Radio Propagation Characteristics for Line-of-Sight Microcellular and Personal Communications

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***Abstract*—To acquire a knowledge of radio propagation characteristics in the microcellular environments for personal communications services (PCS), a comprehensive measurement program was conducted by Telesis Technologies Laboratory (TTL) in the San Francisco Bay area using three base station antenna heights of 3.2 m, 8.7 m, and 13.4 m and two frequencies at 900 MHz and 1900 MHz. Five test settings were chosen in urban, suburban, and rural areas in order to study propagation in a variety of environments. This paper reports the LOS measurements in different environments, all of which show variations of signal strength with distance that have distinct near and far regions separated by a break point. It was also found that the location of the break point for different frequencies and antenna heights can be calculated based on first Fresnel zone clearance. The regression analysis reveals a slope that is less than two before the break point, while it is greater than two after the break point. This break distance can be used to define the size of microcell and to design for fast hand-off. Beyond the first Fresnel zone break distance the base station antenna height gain was observed to approximately follow the square power law of antenna height.**

I. Introduction

FUTURE personal communications services (PCS) will rely on the microcellular concept to make efficient use of the scarce frequency spectrum, and to provide inexpensive infrastructure and small size subscriber units [1]–[6]. This concept involves relatively short radio paths (on the order of 200 m to 1000 m), low base station antennas (about the same height as lamp posts), and low transmitting powers (typically on the order of 10 mW). Over a relatively short propagation path, it is often possible to arrange the radio link between the transmitter and receiver to be a clear line-of-sight (LOS) path, so that the microcell can operate in a Rician channel, which has significantly less multipath fading than the Rayleigh channel of conventional cellular systems. The relatively low antenna can be located above the local vehicular traffic but below the surrounding buildings. This benefits the microcellular systems in two ways. First, the shadow fading due to the local traffic can be eliminated, and second the radio signal can be confined and directed into a limited size microcell. Moreover, the lower microcellular base station antenna limits excess signal delay spread due to the multipath reflection, which can cause intersymbol interference (ISI) in digital radio systems, since the distant reflectors are blocked [7].

Perceiving the importance of radio propagation characteristics in such a small cell environment for frequency allocation and for future system implementation [1], a comprehensive radio propagation measurement program was conducted by Telesis Technologies Laboratory (TTL) in the San Francisco Bay area. Measurements were performed using two of the potential PCS frequency bands (900 MHz and 1900 MHz), in carefully chosen urban, suburban, and rural environments. Because the base station antenna height will be an important parameter in PCS system design to assure signal coverage and to prevent interference, three potential PCS antenna heights of 3.2 m, 8.7 m, and 13.4 m were used. The mobile antenna was fixed at 1.6 m, which is considered to be typical PCS public use.

This paper discusses the measurements made on LOS paths. Measurements made on non-LOS paths are discussed in companion papers [8]–[10]. Rural LOS measurements served to validate the measurement systems and to test the applicability of a theoretical two-ray model. Alternatively, LOS measurements in urban and suburban areas are designed to study the channelling effects along the street where both the transmitting antenna and receiving antennas are located. For all environments, the variation of signal strength with distance on LOS paths was found to show distinct near and far regions. These regions are separated by a break point whose distance from the base station is equal to the maximum distance that has first Fresnel zone clearance. This distinction serves as the basis for a two segment regression fit to the LOS measurements, where one segment applies to the signal before the break point, and the second segment to the signal beyond it. These fits are characterized by a slope that is less than two before the break point, while it is greater than two after the break point. The break distance can therefore be used to define the size of the microcell. Results obtained for the three antenna heights are studied to determine

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the base station antenna height gain. Beyond the first Fresnel zone break distance, an antenna height gain was observed to vary approximately as the square of antenna height. For non-LOS paths, where propagation takes place over the rooftops of intervening buildings in suburban areas, or around street corners in urban areas, show much higher radio path loss, which is significantly affected by the height of surrounding buildings [8]–[10].

II. Measurement System

The measurements involve transmitting a continuous carrier wave from a stationary transmitting vehicle and sampling the envelope of the signal as a function of time in a mobile receiving vehicle. The measured signal, together with an accurate record of the mobile's position, are stored in the mobile for later processing.

A. System Description

The transmitting vehicle is a converted van fitted with a 14.5 m telescopic mast, as depicted in Fig. 1. The top of the mast permits the mounting of the biconical transmitting antenna. The bicnical antenna has a gain of -1.0 dBi at 800 MHz and a gain of 1.6 dBi at 1850 MHz. It is both omnidirectional (in azimuth) and vertically polarized. The receiving vehicle, which contains the receiver and position location equipment, is a station wagon chosen to give an antenna height of 1.6 m. A navigation system was installed in the vehicle providing both longitude and latitude information along with distance travelled, speed, and heading. The receiver comprises of a band pass filter, a low noise amplifier and a spectrum analyzer. The measurement system makes use of a spectrum analyzer in two ways. First, the analyzer samples the video signal at 1 kHz, and from these samples it determines the average signal over one-second intervals. In all but the system verification tests, the receiving vehicle was driven at approximately 30 mph, so that the one second average supplied by the spectrum analyzer corresponds to spatial average over approximately 13.4 m. Second, the video signal output is sampled at 48 kHz by a digital audio tape (DAT) recorder. The fast sampling DAT data is primarily used for the analysis of severe signal variations for a range close to the transmitting antenna and for the study of fast fading statistics.

