

A Radio Access System with Distributed Antennas

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Abstract— This paper analyzes a radio access system that has multiple antennas spatially distributed throughout each cell, instead of a single antenna at each cell. The same signal is simulcast by each antenna in the cell. The signals at a given cell could be multiplexed and modulated for radio transmission at a single node, then transmitted on a coaxial cable distribution system to and from the distributed antennas in a cell. Frequency translation and radio frequency (RF) amplification may need to be performed at each antenna, except for indoor applications with short coaxial cables. This paper presents calculations of signal-to-interference ratios (SIR) and handoff performance for cells with distributed antennas. It is shown that the use of distributed antennas can substantially increase the SIR above a system with a single antenna per cell, and this increase is quantified. It is also shown that increasing the number of antennas results in better overall handoff performance, with a lower number of handoffs and higher received signal power. Minimizing the number of handoffs will reduce the impact of wireless services on network elements.

I. INTRODUCTION

PERSONAL communications systems (PCS) are proposed to divide the radio spectrum into a number of frequency sets, with each cell having its own set of frequencies [1]. The frequency sets are reused at spatially separated cells to minimize co-channel interference. Similar to existing PCS proposals, this paper assumes frequency reuse with one set of channels for each cell. The cells described here, however, each have a number of spatially separated antennas [2], [3]. The antennas are widely spaced, typically by hundreds of feet. Each cell broadcasts the same down-link signal on all of its antennas. This is sometimes called simulcasting. The up-link signals are received by all the antennas of a cell and combined into one or more sum and transmitted back to a central processing node. This paper calculates the performance of distributed antenna cells. It is shown that the minimum signal-to-interference ratio (SIR) can increase by more than 12 dB with a large number of antennas in each cell instead of a single antenna. It is also shown that the number of handoffs can be reduced by using distributed antennas. Minimizing the number of handoffs will reduce the impact of wireless services on network elements.

Hybrid fiber-coax (HFC) [4] is a new architecture for providing bidirectional broadband services to residences. It has fiber-fed remote nodes, from which coaxial cable tree-and-branch distribution systems emanate to provide access to the residences. HFC is likely to be widely deployed in the

future by cable TV and telecommunications access providers. HFC is synergistic with distributed antenna cells. Each coaxial cable tree-and-branch distribution system would serve up to a few hundred of residences, about the same number as a PCS cell. A number of antennas would be placed along the coax distribution system, and each antenna broadcasts radio signals on the same carrier. Existing radio transmission formats proposed by Bellcore [5] and others could be used. Demodulation, baseband signal processing, and switching electronics could be centrally located at the fiber node or central office.

A similar system, called macrodiversity, was analyzed previously by Bernhardt [6]. Macrodiversity also has multiple antennas in each cell. Macrodiversity cells, however, transceive on only the single best antenna, but the distributed antenna systems of this paper simulcast on all antennas simultaneously. More recently, Lee has also proposed a macrodiversity system [7]. These selection switching macrodiversity systems could provide higher performance than simulcasting on distributed antennas, but they are more complicated since they require rapid monitoring and switching between different antennas.

The European digital audio broadcasting (DAB) system uses a similar distributed antenna technique for broadcasting. A single-frequency DAB network digitally broadcasts a station on the same frequency at every transmitter [8], [9]. It was found that the single frequency network can increase the multipath delay spread [10]. This, however, was for high-power broadcast transmission, and multipath delay spread might not increase with the low-power distributed antenna cells. Experimental indoor measurements reported by Saleh *et al.* [11], showed a decrease in delay spread with distributed antennas. If the radio signals are distributed over long coaxial cables with long delays, then the cables themselves could exacerbate the delay spread. If code division multiple access (CDMA) is used, then the multipath could be resolved with a RAKE receiver.

