Wireless Loop Telephone Termination

The last few hundred feet of telephone system wiring may be the most expensive. The authors describe the design and first field trials of a TDMA wireless system which links telephone subscribers to a radio port terminus of the telephone system.

A. J. Dagen
S. Akinsola
C. Banerjee
A. Iskandar
E. Hirsch
A. Kolodzinski
G. Nease
J. Vancraeynest
NYNEX Science and Technology, Inc.
White Plains, New York

In this paper we summarize the architecture and the experimental findings of the NYNEX Fixed Wireless Loop trial in Brooklyn, New York. Ten telephone subscriber volunteers for the trial were taken from a representative group of potential customers from the general public who are presently customers of regular telephone service in order that we might gauge customer satisfaction of this telephone subsystem. They were given equipment permitting telephone calls and data transfer using TDMA radio links between Subscriber Units (SUs) located in the home and a Radio Port (RP) centrally located in the block.

We will show values of radio link parameters such as Word Error Rate, Received Signal Strength Intensity (RSSI), and a technology dependent metric for quality measurements, for fixed links to both customer and other locations in the area. These parameters, gathered through a remote monitoring and control system permit correlation to perception of service as measured in the laboratory and will be used in conjunction with customer feedback to better gauge the applicability of this particular wireless technology for wireless loop access. Finally, we will describe the efficacy of data transfer over these links.

The use of radio links to replace the last few hundred feet of the telephone loop, in particular the "drop portion" which is the last connection between the telephone system and the subscriber has been proposed to simplify the distribution of the infrastructure and the activation or changes of customers' services, and to alleviate the costs and disruptions associated with installing and maintaining those portions of the outside plant situated on private property or in other relatively inaccessible areas. We are conducting such a "Fixed Wireless Loop Access" trial in Brooklyn, under the auspices of an FCC Experimental License (Call Sign KF2XEG), in the Emerging Technologies Band (1850-1990 MHz). Ten trial customers have been given equipment permitting telephone calls using radio links between Subscriber Units (SUs) located in the home and a Radio Port (RP) centrally located in the block. These links, which when deployed will be transparent to the customer, have been shown to support standard voice and data services.

The radio links are based on the Bell Communications Research Time Division Multiple Access (TDMA) technology. Radio link and performance metrics, such as Word Error Rate (WER), Received Signal Strength Intensity (RSSI), quality metric, on/off hook indicator and other call statistics and error diagnostic messages, are gathered through a remote monitoring and control system, the Wireless Loop Monitoring And Control System (WILMACS). This system also can adjust operating conditions, such as changing the carrier frequency or shifting the SUs between totally wired and wireless loops, facilitating more effective examination of the feedback forms that the trial customers fill out for every call.

This paper summarizes the results of the trial to date. Radio link parameters are examined for the fixed links to the customer locations and to other locations on the block for both fixed and mobile links. These measurements are correlated to perception of service as determined in the laboratory. Other laboratory measurements, including interference rejection capabilities which determine system parameters such as frequency reuse and the efficacy of data links are also described.

Setup

During this evaluation portion of the trial, the RP is mounted on a telephone pole in the center, and along the spine, of a block with dimensions 650 feet by 234 feet [Figure 1]. The RP antenna height is 15 feet at the base of the two diversity antennas. Each antenna is a linearly polarized omnidirectional antenna with 9 dBi gain, oriented vertically upward and separated from each other by 1.2 m in a plane perpendicular to the long axis of the block. The enclosed RP and its antennae at its trial location is shown in Figure 2. For this phase of the trial, the RP transmits continuously with a carrier frequency 1940.5 MHz, and its peak transmit power of +24 dBm is equivalent to, after adjustment for the antenna gain and 1 dB cable loss, a nominal peak +32 dBm Effective Isotropic Radiated Power (EIRP). The RP contains two separate receivers for each antenna, with diversity selection based on the highest signal quality measurement of the two antennas. The transmit section shares one of the antennas through a diplexer.

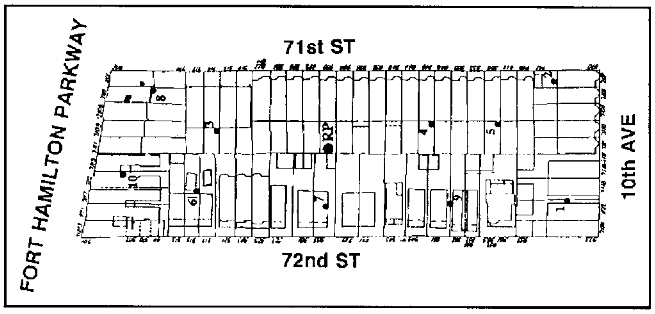

Figure 1. Map of Brooklyn trial block with RP location and customer locations.

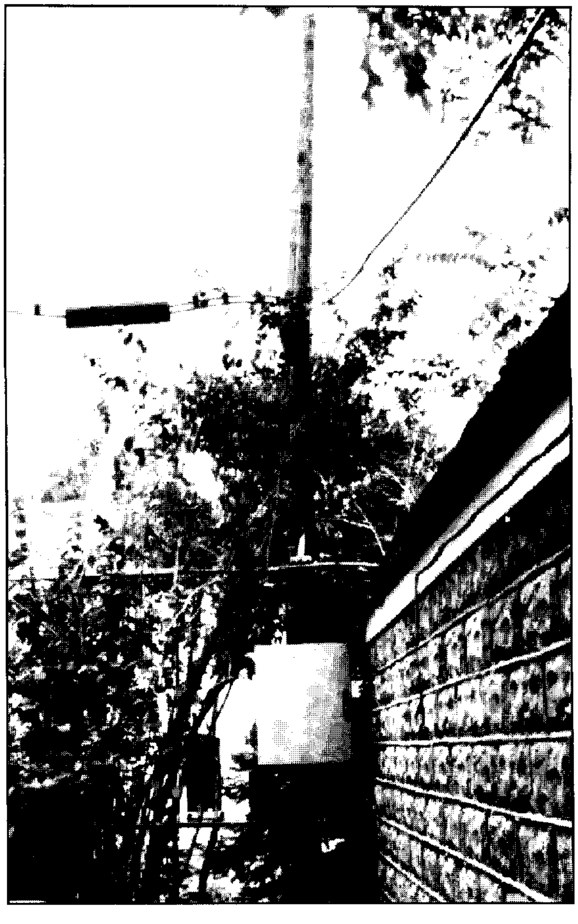

Figure 2. RP (enclosed in box) and antennae at trial location.

