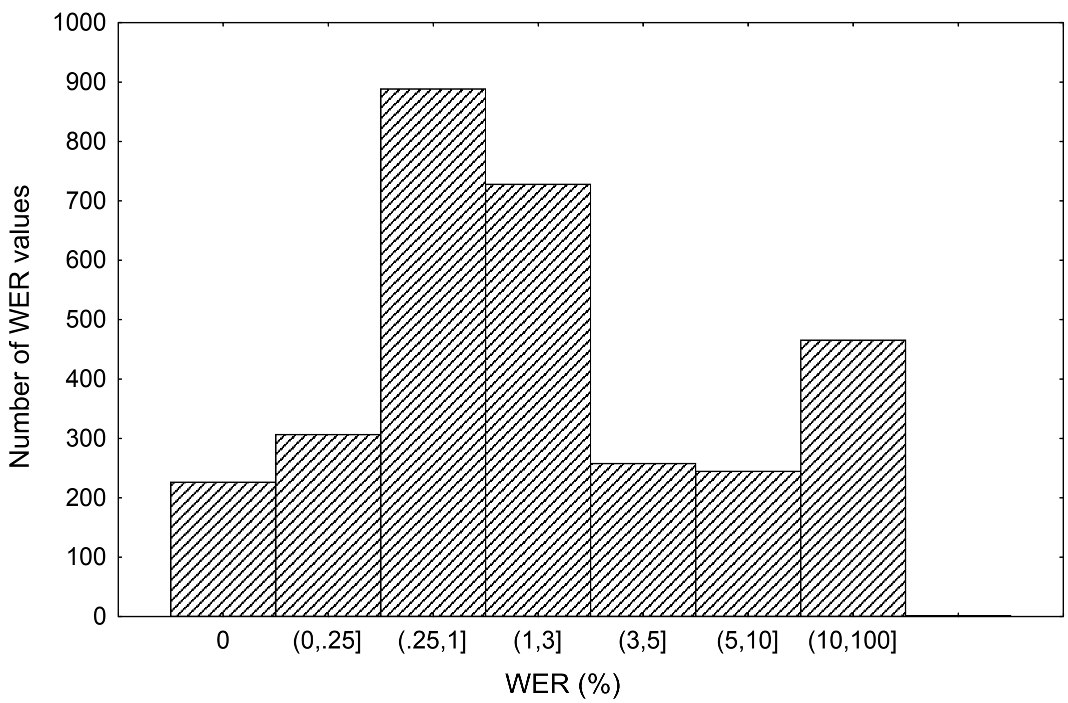


Figure 7.6. Histogram of uplink word error rate (WER; TAG 3, microcell site 1).

was 14.85 dB. Figure 7.14 shows the histogram of downlink WER values. From this histogram it is seen that most of the data points had a WER less than or equal to 0.25%. The uplink RSS histogram is given in Figure 7.15. As in the uplink RSS histogram for Site 1, RSS values less than -118 dBm were excluded. The histogram shows a different distribution than for the downlink case in this microcell; RSS values around -70 dBm occur much more

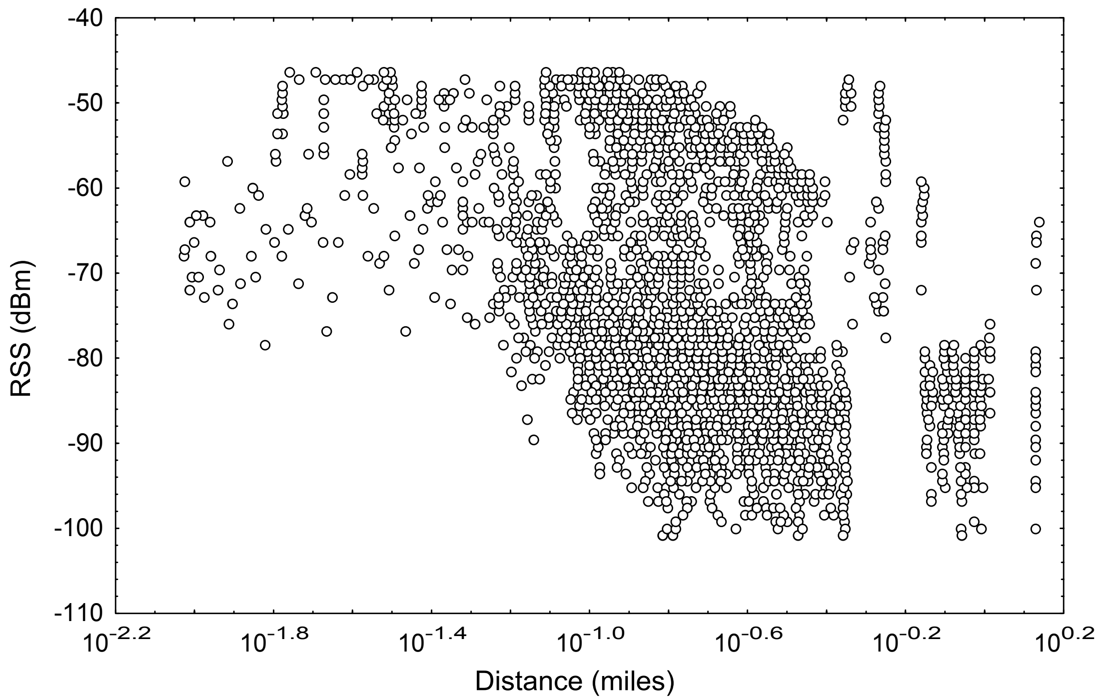


Figure 7.7. Downlink received signal strength (RSS) vs. distance (TAG 3, microcell site 3).

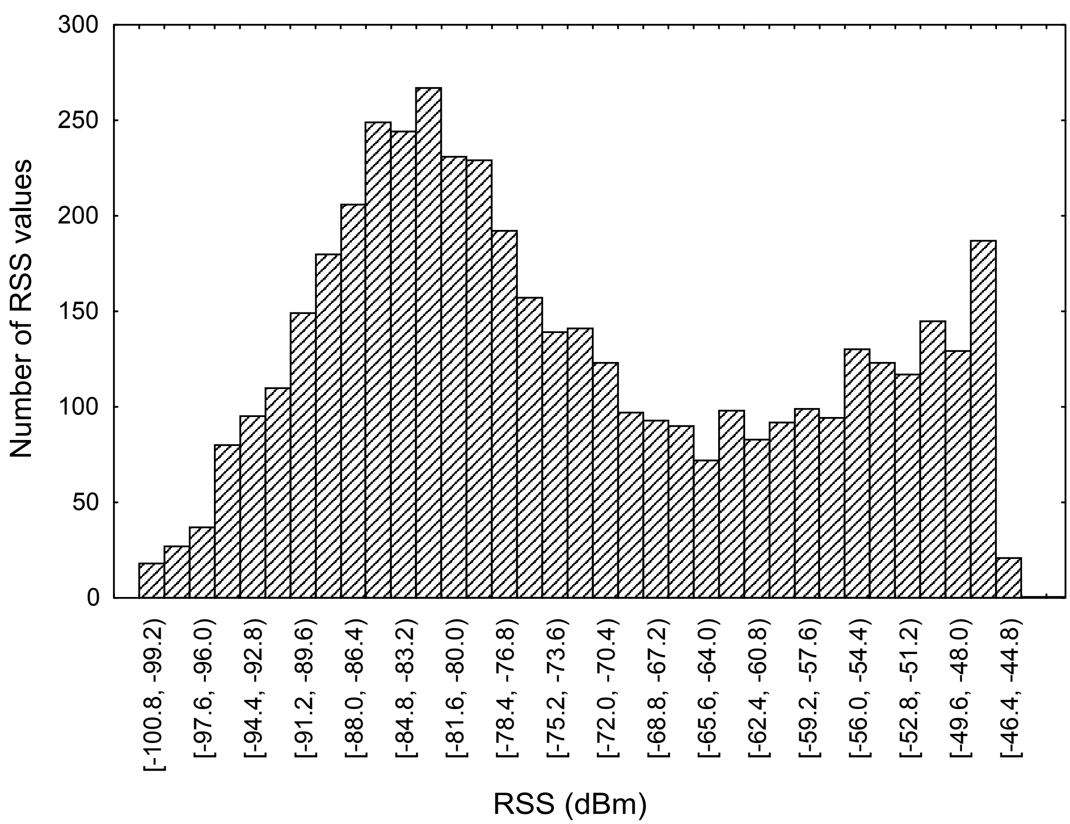


Figure 7.8. Histogram of downlink received signal strength (RSS; TAG 3, microcell site 3).

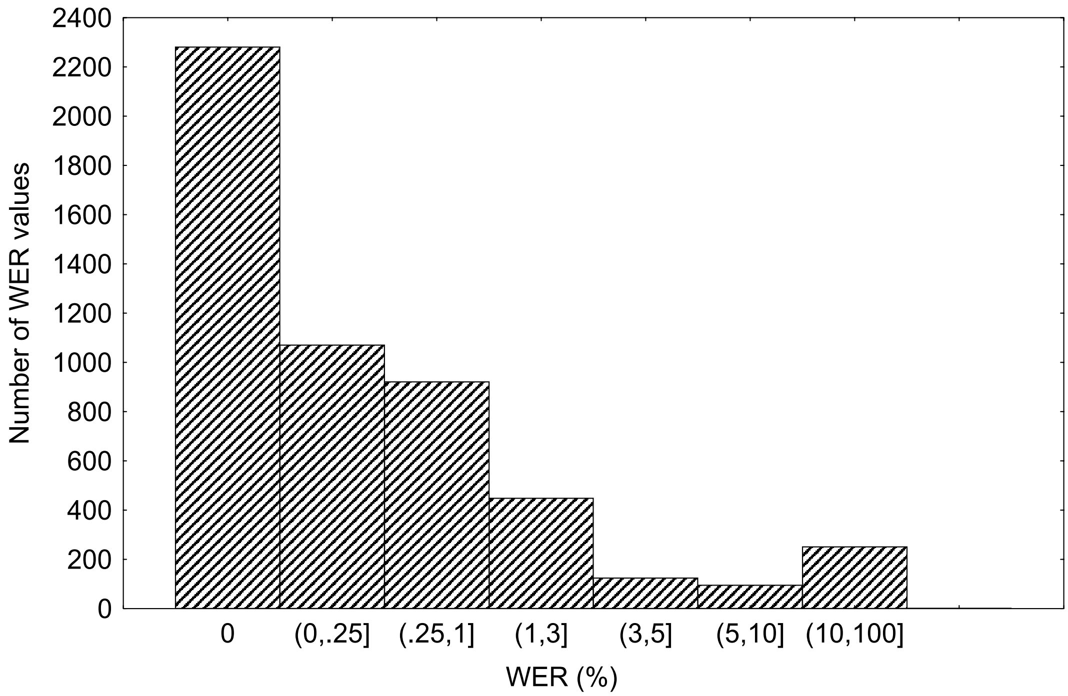


Figure 7.9. Histogram of downlink word error rate (WER; TAG 3, microcell site 3).

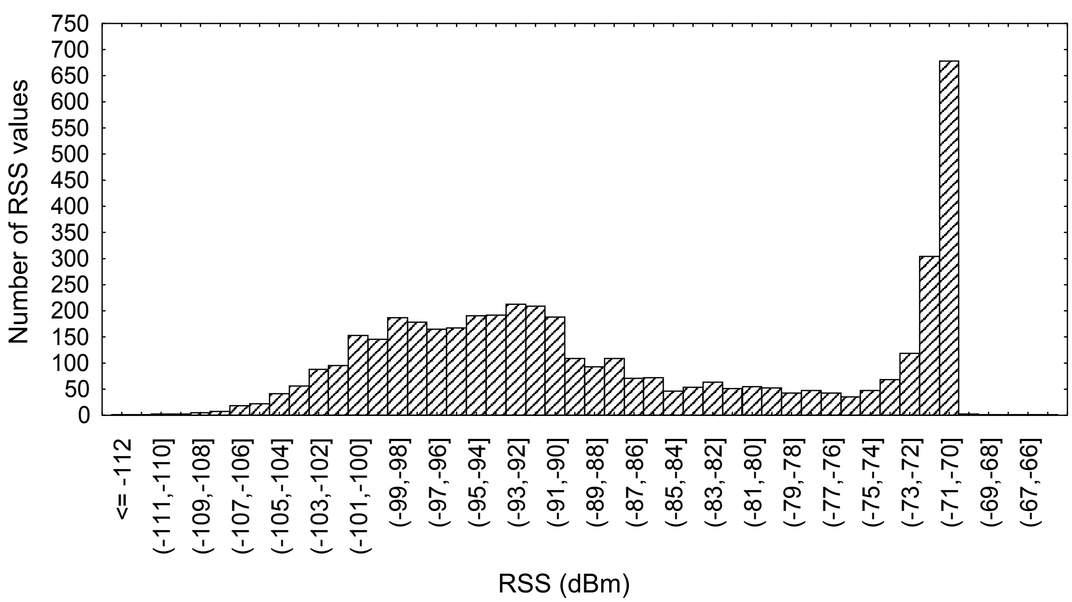


Figure 7.10. Histogram of uplink received signal strength (RSS; TAG 3, microcell site 3).

frequently than any other RSS values. The mean uplink RSS was -91.24 dBm and the standard deviation was 11.28 dB. Figure 7.16 shows the uplink WER histogram. Here most of the data points had a WER less than or equal to 3%. A relatively large number of data points had a WER greater than 10%.

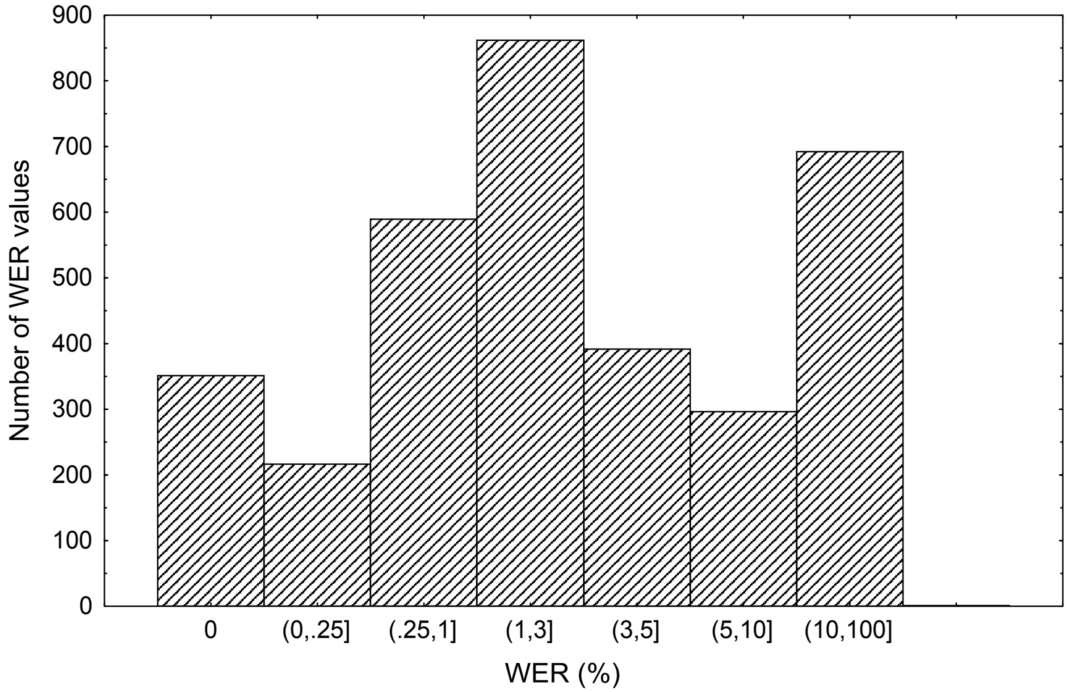


Figure 7.11. Histogram of uplink word error rate (WER; TAG 3, microcell site 3).

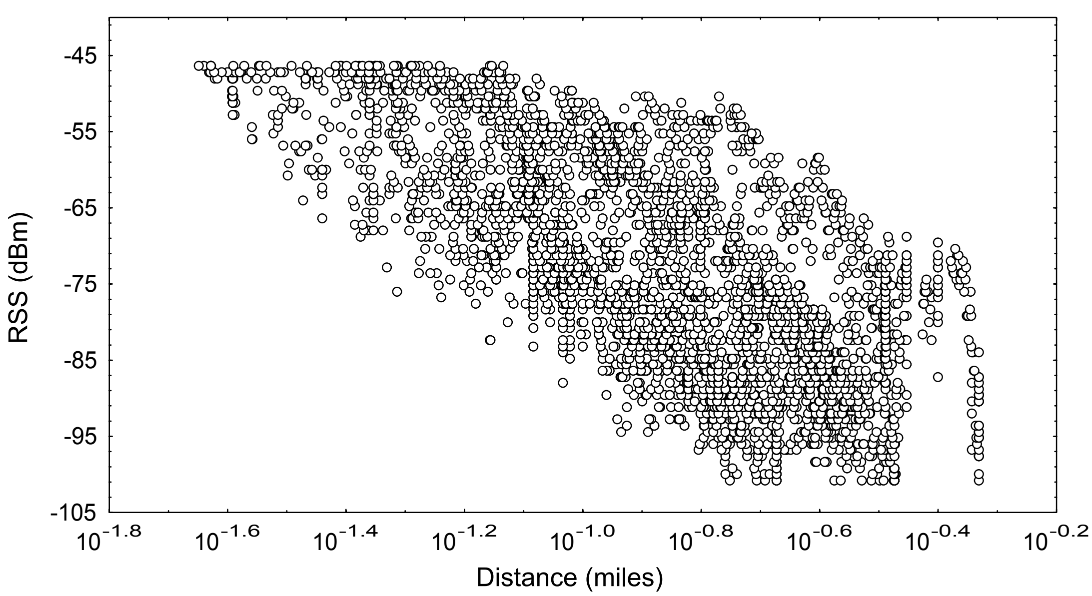


Figure 7.12. Downlink received signal strength (RSS) vs. distance (TAG 3, microcell site 9).

7.3.4 Low-Tier Microcell Site 11 Area Coverage Data

Downlink RSS as a function of distance is shown in Figure 7.17. The data included in this figure are the overall data for this cell, excluding RSS values less than -101 dBm. The large variation in

RSS seen in Figure 7.17 occurs mostly because of shadowing in the environment. Note that signals up to approximately -80 dBm existed out to approximately 0.50 mi. Those signals were recorded in areas where a clear LOS propagation path existed between the mobile unit and the base station.

The estimate of the coverage area for Site 11 was determined in the same way as that for Site 1. The coverage boundaries were approximately 0.35 mi to the west-southwest, 0.28 mi to the east-northeast, and 0.48 mi to the south-southeast. Since there is a hill immediately north of Site 11 that obstructed coverage in that direction, very little data were collected there.

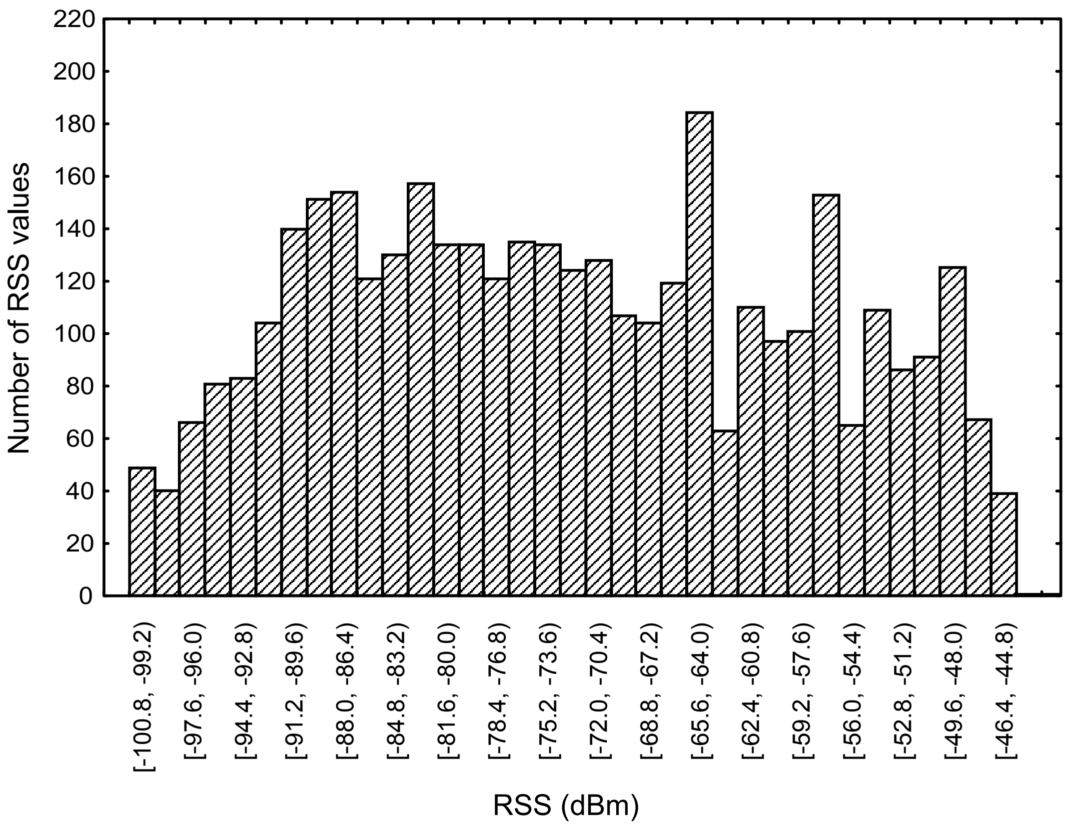


Figure 7.13. Histogram of downlink received signal strength (RSS; TAG 3, microcell site 9).

Figure 7.18 shows the histogram of downlink RSS values. Again, RSS values less than -101 dBm were excluded. The mean downlink RSS was -74.14 dBm and the standard deviation was 13.28 dB. Figure 7.19 shows the histogram of downlink WER values. From this histogram it is seen that most of the data points had a WER less than or equal to 0.1%. The uplink RSS histogram is given in Figure 7.20. As in the uplink RSS histogram for Site 1, RSS values less than -118 dBm were excluded. The histogram shows a different distribution than for the downlink case in this microcell; RSS values around -71 dBm occur much more frequently than any other RSS values. The mean uplink RSS was -88.79 dBm and the standard deviation was 11.95 dB. Figure 7.21 shows the uplink WER histogram. This histogram shows that higher uplink WER's were more prevalent in this microcell. A large number of data points had a WER greater than 5%.