The vehicles, at the start of the test, were placed back to back, as shown in Fig. 1. This position is taken as the reference distance of 0 m. At this reference distance the receiving antenna is horizontally displaced from the transmitting antenna by a separation of 3.18 m. The line-of-sight distance between the transmitting and receiving antennas at the reference distance of 0 m is dependent on the transmitting antenna height. The initial distance between transmitting and receiving antennas is equal to 3.6 m, 7.8 m, and 12.2 m for the transmitting antenna heights of 3.2 m, 8.7 m, and 13.4 m, respectively.

B. System Verification

A rural site near the Sherman Island area was chosen for carrying out measurement system validation studies.

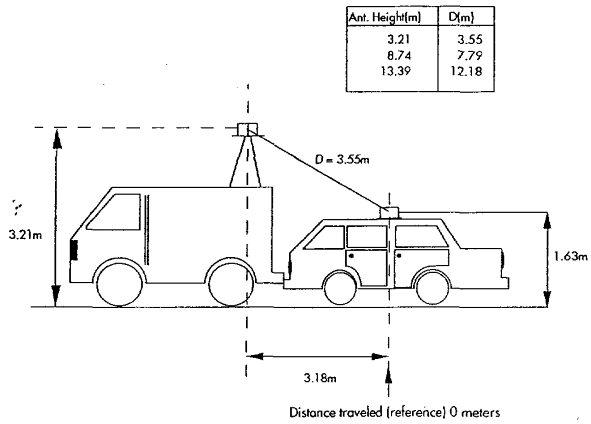

Fig. 1. Initial reference position for stationary transmitting van and mobile receiving van.

The area is very flat, there are no buildings, and little traffic is present. The vegetation consists entirely of low growing ground cover. Measurements made in this environment show only a small degree of multipath fading. To verify how the antenna patterns affect the path loss measurements, in addition to changing the frequency and transmitting antenna height, various combinations of biconical and dipole antennas were used for the transmitter and receiver.

Fig. 2 shows the one-second signal average obtained from measurements at 800 MHz for a transmitter height of 3.2 m when biconical antennas were used for both transmitter and receiver, and when dipole antennas were used. For these tests, the receiver vehicle was driven at 3 mph, so that the one second average covers a distance of 1.3 m. Both of the measurements curves in Fig. 2 represent absolute received power for 1 W input power to the transmitting antenna. Because each bicone has a gain of -1 dBi at 800 MHz, and each dipole has a gain of approximately 2.2 dBi, the received signal in the two cases should differ differ by 6.4 dB, as is seen to be the case in Fig. 2 for distances greater than 10 m. Except for this offset, the two curves are seen to agree closely for distances greater than 10 m including many minor variations. However, the differences in antenna pattern between the bicone and dipole antennas are responsible for a different signal variation for distances less than 10 m. This comparison implies that the system is accurately measuring environmental propagation effects at distances greater than 10 m.

As further validation, in Fig. 2 we have drawn the corresponding theoretical curve of the two-ray model for isotropic antennas, which will be discussed in detail in Section III. Except for the offsets due to differences in antenna gain, the theoretical curve is seen to be in excellent agreement with the measurements for distances beyond 10 m where antenna pattern effects are not significant. This agreement demonstrates the applicability of the two-ray model to rural LOS measurements, and lends

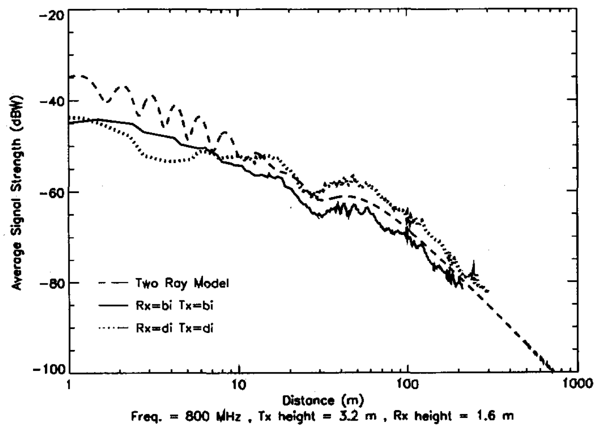

Fig. 2. Validation measurements for a rural LOS path.

further credence to the measurements made using the biconical antennas. Similar agreement was obtained for measurements made at 1850 MHz. The biconical antennas were used for the remainder of the propagation measurements.

III. Two-Ray Model and Regression Analysis

In this section we briefly review the two-ray theory because of its importance for modeling the LOS radio channel, and because it motivates the use of the two segment regression to fit the measured data for LOS paths.