The SU transmits only during its time slot at a carrier frequency fixed, for this phase of the trial, at 1870.5 MHz with peak transmit power +21 dBm. Each SU is powered from a 14 VDC external power supply plugged into the customer's 110 VAC/60 Hz outlet. Power consumption is approximately 21 W on-hook and 24 W off-hook. Each SU connects to two linearly polarized omnidirectional diversity antennas with 2 dBi elevation gain over 6.5 m of low loss coax cable. As will be described later, during this phase of the trial, SU antennae at two trial customer locations were changed to Yagi-Uda to provide more gain. The SU transmitter always uses the same antenna which it shares with the receive section through a transmit/receive RF switch. The SU antennas range in height from 3 to 6 m above the local ground elevation. They are all externally mounted, mostly on the side or rear of buildings. The RP-SU configurations are summarized in Figure 3. The SU capabilities are summarized in Figure 5. Pictures of each site and the area may be found in the references [1, 2].

Customer	SU#	time slot	SU Antenna Height (m)	SU Antenna Type	Distance to RP (m)	LOS to RP
1	4	8	3.5	Yagi-Uda	105	no
2	10	4	3	Yagi-Uda	102	no
3	11	2	3.5	Omni (2dBi)	69	yes
4	1	7	6	Omni (2dBi)	47	yes
5	7	3	3	Omni (2dBi)	81	yes
6	8	0	3	Omni (2dBi)	58	no
7	9	1	3.5	Omni (2dBi)	31	no
8	6	5	6	Omni (2dBi)	79	no
9	3	6	3.5	Omni (2dBi)	57	no
10	5	9	3.5	Omni (2dBi)	31	no

Figure 3. Summary of Extant RP-SU Configuration for Fixed Trial Customer Phase

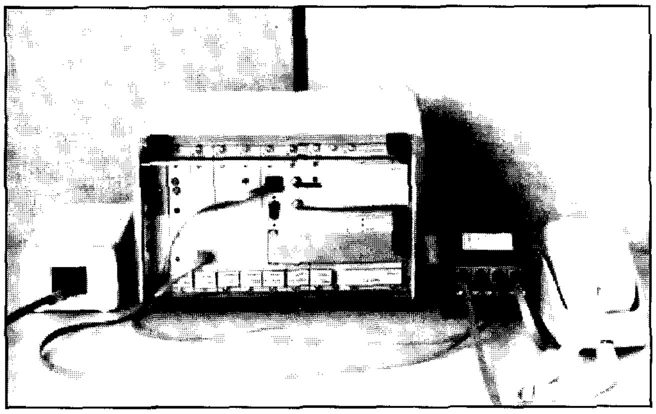

Figure 4. SU connected to a customer phone. Box in middle permits remote "double blind" switching between the standard wired connection and one of two (only one currently in use) "wireless" links to the RP

Antenna height:	3 to 6 meters above local ground
Antennae:	Omidirectional (linear polarization) -2 dBi gain. 5 element Yagi-Uda at two locations -11 dBi gain. All externally mounted.
Transmit frequency:	1870.5 MHz
Peak transmit power:	21 dBm (32 dBm ERP)
Architecture:	TX uses same antenna shared with RX by RF switch
Antenna selection:	Based on highest signal quality measurement
Sensitivity (WER = 0.01):	~-98 dBm (unit-dependent)
Wideband co-channel rejection capabilities (WER = 0.01):	-12 dB
C/I requirement (WER = 0.01):	22 dB

Figure 5. Summary of trial SU capabilities

The radio links are based on the Bellcore TDMA technology [3,4]. The RP communicates in full-duplex mode with 10 SUs simultaneously over one 1 MHz RF channel (500 kHz each direction). The RP capabilities and radio link characteristics are summarized in Figure 6. The 32 kbps Adaptive Differential Pulse Code Modulation (ADPCM) coding ensures high voice quality, low processing delay and support for fax and modem signals used on the wired PSTN. The 10 TDMA timeslots, each 200 microseconds long, are contained in a relatively short, low-delay 2 millisecond frame structure, obviating the need for echo cancelers. The error detection coding and small synchronization overhead and 9 bits used for out-of band signalling added to each time slot yield a total bit rate of 500 kbps. Error correction is not employed in order to minimize delay. Bad 2 ms frames are blanked out. The modulator generates digital QAM modulation with a symbol rate of 250 kbps and uses spectral shaping during transmitter turn-on and turn-off to reduce spectral spreading.

Antenna height:	15 feet at base two diversity antennae
Antennae:	Omidirectional (linear polarization) -9 dBi gain. Separated by 1.2 m.
Transmit frequency:	1940.5 MHz (continuous)
Peak transmit power:	24 dBm (32 dBm ERP)
Architecture:	Two separate receivers (for each antenna)
Antenna selection:	Based on highest signal quality measurement
Radio link:	Bellcore TDMA - 10 voice channels - full duplex
RF channel bandwith:	500 kHz (one way)
Modulatuion:	QAM (250 ksps)
Voice coding:	32 kbps ADPCM
Time slot:	200 μs
Frame structure:	2 ms
Echo cancellation:	None
Error correction:	None (frame-by-frame error detection)

Figure 6. Summary of trial RP capabilities and radio link characteristics.