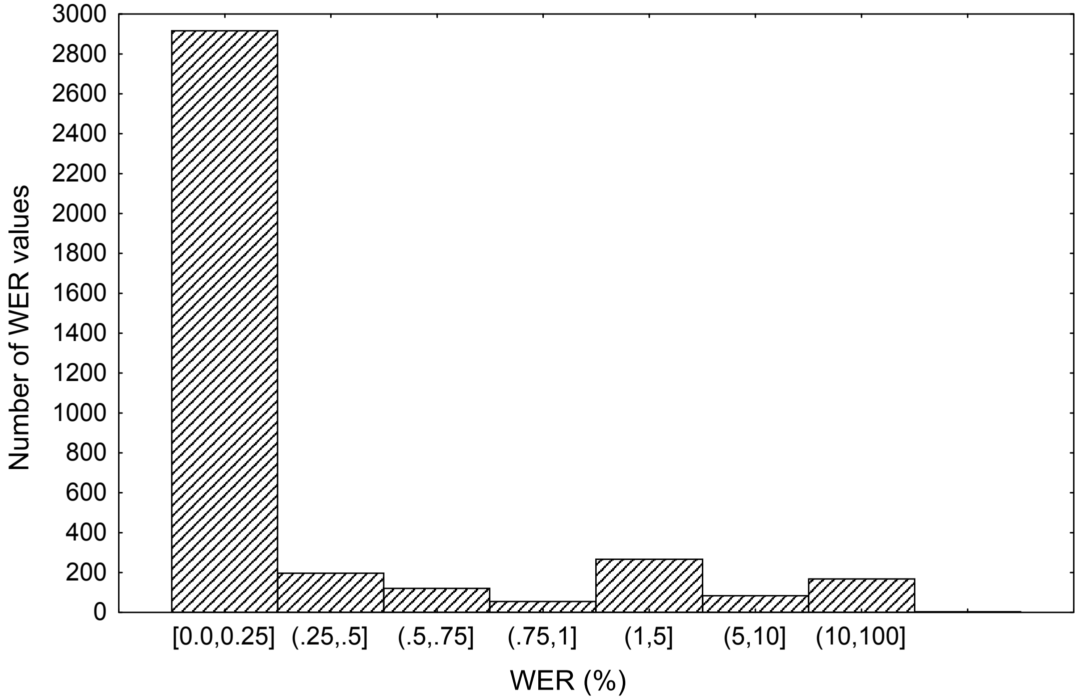


Figure 7.14. Histogram of downlink word error rate (WER; TAG 3, microcell site 9).

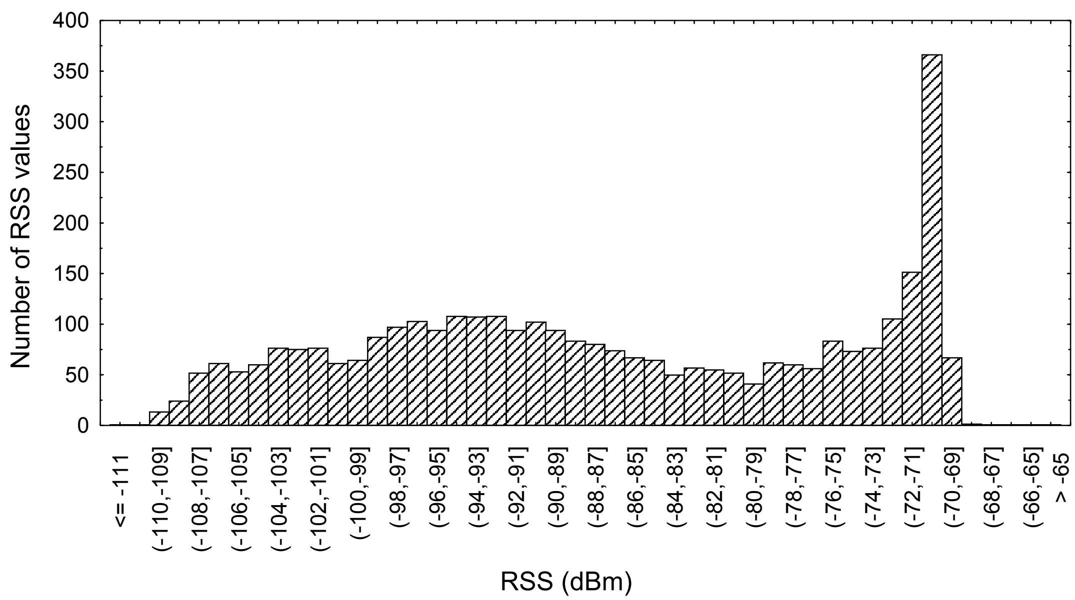


Figure 7.15. Histogram of uplink received signal strength (RSS; TAG 3, microcell site 9).

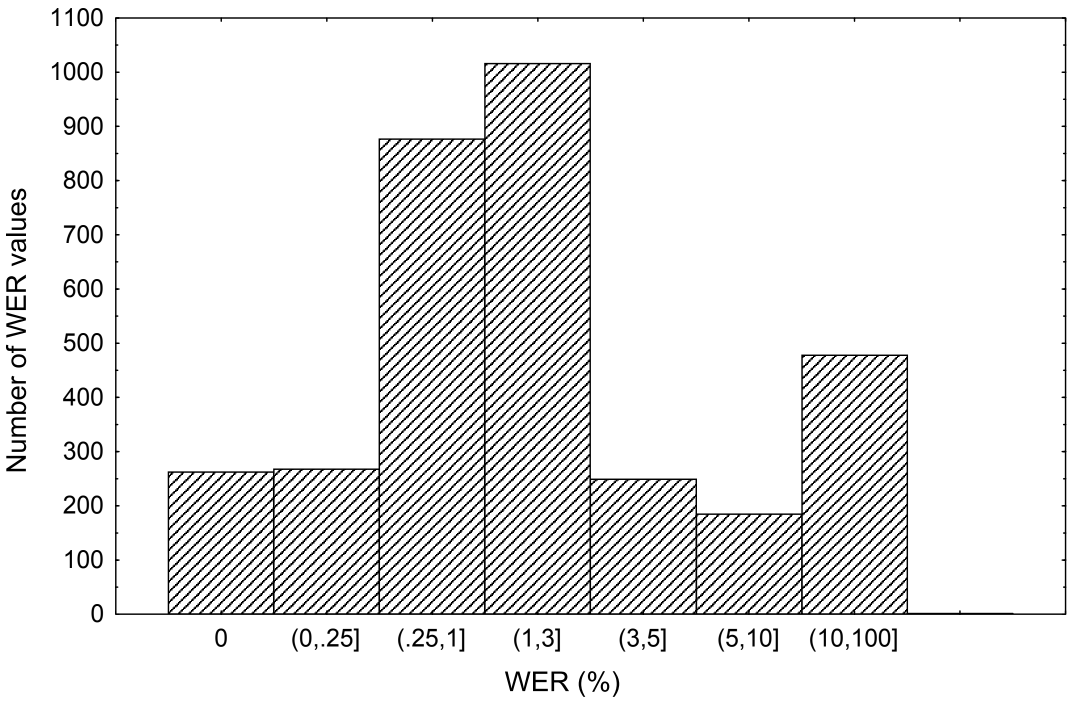


Figure 7.16. Histogram of uplink word error rate (WER; TAG 3, microcell site 9).

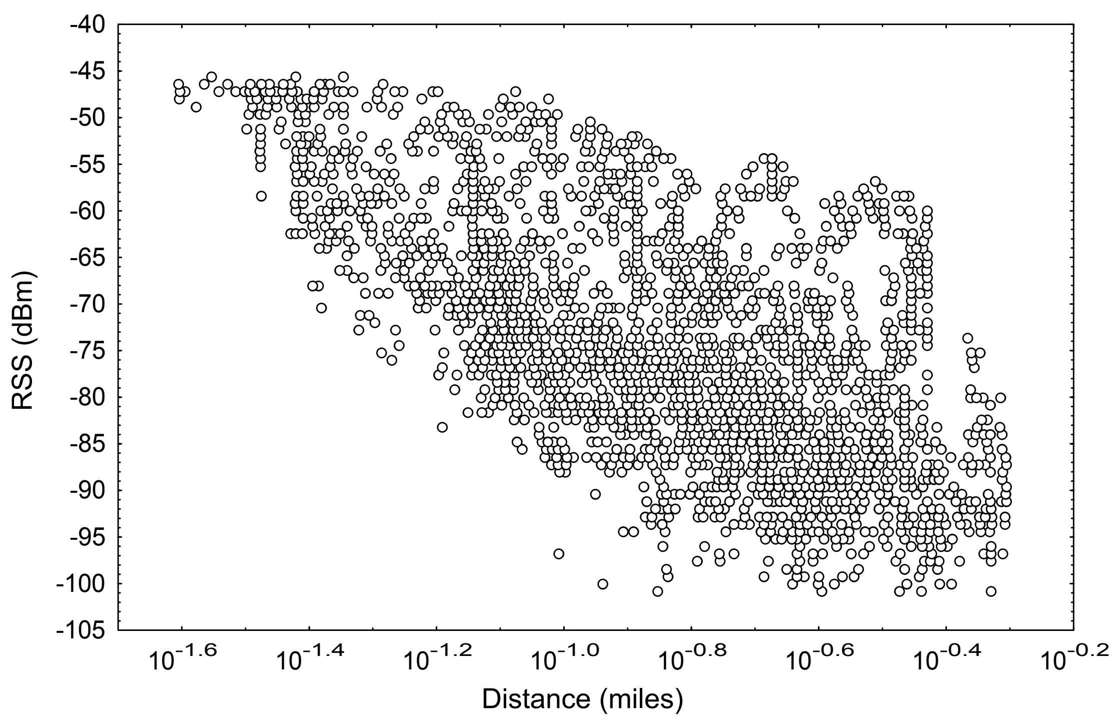


Figure 7.17. Downlink received signal strength (RSS) vs. distance (TAG 3, microcell site 11).

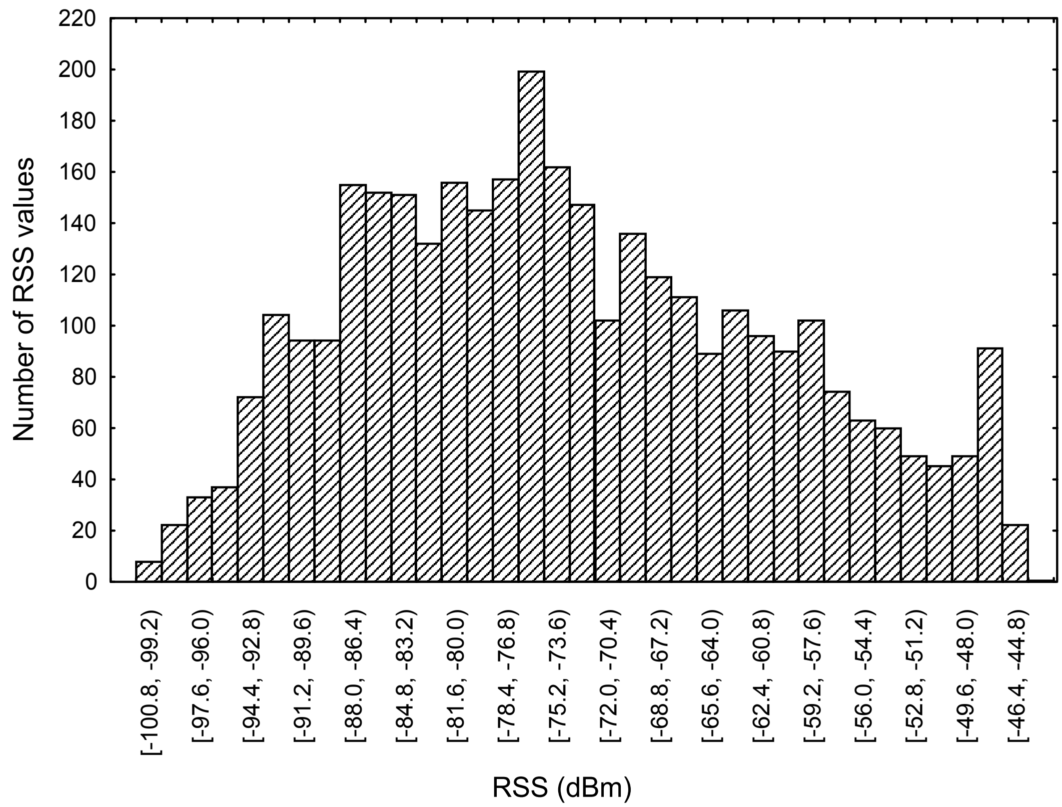


Figure 7.18. Histogram of downlink received signal strength (RSS; TAG 3, microcell site 11).

7.3.5 Link Balance Analysis for Combined Microcell Sites

For the link balance analysis, the data for Sites 1, 3, 9, and 11 were combined into a single file. The data were then analyzed to generate separate plots of average uplink and downlink WER as a function of RSS.

In generating the average uplink WER vs. RSS plot, the uplink RSS values were rounded to an integer value. For a particular uplink RSS value, all corresponding uplink WER values were averaged. The same procedure was repeated for all available uplink RSS values greater than -118 dBm. The result of this analysis is represented in Figure 7.22. As expected, in general, as the RSS is increased, the WER decreases.

The same methodology used in generating the average uplink WER vs. RSS plot was used to generate the average downlink WER vs. RSS plot except that RSS values less than -101 dBm were not included. The resulting plot of average downlink WER vs. RSS is shown in Figure 7.23. Here, also as expected, the WER decreases as the RSS increases.

By comparing Figures 7.22 and 7.23, note that the corresponding RSS for a given WER is different between the uplink and downlink. As an example, for a 10% WER, the RSS on the uplink is -98 dBm and on the downlink is -91 dBm.

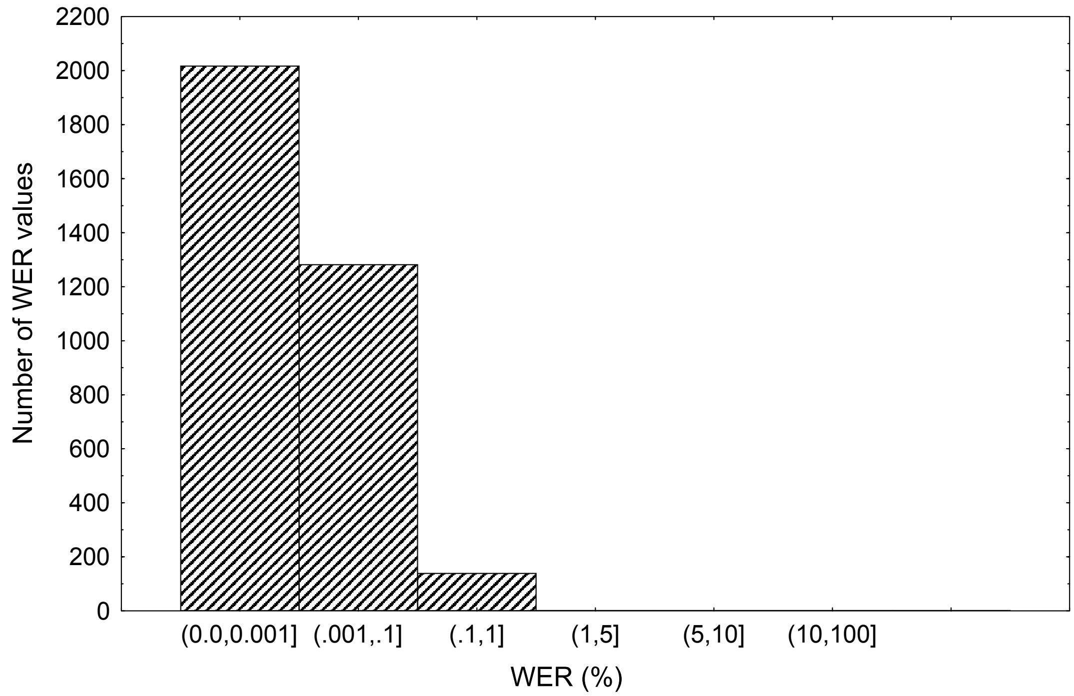


Figure 7.19. Histogram of downlink word error rate (WER; TAG 3, microcell site 11).

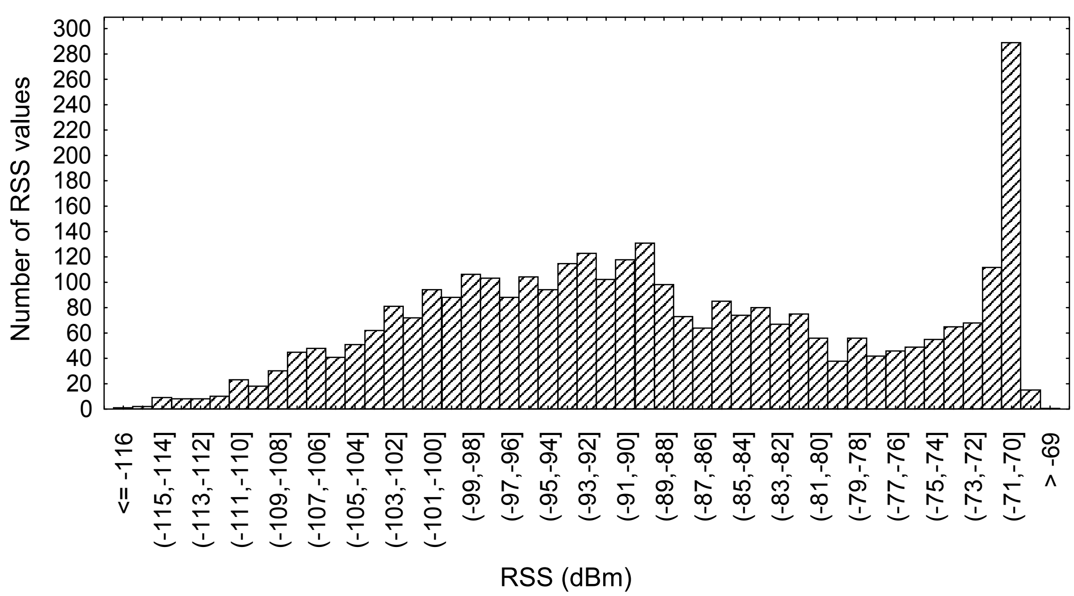


Figure 7.20. Histogram of uplink received signal strength (RSS; TAG 3, microcell site 11).

To determine if the link was balanced, and if not, to estimate the amount of link unbalance, a histogram of the difference between the downlink and uplink RSS was generated. This histogram is shown in Figure 7.24. The mean difference between downlink and uplink RSS is 14.46 dB with a standard deviation of 5.60 dB. In other words, the RSS at the base station was typically weaker than the RSS at the mobile unit.

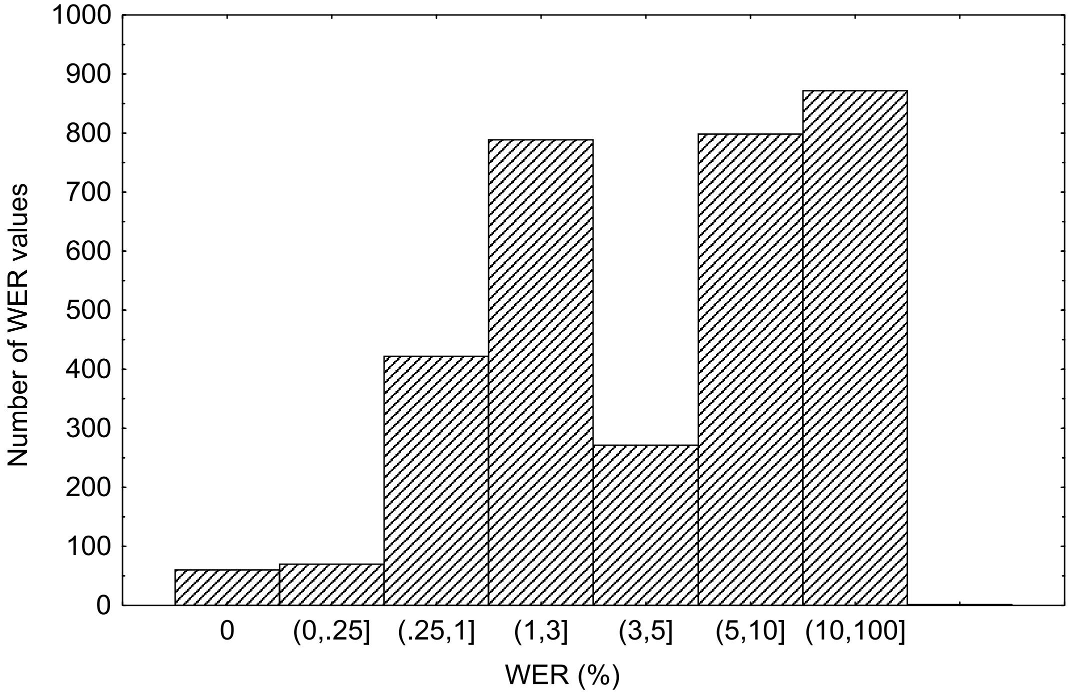


Figure 7.21. Histogram of uplink word error rate (WER; TAG 3, microcell site 11).

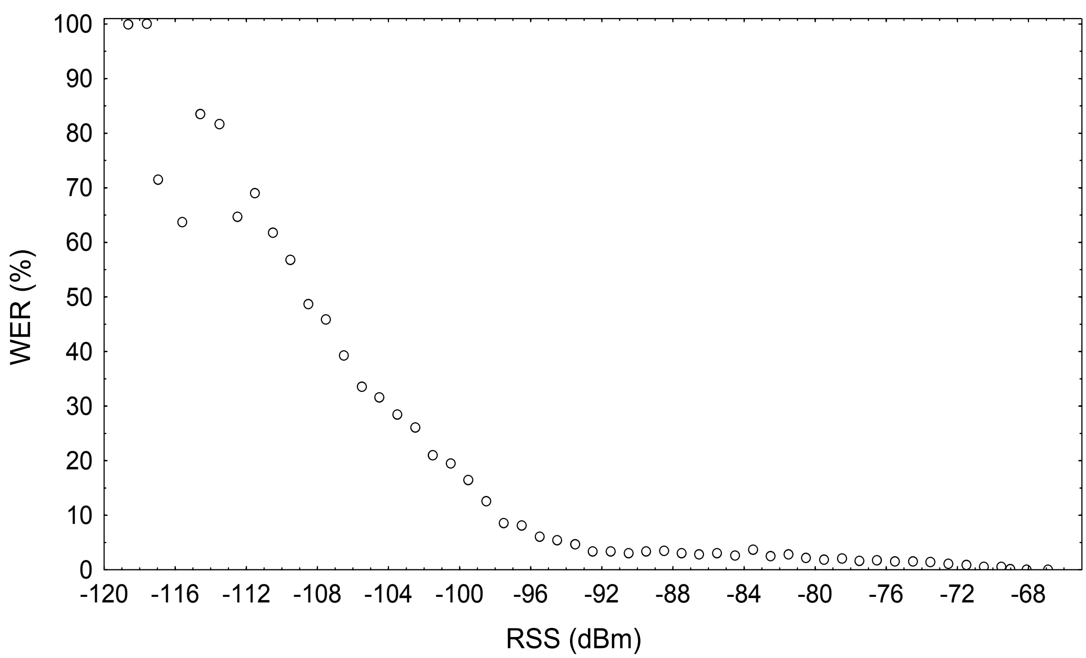


Figure 7.22. Average uplink word error rate (WER) vs. received signal strength (RSS; TAG 3).