Coaxial cable has less attenuation at low frequencies, so the signals on a long cable should be transmitted at low frequencies, then mixed to RF frequencies and amplified at each antenna. In this case, each antenna would require a filter, mixer, and RF amplifier. Pedestrian PCS systems are likely to use low-power time-multiplexed transmission, with simple modulation and little or no signal processing. In this case, there is little to gain by concentrating demodulation and signal processing at the central node. So, for low-power PCS access, each antenna could be almost as complicated as a full radio port, and the SIR increase that distributed antennas could provide would be accompanied by a substantial cost increase. If adding distributed antennas is used as a method of increasing the size of each cell, and the traffic density is low,

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then distributed antennas could cost less than using a single antenna per cell.

High-power transmission systems such as those used in cellular systems require complicated demodulation, decoding, and signal processing. In this application, the cost of each antenna would be well below the total cost of each cell's electronics. For indoor applications, the distances between the distributed antennas may be short enough that each antenna doesn't need a separate RF amplifier. Distributed antennas are best suited to both of these applications.

This paper presents calculations of the performance of distributed antenna cells. Section II gives the parameters and the cell geometry that are used in the calculations throughout the rest of the paper. Section III of this paper describes the Rayleigh and shadow fading models used for evaluating distributed antennas here. Approximate SIR and signal-to-noise ratio (SNR) calculations are presented in Section IV. Section V of this paper gives the results of calculations of the SIR for a portable located in the corner of a cell, with $A = 1, 4, 9, 16, 25, 36, 49$ antennas per cell. Section VI presents simulation results that give the average percentage of a cell that has insufficient SIR, with $A = 1, 4, 9, 16$ antennas per cell. Section VII describes handoff performance with distributed antenna cells. Appendix A shows that the sum of the signals from the distributed antennas in a cell experiences Rayleigh fading similar to most wireless access systems. Appendix B describes the shadow fading autocorrelation model used for evaluating handoff in Section VII.

II. GEOMETRY AND SIR FOR CALCULATIONS AND SIMULATIONS

This paper presents calculations of the performance of distributed antenna systems. All calculations use the same propagation model, transmission parameters, and antenna location geometry. All antennas are located on a square grid, and all cells have a square shape. The number of antennas per cell, A , is assumed to be a perfect square, so a $\sqrt{A} \times \sqrt{A}$ square grid of equally spaced antennas occupies each cell. An example of the geometry is shown in Fig. 1. The length of the side of each square cell is $2r_s\sqrt{A}$.

The best uncoded modulation for radio access is four-point quadrature amplitude modulation (QAM), sometimes called quadrature phase shift keying (QPSK) [1]. The SIR is defined as the total received signal power divided by the power of all the received interference. Allowing for a fade margin, QPSK achieves adequate performance if the SIR is greater than 15 dB [12]. The objective for PCS here is to achieve adequate performance (>15 dB SIR) in at least 99% of all locations.

Define d_k as the distance between the portable and port antenna k . The mean, or average, received signal power from antenna k is Cd_k^{-m} , where m is the path-loss exponent and C is a constant of proportionality. It is assumed here that $m = 4$. Recent results have shown that $m = 4$ is pessimistic, and a value of 4.5 may occur more often [13], [14], but $m = 4$ is used here. It is also assumed that the signals to and from the A antennas have random phase, so the total mean received

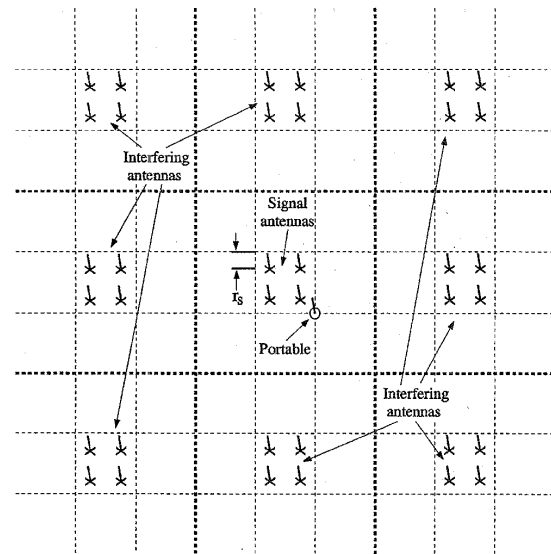


Fig. 1. Signal and interference. $N = 9$ channel sets, $A = 4$ antennas per cell.