Link and performance parameters as well as calling statistics and error messages, are acquired at each of the SUs and the RP, and transferred over a data link through a standard RS-232C serial interface to WILMACS, permitting real-time monitoring (and control) of the SUs and RP from centralized terminals at remote sites. The inside of the RP, including the local WILMACS data controller, is shown in Figure 7. The ten line interface modules each provide one physical analog voice frequency interface to the central office for each TDMA slot.

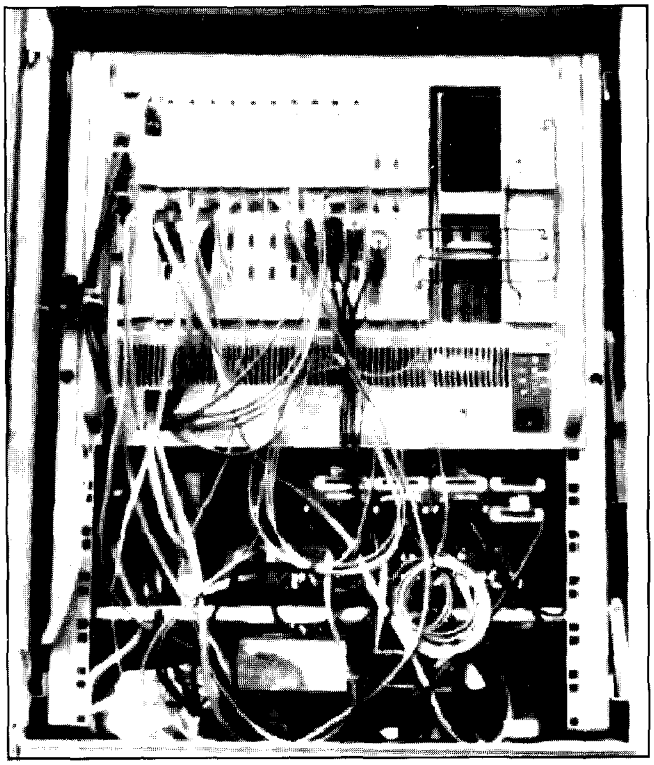

Figure 7. Detail of Radio Port showing all 10 channel cards and WILMACS monitoring equipment.

The link performance parameters, collected at both the RP and SU, are the

a) WER - sampled every 500 ms, representing the average over the previous 250 frames;
b) RSSI - 250 samples averaged over 500 ms;
c) Quality metrics at both antennas (250 samples averaged over 500 ms);
d) Instantaneous (each 500 ms) transmit power and RSSI and quality metrics (for each antenna).

The link performance data collected by WILMACS is summarized in Figure 8. At the RP, RF monitoring functions are implemented in the control processor common to all 10 channels (11th processor) and the WER monitoring functions are done on a per channel basis in the individual channel cards. A typical real-time display of the Brooklyn environment in the White Plains control center is shown in Figure 9. The quality metric is an indication of the eye opening of the signal as received from either diversity antenna and demodulated by the patented Bellcore carrier recovery/demodulation ICs [3]. At the subscriber unit, the signal quality metric is used to select the diversity antenna for each received frame. At the RP, the signal quality from each diversity antenna is compared to select the best signal at the outputs of the two diversity receivers/demodulators.

Each parameter sampled every 500 ms	
Radio Port channel cards:	WER - average over previous 250 frames
Radio Port 11th processor:	WER - average over previous 250 frames RSSI - average over previous 250 frames Quality metric - antenna 1: average over previous 250 frames Quality metric - antenna 2: average over previous 250 frames Number selections of each diversity antenna (250 max) Quality metric - antenna 1: value of metric in last frame Quality metric - antenna 2: value of metric in last frame Instantaneous transmit power of last frame Instantaneous RSSI of last frame received
Subscriber Unit:	WER - average over previous 250 frames RSSI - average over previous 250 frames Quality metric - antenna 1: average over previous 250 frames Quality metric - antenna 2: average over previous 250 frames Number selections of each diversity antenna (250 max) Quality metric - antenna 1: value of metric in last frame Quality metric - antenna 2: value of metric in last frame Instantaneous transmit power of last frame Instantaneous RSSI of last frame received

Figure 8. Link performance parameters collected by WILMACS.

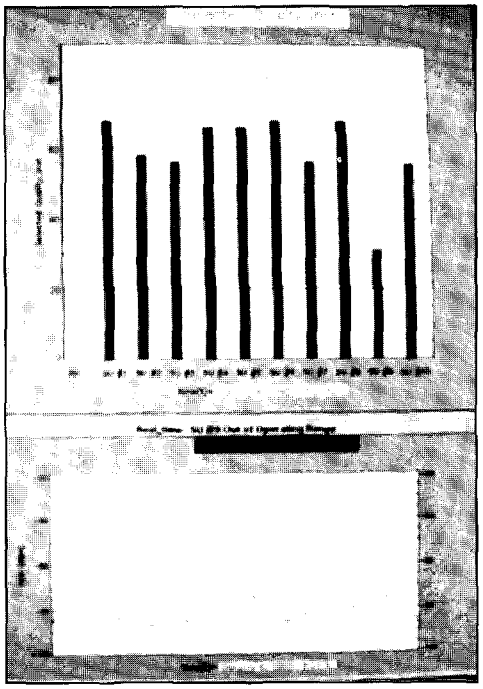

Figure 9. Typical real-time display of the Brooklyn environment at WILMACS unit in White Plains. Bars show maximum value of instantaneous quality metric measured at that time for each SU and lower graph shows RSSI versus time measured at SU with quality metric lower than threshold.