One way of determining if the system is uplink or downlink limited is to compare the WER's between the uplink and downlink. The procedure to compare the WER's between the two

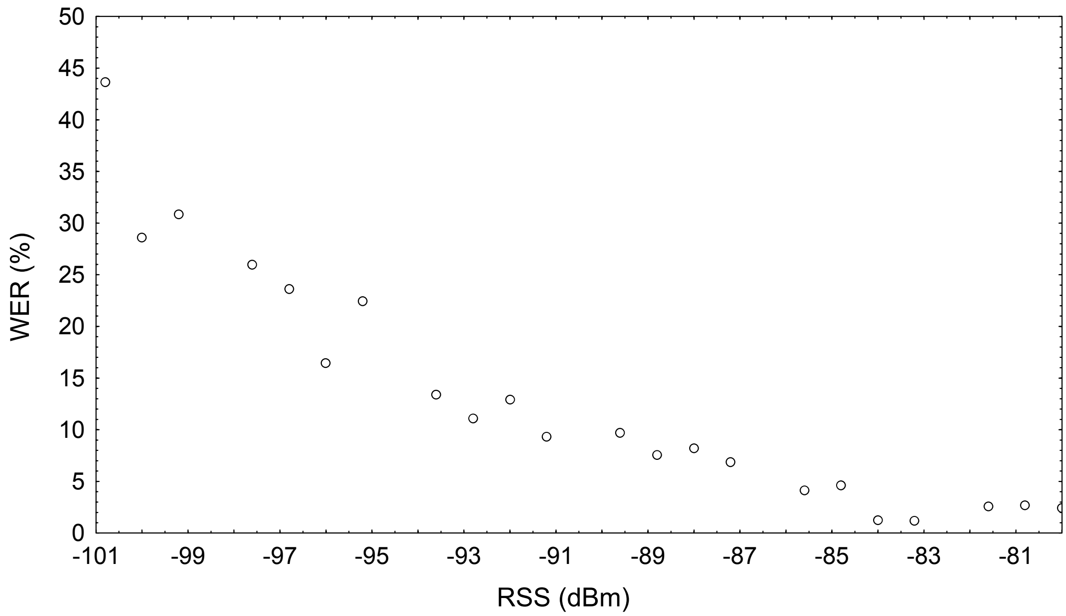


Figure 7.23. Average downlink word error rate (WER) vs. received signal strength (RSS; TAG 3).

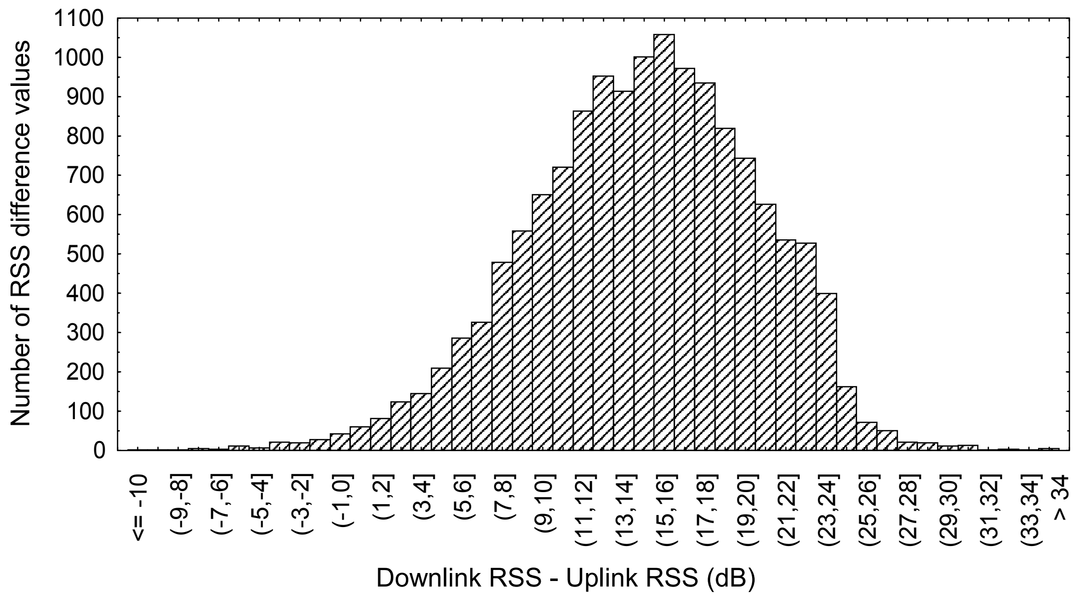


Figure 7.24. Histogram of difference between downlink and uplink received signal strength (RSS; TAG 3).

links is best illustrated with an example. First select a specific downlink RSS such as -92 dBm. The corresponding downlink WER, found from Figure 7.23, is 13%. Now to compare this to the corresponding uplink WER, recall that there is a difference between the downlink and uplink RSS. Using the mean difference between the downlink and uplink RSS values, an uplink RSS of -106.5 dB corresponds to the downlink RSS of -92 dBm used in this example. Using the uplink RSS value of -106.5 dBm in Figure 7.22, an uplink WER of 39% is obtained. Therefore the uplink WER (39%) is larger than the corresponding downlink WER (13%). Repeating this analysis for any other RSS value yields the same result: the uplink WER is consistently higher than the downlink WER. Therefore, the system is uplink limited.

7.4 Handoff Testing

The TAG 3 PACS technology was designed to support low-speed (up to 35 mph) handoff. As per JTC requirements, the low-speed handoff testing was performed. The low-speed handoff testing was conducted in downtown Boulder. In addition to low-speed handoff testing, high-speed handoff testing was performed in south Boulder as an optional test. The purpose of the high-speed handoff testing was to determine handoff functionality for speeds greater than 35 mph.

Low-speed handoff testing was performed by pushing a cart containing the mobile unit at pedestrian speeds along chosen routes in downtown Boulder. All four microcells used in the area coverage testing were used here. All four microcells were activated and handoff was allowed between the microcells. The routes were chosen to maximize the number of handoffs between the microcells. Typically, a call was initiated within a block of a base station, and the data (objective measures such as RSS, WER, and time) were collected as the measurement cart was pushed along the sidewalk of a street toward a particular base station. The uplink and downlink objective measures were recorded at the same time. A measurement run was considered completed when the mobile unit went out of the coverage area and the call was dropped. Although a typical measurement run consisted of only one handoff between two base stations, some runs had multiple handoffs between more than two base stations, due to the choice of a particular route, base station configuration, and propagation environment.

Three types of handoff parameters were determined from the data analysis:

1) the difference between RSS before and after handoff,
2) the difference between WER before and after handoff, and
3) the time between two successive handoffs.

Table 7.1 shows the values of these parameters for all of the handoffs recorded during the low-speed handoff testing. There were a total of 31 handoffs recorded during 14 measurement runs. All values were calculated based on readings taken immediately before and after an individual handoff occurred (a 1-s difference).

Table 7.1 shows that 16 out of the 31 handoffs had no changes in both the RSS and WER readings before and after handoff. This is unusual, since handoff is initiated when either the RSS or WER deteriorate significantly with respect to the RSS or WER readings from neighboring base stations. There was one instance when both the RSS and WER had worse readings after handoff than before handoff. In three other cases, either the RSS or the WER had a worse reading after handoff than before handoff. In six cases, both the RSS and WER improved after a handoff.

Table 7.1 also shows that the minimum time between successive handoffs was 13 s. This implies that no ping-ponging occurred during the handoff testing. Recall that ping-ponging was defined in Section 3.4 as a rapid sequence of handoffs between cell sites and/or sectors.

The high-speed handoff measurements were made in south Boulder. Three base stations (at Sites 17, 18, and 19) were activated for this testing. The output of each base station transmitter was set to provide an EIRP of 6.3 W. The mobile unit was mounted inside a measurement van with its antenna mounted on the roof of the vehicle. Measurements were taken as the measurement van traveled along Broadway near the Table Mesa shopping center. A separate measurement run was made in the northbound direction and then in the southbound direction at each of the following speeds: 20, 30, 40, 50, and 60 mph. For the southbound measurement runs, calls were initiated with the measurement van close to Site 17 (Broadway and Hanover Street). For the northbound measurement runs, calls were initiated with the measurement van close to Site 19 (Broadway and Grinnell Street). After initiation of the call, data were collected as the measurement van traveled in the specified direction. Both uplink and downlink data were collected for each measurement run.

The handoff data for the 40-mph case showed that coverage was provided by each base station when the measurement van was in the vicinity of that base station. The coverage area for each base station was roughly centered about each base station. On the other hand, at 60 mph, the coverage area for each base station was shifted in the direction opposite of the direction that the measurement van was traveling. Therefore, at 60-mph speeds, coverage was affected. This implies that special consideration would be needed in the cell layout plan to support up to 60-mph handoff while not necessarily needed to support handoff up to 35 or 40 mph.

7.5 Interference Testing

The interference testing consisted of both co-channel and adjacent channel interference measurements. The interference measurements for this system, however, differed from the interference measurements of the other JTC PCS technologies. The interference measurements for the PACS TAG 3 system were made indoors under stationary conditions. The operation of the PACS TAG 3 system was not suited for outdoor interference measurements. All of the interference measurements for the PACS TAG 3 system were conducted inside the building on the 3rd floor at the WCO. The base station located at Site 3 was used as the intended source. A signal generator, located on the 3rd floor of the building at the WCO, was used as the interfering signal. In addition, the mobile unit was located on the same floor of the building. While this setup was not ideal because the indoor measurement reduced the shadowing, it was the best possible under the given conditions.

As explained before, these measurements differ from the outdoor measurements because less log-normal shadowing is encountered, but they do give insight on how C/I affects WER.

For the co-channel interference measurements, the transmitters for both the intended source and the interferer were set to 1971.5 MHz. The RSS of the intended source measured at the mobile unit (downlink) was -63 dBm. The level of the interfering signal was changed manually, by adjusting the power output of the signal generator. The interfering signal's

Table 7.1. Handoff Parameter Data

Handoff Number	RSS after - RSS before handoff (dB)	WER before - WER after handoff (%)	Time between successive handoffs (s)
1	2	2	80
2	0	2	140
3	0	0	39
4	0	0	14
5	0	0	38
6	0	0	28
7	-2	0	77
8	0	0	56
9	0	0	36
10	0	3.75	81
11	5	0.25	150
12	0	4	87
13	0	0	37
14	2	-0.25	47
15	-2	2	75
16	19	2.5	53
17	0	0	13
18	-2	-1.25	46
19	0	1.25	68
20	14	1.75	56
21	5	0	116
22	4	6.75	40
23	0	0	52
24	0	0	80
25	0	0	51
26	0	0	88
27	1	0.25	50
28	0	0	42
29	0	0	38
30	0	0	26
31	0	0	28

power was adjusted so that the RSS at the mobile unit was -93 dBm. The level of the interfering signal was increased until the WER started showing non-zero values. While the goal was to show WER (as reported by the mobile unit) as a function of C/I, only the C/I threshold where the WER became non-zero could be readily identified. For the co-channel interference case, when the C/I was greater than 9 dB, the WER was zero. When the C/I was less than 9 dB, the WER was greater than zero.

For the adjacent channel interference measurements, the transmitter for the intended source was set to 1971.5 MHz. The transmitter for the interferer was set to 1971.8 MHz. As for the co-channel interference measurements, the RSS of the intended source measured at the mobile unit (downlink) was -63 dBm. The level of the interfering signal was changed manually, by adjusting the power output of the signal generator. The interfering signal's power was adjusted so that the RSS at the mobile unit was -78 dBm. The level of the interfering signal was increased until the WER started showing nonzero values. As in the co-channel interference measurements, WER as a function of C/I for adjacent channel interference could not be obtained, only the C/I threshold where the WER became nonzero could be readily identified. For the adjacent channel interference case, when the C/I was greater than -17 dB, the WER was zero. When the C/I was less than -17 dB, the WER was greater than zero. As expected, a much lower adjacent channel C/I than co-channel C/I is required to keep the WER zero.

7.6 Voice Quality

As discussed in Section 3.6, two types of voice quality measurements were made for the PCS JTC technology field trials in general: quasi-stationary measurements and handoff measurements. Both types of measurements were performed for the PACS (TAG 3) technology.

7.6.1 Quasi-stationary Measurements

Voice recordings and various objective measures including uplink and downlink RSS and uplink and downlink WER were collected at locations 100 m (approximately one block) apart around Site 1 and Site 3. Measurements were taken at the 62 specific locations shown on the map in Figure 7.25. A total of 120 measurements were taken because both uplink and downlink measurements were taken at most but not all of the locations. Only one microcell was activated at a time. At each location, data were collected as the measurement cart was pushed at a pedestrian speed in a 10-m circle for the duration of the sample time. The same sample time was used for each location. The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement cart was in motion, an audio source tape was transmitted over the radio link in both the uplink and downlink directions simultaneously. The source tape transmitted over each link was the same as that used for TAG 5 testing (see Section 3.6.1).

The received voice transmissions were recorded on digital audio tape at the receiver for the uplink and downlink simultaneously. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. At each location, the objective measures including uplink and downlink RSS, uplink and downlink WER, and GPS time and location were collected every second at the same time as the voice recordings were made.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

7.6.2 Mean Opinion Score Assessment

To accomplish the MOS testing, a pool of 36 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, 35-45, 45-55, and those over 55 years of age. There were 14 male and 17 female subjects. The subjects were cordless, noncellular telephone users.

Three groups consisting of eight subjects each and one group consisting of seven subjects were formed from the subject pool. The subjects were asked to rate voice segments by answering the three questions listed in Section 3.6.2 after each segment was presented.

First, the subjects in each of the four groups were presented 10 practice voice segments to rate. The practice segments were exactly the same as the ones used for TAG 7 testing. The description for these is given in Section 6.6.2.

After the practice segments were presented, the subjects in each of the four groups were asked to rate 33 voice segments: 3 reference voice segments and 30 voice segments from the field trial measurements. Every listener within a group listened to the same voice segments. The reference voice segments consisted of one 64-kbps wireline voice segment and two voice segments collected from field measurements (one with a definitely acceptable expert listener rating and one with an unacceptable expert listener rating). The 30 voice segments from the field trial measurements came from the uplink or downlink measurements at a portion of the 62 measurement locations. The number and type (male or female) of sentences that were used and the order in which they were used to form a voice segment are the same as that described in Section 4.6.2. Subjects were given two breaks during each session. After all segments were presented, subjects filled out a post-trial questionnaire.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain an MOS. The results from all four of the groups, from a total of 120 voice segments are shown in the histogram in Figure 7.26. Overall, the voice segments were rated favorably, with 88% of the segments rated between fair and excellent. The average MOS was 3.68 and the standard deviation was 0.70.

Figures 7.27 and 7.28, show histograms of MOS's for the uplink and downlink, respectively. The average MOS for the uplink was 3.91 and for the downlink was 3.41. Note that the distributions of MOS are quite different for the uplink and downlink. The uplink histogram shows a larger spread in MOS's with higher maximum MOS's and lower minimum MOS's than the downlink histogram. A t-test revealed that there is a statistically significant difference in the average MOS's between the uplink and downlink.

The relationship between the MOS's and some of the objective measures was initially investigated by generating some scatter plots. Figure 7.29 shows the relationship between the MOS's and average RSS for both the uplink and downlink combined. For RSS values between approximately -92 and -70 dBm, a large variation in MOS's is seen. Much less variation in MOS's is seen for RSS values above approximately -70 dBm. For RSS values below approximately -92 dBm, the MOS's tend to degrade rapidly.

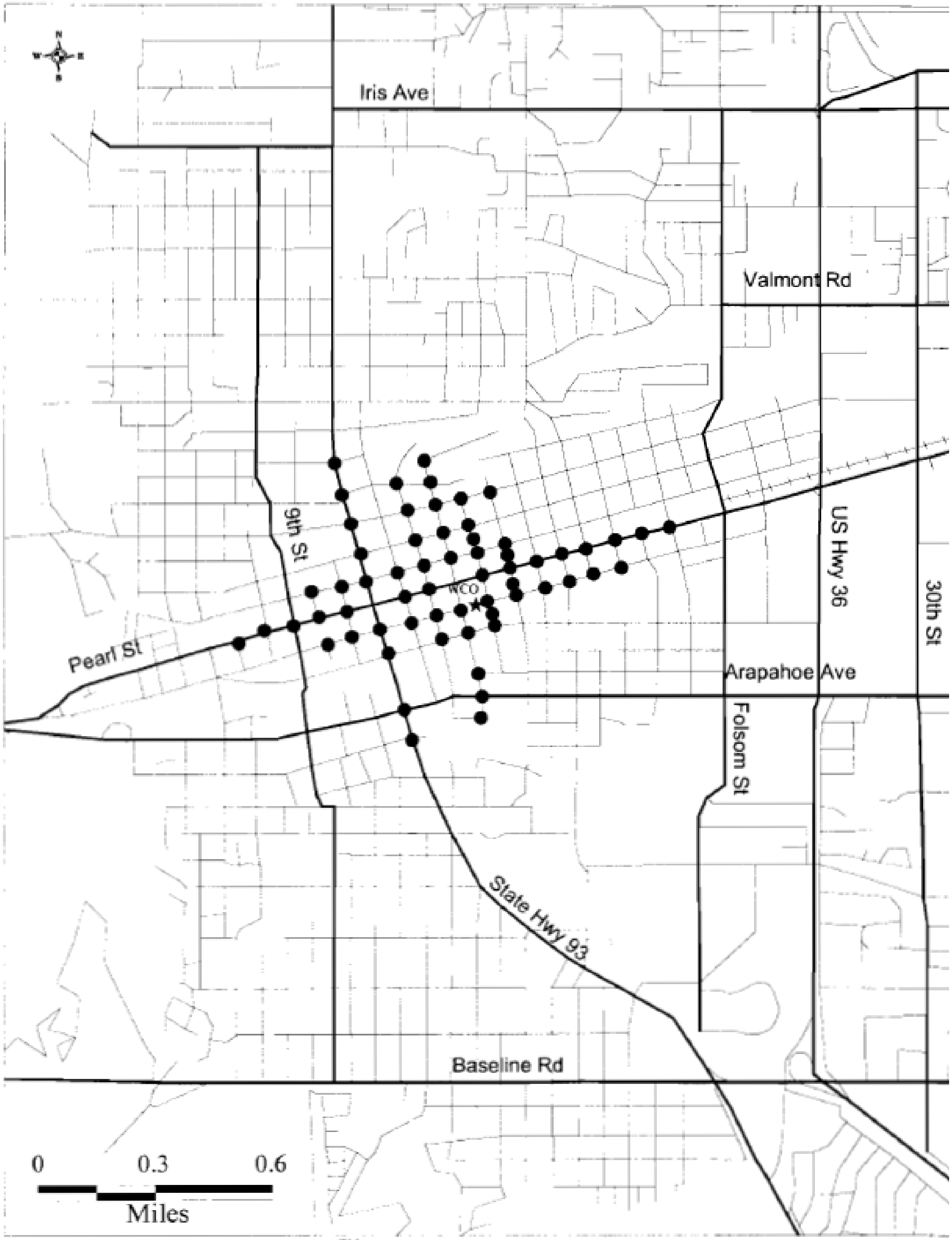


Figure 7.25. Quasi-stationary measurement locations for TAG 3.

Figures 7.30 and 7.31 show the relationship between the MOS's and the average WER for both the uplink and downlink, respectively. Both the uplink and downlink show some variation in MOS for a given RSS. The uplink shows a relationship between high MOS's and low WER; however, the downlink does not show this relationship.

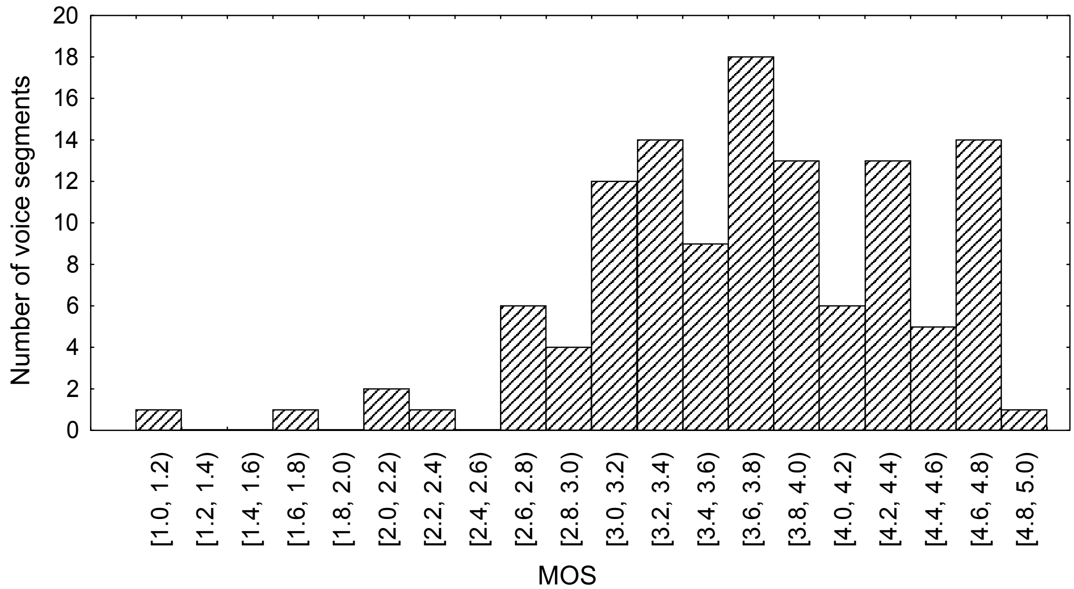


Figure 7.26. Histogram of mean opinion scores (MOS's) for all voice segments (TAG 3).

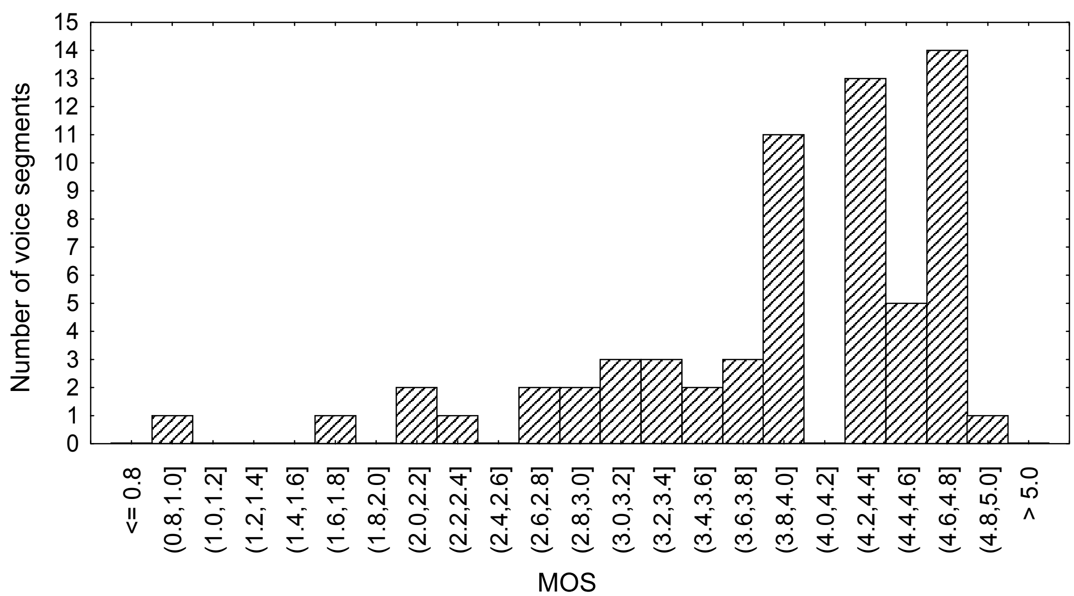


Figure 7.27. Histogram of uplink mean opinion scores (MOS's; TAG 3).