signal power sums to

$$\bar{S} = C \sum_{k=1}^A d_k^{-m}. \quad (1)$$

III. RAYLEIGH AND SHADOW FADING

PCS radio signals propagate over multiple paths. The multipath propagation causes the received envelope at each antenna to have a Rayleigh probability distribution and a uniformly distributed phase. It is proved in Appendix A that the sum of the signals from the distributed antennas in a cell experiences Rayleigh fading, as is the case when there is one antenna in each cell. It is assumed here that all signals experience Rayleigh fading, and the performance of the distributed antenna system relies on this assumption. If the signals do not fade, then using distributed antennas could result in some performance degradation.

On the distributed antenna down link (port-to-portable), the portable receives the sum of A signals, which has Rayleigh fading that can be mitigated by existing microdiversity techniques, such as antenna diversity [1].

On the distributed antenna up link (portable-to-port), A antennas receive the same transmission with independent fading. If the signals were all summed, then there would be no diversity at the central processing node. There are many possible solutions. Two or more separate sums could be carried back upstream to the central processing node, with each sum from different antennas or polarizations. Then the central processing node could perform selection diversity. Summing the signals causes an increase in noise power, since the summands' independent noise powers would add together. If more than two sums are carried back to the central processing node, then each sum has fewer terms and the noise decreases. As more sums are carried upstream,

however, they require more bandwidth on the coax, which could add to the distributed antenna system cost. If there is sufficient available coax bandwidth, then all A signals could be delivered to the central processing node separately, and optimal diversity combining could be performed [15]. Reduced-complexity, suboptimal diversity-combining schemes could be performed, such as equal gain combining [12]. Or the frequency band could be divided, and recently invented zero-bandwidth expansion diversity constellations [16] with higher performance than optimal combining and reasonable complexity could be used. Connecting the distributed antennas to the central processing node is a significant problem in its own accord, and is not further addressed in this paper.

This paper assumes that the effects of Rayleigh fading are averaged out with microdiversity. The signal and interference, however, also experience long-term shadow fading that is not averaged out. Shadow fading causes variance in the SIR. Shadow fading is accurately modeled by a zero-mean log-normal distributed random variable (normal in dB's). Arnold *et al.* [17] modeled shadow fading at portables as the sum of two independent components: a location-specific component and a path-specific component. The location-specific component is the same for all signals to or from a given portable. The path-specific components are distinct and independent for all radio paths.

Similar to previous studies [18], it is assumed here that the location-specific component is log-normal distributed with standard deviation $\sigma_L = 6$ dB, and the path-specific component is log-normal distributed with standard deviation $\sigma_P = 8$ dB. The total signal between a given portable and its port cell is the sum of A signals from different antennas, each with the same location-specific component, but with different path-specific components. The interference on the down link is received by the portable, so all interference components have the same location-specific shadow fading as the signal.

The interference on the up link is from interfering portables into receiving port antennas. There should be few obstructions surrounding port antennas, so they should not have any location-specific shadow fading. Thus, the interference on the up link is assumed to experience independent log-normal distributed shadow fading with standard deviation $\sigma_T = \sqrt{\sigma_L^2 + \sigma_P^2} = 10$ dB.

As will be shown in Section V-A, the signal and interference are the sum of many individual components, and each component has its own log-normal distributed shadow fading. The sum of log-normals is approximately log-normal [19]. The statistics of the sums of shadow-fading signals and interference were found by Monte Carlo techniques.

IV. APPROXIMATE SIR AND SNR GAINS

This section derives approximations that show the major differences between distributed antennas and single-antenna cells. The approximations are close to the exact calculations presented in later sections.

A. Approximate SIR

Each distributed antenna cell has A antenna ports on a square grid. By increasing the number of antennas per cell

from one to A and assuming a uniform distribution of portable locations, the average distance from a portable to the nearest port antenna decreases by a factor of $\sqrt{A}$. This causes the average signal power to increase by about a factor of $1/\sqrt{A^{-4}} = A^2$.