Parameters such as power consumption, on/off hook indication, number of times each diversity antenna is used, and calling statistics are measured only at the individual SUs. Uploading of data and downloading of control messages from the remote test site to each of the SUs is achieved through the RP, with messages to and from the SUs transferred through a telemetry link. The telemetry link permits more than 24 kbits of data to be transferred per second however, because the link is in-band, SUs are not able to transfer data during a call. Each SU is therefore equipped with a disk drive, permitting the storage of up to 46 hours of data for each customer.

Laboratory Test Results

Laboratory tests were conducted to test aspects of transparency of the radio link to network services and to obtain results that will be necessary in planning the system. Full details of the following and other tests may be found in the fifth through ninth NYNEX Periodic FCC Experimental License Reports.

The Word Error Rate (WER) was measured as a function of Received Signal Level (RSL) in the absence of flat or frequency selective fading and with antenna diversity disabled [5]. An informal subjective evaluation of audio quality at different Received Signal Levels was also conducted. Good or excellent (wireline) subjective voice quality was obtained between signal levels of -15 dBm to -101 dBm. At the lower RSL, the WER was 0.01. Signal quality dropped precipitously below the RSL of -101 dBm.

The transparency of the radio link to network services was further tested by experiments testing voice band modem communications over the wireless loop link at the standard speeds of 300, 1200, 2400, 4800 and 9600 bps [1]. Several faxes were also sent over the loop. Both tests were conducted in the indoor environment at a location with a good voice quality link. Faxes were sent using the CCITT Group III protocol at 9600 and 4800 bps. Fax transmissions at both rates were successful without falling back to lower bitrates because of the protocol's use of automatic retransmissions upon the detections of errors. The modems at both ends of the link continuously transmitted a standard message which was compared with the received message.

The tests showed that modems are able to communicate with satisfactory performance at speeds up to 2400 bps. The higher speed modems were able to connect, but the high error rates obtained at the higher rate precluded useful transmissions. This is consistent with previous findings that modem speeds of 4800 bps and higher are not expected to work over a 32 kbps ADPCM vocoder without error correction [6]. The need for higher link margins than are required for voice communications even for 2400 bps communications indicates the possible need for a separate modem/fax/data interface at the SUs and RPs.

The co-channel rejection capabilities of a radio technology play a fundamental role in determining the frequency reuse requirements of the system [7]. The wideband co-channel rejection capabilities of this TDMA technology were tested using an interferer resembling an actual RP for use in determining the reuse requirements in a single technology service environment. The interferer was an RF signal centered at the downlink frequency and QAM modulated at 250 ksymbols/s. A pseudo-random data stream was pre-shaped before the modulator to create an interferer with RF spectral and temporal characteristics similar to the RP signal. The Word Error Rate was set at the lower level for excellent voice communications.

The down-link power level was set to 6 dB above the downlink RF level from the RP, resulting in a 0.01 WER. The RF level of the interferer into the SU was then adjusted until the WER returned to 0.01, the level defined as the co-channel rejection. The result was -12 dB, consistent with other tests and simulations [8]. A factor, dependent on the desired grade of availability, must be added to this static carrier to interference ratio (C/I) result to set the C/I criterion necessary for determining system frequency reuse requirements. Previous results in this environment and a suburban environment [5, 9], indicate that this factor would typically be about 10 dB, resulting in a C/I requirement of about 22 dB. The adjusted C/I value in conjunction with previous propagation results provide the local frequency reuse requirements [10]. The higher grade of availability required for an application such as wireless loop access dictates a higher C/I requirement with concomitant effects on frequency reuse and overall system spectrum efficiency.

Field Results

The field tests to date have been divided into 2 phases:

1) those related to testing the technology over the entire coverage area of previous propagation measurements [5, 9] and

2) those related to testing the technology in trial customer homes.

These trial customers have been provided with standard telephone sets and send back feed back forms after each of their calls over the wireless loop. Figure [1] shows the trial customer locations and Figure 3 summarizes the RP-SU configuration. The parameters measured and the sampling rates, as described in the Setup section, are the same for both phases of the field tests.

The wide area coverage measurements were taken with the RP on the curb on 72 Street directly in line with its volunteer-phase present backyard set-up location. Other factors were the same, although an omnidirectional 2 dBi antenna was used for the RP and the RP transmit power for most locations was 16 dBm. SU antenna heights were 6 and 15 feet. The SU was located at sites at which it would most likely be deployed during a potential customer service as well as at street side locations in order to obtain a more comprehensive description of the environment. Acceptable coverage was found in the range of a few hundred feet, with the maximum acceptable range being a little over 1000 feet. Full details are in [11].

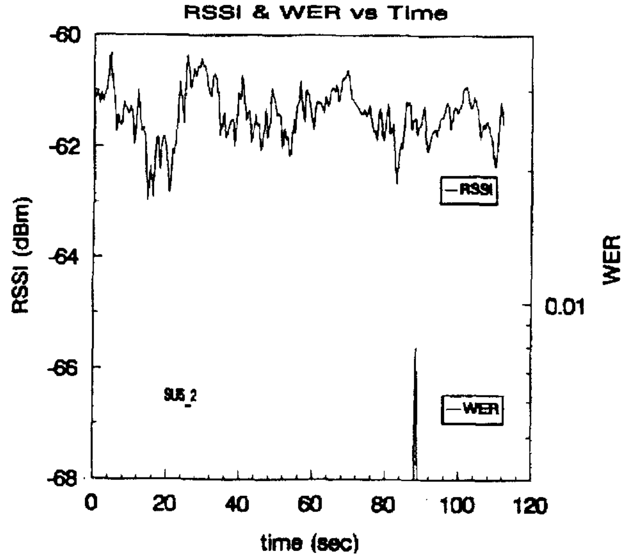

Figure 10. Averaged RSSI and WER versus time at a (non-trial customer) subscriber unit location (RP at curb; good voice quality, LOS).