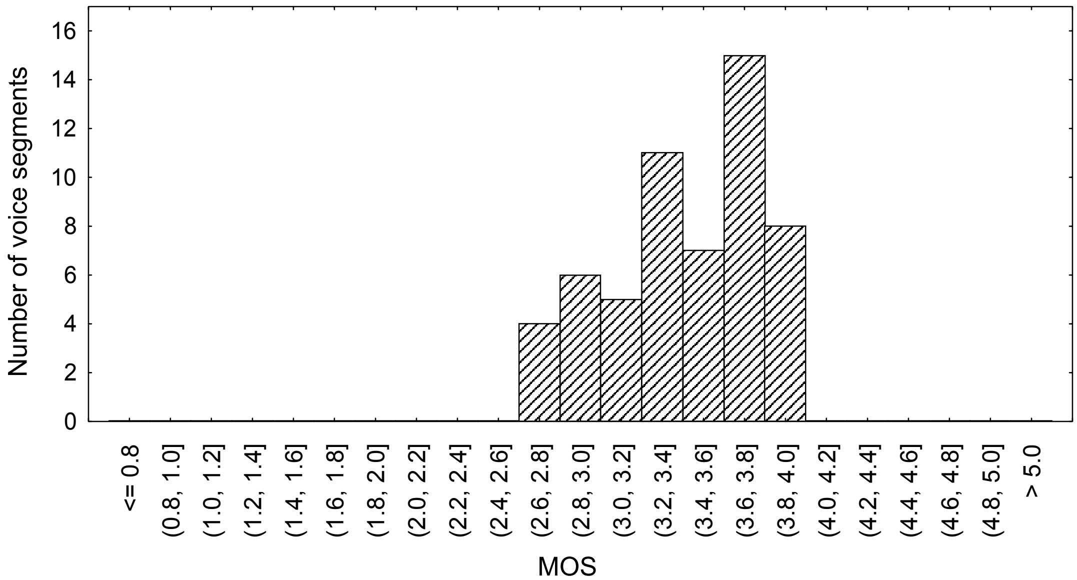


Figure 7.28. Histogram of downlink mean opinion scores (MOS's; TAG 3).

Pearson product-moment correlations were performed to determine the correlation between MOS's and average RSS and MOS's and average WER. These correlations were performed for the data on the uplink first and then for the data on the downlink. For the uplink, the correlation coefficient between MOS and average RSS was 0.63 and that between MOS and average WER was -0.55. These correlation coefficients between MOS and averaged objective measures suggest that a strong linear relationship between MOS and the objective measures on the uplink does not exist. The correlation coefficient between the average RSS and the average WER for the uplink was -0.40. A higher correlation between these measures was expected.

While there does not appear to be a strong linear relationship between MOS and the objective measures for the uplink, there still may be a strong consistently increasing or decreasing relationship between them. The Spearman rank correlation can be used to determine if a consistently increasing or decreasing trend may exist between MOS and the objective measures. For the uplink, Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average RSS and between the ranks of MOS and the ranks of average WER. The Spearman rank correlation coefficient between MOS and average RSS was 0.65 and that between MOS and average WER was -0.78. These rank correlations between MOS and averaged objective measures are higher than the Pearson product-moment correlations. The rank correlation between MOS and average WER is significantly higher than the Pearson product-moment correlation. This suggests that the consistently increasing or decreasing relationship between MOS and WER is stronger than the linear relationship between MOS and WER.

For the downlink, the correlation coefficient between MOS and average RSS was 0.48 and that between MOS and average WER was -0.05. These correlation coefficients suggest that while there is some linear correlation between MOS and average RSS there is very little linear correlation between MOS and average WER. A strong linear relationship between MOS and the objective measures on the downlink does not exist. The correlation coefficient between the average RSS and the average WER for the downlink was -0.14. A higher correlation between these measures was expected.

For the downlink, Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average RSS and between the ranks of MOS and the ranks of average WER. The Spearman rank correlation coefficient between MOS and average RSS was 0.55 and that between MOS and average WER was -0.25. These rank correlations between MOS and averaged objective measures are higher than the Pearson product-moment correlations. This suggests that the consistently increasing or decreasing relationship between MOS and the objective measures is stronger than the linear relationship between MOS and the objective measures.

Note that as in the data analysis of the previous JTC PCS technologies (TAG 5, TAG 2, TAG 4, and TAG 7), the objective measures were averaged over the entire length of the voice segment. By analyzing the instantaneous variation or possibly minimum and maximum values of the objective measures within the voice segment, further insight may be gained on the behavior of MOS's.

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the TAG 3 voice segments according to listeners:

1) "static,"
2) "background noise," and
3) "popping noises."

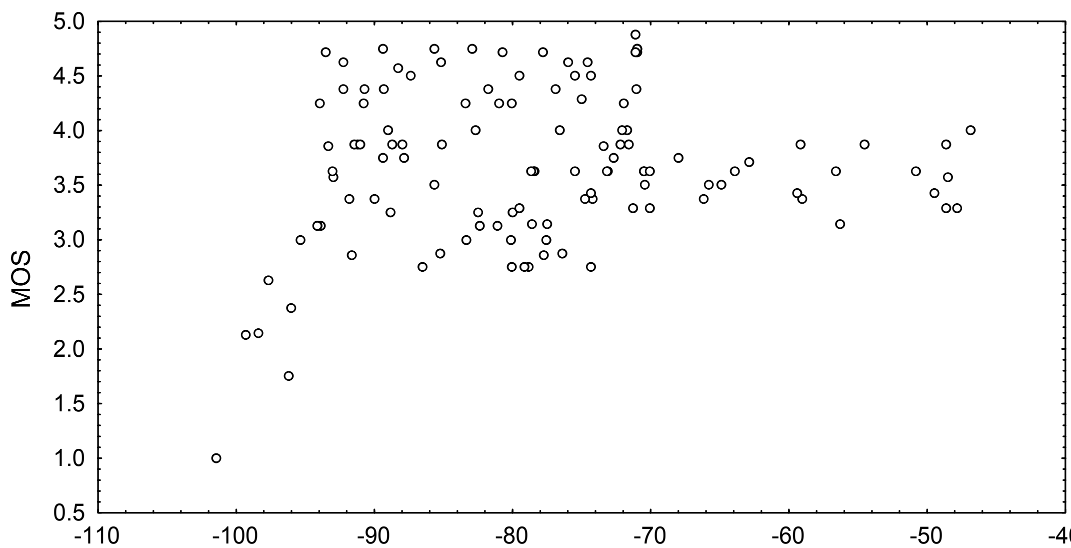


Figure 7.29. Mean opinion score (MOS) vs. average received signal strength (RSS; TAG 3).

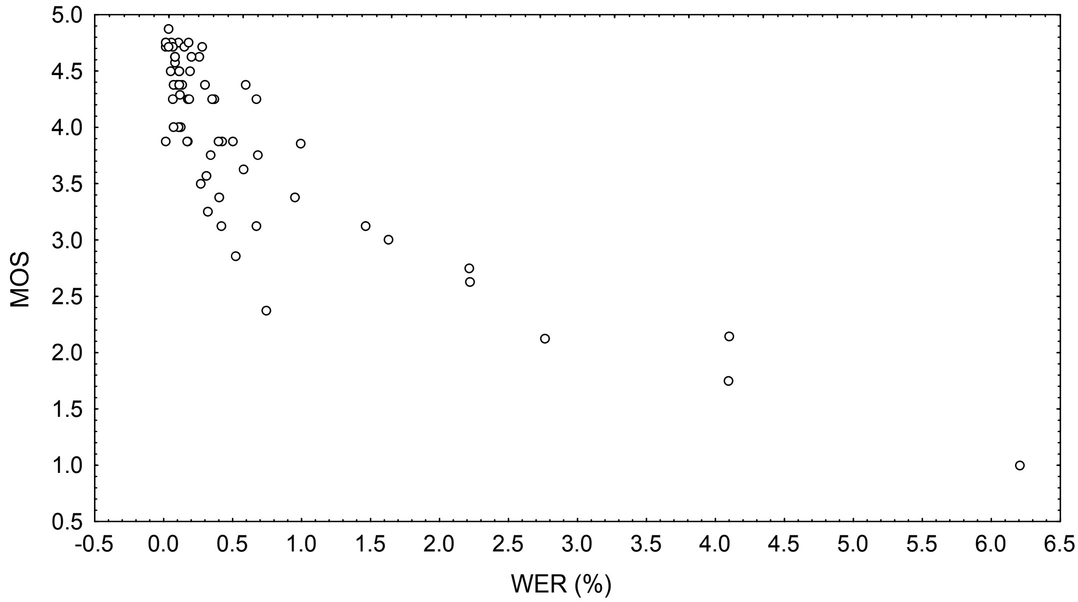


Figure 7.30. Mean opinion score (MOS) vs. average uplink word error rate (WER; TAG 3).

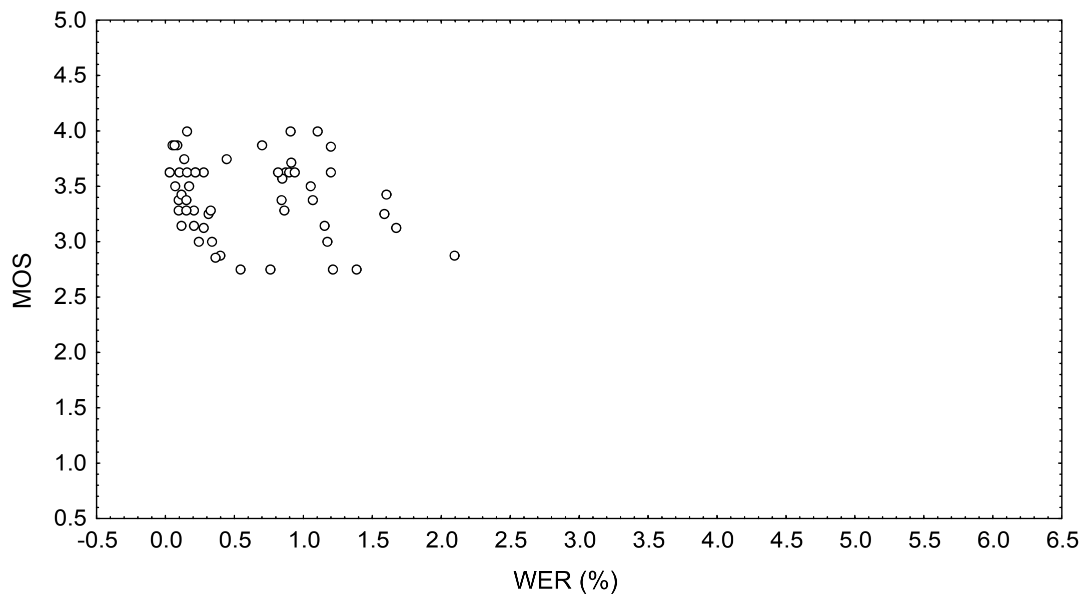


Figure 7.31. Mean opinion score (MOS) vs. average downlink word error rate (WER; TAG 3).

These types of distortions are the exact words used by listeners. The nature of these distortions are likely judged differently by different listeners. Intelligibility and speaker recognition are two main aspects of perceived quality. For most of the voice samples, intelligibility remained high. As a result, overall MOS's were high.

7.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener.[14] The expert listener ratings followed the identical procedure as in the PCS 1900 (TAG 5) testing. This procedure is described in Section 3.6.3.

Figure 7.32 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data.

The expert listener ratings were very good indicators of percent acceptability for the voice segments in the TAG 3 testing. The expert listener ratings accurately predicted the percent acceptability for 114 out of the 120 voice segments recorded.

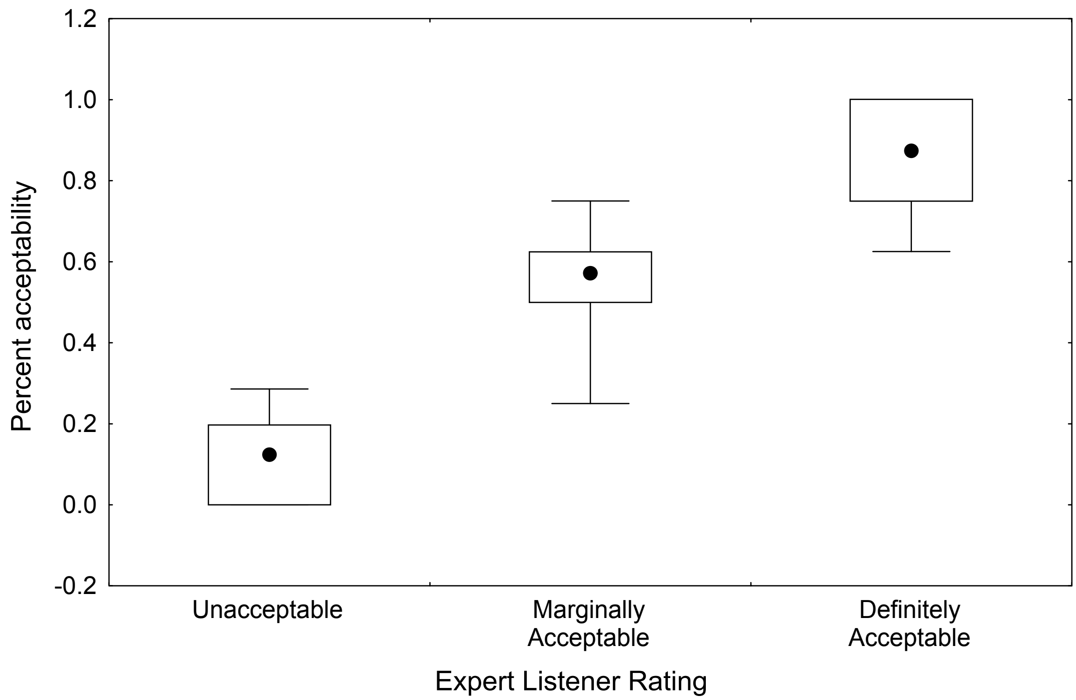


Figure 7.32. Percent acceptability vs. expert listener rating (TAG 3).

The Pearson product-moment correlation coefficient between MOS and percent acceptability was 0.87; this number indicates a strong correlation between these measures, as would be expected. The Pearson product-moment correlation coefficient between MOS and expert listener rating was 0.75; this number indicates a fairly strong correlation between these measures. The Pearson product-moment correlation coefficient between percent acceptability and expert listener rating was 0.90; this number indicates a strong correlation between these measures.

[14] A new expert listener was trained and rated voice segments for the TAG 7 and subsequent JTC PCS technology field trials (TAG 3 and TAG 1). The original expert listener rated voice segments for all of the JTC PCS technology field trials prior to TAG 7 (TAG 5, TAG 2, and TAG 4).

7.6.4 Voice Quality Handoff Measurements

Voice recordings of transmitted voice signals were made during the low-speed handoff testing that was described in Section 7.4. These voice recordings were made simultaneously on the uplink and downlink at the same time as the other handoff data (objective measures described in Section 7.4) were collected. Data were collected as the measurement cart was pushed at a pedestrian speed during 14 measurement runs.

For the voice quality handoff testing, an expert listener rating was made for each 4-s period of the continuous voice recordings taken along each measurement run. Voice quality remained acceptable for the uplink over the length of each measurement run, with no degradation until the call was dropped. None of the uplink handoffs were distinguishable to the expert listener. Voice quality was primarily acceptable for the downlink over the length of each measurement run, however 8 of the 14 measurement runs did have brief periods (less than 3 s) of marginally acceptable voice quality. These periods were not associated with handoffs. None of the downlink handoffs were distinguishable to the expert listener.

Voice quality measurements were also made during the optional high-speed handoff testing. Voice recordings of transmitted voice signals were made as the measurement van traveled along Broadway as described in Section 7.4. An expert listener rating was made for each 4-s period of the continuous voice recordings taken along each measurement run. On the uplink, voice quality remained acceptable for the duration of each measurement run with no degradation until the call was dropped. On the uplink, approximately 28% of the handoffs were distinguishable to the expert listener as a 200- to 400-ms period of muting. The remaining uplink handoffs were not perceptible to the expert listener at all.

On the downlink, 40% of the measurement runs had voice quality degradation as the call approached the edge of coverage. Approximately 50% of the downlink handoffs were perceptible by the expert listener as a 200- to 400-ms period of muting. The remaining downlink handoffs were not perceptible to the expert listener at all.

7.7. Manufacturers' Statements

Statements provided by the manufacturers involved in the testing are included in this section. These statements are identical to those given in [6], except for some minor editorial changes.

7.7.1 Motorola, Inc.

The PACS development team from Motorola believes the primary BITB trial objectives to record range, voice quality, and handoff performance were successfully completed. The trial results indicate the low-tier, low-power PACS system has good range, excellent voice quality, and nearly indiscernible handoff characteristics. Additionally, the initial high-speed test results indicate the PACS standard may have very good wireless telephony performance even in this demanding environment. Antenna diversity both at the radio ports (base stations) and subscriber (mobile) units along with the short frame rate helps improve performance for all of these parameters.

Motorola would like to thank U S West Advanced Technologies for providing the facilities to perform the required tests and ITS for their participation in the calibration and test phases of the trial. More importantly, Motorola would like to thank the U S West Advanced Technologies personnel for their support in getting the PACS system up and functional in such a short time. Finally, Motorola would like to acknowledge the cooperation from the NEC and Matsushita engineering teams in helping Motorola polish the last few remaining system issues that subsequently facilitated a very successful field trial.

7.7.2 NEC

NEC would like to thank U S West Advanced Technologies and ITS for all of their hard work in the BITB field trial in Colorado. NEC believes that the achievement of the trial was due to their great efforts. NEC would further like to acknowledge the support and cooperation from the Motorola and Panasonic development teams during the trial. NEC was pleased to provide the infrastructure for the trial of the PACS radio air interface in the BITB. The subscriber (mobile) units were provided by Motorola and Panasonic.

As can be seen from this section of the report and the visitor's day demonstrations, the PACS system performed quite well. The trial results indicate the PACS system has good coverage, pure natural voice quality, and excellent handoff functionality. In particular, high-speed handoff test results show that the PACS radio air interface has enough capability to support mobile communications in all environments.

Finally, NEC deeply acknowledges all TAG 3 participants including Hughes Network Systems, Pacific Communication Sciences, Inc., Hitachi, and Lucent Technologies for their efforts in completing the JTC standardization process for the PACS air interface. Special thanks are extended to Bellcore for their contribution.

7.7.3 Panasonic

Panasonic would like to recognize the efforts of all the TAG 3 members and supporters in the successful completion of the PACS field trial in Boulder, Colorado. The trial satisfied the JTC requirement to use working equipment in the field to verify the standard. Although not required, equipment was supplied by multiple manufacturers demonstrating interoperability of PACS equipment.

The TAG 3 trial was the first to use the low-tier cell sites in downtown Boulder, Colorado and the surrounding residential areas. At these locations, the system demonstrated good range and excellent voice quality in a heavily obstructed environment. In addition, the high-speed testing at the Table Mesa site indicated no degradation at vehicular speeds (60 mph) and handoff was successfully verified as well with no discernible speech interruption.

These results demonstrate that PACS can provide good coverage and high mobility while maintaining the advantages of its microcell architecture. Also, the interoperability demonstrated among equipment from different vendors only a few months after the standard was approved is a good indication of the lower complexity of PACS and the completeness of the standard. It is also a testament to the efforts of all of the TAG 3 members.

Panasonic would like to thank U S West Advanced Technologies for making the BITB facilities available for these tests. Panasonic sincerely appreciates the efforts of J. Corliss and the entire U S West Advanced Technologies team for the long hours and hard work in making the field trial successful. Panasonic would also like to thank ITS for their participation as the independent observer collecting data and monitoring the tests, and Anritsu for supporting the equipment calibration. In addition, Panasonic thanks NEC and Motorola for their help and support in making the PACS field trial successful. It could not have happened without the cooperation and team effort given by all of the participants.

8. TAG 1 (COMPOSITE CDMA/TDMA SYSTEM) TESTING

This section describes the test plan, methodology, and results for the technology field trial conducted by TAG 1. The technology tested was the PCS composite CDMA/TDMA IS-661 standard. All of the radio equipment, including the base stations and the mobile units, were provided by Omnipoint Corporation. The telephony portion of the system was a Meridian system supplied by Nortel. The TAG 1 field tests examined area coverage, handoff, and voice quality, and the effects of co-channel and adjacent channel interference on system performance.

The information presented in this section is taken from [7]. The reader is referred to [7] for a more complete and detailed presentation of the TAG 1 technology field testing at the BITB.

8.1 TAG 1 Test System Configuration

Two different test system configurations were used for the TAG 1 field technology testing: a high-tier configuration using three cell sites and a low-tier configuration using a single microcell site.

A block diagram of the high-tier test system configuration is shown in Figure 8.1. This test system consisted of three cell sites in Boulder, Colorado (WCO, TMCO, and GMM) and a Nortel Meridian M1 network controller. The Meridian M1 network controller was located at the WCO and was connected to the three WCO base stations (one for each sector). The two GMM base stations (one for each active sector) were connected to the network controller via an LOS microwave link with a D4 channel bank on each end of the link. The LOS microwave link was used to provide a partial T1 link between the GMM base station and the WCO base station. A T1 connection between the TMCO base station and the network controller was provided by a fiber optic link with a SONET add/drop multiplexer and D4 channel bank on each end of the link. The base station transmit frequencies used during the high-tier testing for each cell site and sector are given in Table 8.1. Four antennas, used for both transmitting and receiving, were employed during high-tier testing for every sector in every cell.

For the low-tier testing, a single microcell (Site 3, located at the intersection of Pearl Street and 15^{th} Street in downtown Boulder) was used. The base station was mounted on a traffic light pole 24 ft above the street level. Two 6-dBi omnidirectional antennas used for both transmitting and receiving were employed.

8.2 Calibration

Calibration of the mobile unit used in the TAG 1 field trial consisted of checking the accuracy of the RSS values reported. This was done by injecting a digitally modulated signal of known level into the mobile unit's receiver and comparing this signal level with the RSS value reported by the mobile unit. The input signal into the mobile unit receiver was provided by the base station through a coaxial cable and fixed and variable step attenuators. Losses through the coaxial cable and attenuators were measured. A correction, or offset, was added to the signal power output by the base station to obtain the signal level input into the mobile unit's receiver. The level of the injected signal at the mobile unit's receiver was varied from -65 to -95 dBm in 5-dB steps to find the difference between the actual RSS and the RSS reported by the mobile unit's receiver. The maximum difference was found to be 2.7 dB. Another part of the calibration procedure entailed measuring the base station transmit power. The results of this procedure, however, are not presented in this report.