A. Two-Ray Model

The two-ray model is depicted in Fig. 3(a) for transmitting antenna of height h_1 and receiving antenna of height h_2. By summing the contribution from each ray, the received signal P_r for isotropic antennas can be expressed as

$$P_r = P_t\left(\frac{\lambda}{4\pi}\right)^2 \left|\frac{1}{r_1}\exp(-jkr_1) + \Gamma(\alpha)\frac{1}{r_2}\exp(-jkr_2)\right|^2, \tag{1}$$

where P_t is the transmitter power, r_1 is the direct distance from the transmitter to the receiver, r_2 is the distance through reflection on the ground, and $\Gamma(\alpha)$ is the reflection coefficient. The reflection coefficient, which depends on the angle of incidence α, and the polarization, is given by

$$\Gamma(\theta) = \frac{\cos\theta - a\sqrt{\epsilon_r - \sin^2\theta}}{\cos\theta + a\sqrt{\epsilon_r - \sin^2\theta}}, \tag{2}$$

where $\theta = 90° - \alpha$ and $a = 1/\epsilon_r$ or 1 for vertical or horizontal polarization, respectively. For average ground, the relative dielectric constant is $\epsilon_r = 15 - j60\sigma\lambda$, and we take the conductivity σ of the surface to be 0.005 mho/m [11].

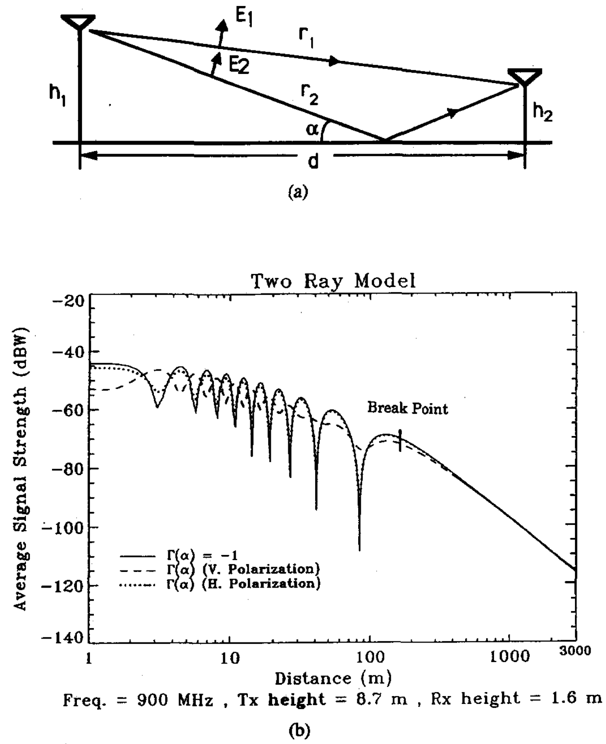

Fig. 3. Two-ray model showing: (a) the ray paths; and (b) the receiving power for vertical and horizontal polarization and assuming $\Gamma = 1$.

In Fig. 3(b), the received power given by (1) is plotted as a function of distance for the cases of vertical polarization and horizontal polarization, as well as the case assuming $\Gamma(\theta) = -1$, where $P_t = 1$ W, $f = 900$ MHz, $h_1 = 8.7$ m, and $h_2 = 1.6$ m. For large distances, α is small ($\theta \sim 90°$), and $\Gamma(\theta)$ is approximately equal to -1. But when α increases, i.e., for short distances, the value of $\Gamma(\theta)$ decreases and it can even be zero for vertical polarization (at the Brewster's angle). Consequently, in the near region, the approximation of $\Gamma(\theta) = -1$ overestimates the peaks of the signal as well as the depth of the fades. Because $|\Gamma(\theta)|$ is larger for horizontal polarization than for vertical polarization, the signal variation for vertical polarization is much less severe than for horizontal polarization, even up to a few hundred meters.

B. Two-Segment Regression Analysis

The primary tool used in the study of radio signal variation over distance is regression analysis, in which a linear fit is made to the signal in dB versus distance from transmitter to receiver on a logarithmic scale. Typically, a single straight line is fitted to all of the data over the given measurement range. However, it can be seen from the measurements in Fig. 2, and from the theoretical predictions in Fig. 3(b), that for LOS paths two regions may be distinguished, which are separated by a "break point." In order to provide a more precise fitting to the data, a two segment approach is called for that divides the overall data into two subsets with one slope for each set.

Before the break point, the radio signal oscillates severely due to destructive and constructive combination of the two rays, while after the break point, it decreases more rapidly with distance. The break point can be studied in association with Fresnel zone clearance. The first Fresnel zone is defined as an ellipsoid whose foci are the transmitting and receiving antennas. The distance from either antenna to a point on the ellipsoid and back to the other antenna is $\lambda/2$ greater than the direct path distance between the two antennas. The break point is defined here as the distance between antennas for which the ground just begins to obstruct the first Fresnel zone.