A typical measurement of average RSSI (the average of 250 frames of the 500 ms measurement period) versus WER (similarly averaged) versus time is shown in Figure 10. As noted in [11], where several similar graphs for different locations were examined, WER generally approaches 1 for values of about -95 dBm and generally tracks the RSSI, with increases in WER resulting from dips in RSSI and decreases in WER occurring when RSSI increases. This is consistent with the studies in [5], where voice quality was poor below a value around -100 dBm without multipath and about -95 dBm with simulated multipath using actual previous Brooklyn measurements. These results are more vividly illustrated in Figure 11, which shows the WER as a function of RSSI for 45 measurements. The WER breaks away from 1 at a value of about -100 dBm, approaching a value of 0.01 at about -90 dBm, a drop off not as steep as seen in the simulations of [5] and probably attributable to the selected fading of the actual environment as opposed to the simulations. The higher WER samples at -60 to -50 dBm are due to overload of the SU receiver.

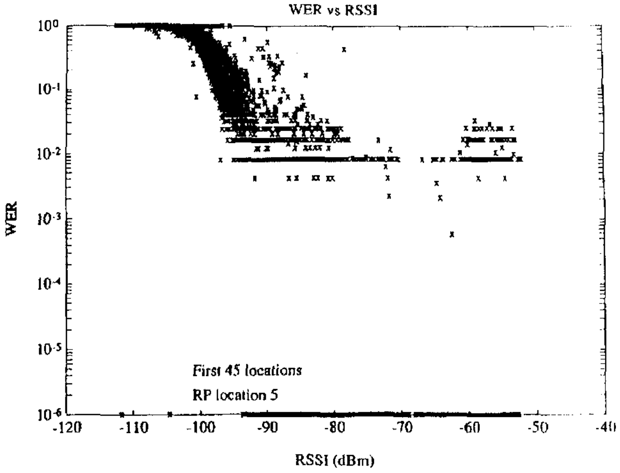

Figure 11. WER versus average RSSI for 45 subscriber unit locations (on plot indicates).

The instantaneous RSSI (the actual value at the end of the sampled 500 ms period) versus the value of the two quality metrics, similarly measured, is shown in Figure 12. It is this higher value of the quality metric which is used to select the antennas used to receive the timeslot from the RP. Several measurements showed [11] that the selected quality metric is high for values of RSSI above approximately -95 to -102 dBm, with neither antenna showing a sufficient quality metric for values below those values. The dependence of good voice quality and low WER on the measured RSSI alone - and not on the location as would be expected if multipath fading affected quality - indicate that diversity provides excellent protection against fades. The quality metric is shown in Figure 13 in another way by displaying the percent of the 250 possible times with the 500 ms sample period a particular antenna (#2) was chosen against the difference of the total quality of antenna #2 minus that of antenna #1 for that period. Total quality refers to the measurement of the average quality over the period before division by the 250 samples, as opposed to the instantaneous quality measurement. It clearly shows that the antenna is chosen more often as its total quality metric increases over that of the total quality metric of the other antenna. The low, but finite, chances of selection of antenna #2 when the abscissa is negative reflects the variation of the relative values of the quality metrics within the 250 samples.

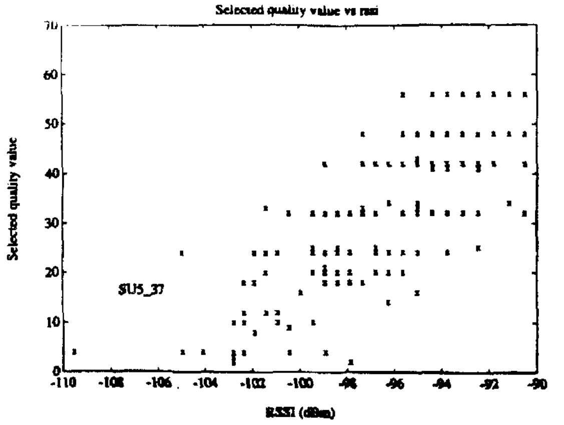

Figure 12. Selected quality metric versus RSSI

Measurements taken for the SU in motion are in [11]. Measurements taken over a half hour period - including those taken during a call during the trial customer phase of the tests - are in [12].

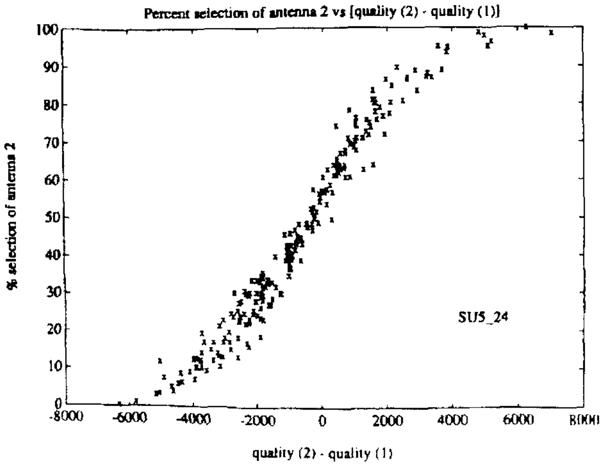

Figure 13. Percent antenna selection versus antenna signal quality difference.