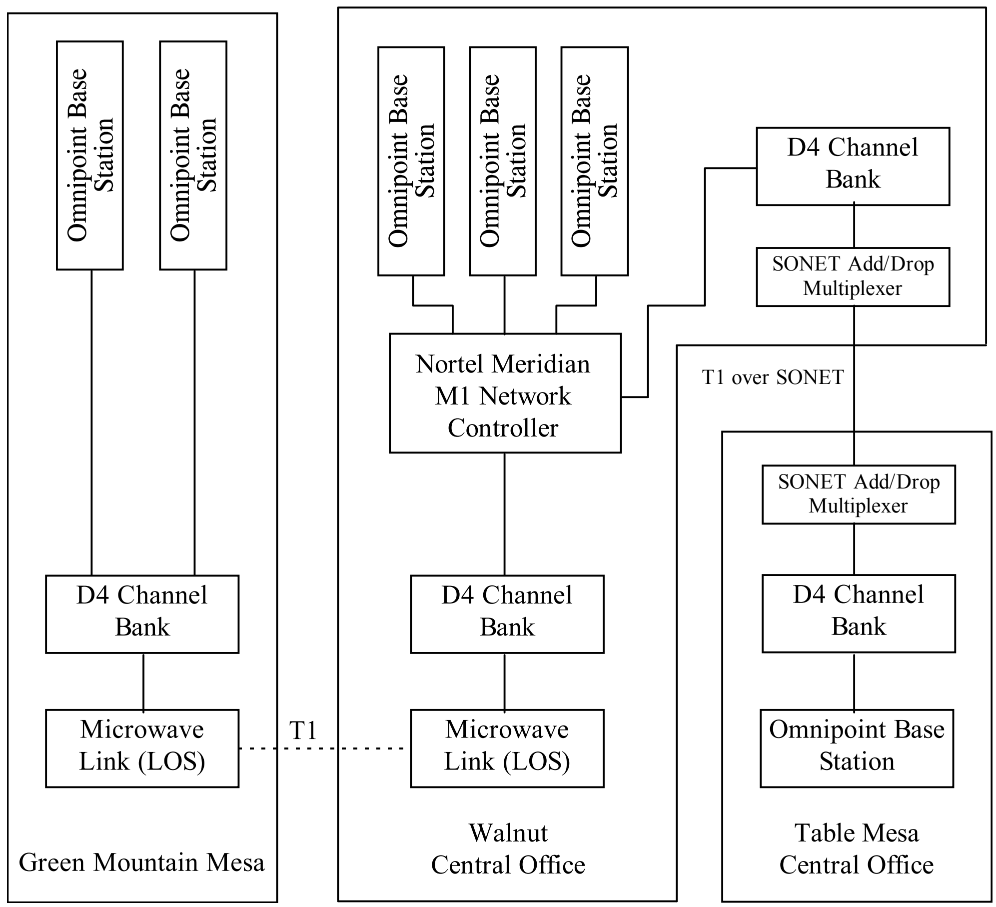


Figure 8.1. Block diagram of the TAG 1 test system configuration.

Table 8.1. Base Station Transmit Frequencies

Cell Site	Sector	Operating Frequency (MHz)
WCO	North	1871.875
WCO	Southeast	1883.125
WCO	Southwest	1877.500
GMM	North	1873.750
GMM	Southeast	1957.500
TMCO	North	1963.125

8.3 Area Coverage Testing

The area coverage testing for TAG 1 included the three high-tier cell sites and the one low-tier microcell site. The nominal EIRP for each cell site is listed in Table 8.2. The nominal EIRP for each cell site is found by averaging the transmit power into every antenna for every sector in the cell and then adding the nominal antenna gain.

Table 8.2. Nominal Radiated Power for Each Cell Site

Cell Site	Nominal EIRP (dBm)
GMM	44.4
TMCO	47.5
WCO	48.0
Site 3 (Low Tier Site)	31.0

The mobile unit transmitter used a nominal EIRP of 26.7 dBm for the high-tier testing and a nominal EIRP of 25.8 dBm for the low-tier testing.

Measurements to show area coverage were taken with the mobile unit[15] located in a mini-van as in the previous field trials. Four passengers were allowed in the vehicle. The mobile unit was mounted inside the van on the same wooden structure used in all of the JTC PCS technology field trials. This structure is described in Section 3.3. For the low-tier microcell, an antenna mounted on the roof of the measurement van was used. The measurements were taken by driving along routes (radials) away from the cell site. When time permitted, measurements along additional routes in between the radials were taken. Vehicle speed was limited to 35 mph or less for the low-tier testing.

Only one cell site was activated at a time during area coverage testing; all other cell sites were powered down. Handoff was allowed between the sectors of the active cell. The data were collected both at the mobile unit (downlink) and at the base station (uplink) simultaneously during the same measurement run at the TMCO cell site. Because of both time and measurement equipment constraints, for all other high-tier cell sites and the low-tier microcell site, the data were collected only at the mobile unit (downlink). The data collected at the mobile unit included GPS location and time, downlink RSS, average downlink BER, and other system parameters. The data collected at the base station included GPS time and location and average uplink BER. Uplink RSS values were not collected for the TAG 1 testing.

Calls were originated at the beginning of a measurement route prior to the start of data collection. Collection of mobile data and base station data was initiated as the measurement van began traveling away from the cell site along the drive route. At the end of the route, the data collection was stopped and the data were saved to disk. For the low-tier cell, the point along the

[15] Measurements in the GMM cell were also taken with an antenna mounted on the roof outside of the mini-van. For purposes of brevity and because it was not a formal part of the JTC PCS technology field trials, the measurements performed with the antenna located out of the measurement van for the GMM cell during area coverage testing are not discussed in this NTIA report.

route where the call was dropped marked the end of the coverage test for that particular route. All analyzed data for the area coverage testing represented the average of measured data taken over a 300-ft interval for the high-tier testing and taken over a 60-ft interval for the low-tier testing. Each individual measurement was triggered by a 3-ft vehicle movement.

For determining the area coverage boundaries in a cell, a minimum acceptable RSS needed to be defined. A minimum acceptable RSS was determined by first combining all of the downlink data from all of the high-tier cells and the low-tier microcell. Downlink RSS values were rounded off to the nearest integer. For each given integer downlink RSS value greater than -100 dBm, all of the corresponding BER values were averaged. Figure 8.2 shows a plot of the average downlink BER vs. RSS.

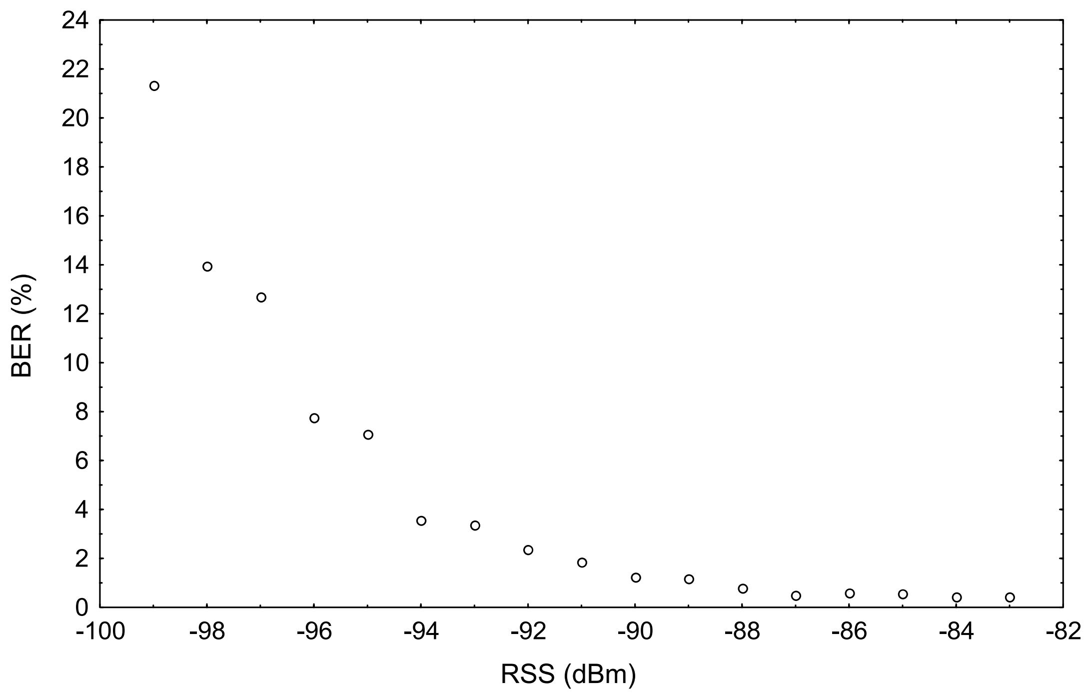


Figure 8.2. Average downlink bit error rate (BER) vs. received signal strength (RSS) for all high-tier cells and the low-tier microcell (TAG 1).

By defining a maximum acceptable average BER value and using Figure 8.2, a minimum acceptable RSS for area coverage could be determined. A maximum acceptable average BER of 5% was chosen because average BER values greater than 5% are very likely to imply unacceptable voice quality. Therefore, from Figure 8.2, a minimum acceptable RSS of -95 dBm was chosen (corresponding to a BER of 7%) as an area coverage threshold. This threshold value was used to determine area coverage for all of the high-tier cells and the low-tier microcell.

8.3.1 TMCO Area Coverage Data

The test procedure followed and data collection methodology used are explained in Section 8.3. Only the north sector was active for this cell site.

Downlink RSS as a function of distance is shown in Figure 8.3. The data included in this figure are the overall data for this cell with -100 dBm being the lowest recorded RSS. The large variation in RSS seen in Figure 8.3 is due to the irregularity of the terrain. Note that relatively strong signals (approximately -84 to -86 dBm) existed far away from the cell (approximately 5 mi). Those signals were recorded in areas having LOS propagation between the mobile unit and the base station.

A rough estimate of the coverage area was determined by assuming that an RSS of -95 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. Due to the irregularity of the terrain, the RSS varied significantly along the TMCO routes, crossing the -95 dBm level several times before finally staying below -95 dBm. The point along each route where the RSS first dropped below -95 dBm was used to define the coverage boundaries. For this case, the coverage boundaries were approximately 0.76 mi northwest, 2.1 mi northeast, and 2.15 mi east.

Figure 8.4 shows the histogram of downlink RSS values. The mean RSS was -91.6 dBm with a standard deviation of 11.3 dB.

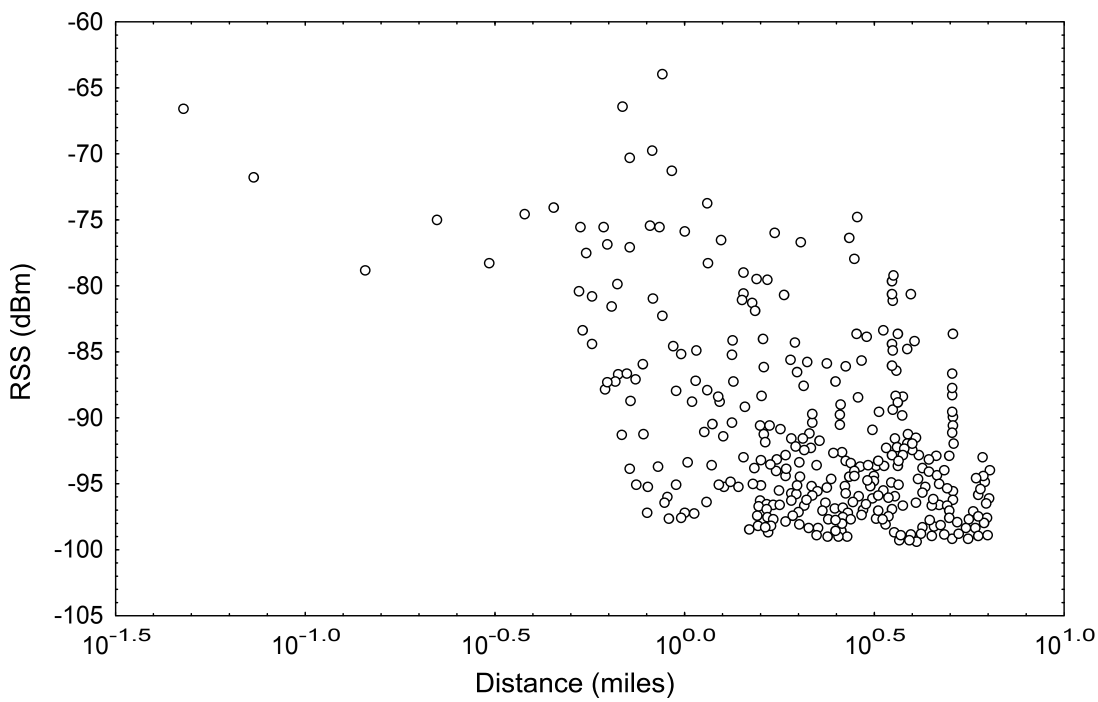


Figure 8.3. Downlink received signal strength (RSS) vs. distance (TAG 1, TMCO cell).

The downlink average BER histogram is shown in Figure 8.5. Approximately 42% of all downlink data points had an average BER less than 1%. Figure 8.6 shows the uplink average BER histogram. For the uplink, approximately 65% of the data points had an average BER less than 1%.

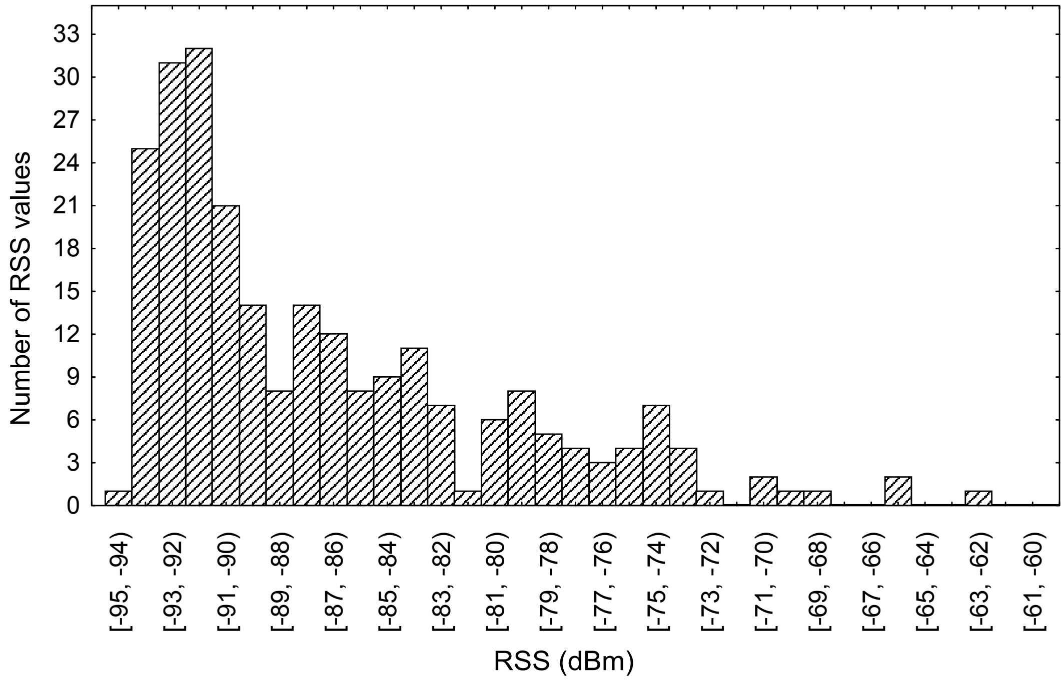


Figure 8.4. Histogram of downlink received signal strength (RSS; TAG 1, TMCO cell).

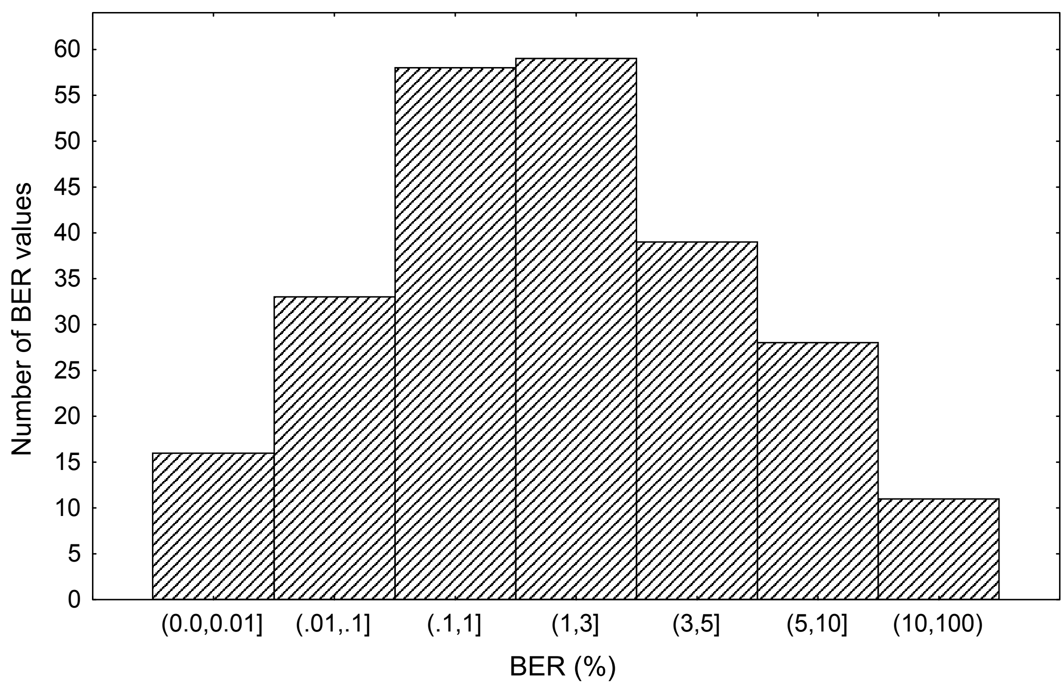


Figure 8.5. Histogram of average downlink bit error rate (BER; TAG 1, TMCO cell).

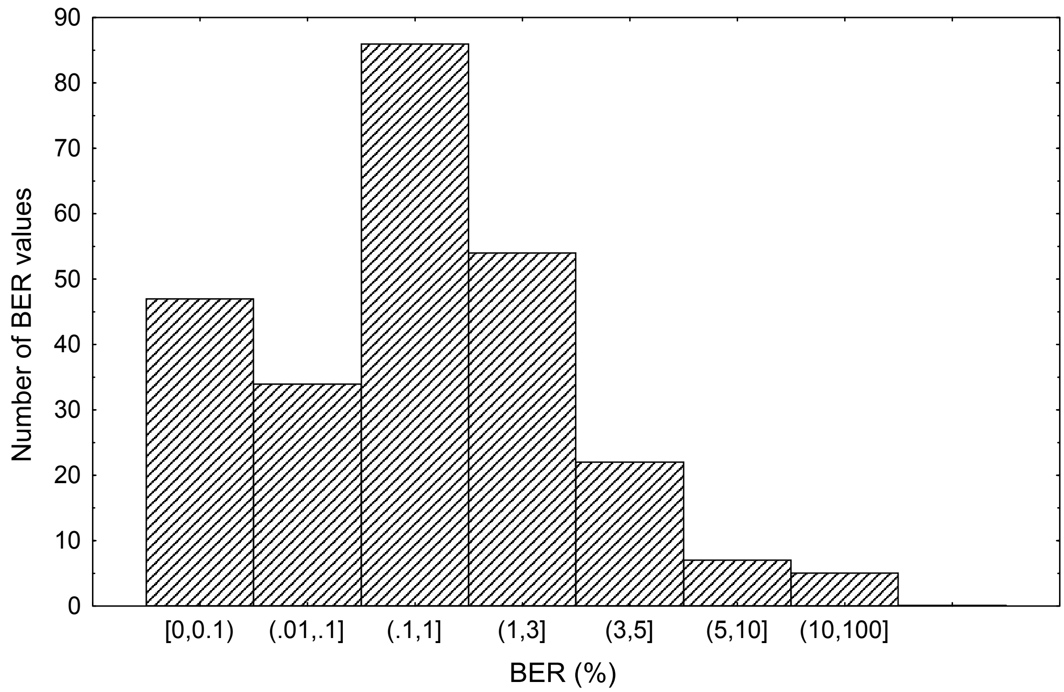


Figure 8.6. Histogram of average uplink bit error rate (BER; TAG 1, TMCO cell).

A link balance analysis was performed to determine if the uplink and downlink were balanced, and if not, which link was weaker. The presence of severe imbalance may contribute to a higher BER at the weaker link, and thus limit coverage in a cell.

The link balance analysis was performed for the TMCO cell only since the TMCO cell was the only one to record both uplink and downlink average BER. BER data for both links were taken simultaneously. The difference between average downlink and uplink BER values was computed. The histogram showing this difference is given in Figure 8.7. While data points with an RSS less than -95 dBm were excluded from the coverage area analysis, they were included in the link balance analysis. The mean difference between average downlink BER and uplink BER (average downlink BER given as a percentage minus average uplink BER given as a percentage) is 7.41%; the standard deviation is 9.93%. Therefore, the system was downlink limited.

8.3.2 WCO Area Coverage Data

The test procedure followed and data collection methodology used are explained in Section 8.3. All three sectors were active for this cell site. Downlink RSS as a function of distance is shown in Figure 8.8. The data included in this figure are the overall data for this cell with -100 dBm being the lowest recorded RSS. As in the TMCO cell, there is a large variation in RSS values for a given distance. This variation is caused by shadowing and the choice of the measurement routes. Note that a strong signal (approximately -60 dBm) exists approximately 1.8 mi away from the cell site. Comparing the downlink RSS vs. distance plots between the

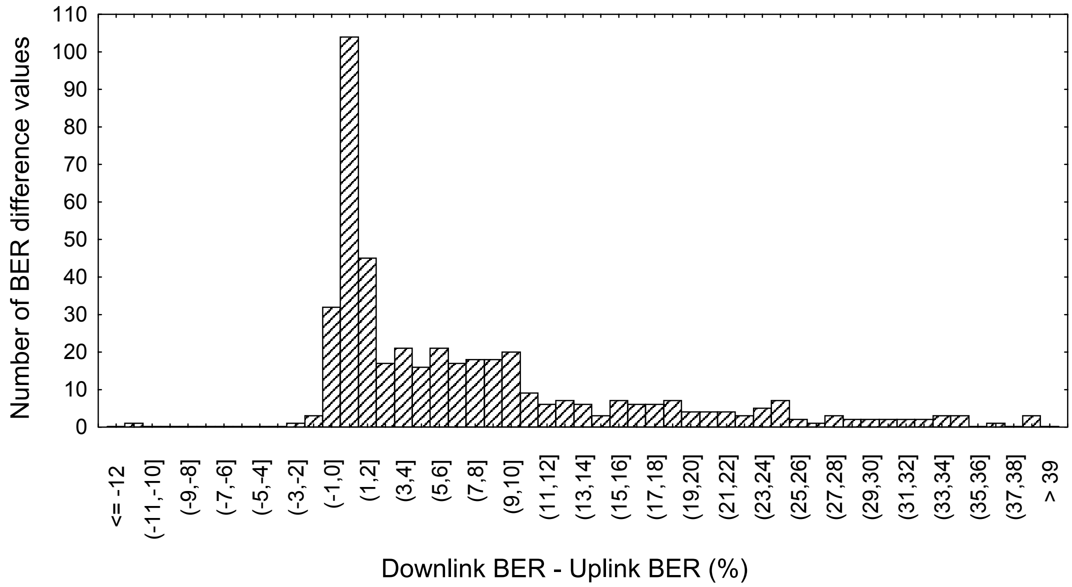


Figure 8.7. Histogram of difference between average downlink and uplink bit error rate (BER; TAG 1, TMCO cell).