Since the frequency reuse pattern is invariant, the distance to interferers is approximately the same for any number of antennas, A . The interference on the uplink (portables-to-port cell), however, is the sum of A signals from the A receiving antennas. And the interference on the down link (port cells-to-portables) is the sum of A interfering signals from A antennas in each distributed antenna cell. Since the phase is random and independent, the mean received interference power is approximately proportional to A . So, the mean SIR, in dB, is approximately proportional to $10 \log_{10}(A^2/A) = 10 \log_{10}(A)$. And, since $\log_{10}(1) = 0$, the gain in SIR of A distributed antennas over a single antenna is approximately $10 \log_{10}(A)$. Note that this gain is true only for $m < 4$. It is not true for close co-channel interfering cells ($N = 1$), since in this case the relative distance to the interfering cells changes with the number of antennas.

B. Approximate SNR

Other sections of this paper assume that the limiting impairment is interference from other cells. This subsection assumes that the limiting impairment is additive background noise. This is the case for areas with a low density of subscribers. In this case, maximizing the SNR will maximize the coverage area of the cells.

Using distributed antennas per cell can increase the SNR. Similar to the SIR approximation above, increasing the number of antennas per cell from one to A decreases the average propagation distance and causes the average signal power to increase by about a factor of $1/\sqrt{A^{-4}} = A^2$. If the signals from the A antennas are summed on the uplink, however, then the additive noise power increases by a factor of A , which is noise ingress. So the SNR increases by a factor of $A^2/A = A$.

Alternatively, increasing the number of cells also increases the SNR. This is called cell splitting in cellular systems. Similar to the last paragraph, by increasing the number of cells from one to P , the average signal power increases by about a factor of P^2 . In this case, however, there is no noise ingress, so the average SNR increases by a factor of P^2 . Notice that for a constant number of channel sets, N , the SIR does not change when the number of cells is increased.

A comparison is made between these two techniques. Assume the required SNR is the same for both techniques. Then $A = P^2$. Denote the cost of the per-cell shared-port electronics as C_P , and denote the cost of each antenna (which may include a mixer and RF amplifier) as C_A . Then the cost of using A distributed antennas is proportional to $C_P + AC_A$, and the cost of using P multiple cells is proportional to $P(C_P + C_A)$. So it costs less to use distributed antennas than multiple cells if $C_P + AC_A < P(C_P + C_A)$, and since $A = P^2$, this is simplified to if $PC_A < C_P$. That is, for the noise-limited case, increasing the number of antennas per cell costs less than increasing the number of cells if and only if the number

of cell splits times the cost per antenna is less than the cost of a cell's electronics.

V. SIR OF A PORTABLE IN A CORNER-FOUND BY CALCULATION

This section will present SIR calculations for a portable located in the corner of a square cell. Also, only the first tier of eight interfering cells cause interference here, and the portable can be served only by its first tier of four adjacent cells. The consideration of only the first tier of interferers causes little error [20]. The assumption that the portable is located in the corner makes the SIR estimates pessimistic. Almost all previous studies assumed one antenna per cell. This case is included in the results given here as entries labeled $A = 1$.

A. Mean SIR in a Corner

Let the spacing between antennas be $2r_s$. Then, it can be shown that the total mean received signal power, $\bar{S}$, for a portable in the corner of a cell is

$$\bar{S} = \frac{C}{r_s^m} \sum_{j=1, j \text{ odd}}^{2\sqrt{A}-1} \sum_{i=1, i \text{ odd}}^{2\sqrt{A}-1} (i^2 + j^2)^{-m/2}. \quad (2)$$

The total mean received signal power is the same on the up link as it is on the down link.