The SUs were also initially connected to the two diversity 2 dBi elevation gain antennas during the second fixed phase of the field tests. Measurements at customer 1 and customer 2 (timeslots 8 and 4, respectively), located the furthest from the RP and obstructed by multi-story brick buildings however, indicated RSSI measurements in the vicinity of -90 dBm during non-fading periods. In order to rectify this inadequate RF link margin for reliable operation and good voice quality, directional 5-element Yagi-Uda antennae were placed at those locations and aimed to maximize the down-link signal strength measurement. The 11 dBi gain of theYagi-Uda antenna exceeds the gain of the original antenna by 9 dB. The result was as to be expected. The RSSI at customer 1 improved by approximately 6 dB in the down-link and 10. We attribute the deviation of these values from the 9 dB increase in antenna gain to imperfect antenna aiming as well as the effects of the microcellular propagation environment on the effectiveness of a directional antenna [9].

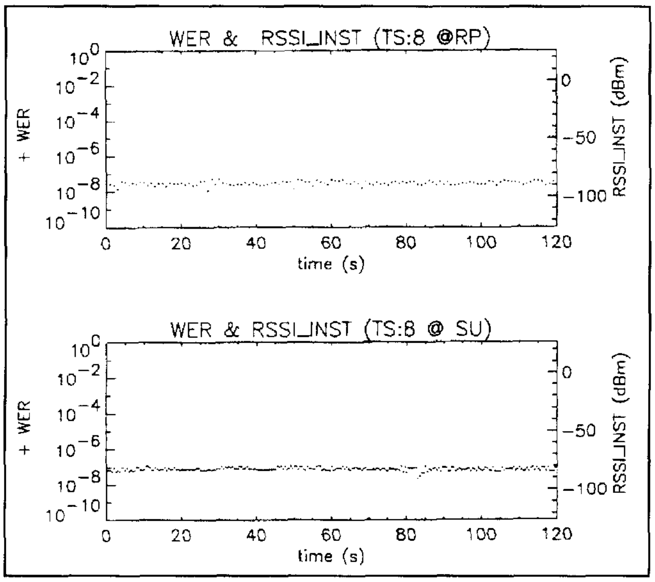

Figure 14a. RSSI and WER for timeslot 8 (customer 1).

A sample two minutes of WER and instantaneously measured RSSI (every 500 ms) for trial customer 1, timeslot 8 and customer 2, timeslot 4, taken during the second phase of the field tests with t of Figure 14 from the other fixed trial customer locations, and with the initial 2 dBi antennae, are in [13] and reproduced in Figure 15. The low values of WER at that location are indicative of the excellent service the trial customer has experienced, as indicated in feedback forms. Similar high quality service, indicating service at least as good as wireline, has been reported at the other nine locations.

A comparison of uplink RSSI for customer 9 obtained during a steady downpour and another during a dry day three days later is shown in Figure 16. Though at 2 GHz Boithias [14] predicts less than 0.02 dB/km attenuation due to rain, the increased path loss of 5 dB during precipitation may be due to other effects such as decreased antenna efficiency resulting from the film of water accumulating on its surface during rain.

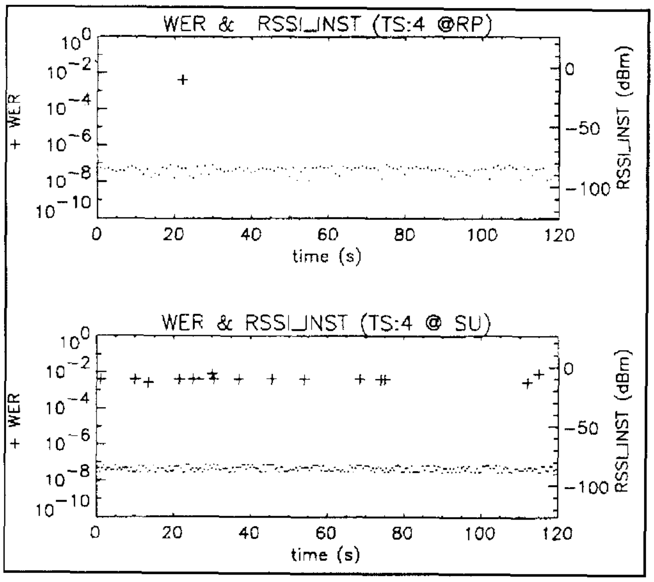

Figure 14b. RSSI and WER for timeslot 4 (customer 2).

Figure 15 (a-g): RSSI and WER (measured at same time as Figure 10) for remaining customers (except timeslot 3).

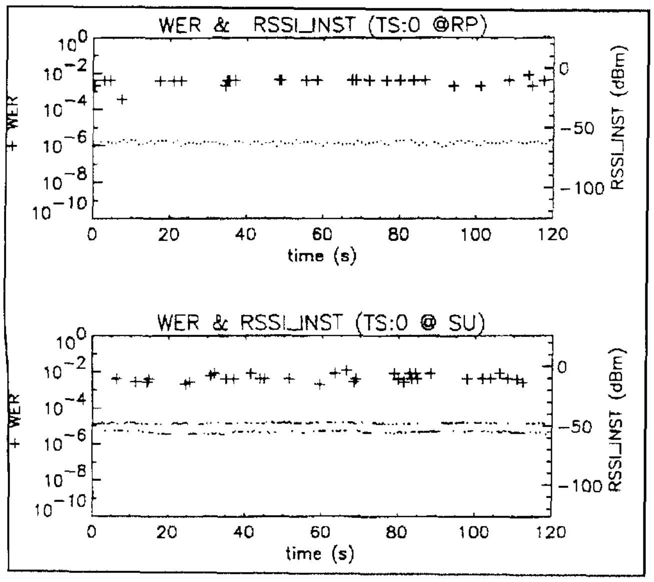

Figure 15a

Further detailed studies of the radio links, correlated with customer feedback forms are planned for future studies. These studies will also include “double blind” tests in which the trial customers will be commenting on links that will be switched between wireless and totally wired connections without their knowledge.