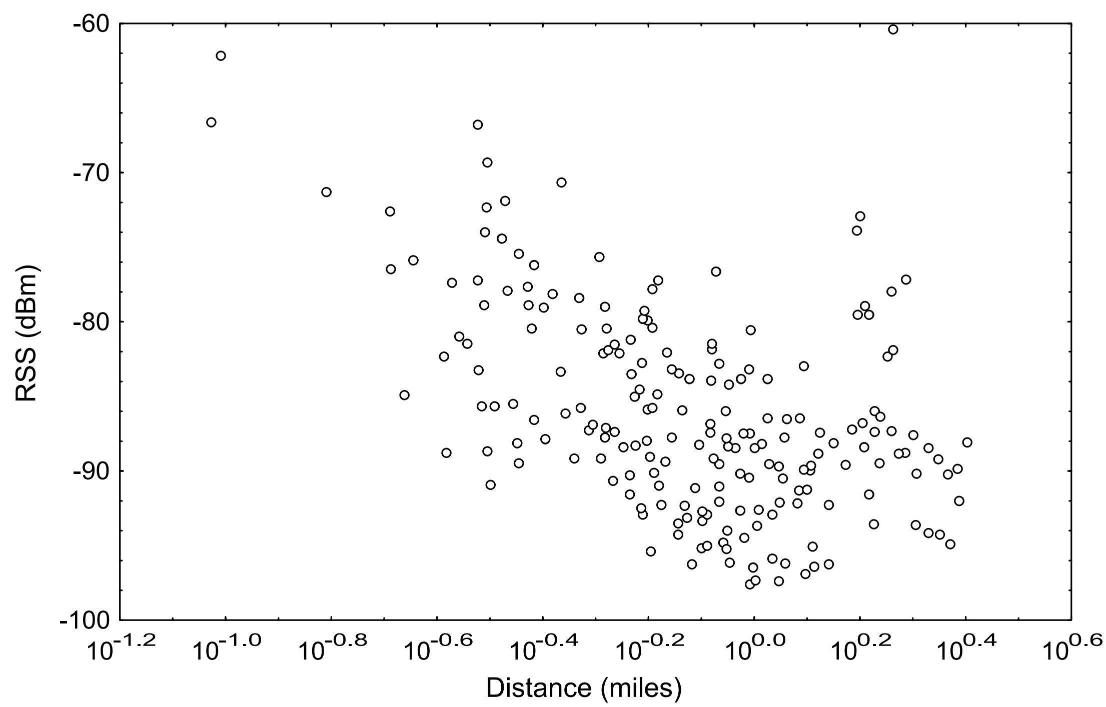


Figure 8.8. Downlink received signal strength (RSS) vs. distance (TAG 1, WCO cell).

WCO and TMCO cells (Figures 8.2 and 8.8) suggests that the WCO cell has a smaller coverage area than the TMCO cell.

A rough estimate of the coverage area was determined by assuming that an RSS of -95 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. For this case, the coverage boundaries were approximately 0.9 mi to the northwest, 1.85 mi to the east, and 0.74 mi to the west. Once the RSS fell below -95 dBm in these directions, it generally stayed below -95 dBm. Because of the lower elevation of the WCO cell site (relative to the TMCO cell site) and the terrain profile, the WCO cell had a smaller coverage area than the TMCO cell.

Figure 8.9 shows the histogram of downlink RSS values for the WCO cell. The mean RSS was -86 dBm and the standard deviation was 16 dB.

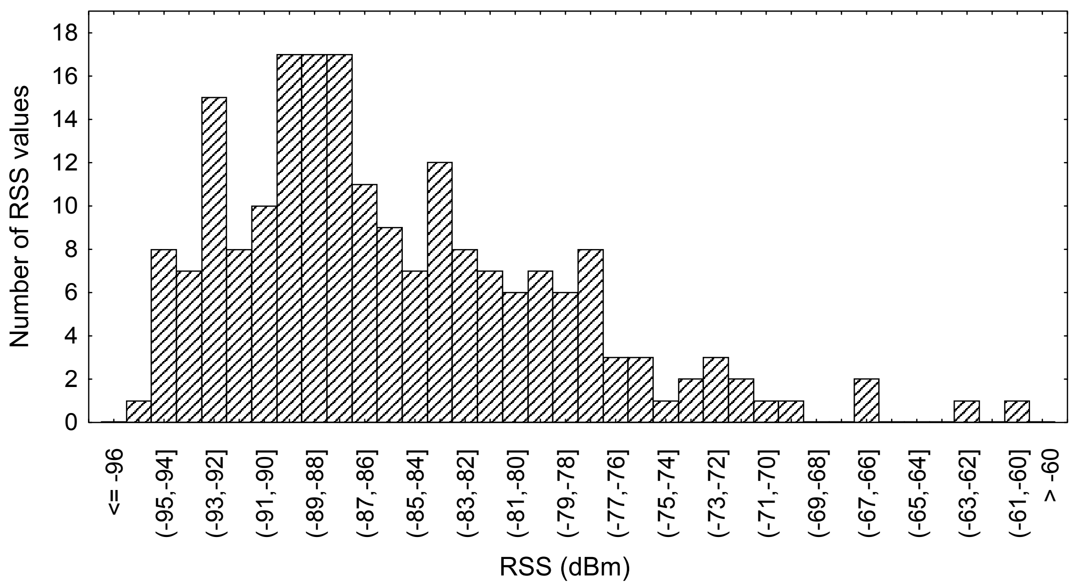


Figure 8.9. Histogram of downlink received signal strength (RSS; TAG 1, WCO cell).

The downlink average BER histogram is shown in Figure 8.10. For the downlink, approximately 70% of all data points had an average BER less than 1%. (Recall that average uplink BER was collected at the TMCO cell only.)

8.3.3 GMM Area Coverage Data

As for the TMCO and WCO area coverage testing, the test procedure followed and data collection methodology used are explained in Section 8.3. As mentioned in Section 8.3, for the GMM cell, measurements were made with an antenna mounted on the roof of the measurement van and with the antenna inside the vehicle. A penetration loss analysis was performed using the results from the measurements made with the antenna both inside and outside of the vehicle.

For the sake of brevity and because they were not a formal part of the JTC testing, the measurements made with the antenna mounted on the roof in the GMM cell and the penetration loss analysis are not discussed in this report. Two sectors (the northeast and southeast sectors) were active for this cell site.

Downlink RSS as a function of distance is shown in Figure 8.11. The data included in this figure are the overall data for this cell (in-vehicle antenna only) with -100 dBm being the lowest recorded RSS. As in the TMCO and WCO cells, there is a large variation in RSS

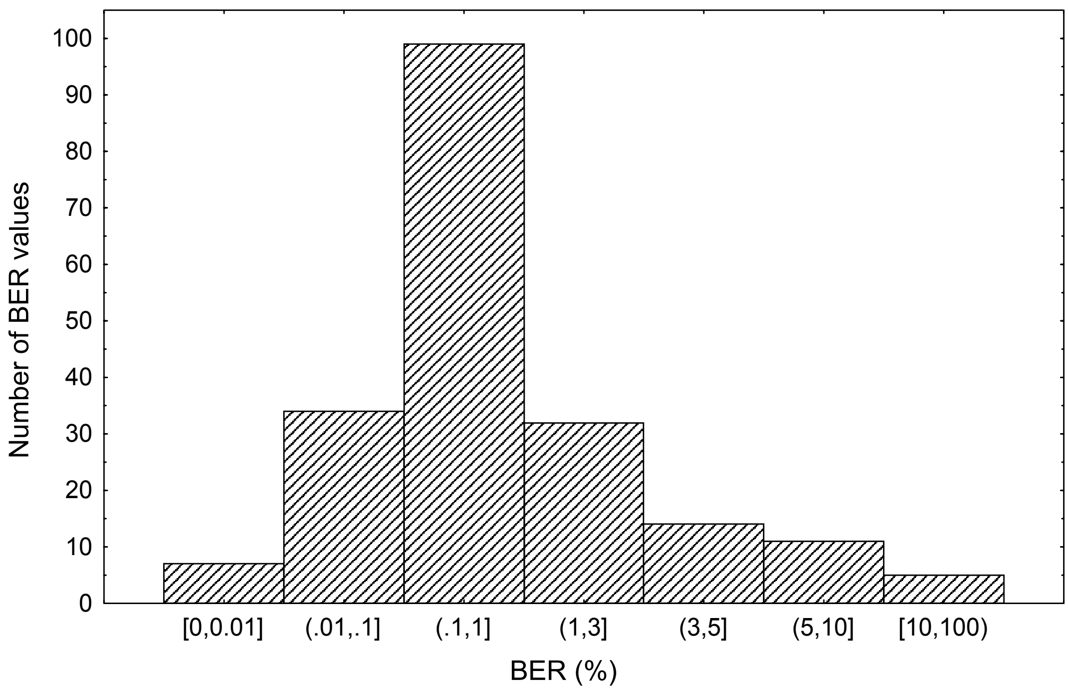


Figure 8.10. Histogram of average downlink bit error rate (BER; TAG 1, WCO cell).

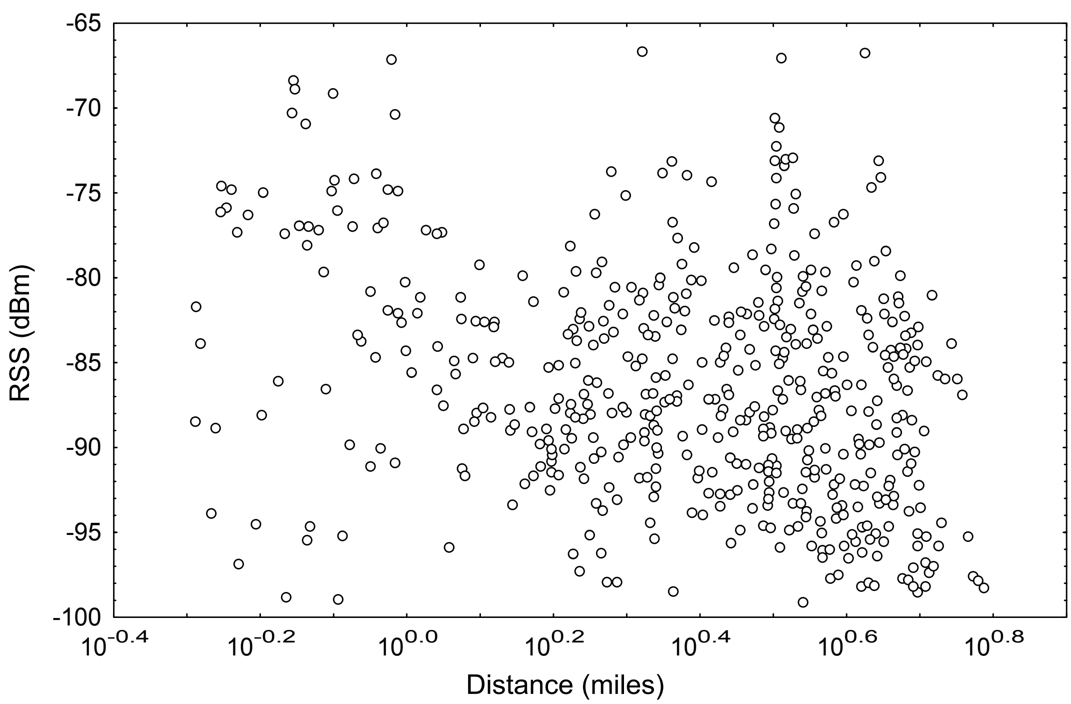


Figure 8.11. Downlink received signal strength (RSS) vs. distance (TAG 1, GMM cell).

values for a given distance. This variation is caused by large differences in the environment and terrain in the different areas where measurements were taken for this cell. To the northeast and east, the environment was mostly residential with less terrain obstructions than to the north. To the north, the environment was mostly light urban. Relatively strong signals as high as -81 dBm were measured as far as 5 mi from the cell site to the east.

A rough estimate of the coverage area was determined by assuming that an RSS of -95 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. For this case, the coverage boundaries were approximately 3.7 mi to the north, 5.5 mi to the east, 4.9 mi to the northeast, and 4.5 mi to the southeast. Because of the significantly higher elevation of the GMM cell site than the other two cell sites, good coverage was seen to the north, east, and southeast. Coverage to the south was poorer than in the other directions because of the terrain profile.

Figure 8.12 shows the histogram of downlink RSS values for the GMM cell. The mean RSS was -85.2 dBm and the standard deviation was 11.2 dB. The large standard deviation is caused by large differences in the environment and terrain in the different areas where measurements were taken for this cell.

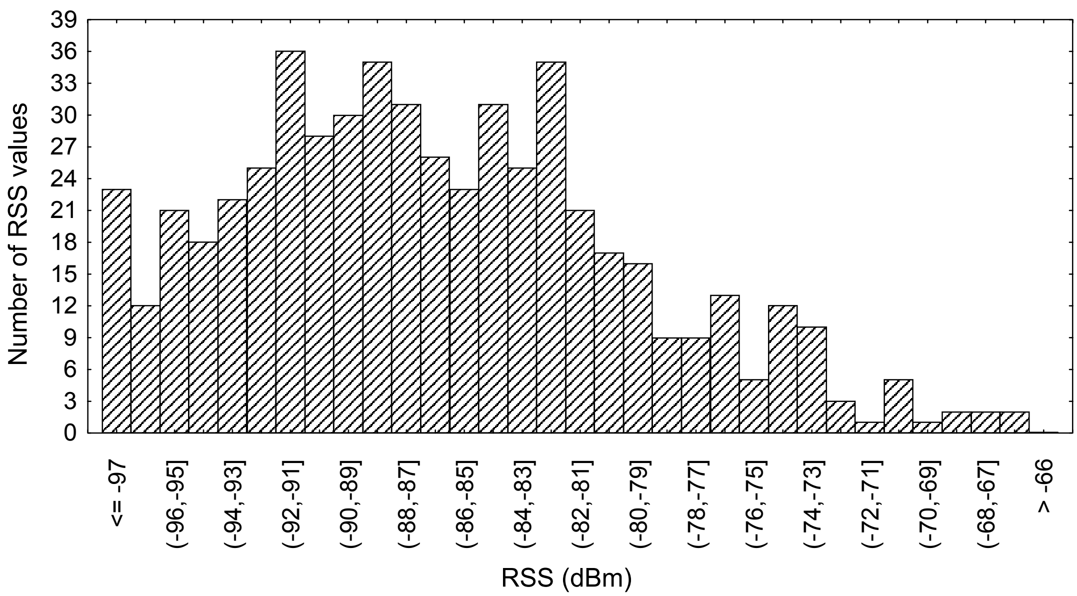


Figure 8.12. Histogram of downlink received signal strength (RSS; TAG 1, GMM cell).

The downlink average BER histogram is shown in Figure 8.13. For the downlink, approximately 65% of all data points had an average BER less than 1%. (Recall that average uplink BER was collected at the TMCO cell only.)

8.3.4 Low-Tier Microcell Site 3 Area Coverage Data

The test procedure followed and data collection methodology used for the low-tier testing are explained in Section 8.3.

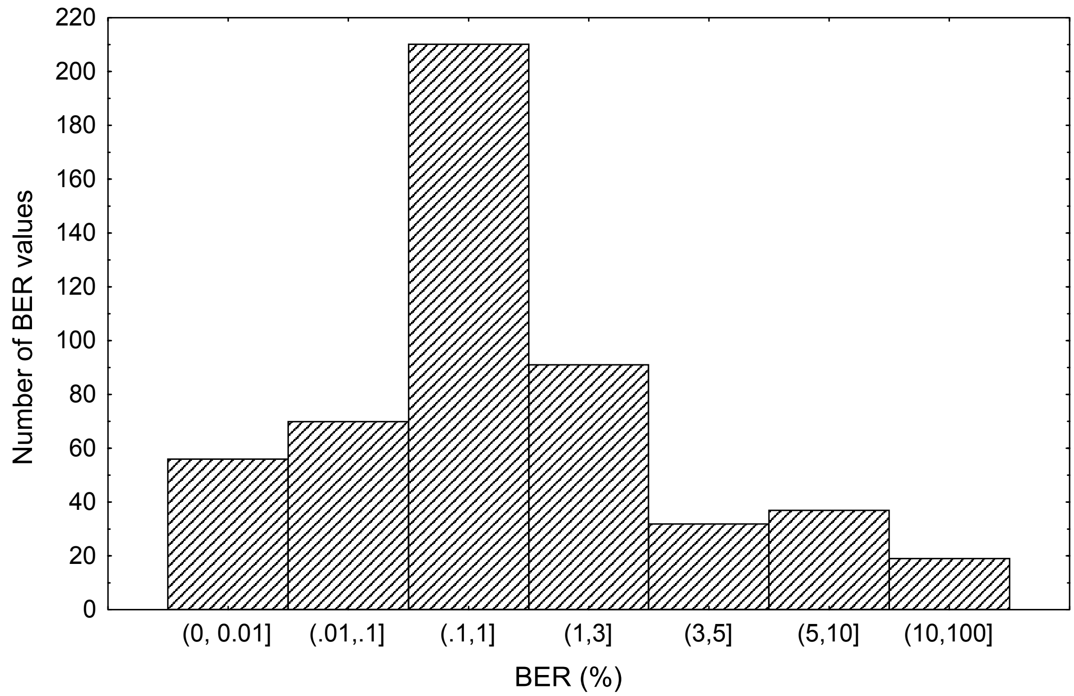


Figure 8.13. Histogram of average downlink bit error rate (BER; TAG 1, GMM cell).

Downlink RSS as a function of distance is shown in Figure 8.14. The data included in this figure are the overall data for this microcell with -100 dBm being the lowest recorded RSS. As in the high-tier cells, there is a large variation in RSS values for a given distance. This variation is caused by shadowing which is more pronounced because the base station is mounted on a traffic light pole in the middle of the street. Relatively strong signals (approximately -61 dBm) were seen relatively far away from the microcell site (approximately 1 mi). Those signals were recorded along 15th Street, where minimal shadowing occurred.

A rough estimate of the coverage area was determined by assuming that an RSS of -95 dBm or greater is desired. The measured RSS data along all of the routes driven within the cell were used to determine the coverage area. For this case, the coverage boundary was approximately 1.32 mi to the east. Coverage boundaries to the south and north were difficult to estimate. This was because all of the streets that run in a south-north direction and are the closest to the low-tier microcell site end abruptly after a few blocks, due to natural obstructions (a steep hill to the north and Boulder Creek to the south). Figure 8.15 shows the histogram of downlink RSS values for the Site 3 microcell. The mean RSS was -80.5 dBm and the standard deviation was 15.81 dB.

The downlink average BER histogram is shown in Figure 8.16. For the downlink, approximately 90% of all data points had an average BER less than 1%. (Recall that average uplink BER was collected at the TMCO cell only.)

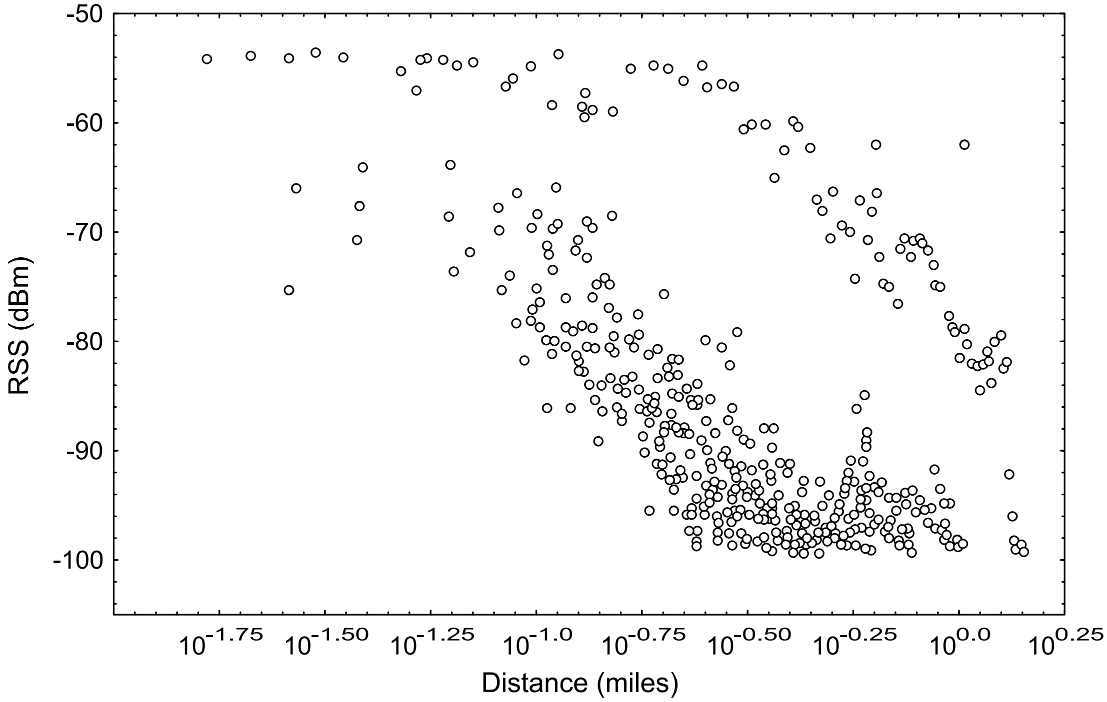


Figure 8.14. Downlink received signal strength (RSS) vs. distance (TAG 1, microcell site 3).

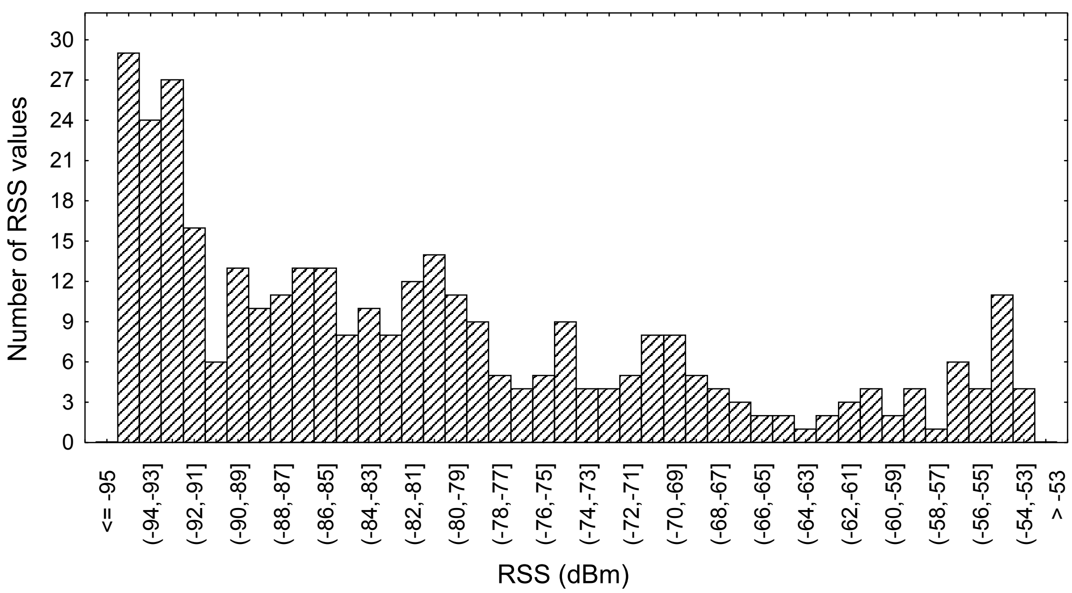


Figure 8.15. Histogram of downlink received signal strength (RSS; TAG 1, microcell site 3).