When the propagation path has first Fresnel zone clearance, the signal attenuation as the mobile moves away from the base station is essentially due to the spreading of the wavefront. However, when the first Fresnel zone starts to become blocked, attenuation in addition to the free space wavefront spreading results from the obstructing of the first Fresnel zone, where most of the radio energy is concentrated. Consequently, a steeper path loss slope is found.

The horizontal separation d at which the first Fresnel zone just touches the ground is given by

$$d = \frac{1}{\lambda}\sqrt{(\Sigma^2 - \Delta^2)^2 - 2(\Sigma^2 + \Delta^2)\left(\frac{\lambda}{2}\right)^2 + \left(\frac{\lambda}{2}\right)^4}, \quad (3)$$

where $\Sigma = h_1 + h_2$ and $\Delta = h_1 - h_2$. For high frequencies, this expression can be approximated as a simple function of wavelength and antenna heights

$$d = \frac{4h_1h_2}{\lambda}. \quad (4)$$

The two segment regression fit to the two-ray model is shown in Fig. 4, where the break point has been taken from (3). The slopes of the two segments correspond to distinctly different path loss exponents $n_1 = 1.6$ and $n_2 = 3.7$. A single slope regression fit would give a much higher standard deviation. As seen in Fig. 4, the first Fresnel zone break point does naturally divide the LOS propagation path into two physically distinctive regions. In the close-in region, the radio signal shows relatively gradual slope due to reinforcement by the wave reflected from the ground, but severe variation. In the far region the radio signal attenuates with much steeper slope.

C. Data Presentation

To highlight the influence of interference between the direct ray and the ground reflected ray, which is a dominate factor in the signal variation in each region, the LOS measurement data is presented by a file of composite signal strength, which combines data from the DAT with the one-second average data from the spectrum analyzer. Before the break point, the signal varies over a scale of several meters due to the interference between direct and ground reflected rays, which could only be captured by processing the measurements with high spatial resolution. On the other hand, beyond the break point, the two-ray interference results in monotonous signal attenuation, which is easily captured using the lower spatial resolution. Interference from other scattered rays is always present, and results in signal variations over a much smaller scale that is on the order of $\lambda/2$ (< 0.16 m). The fast fading statistics are not the subject of this paper. Therefore, for distances less than the break point defined by (3), every 32nd value of the 48 kHz DAT signal strength data is extracted and entered into a new file. For distances greater than the break point, the file consists of the one second averages from the spectrum analyzer. The values in the file are then normalized to the received signal for isotropic antennas in free space separated by 1 m for the same radiated power. The resulting file, when plotted, gives a composite curve of the signal variation.

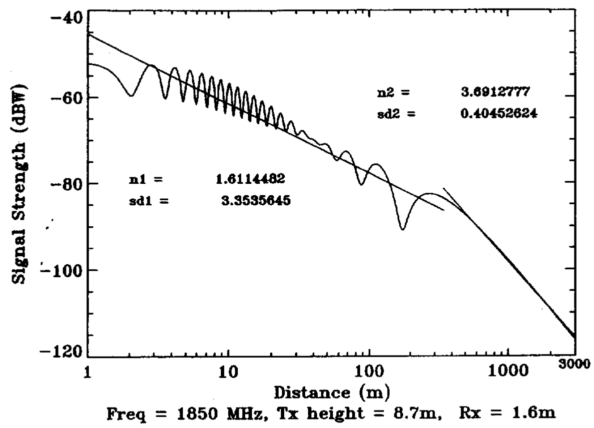

Fig. 4. Multiple slope regression fit to the two-ray model.

IV. Propagation in Rural Environments

A typical normalized composite signal curve of rural LOS measurements made in the Sherman Island area at 1850 MHz for an antenna height of 3.2 m is presented in Fig. 5. The two segment regression fit is shown in this plot together with slope index n and standard deviation for each segment. The slope indices shown in Fig. 5 and in all other LOS measurements are less than two before the regression break point, and larger than two after the break point.

Three factors contribute to the lower decay slope index before the break point as opposed to free space propagation. The first factor results from the vertical antenna pattern due to the vertical offset of the transmitting and receiving antennas. This effect is evident from the validation measurements shown in Fig. 2. For separation distances less than 10 m, the measured signal is below the theoretical curve calculated using the two-ray model for isotropic transmitting and receiving antennas. The measured signal approaches the theoretical result as the receiver travels away from the transmitter since the propagation path becomes closer to antenna boresight. However, even for isotropic antennas, the slope before the break point is less than two, as seen from the regression line applied to the two-ray model in Fig. 4. This effect comes from the remaining two factors. First, due to the offset between the antennas as shown in Fig. 1, there is a separation of 3.5 m or greater between the transmitting and receiving antennas when the test vehicle are bumper-to-bumper (distance = 0 m). As a result, a few tens of dB initial signal attenuation are incurred at the zero reference position. This offset effect becomes minimal when the receiving van travels away from the transmitter so that the actual separation distance between the transmitting antenna and receiving antenna approaches their horizontal separation. The final factor contributing strongly to the gradual slope results from the variation of ground reflection coefficient as a function of the incident angle [1]. In the case of vertical polarization, for distances greater than that corresponding to incidence at the Brewster's angle, the magnitude of reflection coefficient increases from zero toward unity. Thus, the additive effect of the ground reflection increases with distance. The combination of the above factors reduces the signal for smaller distances and increases it for larger distances, so that the regression slope is less than 2 before the break point.