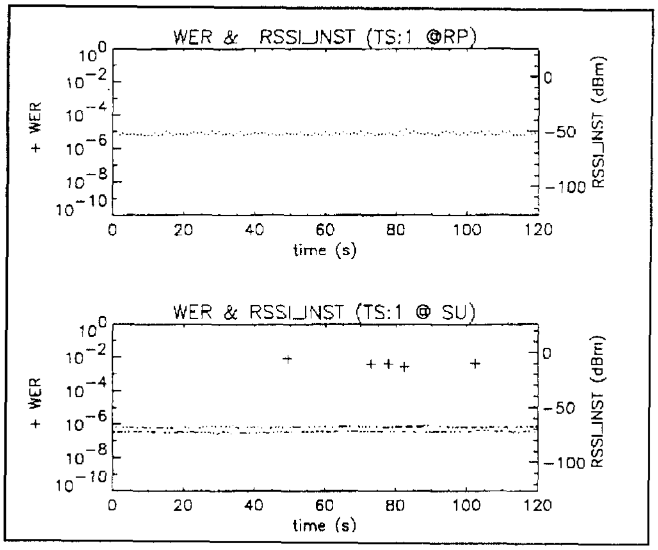

Figure 15b

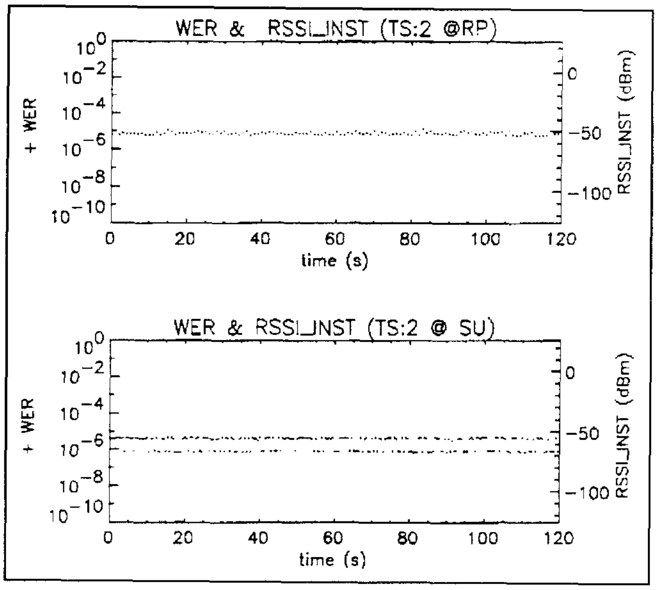

Figure 15c

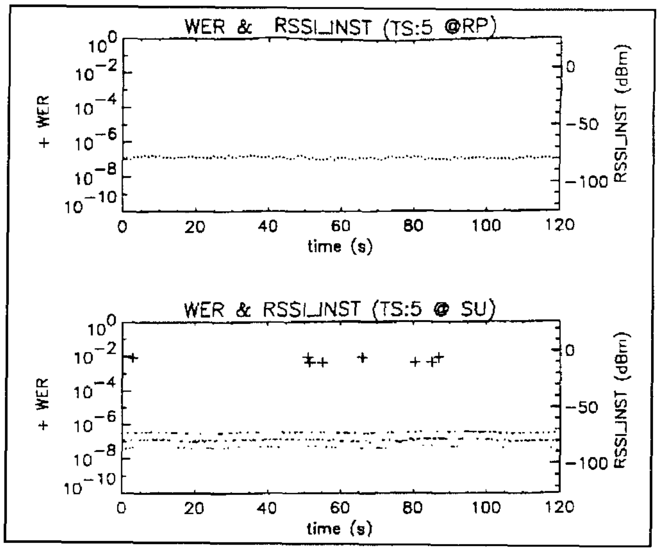

Figure 15d

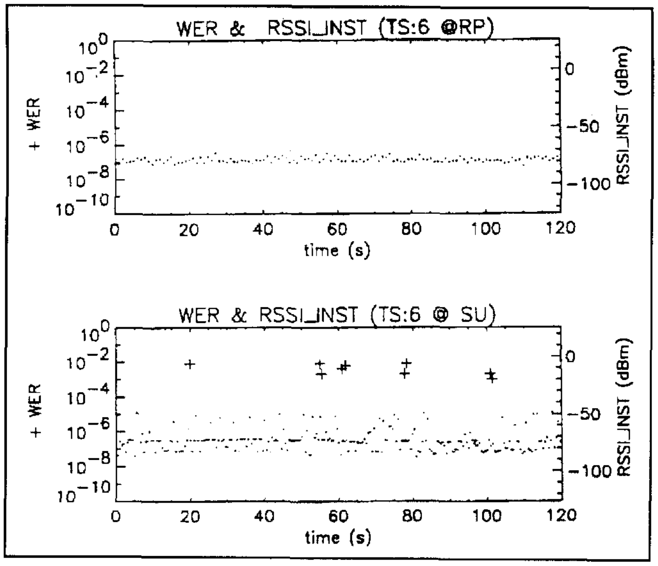

Figure 15e

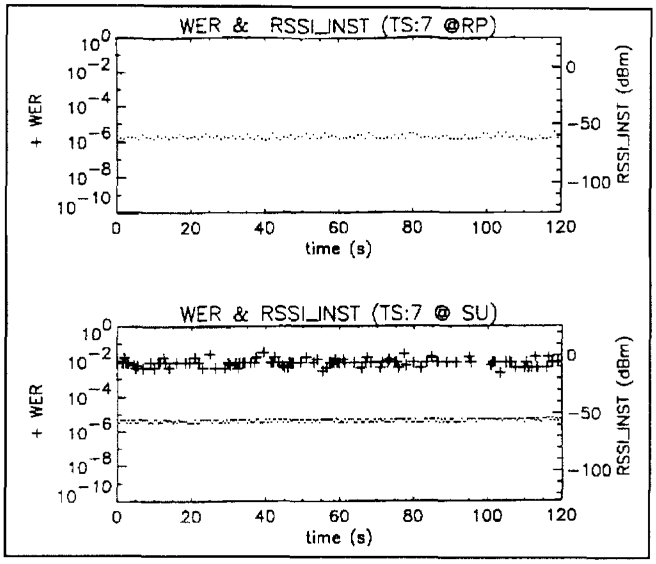

Figure 15f

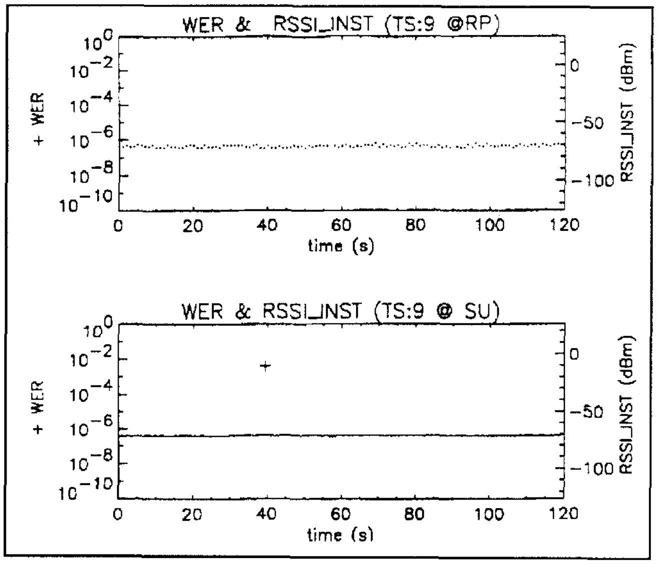

Figure 15g

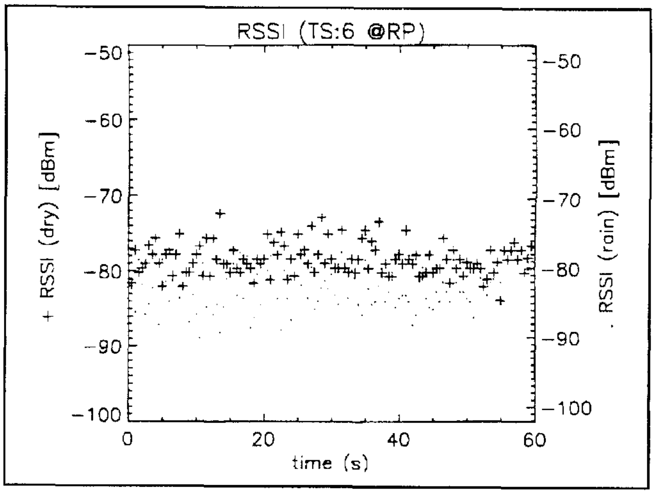

Figure 16: Comparison of uplink RSSI for customer 9 (timeslot 6) between rain and dry conditions.

Generally, the volunteers have evaluated the service as being at least as good as wireline, though more tests are planned to calibrate customer perception through "double blind" tests and to define better the radio link environment under various operating parameters.

Acknowledgment

We thank Dr. T. Walzman, J. Waldhuter and S. Solcz for their continued support of this project.

References

[1] NYNEX Seventh FCC Experimental License Periodic Progress Report, October 1, 1992

[2] NYNEX Ninth FCC Experimental License Periodic Progress Report, May 12, 1993

[3] Generic Framework Criteria for Universal Digital Personal Communications Systems (PCS), FA-NWT-001013, Issue 2, Bellcore, 12/90

[4] Generic Framework Criteria for Version 1.0 Wireless Access Communications Systems (WACS), FA-NWT-001318, Issue 1, Bellcore, 6/92

[5] NYNEX Fifth FCC Experimental License Periodic Progress Report, April, 1992