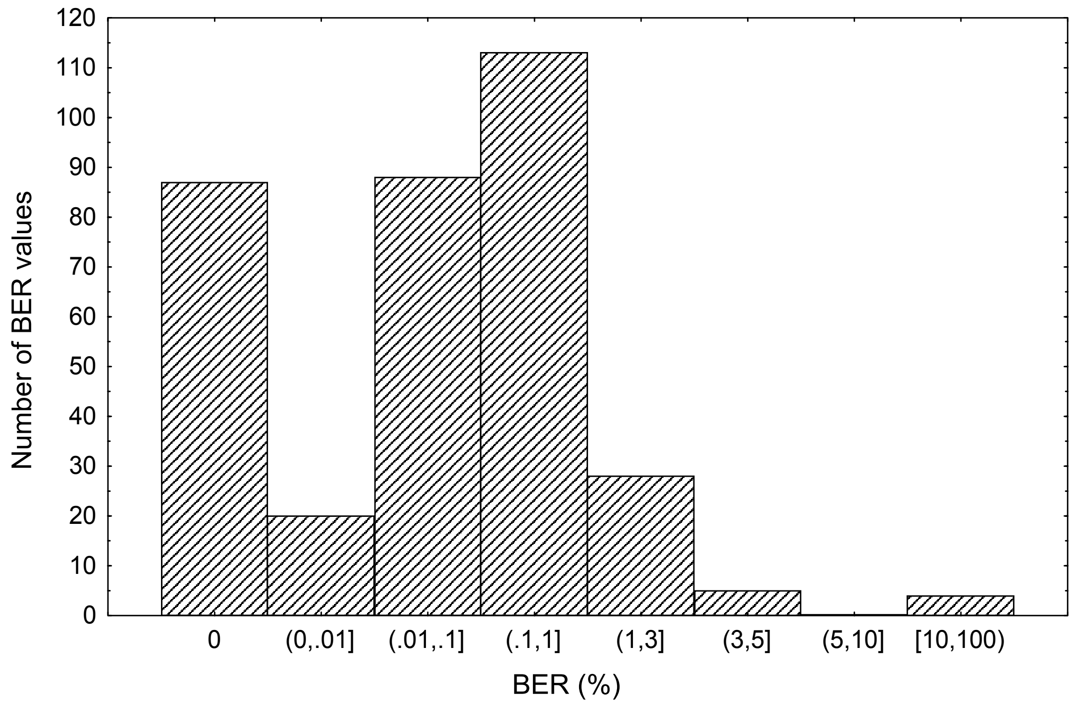


Figure 8.16. Histogram of average downlink bit error rate (BER; TAG 1, microcell site 3).

8.4 Handoff Testing

The TAG 1 technology was designed to support both low- and high-speed handoff. Therefore, handoff testing was conducted at speeds up to 60 mph. For the handoff testing, all high-tier cells were used. All sectors of the high-tier cells that were used during area coverage testing were activated for handoff testing. The low-tier microcell was not used during the handoff testing.

Handoff testing was performed by driving the measurement van on two routes that were chosen for handoff testing. One route was along Broadway between Norwood Avenue and Ludlow Street while the other was along Foothills Parkway between Jay Road and the hilltop overlooking Boulder just south of Boulder. These routes were driven in both the northbound and southbound directions.

In the TAG 1 handoff testing, handoff locations could only be pinpointed to within a 300-ft accuracy. Additionally, the exact difference between RSS values before and after a handoff and between BER values before and after a handoff could not be determined. Therefore, no data plots showing a change in values before and after handoff are available. A histogram of the average RSS values taken during all of the handoff measurement runs is given in Figure 8.17. The mean RSS was -82 dBm with a standard deviation of 10 dB. This mean RSS value is greater than the mean RSS value for any of the high-tier cells tested individually. This was expected, because the handoff routes were chosen in areas that had sufficient radio coverage to avoid dropped calls during the measurement runs.

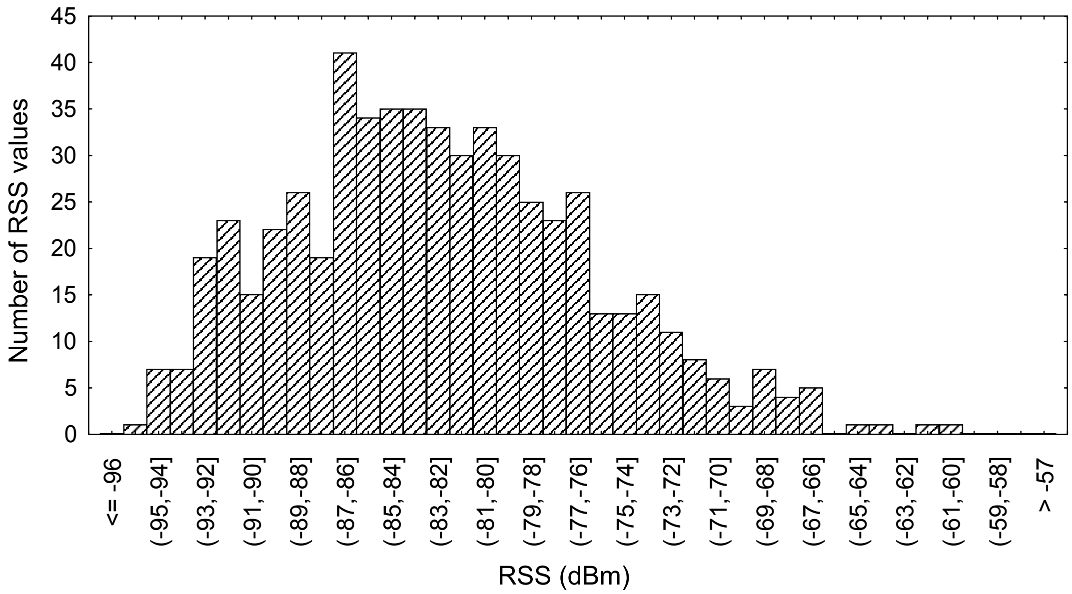


Figure 8.17. Histogram of average received signal strength (RSS) values taken during all handoff measurement runs (TAG 1).

8.5 Interference Testing

All interference measurements were conducted in downtown Boulder. The interference measurements consisted of both co-channel and adjacent channel interference measurements and were performed for the downlink only. This provided interference performance characterization for the mobile unit only. An antenna was mounted on the roof of the measurement van for these measurements. No interference measurements were taken for the base station receiver.

For the adjacent channel interference measurement, the WCO southwest sector was used as the intended source. The carrier for the intended source was set to 1875.625 MHz. The GMM north sector was used as the source for the adjacent channel interference. The carrier for the adjacent channel interferer was set to 1873.75 MHz, the channel immediately adjacent to the channel used for the intended source. For the adjacent channel interference testing, measurements were made under three different operating conditions: the interfering signal only, the desired signal only, and the desired signal in the presence of the interfering signal. Measurements under each operating condition were made on a separate measurement run along the same measurement route. The measurement route used for the adjacent channel interference measurements was along Broadway starting at the intersection of Broadway and Euclid Avenue and continuing north to Elder Street. For the interfering signal only measurements, a call was established at the beginning of the measurement route and downlink RSS data were collected, averaged, and saved to disk every 60 ft that the measurement van traveled. For the desired signal only measurements, a call was established and downlink RSS and BER data were collected, averaged, and saved to disk every 60 ft that the measurement van traveled. The same procedure was followed for the measurements of the desired signal in the presence of the interfering signal.

Figure 8.18 shows a plot of the average downlink BER as a function of the adjacent channel C/I. From this plot note that C/I values of -2 dB and greater provide a BER of less than about 1.25%. For C/I values less than -2 dB, while the average downlink BER generally increases, it does not increase monotonically as would be expected. A possible explanation for this is that an insufficient number of data points were taken to fully characterize the relationship between BER and adjacent channel C/I. Because the BER does not increase monotonically for C/I values less than -2 dB, a C/I threshold for which the BER begins to increase rapidly cannot be identified.

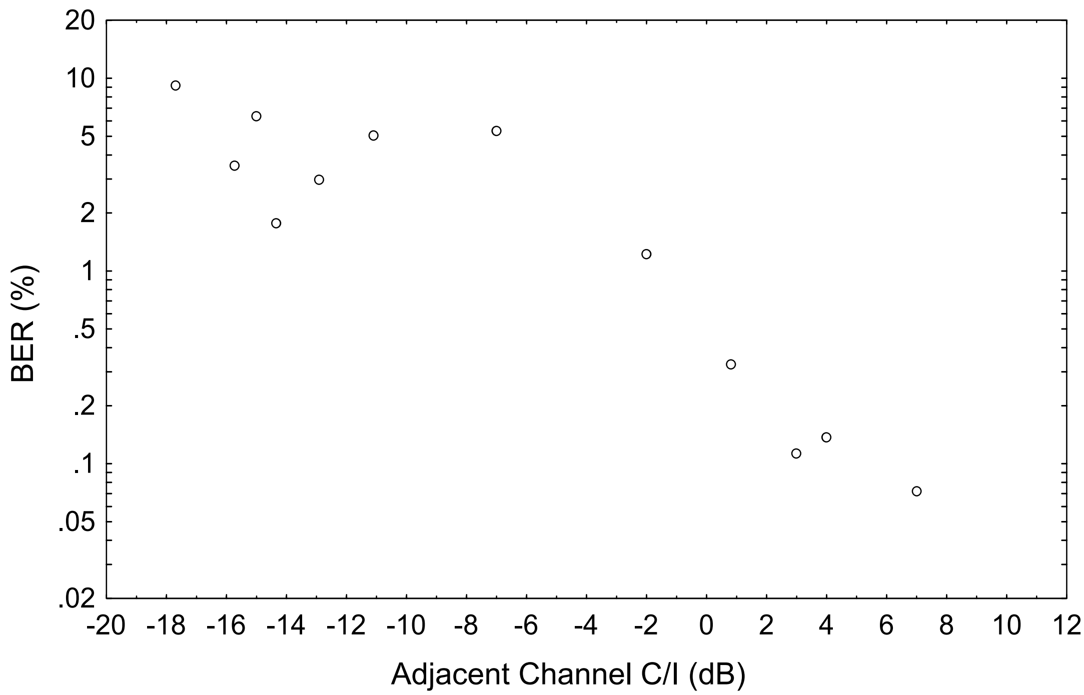


Figure 8.18. Average downlink bit error rate (BER) vs. adjacent channel carrier-to-interference ratio (C/I; TAG 1).

For the co-channel interference measurement, the WCO north sector was used as the intended source. The GMM north sector was used as the source for the co-channel interference. Both the GMM north sector and the WCO north sector were tuned to the same frequency (1873.75 MHz). As for the adjacent channel interference testing, for the co-channel interference testing, measurements were made under three different operating conditions: the interfering signal only, the desired signal only, and the desired signal in the presence of the interfering signal.

For the measurements of the desired signal only and the desired signal in the presence of the interferer, the measurement van followed a loop route. The van started at the intersection of Pearl Street and 15th Street, went east on Pearl Street, north on 19th Street, west on Mapleton Avenue, south on Broadway, east on Canyon Boulevard, north on 15th Street, and ended at the intersection of Walnut Street and 15th Street (one block south of the starting point). For the measurements of the interfering signal only, the measurement van followed the same loop route but started and ended at the intersection of Broadway and Mapleton Avenue,[16] thus completing the loop. Because the starting points along the loop route were different between the measurements for the interfering signal only and the other two operating conditions, the data could not be processed to provide a relationship between BER and the co-channel C/I.

8.6 Voice Quality

As discussed in Section 3.6, two types of voice quality measurements were made for the PCS JTC technology field trials in general: quasi-stationary measurements and handoff measurements. Both types of measurements were performed for the composite CDMA/TDMA (TAG 1) technology.

8.6.1 Quasi-stationary Measurements

Voice recordings and various objective measures including downlink RSS and uplink and downlink BER were collected at locations on a 0.5-mi grid that encompassed the expected coverage area for the TMCO, WCO, and GMM high-tier cell sites. Measurements were taken at 61 of the 82 locations that were identified for the quasi-stationary measurements as discussed in Section 3.6.1. These locations are shown on the map in Figure 8.19. For the TAG 1 voice quality testing, only one sector of one cell site was activated at a time. Intracell and intercell handoffs were not allowed.

At each location, data were collected as the measurement van traveled at one of two speeds. The vehicle traveled either 10 m or 100 m over the sample time. The particular vehicular speed used at each location (distance traveled over a fixed sample time) is shown on the map in Figure 8.19. Voice recordings were taken over the same sample time at all locations.

The measurements were taken at each location by establishing a call between the mobile and landline telephones. While the measurement van was in motion, an audio source tape was transmitted over the radio link in the uplink direction. After the uplink measurement was made, a downlink measurement was made. The source tape transmitted over each link was the same as that used for TAG 5 testing (see Section 3.6.1).

[16] The intersection of Broadway and Mapleton Avenue was the originally intended starting point and ending point of the loop route for all of the co-channel interference measurements under all three operating conditions. First, measurements were made for the interfering signal only along the loop route starting at this location. Next, for the measurements of the desired signal in the presence of the interferer, the call could not be established at the intersection of Broadway and Mapleton Avenue because the interference level was too high. The starting point of the loop route had to be changed to the intersection of Pearl Street and 15th Street (where the interference level was low enough to establish the call). Measurements of the desired signal in the presence of the interferer and of the desired signal only were then made along the loop route starting at the intersection of Pearl Street and 15th Street. Measurements of the interfering signal only were not repeated along the loop route starting at the intersection of Pearl Street and 15th Street.

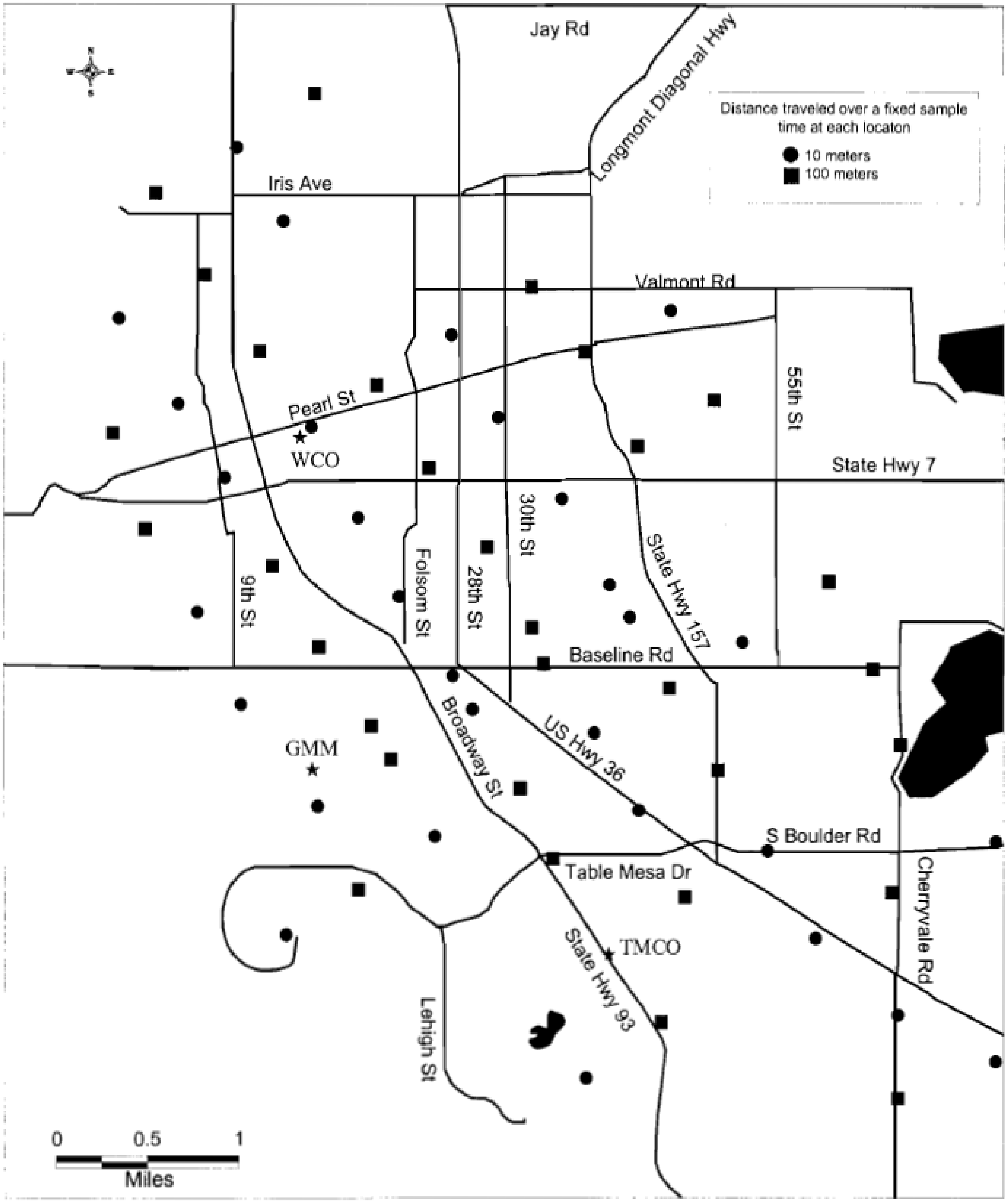


Figure 8.19. Quasi-stationary measurement locations and vehicular speed used at each location for TAG 1.

The received voice transmissions were recorded on digital audio tape at the receiver for the uplink and then at the receiver for the downlink. The recorded voice segments were then digitized with 16-bit resolution at a 22-Ksample/s rate and stored on a hard disk drive. At each location, the objective measures including average downlink RSS and average uplink and downlink BER were collected during separate measurement runs on the following day.

For the quasi-stationary measurements, voice quality of the voice segments was determined by both mean opinion score (MOS) and expert listener techniques. The following sections discuss these techniques and present the results based on the application of these techniques.

8.6.2 Mean Opinion Score Assessment

To accomplish the MOS testing, a pool of 32 subjects was recruited from the Boulder, Colorado area. Each of the following age groups were represented within the subject pool: 18-25, 25-35, 35-45, 45-55, and those over 55 years of age. There were an equal number of male and female subjects. The subjects were cordless, noncellular telephone users.

Four groups consisting of eight subjects from the subject pool were formed. The subjects were asked to rate voice segments by answering the three questions listed in Section 3.6.2 after each segment was presented.

First the subjects in each of the 4 groups were presented 10 practice voice segments to rate. The practice segments included one 64-kbps wireline voice segment, two voice segments collected from field measurements (one with an expert listener rating of definitely acceptable and one with an expert listener rating of unacceptable), and seven segments created in a laboratory environment by the TAG 1 vendor. The laboratory segments simulated speech with various BER's in three different environments: residential, urban, and rural. The seven segments represented the following environments and BER's: unimpaired speech, residential with a BER of 1%, residential with a BER of 10%, urban with a BER of 1%, urban with a BER of 10%, rural with a BER of 1%, and rural with a BER of 10%.

After the practice segments were presented, the subjects in each of the 4 groups were asked to rate 33 voice segments: 3 reference voice segments and 30 voice segments from the field trial measurements. Every listener within a group listened to the same voice segments. The reference voice segments included one 64-kbps wireline voice segment and two voice segments collected from field measurements (one with an expert listener rating of definitely acceptable and one with an expert listener rating of unacceptable). The 30 voice segments from the field trial measurements came from the uplink or downlink measurements at a portion of the 61 measurement locations.

The number and type (male or female) of sentences that were used and the order in which they were used to form a voice segment were the same as that described in Section 4.6.2. Subjects were given two breaks during the testing session. After all segments were presented, subjects filled out a post-trial questionnaire.

For each voice segment, voice quality ratings (answers to the question "How would you rate the overall quality of the sound?") from each subject within a group were averaged to obtain an MOS. Voice segments from only 57 out of the 61 locations were used in the analysis since the voice segments from 4 of the 61 locations were not successfully tested. The results from all four of the groups are shown in the histogram in Figure 8.20. Overall, the voice segments were rated favorably, with 84.2% of the segments rated between fair and excellent. The average MOS was 3.65 and the standard deviation was 0.63.

Figures 8.21 and 8.22, show histograms of MOS's for the uplink and downlink, respectively. The average MOS for the uplink was 3.54 and for the downlink was 3.76. A t-test revealed that there is no statistically significant difference in the average MOS's between the uplink and downlink.

The relationship between the MOS's and some of the objective measures was initially investigated by generating some scatter plots. Figure 8.23 shows the relationship between the MOS's and average downlink RSS. In Figure 8.23, variation in MOS's tends to lessen as RSS values increase. MOS's tend to degrade as the RSS value drops below about -89 dBm. Figures 8.24 and 8.25 show the relationship between the MOS's and the average BER for both the uplink and downlink, respectively. From Figure 8.25, note that the MOS tends to degrade as the average downlink BER increases, as expected. As seen in Figure 8.24, this trend is not as evident for the uplink.

Pearson product-moment correlations were performed to determine the correlation between MOS and average downlink RSS and MOS and average downlink BER. The correlation coefficient between MOS and average downlink RSS was 0.40 and that between MOS and average downlink BER was -0.75. This suggests that a fairly strong linear relationship exists between MOS and average downlink BER; a weaker linear relationship exists between MOS and average downlink RSS. The correlation coefficient between the average downlink RSS and the average downlink BER was -0.51.

Spearman rank correlations were performed to determine the correlation between the ranks of MOS and the ranks of average downlink RSS and between the ranks of MOS and the ranks of average downlink BER. The Spearman rank correlation coefficient between MOS and average downlink RSS was 0.35 and that between MOS and average downlink BER was -0.49. These correlation coefficients between MOS and the averaged objective measures are lower than the Pearson product moment correlations; this suggests that a consistently increasing or decreasing relationship between MOS and the objective measures does not exist. The Spearman rank correlation coefficient between the average downlink RSS and BER was -0.66 and is greater than the Pearson product moment correlation coefficient between these measures.

Next, a Pearson product-moment correlation was performed to determine the correlation between MOS and average uplink BER. The correlation coefficient between MOS and average uplink BER was -0.20. Therefore, a strong linear relationship between MOS and average uplink BER does not exist.

A Spearman rank correlation was performed to determine the correlation between the ranks of MOS and the ranks of average uplink BER. The Spearman rank correlation coefficient between MOS and average uplink BER was -0.36. This correlation coefficient, while higher than the Pearson product moment correlation coefficient, is still fairly low and suggests that a consistently increasing or decreasing relationship between MOS and average uplink BER does not exist.