While the radio signal shows little path loss before the first Fresnel zone break point as discussed above, severe fading about the regression line is seen in Fig. 5, which results from two-ray cancellation. Unlike multipath fading, which appears only over distances on the order of $\lambda/2$, two-path fading occurs over much longer distance, and must therefore be considered in regard to the system performance. We have found that two-path fading, as measured by the standard deviation for the regression fit before the break point, is worse for higher antennas and for higher frequency. For example, the standard deviation, which is 3.2 dB in Fig. 5 for a 3.2 m high antenna at 1850 MHz, increases to 5.7 dB for a 8.7 m high antenna at the same frequency, and decreases to 1.4 dB for the same antenna height at a lower frequency of 900 MHz. After the break point, only minor variations having a standard deviation of about 1 dB appear on top of the second regression line.

V. LOS Propagation in Urban and Suburban Environments

Two built up urban environments were studied, one being downtown San Francisco, and the other downtown Oakland. These environments differ in that San Francisco is hilly and uniformly built up with most buildings being significantly higher than the greatest antenna height used. Oakland, on the other hand, is flat, and has an irregular mixture of building heights ranging from one or two stories to twenty-nine stories. The Sunset District in San Francisco was selected as a representation of suburban/residential environments. It is typified by two story row houses lining wide streets that form a rectangular grid. The topography has gradual constant slope. The Mission District is considered to be representative of commercial/residential areas. It is composed of a mixture of residential and commercial structures which are about four to six stories high, so that the tallest antenna height of 13.4 m is close to or above the rooftop level. The terrain is flat.

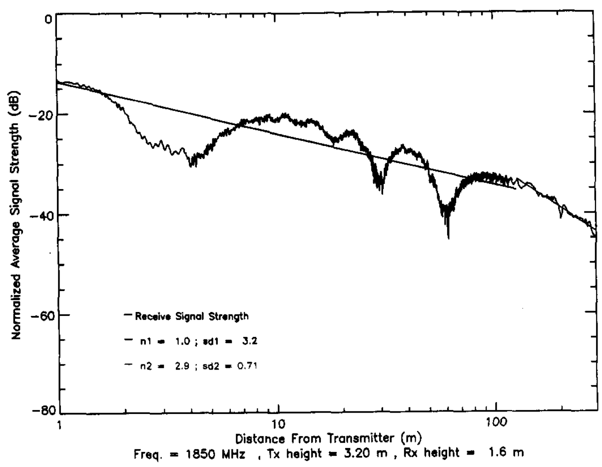

Fig. 5. Composite signal curves for a rural LOS path in Sherman Island.

A typical example of the composite signal curves obtained for the LOS path in Mission Street is shown in Fig. 6 for a transmitting antenna of 8.7 m and a frequency of 1937 MHz. The two-segment regression fit is also shown, using the break point calculated from (3). Since the receiving antenna is closer to the ground (1.6 m) than to the building facades, as the distance between the base and mobile stations increases, the Fresnel zone first touches the ground vertically before touching the buildings laterally. Thus the same break point used in a flat open area can also be applied to both urban and suburban areas where buildings are present along both sides of the LOS test route. This break point does split the average signal curve into two regions with distinct regression slope as evident in Fig. 6. As in the rural environment, the slope index n is close to 1 for the near-in segment, and increases substantially for the segment beyond the break point. However, unlike the rural environment, the standard deviation is larger for the segment beyond the break point than for points before the break point, which is expected due to significant multipath fading along a city street.

Fig. 7 shows another LOS measurement made in downtown San Francisco. Because the terrain for downtown San Francisco has hills, the use of the flat earth break point for the LOS measurements is no longer valid. Instead a break point at 1 km was chosen since it is approximately the distance to the top of the first hill. The hills are also responsible for the steep drop in the regression line past the break point (shown by index n_2), where radio signals suffer significant loss due to diffraction over the hill.

All other LOS paths in urban and suburban settings, with different antenna height or frequency, show signal

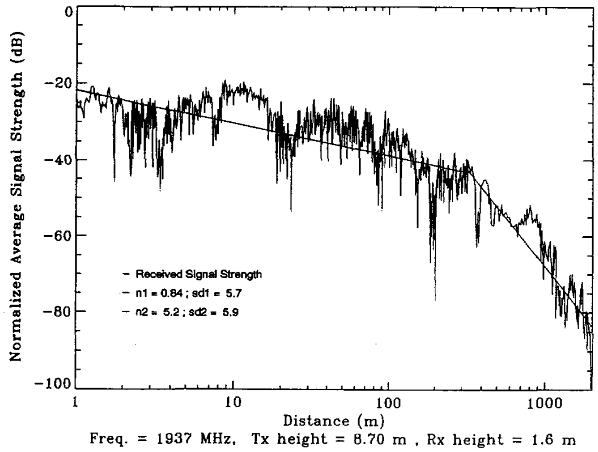

Fig. 6. Normalized composite signal curve for a suburban LOS path along Mission Street, San Francisco.