There are many interfering antennas. This paper considers only the first tier of eight interfering cells. On the down link (port-to-portable), each co-channel cell antenna causes interference, for a total of $8A$ interfering antennas. An example is depicted in Fig. 1. Let the number of channel sets (frequency reuse), N , be a perfect square, so $N = R^2$. Assuming that all interfering antennas in the first tier are continuously transmitting and their phases are random, the mean interference power on the down link into the portable in the corner is

$$\begin{aligned} \bar{I}_d = \frac{C}{r_s^m} \sum_{j=1, j \text{ odd}}^{2\sqrt{A}-1} \sum_{i=1, i \text{ odd}}^{2\sqrt{A}-1} & 2((i + 2\sqrt{A}(R-1))^2 + j^2)^{-m/2} \\ & + 2((i + 2\sqrt{A}R)^2 + j^2)^{-m/2} \\ & + ((i + 2\sqrt{A}(R-1))^2 + (j + 2\sqrt{A}(R-1))^2)^{-m/2} \\ & + 2((i + 2\sqrt{A}R)^2 + (j + 2\sqrt{A}(R-1))^2)^{-m/2} \\ & + ((i + 2\sqrt{A}R)^2 + (j + 2\sqrt{A}R)^2)^{-m/2}. \end{aligned} \quad (3)$$

The mean interference on the up link (portable-to-port) was found similarly. Two assumptions are made: each interfering portable has a 50% chance of transmitting, with at least one interfering portable transmitting, and all interfering portables are located in the center of the co-channel cells. Thus, there is interference from eight portables in the first tier into the A -receiving antennas in the cell. The mean interfering power on the up link is

$$\begin{aligned} \bar{I}_u = \frac{C}{2r_s^m} \sum_{j=1, j \text{ odd}}^{2\sqrt{A}-1} \sum_{i=1, i \text{ odd}}^{2\sqrt{A}-1} & 4((i + 2\sqrt{A}(R-1/2))^2 \\ & + (j - \sqrt{A})^2)^{-m/2} + 4((i + 2\sqrt{A}(R-1/2))^2 \\ & + (j + 2\sqrt{A}(R-1/2))^2)^{-m/2}. \end{aligned} \quad (4)$$

TABLE I
MEAN UP-LINK SIR, dB, PORTABLE IN CORNER.
NUMBER OF CHANNEL SETS, $N = R^2$

		4	9	16	25	36	49
Number of antennas per cell,	1	14.1	21.1	26.1	30.0	33.2	35.8
	4	20.0	27.3	32.4	36.3	39.5	42.2
	9	23.5	30.9	36.0	39.9	43.1	45.8
	16	26.0	33.4	38.5	42.4	45.6	48.3
	25	27.9	35.3	40.4	44.4	47.6	50.3
A	36	29.5	36.9	42.0	45.0	49.2	51.9
	49	30.9	38.3	43.4	47.3	50.5	53.2

TABLE II
MEAN DOWN-LINK SIR, dB, PORTABLE IN CORNER.
NUMBER OF CHANNEL SETS, $N = R^2$

		4	9	16	25	36	49
Number of antennas per cell,	1	9.5	17.3	22.7	26.7	29.9	32.7
	4	15.2	23.5	28.9	33.0	36.3	39.0
	9	18.6	27.0	32.5	36.6	39.9	42.6
	16	21.1	29.5	35.0	39.1	42.4	45.2
	25	23.0	31.5	37.0	41.1	44.4	47.1
A	36	24.6	33.1	38.5	42.7	45.9	48.7
	49	25.9	34.4	39.9	44.0	47.3	50.0

The mean SIR on the up link, $\bar{S}/\bar{I}_u$, is given in Table I for a portable located in the corner of a square cell. Similarly, the mean SIR on the down link is given in Table II. The mean SIR's in Tables I and II are for a single serving cell. The portable could be served, however, by a number of cells, and the cell with the maximum SIR should serve the portable.

B. Probability of Insufficient SIR in a Corner

A bit error rate less than 10^{-3} is achieved by QPSK with an SIR greater than 15 dB, assuming two-branch microdiversity and Rayleigh fading [12]. SIR's are modeled with log-normal distributions, so the probability that the SIR at a given cell is less than 15 dB is found by integrating a normal density from negative infinity to 15 dB.

This section assumes that the portable is located in the corner of a square cell, so it may be served by any of four cells. There is a much lower probability that the SIR will be less than 15 dB in all four adjacent cells than there is in any one cell. Thus, allowing the portable to be served by the cell with highest SIR greatly enhances system performance.