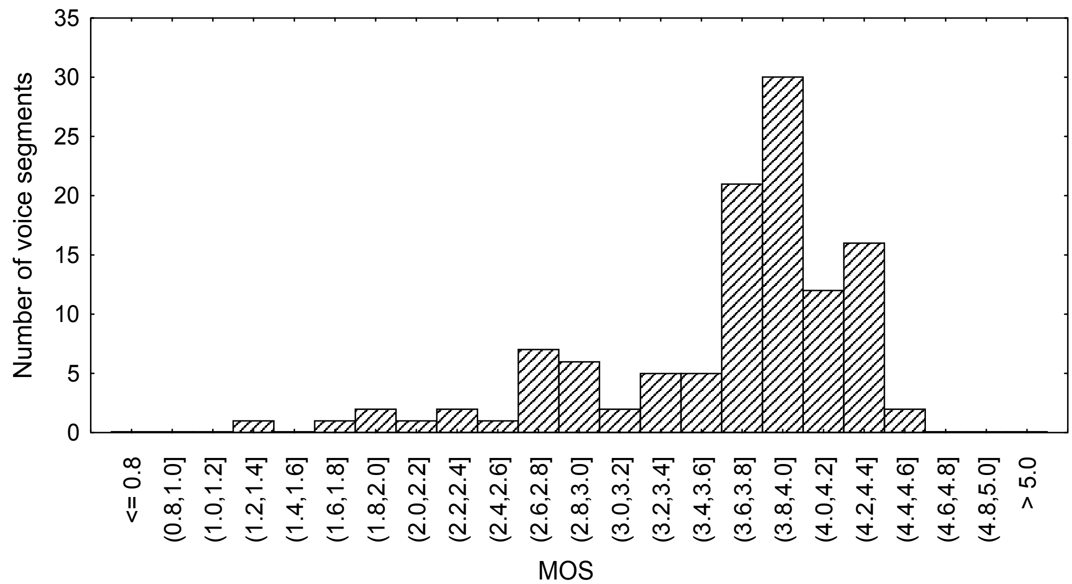


Figure 8.20. Histogram of mean opinion scores (MOS's) for all voice segments (TAG 1).

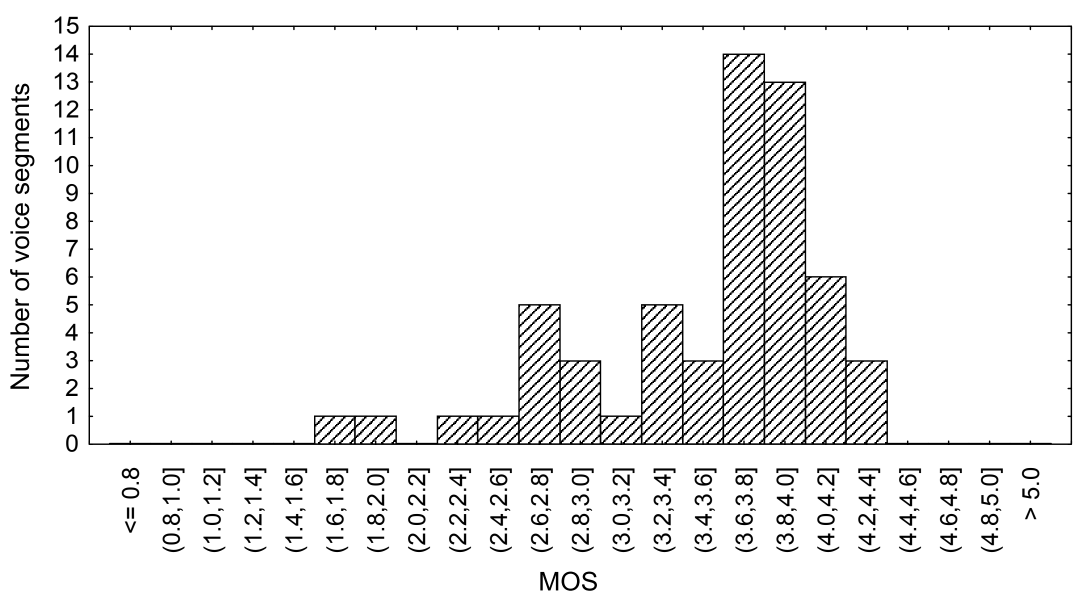


Figure 8.21. Histogram of mean opinion scores (MOS's) for the uplink (TAG 1).

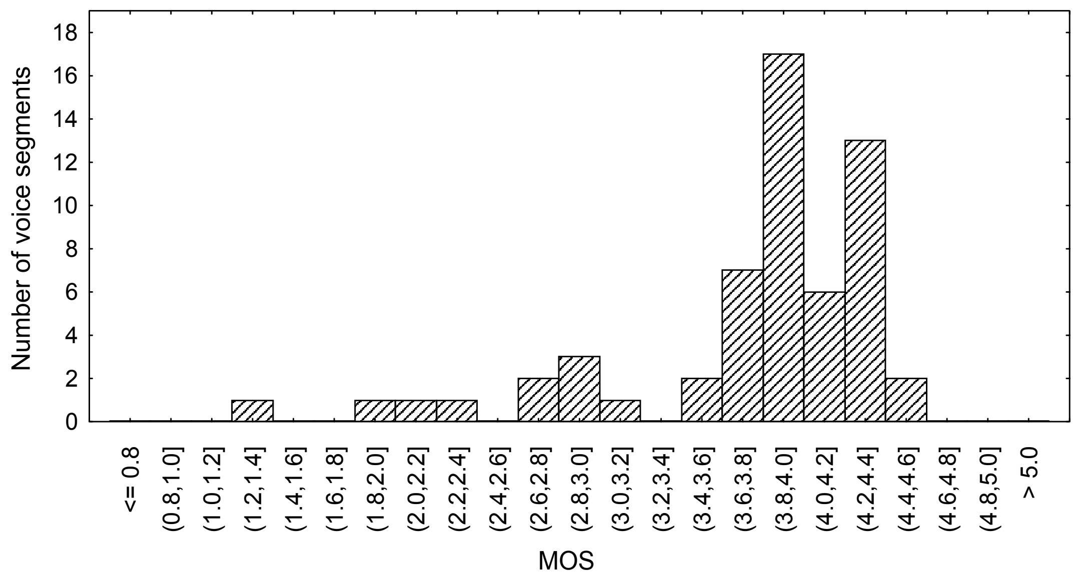


Figure 8.22. Histogram of mean opinion scores (MOS's) for the downlink (TAG 1).

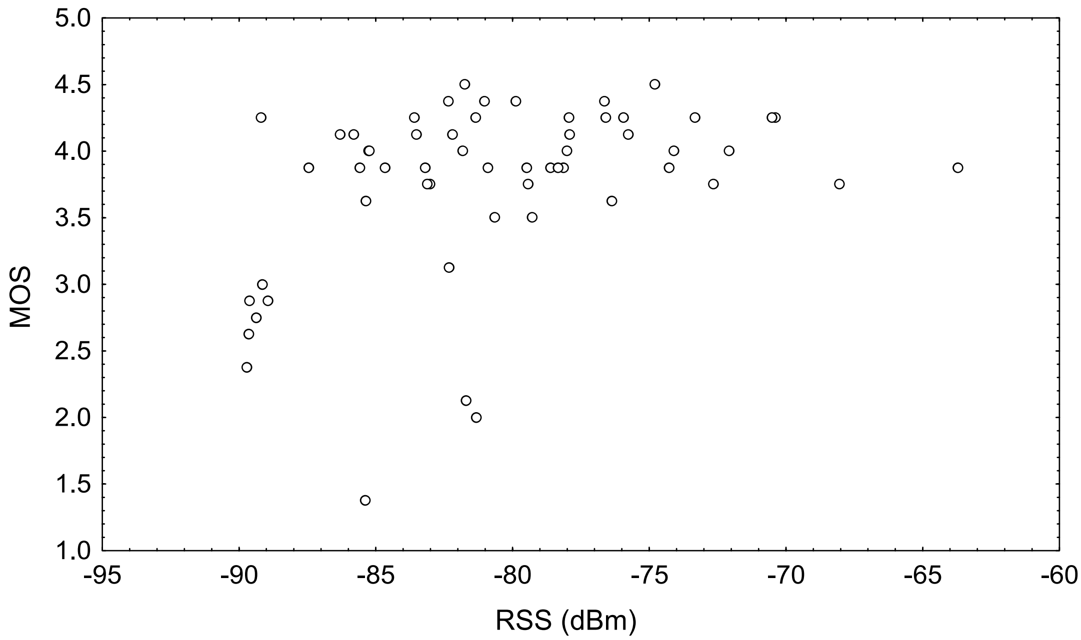


Figure 8.23. Mean opinion score (MOS) vs. average received signal strength (RSS; TAG 1).

Note that as in the voice quality data analysis of the previous JTC PCS technology field trials, the objective measures were averaged over the entire length of the voice segment. By analyzing the instantaneous variation or possibly minimum and maximum values of the objective measures within the voice segment, further insight may be gained on the behavior of MOS's and higher correlations to MOS's might be obtained.

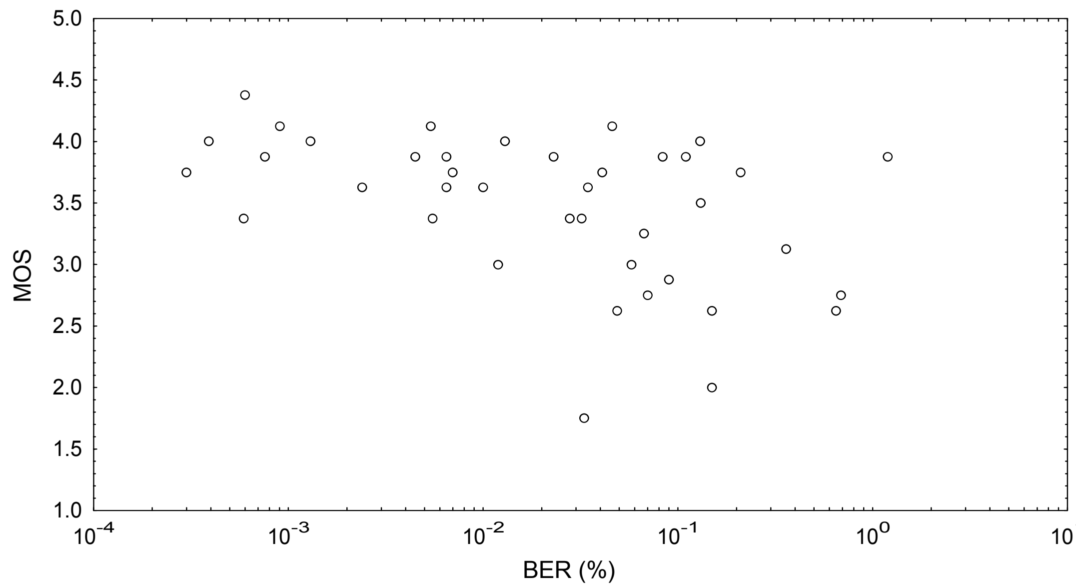


Figure 8.24. Mean opinion score (MOS) vs. uplink bit error rate (BER; TAG 1).

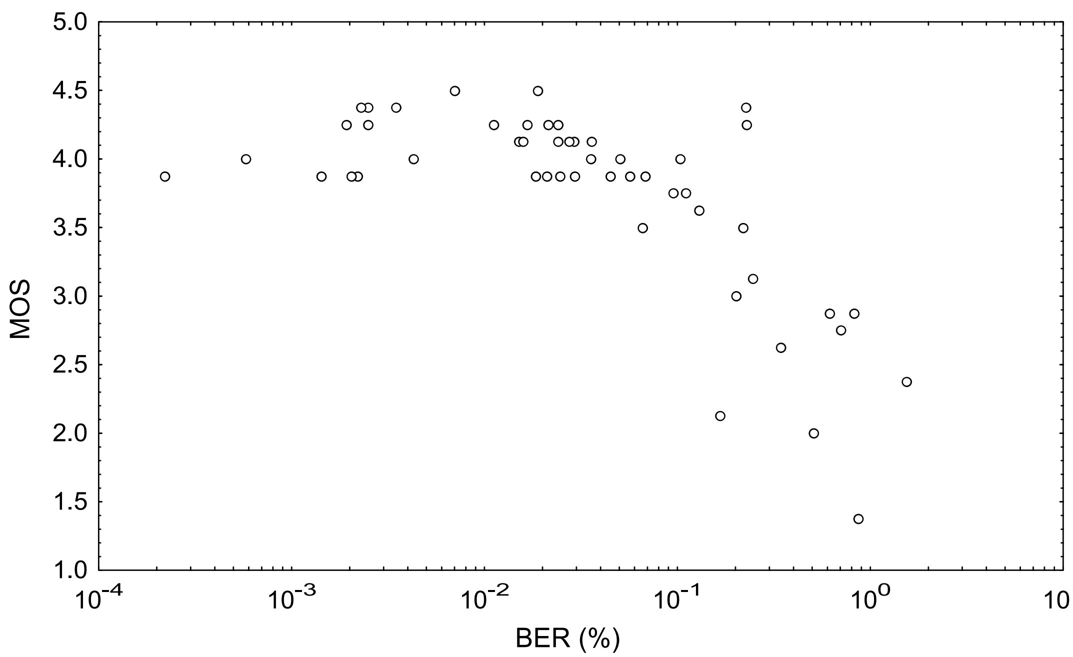


Figure 8.25. Mean opinion score (MOS) vs. downlink bit error rate (BER; TAG 1).

By gathering listeners' comments from post-test questionnaires, more information about the nature of MOS's was obtained. Namely, it is evident from questionnaires that there are several types of distortions in quality possible in the voice segments according to listeners:

1) "static,"
2) "background noise,"

3) "echo," and
4) "muffled or hollow sound."

Note that these are the exact words used by listeners. The nature of these distortions are likely judged differently by different listeners. Intelligibility and speaker recognition are two main aspects of perceived quality. For most of the voice segments, intelligibility remained high. As a result, overall MOS's were high and overall listener's comments were quite positive.

8.6.3 Expert Listener Assessment

In addition to being rated by listener panels in MOS testing, the voice segments were rated by an expert listener. The expert listener ratings followed the identical procedure as in the PCS 1900 (TAG 5) testing. This procedure is described in Section 3.6.3.

Figure 8.26 shows the relationship between expert listener ratings and percent acceptability (the percentage of listeners rating a given voice segment as acceptable). The boxes represent the middle half of the data (from the 25th percentile to the 75th percentile). The solid circles represent the median percent acceptabilities for each of the expert listener ratings. The lines extending out of the boxes depict the spread of the data.

The expert listener ratings were very good indicators of percent acceptability for the voice segments in the TAG 1 testing. The expert listener ratings accurately predicted the percent acceptability for 105 out of the 114 voice segments evaluated by listener panels.

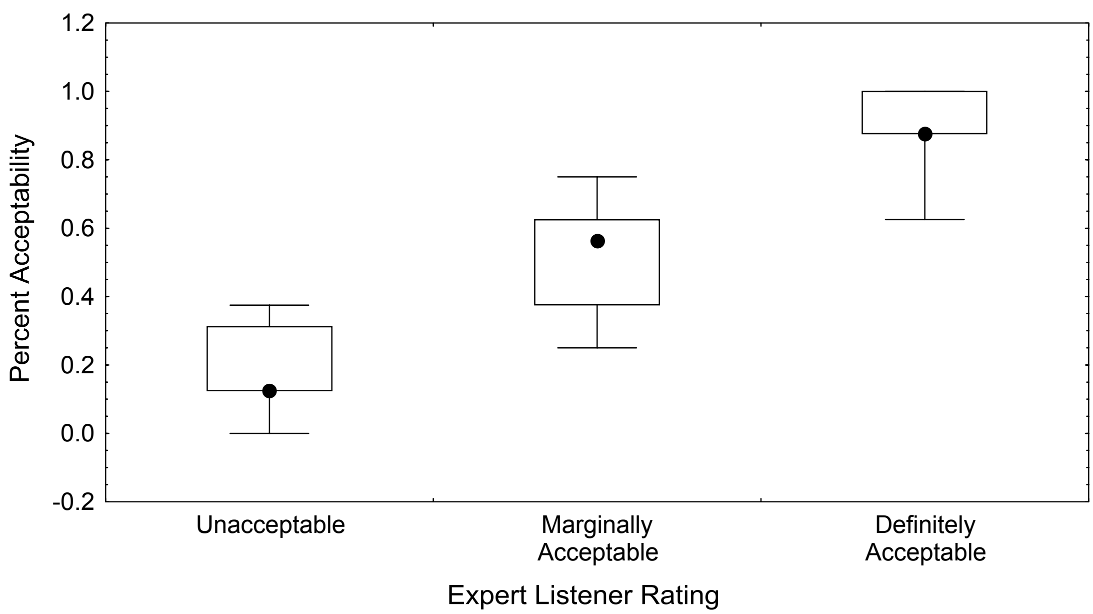


Figure 8.26. Percent acceptability vs. expert listener rating (TAG 1).

The Pearson product-moment correlation coefficients between MOS and uplink and downlink percent acceptability were 0.90 and 0.87, respectively, showing a strong linear relationship between these measures, as would be expected. The Pearson product-moment correlation coefficients between MOS and uplink and downlink expert listener ratings were 0.87 and 0.92, respectively, indicating a strong linear relationship between these measures. Expert listener ratings were also highly correlated with percent acceptability with Pearson product-moment correlation coefficients of 0.89 and 0.88 for the uplink and downlink, respectively.

8.6.4 Voice Quality Handoff Measurements

Continuous voice recordings were made as the mobile unit traveled along routes through handoff areas. While the measurement van was in motion, an audio source tape was transmitted over either the uplink or downlink. (Uplink and downlink voice recordings were made during separate runs.) The source tape consisted of Harvard sentences and was played continuously as the measurement van traveled along each route. The received voice transmissions were recorded on digital audio tape at the receiver for either the uplink or downlink. Continuous voice recordings were made along the route until the call was finally dropped. The routes were selected according to previous tests at the BITB. One route was driven along Broadway, at a vehicular speed of 30 mph. The second route was driven along Foothills Parkway, at a vehicular speed of 60 mph. Six measurement runs were conducted along each route. Three measurement runs were made with the measurement van traveling southward along the route: one for collecting a voice recording on the uplink, one for collecting a voice recording on the downlink, and one for recording downlink RSS and BER. The three other runs collected the same data but for the measurement van traveling northward along the route. Voice quality was assessed using the expert listener methodology described in Section 3.6.3.

For the voice quality handoff testing, an expert listener rating was made for each 4-s period of the continuous voice recordings taken along a measurement route. In general, voice quality was good throughout most of the handoff testing. The handoffs were distinguishable to the expert listener and were characterized by brief periods of unacceptable voice quality.

8.7. Manufacturer's Statement

The statement provided by Omnipoint Corporation is included in this section. This statement is identical to that given in [7], except for some minor editorial changes.

Omnipoint Corporation would like to acknowledge the efforts of all TAG 1 members and supporters in the successful completion of the Composite CDMA/TDMA technology field trial in Boulder. Equipment was supplied to demonstrate the Composite CDMA/TDMA PCS air interface in the BITB as part of the standardization requirements of the JTC.

The TAG 1 technology was the only PCS technology to demonstrate both high-tier (macrocell) and low-tier (microcell) performance and capability. The low-tier field testing was conducted with the same equipment as that used for the high-tier field testing. The TAG 1 technology was the only PCS technology to field its equipment outdoors (in weatherproof enclosures) for high-tier testing, taking advantage of its small size.

The TAG 1 composite CDMA/TDMA system performed quite well as Section 8 of this report shows. The system demonstrated excellent voice quality and good coverage with very low base station transmit power: 10-25% of the transmit power used by the other high-tier PCS technologies during the JTC PCS technology field trials. The TAG 1 field trial also demonstrated deployment flexibility for fielding the same equipment in different environments (i.e., microcell and macrocell).

The TAG 1 equipment fielded in the BITB was an early prototype system (Version 2.03a) and the BITB did not allow for optimizing system performance through cell site placement or antenna configurations. As can be noted from Section 8.6 of this report, voice quality was very good. Subsequent equipment development and commercially available equipment have improved receiver sensitivity, receiver selectivity, and greatly enhanced handoff algorithms. These system enhancements would improve coverage, interference rejection, and handoff performance as seen at the BITB, consequently overall system performance would be even better.

Note that the point-to-point microwave T1 link between the GMM and WCO sites at the BITB used a 2.4-GHz system operating in an unlicensed band. For future reference, Omnipoint would strongly urge all standards bodies to implement tests using backhaul from the base stations to the switch that is protected from any interference. This unlicensed band is particularly prone to interference on an episodic basis. Thus, it is possible that the results of all TAG groups using this link could have been susceptible to unmeasureable interference. Use of licensed frequencies in the future would eliminate (or greatly reduce) this susceptibility.

TAG 1 would like to thank U S West Advanced Technologies for making the BITB facilities available for these tests. Omnipoint sincerely appreciates the efforts of the U S West Advanced Technologies team (J. Corliss, V. Jevremovic, M. Owens, and J. Matthews) for the long hours and dedication in making the field trial a success. Omnipoint would also like to thank the ITS team (R. Sanchez, J. Mastrangelo, and J. Wepman) for its participation as the independent observer collecting data and monitoring the tests.

9. SUMMARY

Draft standards for six air-interface technologies for licensed PCS were developed by the Joint Technical Committee on Wireles Access (JTC). These draft standards were then forwarded to the American National Standards Institute (ANSI) to be processed for acceptance as formal standards. The six air-interface technologies include the IS-95 based CDMA, IS-136-based TDMA, personal access communication system (PACS), PCS 1900, Omnipoint TDMA/CDMA, and Wideband CDMA technologies.

Technology field trials for the six air-interface technologies were performed at the U S West Boulder Industry Test Bed (BITB) in cooperation with the JTC. The purpose of the field trials was to 1) demonstrate the performance of the air interface for each technology and 2) to fulfill the JTC requirement that each technology undergo a technology field trial before being forwarded to the ANSI.

Both high-tier and low-tier systems were tested in the JTC PCS technology field trials. The same configuration (cell site layout, antenna type, and antenna orientation) was used for all of the systems tested as high-tier systems. Similarly, another configuration was used for all systems tested as low-tier systems. These configurations were fixed throughout the duration of the field trials and did not vary from one technology to another. This provided a common environment for testing. It did not, however, provide an opportunity for optimizing the performance of each technology. Field testing for all six of the air-interface technologies typically consisted of four general types: area coverage testing, handoff testing, interference testing, and voice quality testing.

While, in general, the same fundamental types of measurements were made for each technology, some variations in the types of measurements are evident, due to differences between each technology. Also, because each technology was different and the mechanisms for reporting data were different, the reported data is sometimes given in different formats. Differences also existed in what types of data were available at the uplink and downlink for the different technologies.

This report describes the cell site configurations, the system configurations, the types of measurements performed, and the results of the analyses of the measured data taken during the six JTC technology field trials performed at the U S West Boulder Industry Test Bed. The report is intended to be an easily accessible reference that represents a consolidation of the six individual JTC reports written for each of the six technology field trials. The original JTC reports present both statistical analyses of the data and maps showing the data as a function of geographical location. In this report, to provide a more concise document, only the statistical analyses of the data are presented. More detailed information about each one of the field trials is available in the individual test reports submitted to the JTC for each air-interface technology [1, 2, and 4-7]. In both the original JTC reports and in this report, no comparison of the different technologies and no comparison of the performance of the different technologies during the field trials is made.

10. REFERENCES

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