[6] Performance of voiceband data modems through 64-, 32-, and 16-kbit/s voice codecs, CCITT Study Group XV ad hoc group on 16-kbit/s speech coding, Contribution No. AH.90-D.2, COMSAT, June 1990

[7] Mobile Cellular Telecommunications Systems, W.C.Y. Lee, McGraw Hill Co., 1989, Ch. 1-2

[8] A. Afrashteh, N. Sollenberger, D. Chukurov; 41st IEEE Vehicu-

lar Technology Society Conference, St. Louis, Mo., IEEE VTS-91

[9] NYNEX Fourth FCC Experimental License Periodic Progress Report, December 20, 1991

[10] A. J. Dagen, A. Iskandar, C. Banerjee, G. Nease, J. Vancraeynest, N. Chan, and P. Campanella; Third IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Boston, Mass., Oct. 19-21, 1992

[11] NYNEX Sixth FCC Experimental License Periodic Progress Report, June 30, 1992

[12] NYNEX Eighth FCC Experimental License Periodic Progress Report, January 22, 1993

[13] NYNEX Eleventh FCC Experimental License Periodic Progress Report, November 19, 1993

[14] Radio Wave Propagation, L. Boithias, McGraw Hill Co., 1987

[15] A. J. Dagen, S. Akinsola, C. Banerjee, A. Iskandar, E. Hirsch, A. Kolodzinski, G. Nease and J. Vancraeynest; "Initial results of first customer field trial of TDMA wireless loop feasibility models in an urban environment;" Fourth International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC93) Yokohama, Japan, September 8-11, 1993