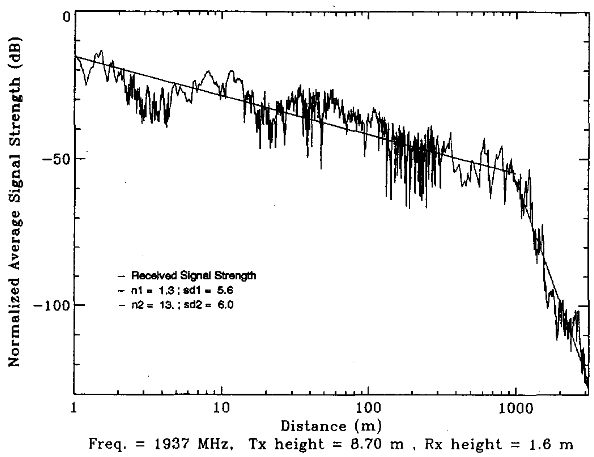

Fig. 7. Normalized composite signal curve for an urban LOS path in downtown San Francisco.

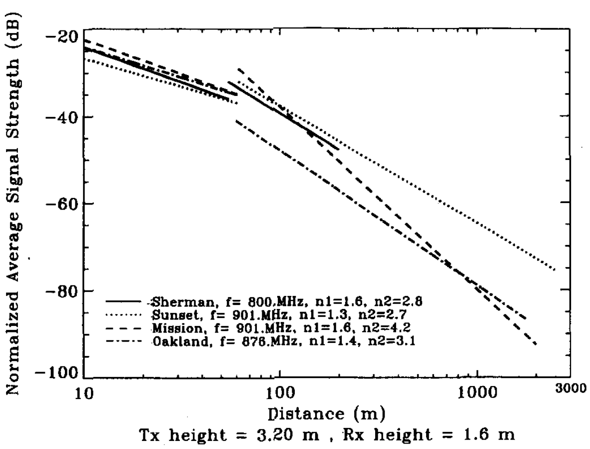

Fig. 8. Regression comparison for LOS measurements in different environments.

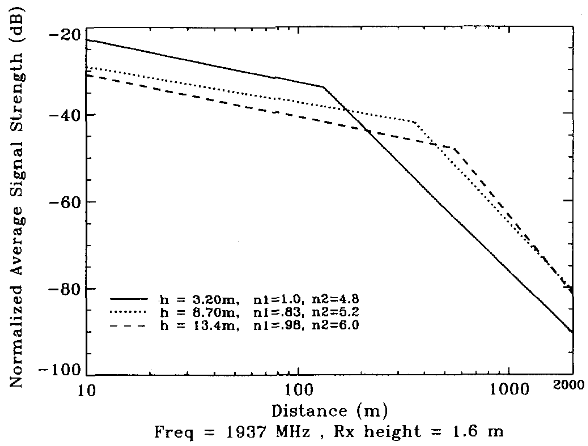

Fig. 9. Regression comparison for LOS measurements at three different antenna heights.

variations similar to those shown in Fig. 6 and Fig. 7. Therefore, the two slope regression fits to the measurements can be used to compare LOS signals in different environments. Fig. 8 shows the comparison of the regression fits obtained for the four flat measurement sites, i.e., Sherman Island (rural), the Sunset and Mission District in San Francisco (suburban), and Downtown Oakland (urban), in the 900 MHz frequency band for an antenna height of 3.2 m. The downtown San Francisco regression lines are not used because the presence of hills resulting in additional effects on the path loss. To the left of the break point all of the curves are remarkably similar. The signal levels obtained from the regression fits are within 5 dB. The slope indices indicated in the figure are close to 1.5. To the right of the break point the slopes are more variable, but tend to group into two sets. One set contains data for Sherman Island and the Sunset District, while the other contains data for the Mission District and Oakland. These groupings may be due to the fact that the streets in the Sunset District are wide, with only low buildings on either side, so that propagation is more nearly like that in a rural environment. Since the Mission District and Oakland have much higher buildings, the Fresnel zone is essentially obstructed laterally as well as on the bottom, and this results in higher path loss.

VI. LOS Cell Size and Antenna Height Gain

Fig. 9 shows an example of regression lines obtained from measurements made on LOS paths in the Mission District for the three different transmitting antenna heights. It is seen from (4), and from this figure, that in a LOS radio path over flat terrain the distance to the first Fresnel zone break point is approximately a linear function of the base station antenna height. As a result, higher antennas will give larger area over which the path loss exhibits a weak dependence on distance.