The SIR variance was found by Monte Carlo techniques. All transmitters have the same power. For a portable located in the

TABLE III
PROBABILITY THAT UP-LINK SIR <15 dB, FOUR POSSIBLE SERVING
CELLS, PORTABLE IN CORNER. NUMBER OF CHANNEL SETS, $N = R^2$

		4	9	16	25	36	49
Number of antennas per cell, A	1	0.1	0.03	0.009	0.002	0.0008	0.0003
	4	0.05	0.005	0.0006	0.0001	2e-05	4e-06
	9	0.02	0.001	0.0001	1e-05	1e-06	2e-07
	16	0.008	0.0003	2e-05	2e-06	2e-07	3e-08
	25	0.004	0.0001	6e-06	4e-07	4e-08	5e-09
	36	0.002	5e-05	2e-06	1e-07	1e-08	1e-09
	49	0.001	2e-05	8e-07	4e-08	3e-09	3e-10

corner of a cell, log-normal random variables were generated with means given by (2)–(4) and with variances from shadow fading, as described in Section III. They were summed and used to estimate the standard deviation of the signals and interference. A total of 100 000 random SIR's were generated for each combination of N and A . By symmetry, the SIR statistics are the same for all four cells that the portable shares a corner with. The signal power at cell k is $S_k = L + \beta_k$, where L is the location-specific shadow fading for the portable and where β_k is the sum of the path-specific components at cell k . The signal power's variance is $\sigma_S^2 = \sigma_L^2 + \sigma_\beta^2$, where σ_β^2 is the variance of the sum of the path-specific components.

On the up link, the interference from cell k , $I_{u,k}$, is received by the cell's antennas, so it is independent with variance $\sigma_{I_u}^2$. The up-link SIR at cell k is $L + \beta_k - I_{u,k}$, with variance $\sigma_S^2 + \sigma_{I_u}^2 = \sigma_L^2 + \sigma_\beta^2 + \sigma_{I_u}^2$. The up-link SIR is correlated between cells, since L is the same for all four adjacent cells.

On the down link, the interference into the portable has the same location-specific shadow fading, L , as the signal. The interference on the down link is $I_d = L + \phi$, where ϕ is the total sum of all path-specific interfering components. The down-link interference has variance $\sigma_{I_d}^2 = \sigma_L^2 + \sigma_\phi^2$, where σ_ϕ^2 is the variance of ϕ . The down-link SIR at cell k , in dB, is $S - I_d = L + \beta_k - (L + \phi) = \beta_k - \phi$. So the down-link SIR is correlated with variance $\sigma_\beta^2 + \sigma_\phi^2 = \sigma_S^2 + \sigma_{I_d}^2 - 2\sigma_L^2$.

The probability of unacceptable service is the probability that the SIR at all four adjacent cells is less than 15 dB. This probability was found by numerically integrating a multivariate correlated normal distribution. Up-link results are given in Table III, and down-link results are given in Table IV. The results show that increasing the number of antennas per cell, A , greatly decreases the probability of unacceptable performance.

VI. SIMULATIONS FOR THE SPATIAL SINR DISTRIBUTION

This section presents detailed Monte Carlo simulations of distributed antennas with a particular set of parameters and assumptions. The simulations give statistics for portables located throughout a cell. The simulations simultaneously consider many variables, which gives an accurate assessment of system performance at the cost of some loss of generality. Simulation parameters are typical of the recently proposed standard for PCS, called WACS [15]. The simulations are

TABLE IV
PROBABILITY THAT DOWN-LINK SIR <15 dB, FOUR POSSIBLE SERVING
CELLS, PORTABLE IN CORNER. NUMBER OF CHANNEL SETS, $N = R^2$

		4	9	16	25	36	49
Number of antennas per cell, A	1	0.4	0.06	0.009	0.001	0.0002	4e-05
	4	0.1	0.001	1e-05	1e-07	2e-09	2e-11
	9	0.02	1e-05	7e-09	1e-11	2e-14	5e-17
	16	0.003	1e-07	1e-11	6e-16	2e-19	9e-23
	25	0.0003	3e-09	2e-14	2e-19	4e-23	1e-26
	36	3e-05	3e-11	1e-16	4e-22	4e-27	2e-31
	49	5e-06	6e-13	9e-20	3e-24	2e-30	8e-37

similar to those previously presented in detail by Bernhardt [18].