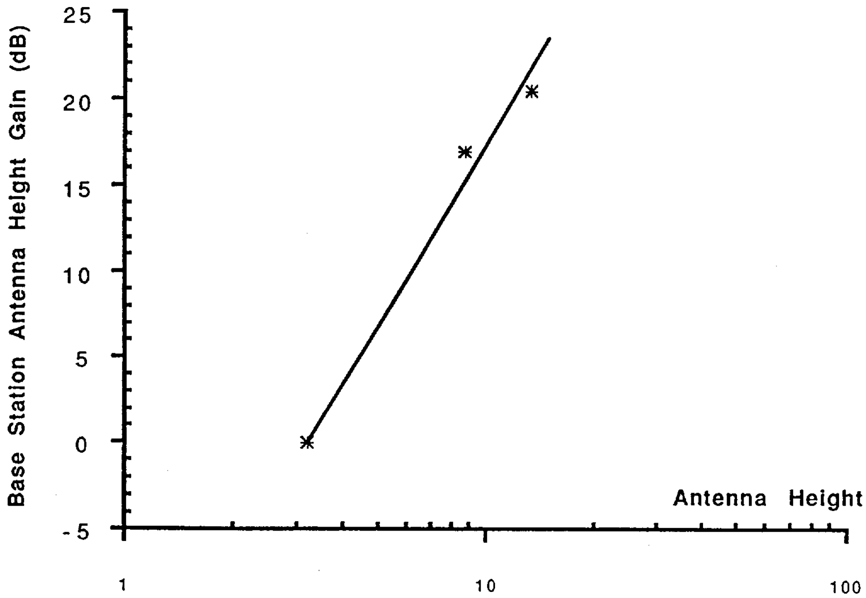

Fig. 10. Base station antenna height gain for a suburban LOS path in Mission, San Francisco.

The foregoing behavior can be used for PCS system design by employing LOS links out to the break distance. No significant path loss is experienced within the cell, so that a low transmitting power can be employed. Yet, outside the cell, the radio signal attenuates more rapidly due to the high slope index, which can be likened to a natural radio propagation "wall" that limits interference in adjacent cells, or to other local users in the same band. However, severe two-ray cancellations, or two-path fading are present before the first Fresnel zone break point, as seen in Figs. 5–7. Because the ground reflection point is much closer to the receiving antenna than the building reflection points, the interference between the direct ray and the ground reflected ray is the dominant effect even in urban and suburban environments. Interference from rays reflected from buildings results in the rapid fluctuations about the two-path variations. Compared with multipath fading, two-path fading occurs over a much greater distance, and may have an important effect on system performance for LOS microcells. However, two-path fading can be easily predicted by the two-ray model, so that its effects can be minimized by proper system design. For example, as shown in Fig. 6, the use of vertically polarized antennas results in significantly less severe two-path fading as opposed to the use of horizontally polarized antennas.

In general, the break distance for the 1900 MHz band is about twice that for the 900 MHz band according to (4). Therefore, if the cell radius is chosen to be equal to the break distance, it can be adjusted by changing the transmitting antenna height for a specific frequency. However, as discussed above, raising the transmit antenna to achieve a larger cell size may result in more severe two-path fading.

The base station antenna height will be an important parameter in PCS system design to assure radio signal coverage and to prevent interference with adjacent cells. Within the break point distance, the received power is seen from Fig. 9 to be lower for higher antennas. However, this negative height gain is a result of the definition used for the distance reference and the vertical antenna pattern, rather than from an environmental propagation effect, as discussed in Section II-A. This distance displacement, together with antenna pattern effects, causes the apparent height dependence. A 6 dB difference is observed between the regression lines in Fig. 9 for the 3.2 m and 8.7 m heights, and an 8 dB difference between the 8.7 m and 13.4 m heights. This height dependence is consistent with regression analysis based on the two-ray model, which gives differences for the regression lines of 6 dB and 9 dB, respectively.

It is seen from Fig. 9 that regression lines to the measured signal at points beyond the first Fresnel zone break distances are approximately parallel to each other, with those for the higher antennas above those for lower antennas, so that the antenna height gain can be calculated by using the average deviation between the regression lines. The antenna height gains obtained from these regression lines are plotted in Fig. 10, taking the 3.2 m height as the reference. The straight line fit to the three points shows a height gain proportional to $h^{2.2}$, so that the received power increases approximately 6 dB per doubling of the antenna height, as predicted by the two-ray model.

VIII. Conclusion

Microcellular propagation studies indicate that a break point based on Fresnel zone clearance can be identified as a basis for a two segment regression fit to the measured

LOS signal strength. The two slopes so obtained can in turn be used to contain the coverage of a cell. Within the cell boundary defined by the break point, no significant path loss is experienced. Outside the cell boundary the radio signal decreases very rapidly with distance according to a high inverse power law. However, severe two-path fading is observed within the cell, whose impact on system performance must be taken into consideration. Theoretical investigation indicates that vertical polarization has significantly less severe two-path fading as compared to the horizontal polarization. The cell size is about double for the 1900 MHz frequency band compared to the 900 MHz frequency band. The higher base station antenna results in a larger cell with the compensation of more severe two-path fading. An antenna height gain was observed to approximately follow the square power law of antenna height for LOS paths beyond the first Fresnel zone break distance. These measurement results are confirmed by using a two-ray model.

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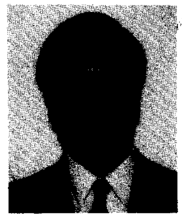
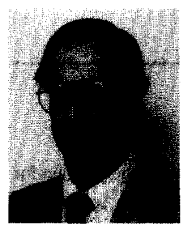


Howard H. Xia was born in Canton, China, on August 16, 1960. He received the B.S. degree in Physics from South China Normal University, Canton, China, in 1982. He received the M.S. degree in Physics in 1986, the M.S. degree in Electrical Engineering in 1988, and the Ph.D. degree in Electrophysics in 1990, all from Polytechnic University, Brooklyn, New York.

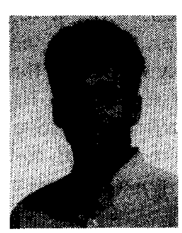
Since September 1990, he has been working with PacTel Corporation and Telesis Technologies Laboratory, Walnut Creek, CA, where he has been engaged in research and development of advanced analog and digital cellular mobile radio networks, and personal communications systems.



Henry L. Bertoni was born in Chicago, IL, on November 15, 1938. He received the B.S. degree in Electrical Engineering from Northwestern University, Evanston, IL in 1960. He was awarded the M.S. degree in Electrical Engineering in 1962, and the Ph.D. degree in Electrophysics in 1967, both from the Polytechnic Institute of Brooklyn (now Polytechnic University)

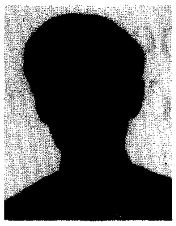
After graduation he joined the faculty of the Polytechnic. He is now Head of the Department of Electrical Engineering. His research has dealt with theoretical aspects of wave phenomena in electromagnetics, ultrasonics, acoustics, and optics. He has authored or co-authored over 90 articles on these topics. During 1982–1983 he spent sabbatical leave at University College London as a Guest Research Fellow of the Royal Society. The research he carried out at University College was the subject of a paper that was awarded the 1984 Best Paper Award of the IEEE Sonics and Ultrasonics Group. During the summer of 1983 held a Faculty Research Fellowship at USAF Rome Air Development Center, Hanscom AFB. His current research in electromagnetics deals with the theoretical prediction of UHF propagation characteristics in urban environments, and he was the first explain the mechanisms underlying characteristics observed for propagation of the Cellular Mobile Radio signals.

Dr. Bertoni is a Fellow of the IEEE, and is currently the Chairman of the Technical Committee on Personal Communications of the IEEE Communications Society. He is chairman of the Hoover Medal Board of Award and has served on the ADCOM of the IEEE Ultrasonics, Ferroelectric and Frequency Control Society. He is also a member of the International Scientific Radio Union and the New York Academy of Science.



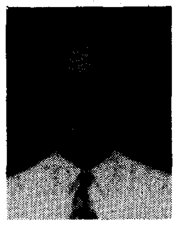
Leandro Rocha Maciel was born in Rio de Janeiro, Brazil, on October 23, 1963. He received the B.S. and M.S. degrees in electrical engineering from the Military Institute of Engineering (IME), Rio de Janeiro, in 1986 and 1988, respectively. In March 1993, he completed the Ph.D. degree in electrical engineering at Polytechnic University of New York, carrying out his research in modeling UHF propagation in urban environments, with a grant from CNPq–Conselho Nacional de Desenvolvimento Científico e Tecnológico–of the Brazilian Government, and in 1992 with a grant from Telesis Technologies Laboratory.

From 1987 to 1988 he worked for the Brazilian Army (CTEx) in microwave devices measurements and rain attenuation of electromagnetic waves in the microwave band, where he developed the research for his master thesis. During the summer of 1991, he was with Telesis Technologies Laboratory (Pac Tel) working in the FCC Experimental License Project for Personal Communication Services (PCS). Now he is a member of the Technical Staff at AT & T Bell Laboratories, working in the development of cellular systems worldwide and new wireless technologies such as PCS.



Andrew Lindsay-Stewart received his B.Sc. in Engineering Science in 1981 from Exeter University, U.K. and subsequently, his M.S. in Digital Communications and Signal Processing from Northeastern University in 1988.

Recently, he has been working with Telesis Technologies Laboratory engaged in the research and development of mobile radio communications with emphasis on personal communications and cellular systems.



Robert Rowe received the Master in Communications Engineering from the University of London, London, England, in August 1989.

He has worked for several communication companies and been involved with the standardization of GSM within ETSI. He is currently a Director within Telesis Technologies Laboratory, Walnut Creek, CA, responsible for the DCS 1900 trial and computer modeling activities.