For each number of channel sets, N , a fixed number of cells are simulated. For $N = 4$, 100 cells (two tiers of interfering cells) are simulated; for $N = 9$, 81 cells (one tier of interfering cells) are simulated; and for $N = 16$, 144 cells (one tier of interfering cells) are simulated. A cell-wrapping technique [18] is used to avoid the edge effect. Portable locations and traffic are pseudorandomly generated for all cells. Mean signal powers, shadow fading, etc., are calculated, and signal-to-interference plus noise (SINR) statistics are culled for the uplink and downlink. Then all random variables are regenerated until 200 000 SINR values have been calculated for each value of A and N .

Additive white background noise is included. The additive noise power is such that each user at the corner of the cell has an average SNR of 26 dB, assuming zero dB of shadow fading. Portables locations are uniformly distributed. Antenna geometry, mean-signal and interference power, and shadow fading are calculated as described in Sections II and III.

A time division multiplexed (TDM) down link/ time division multiple access (TDMA) up link is simulated. Ports are continuously transmitting on the down link. On the up link, only active portables are transmitting, and on average 50% of all up-link time slots are used. That is, each cell is a 10-server blocked-calls-cleared (Erlang B) facility, where a server is a time slot. The average offered traffic is 5 Erlangs per cell, which gives a blocking probability of 2%. Portables select the cell with the maximum down-link SINR. This selection includes the effect of Rayleigh fading with two-branch selection diversity. After selecting the cell, calls are assigned to the cell's idle time slot with the least up-link interference [18]. Blocked calls are not included in the SINR statistics.

A plot of the estimated probability distribution of the SINR is presented in Figs. 2–4 for $N = 4, 9, 16$. An objective is to provide adequate performance in at least 99% of all locations [1]. The probability of failing to meet this objective is called the "SINR at 1%," which is the point where $\Pr(\text{SINR} \leq \text{SINR at 1\%}) = 0.01$. The SINR at 1% is plotted in Fig. 5. The SINR increases as the number of distributed antennas increases. By comparing Figs. 2–5 with Tables I–IV, it can be seen that the

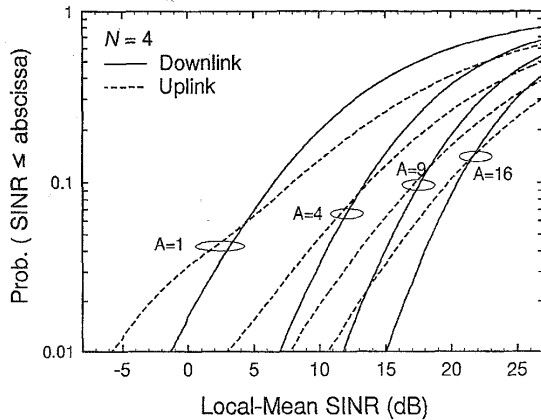


Fig. 2. SINR distribution for $N = 4$ channel sets, $A = 1, 4, 9, 16$ antennas per cell.

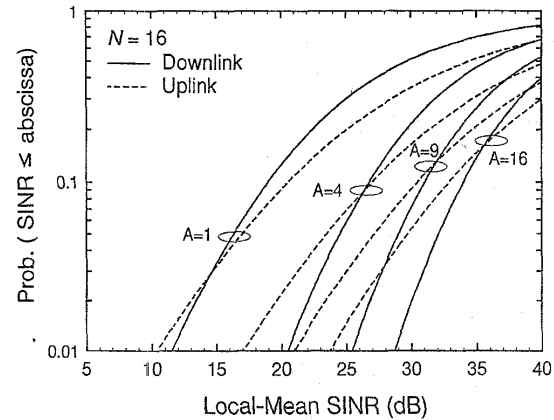


Fig. 4. SINR distribution for $N = 16$ channel sets, $A = 1, 4, 9, 16$ antennas per cell.

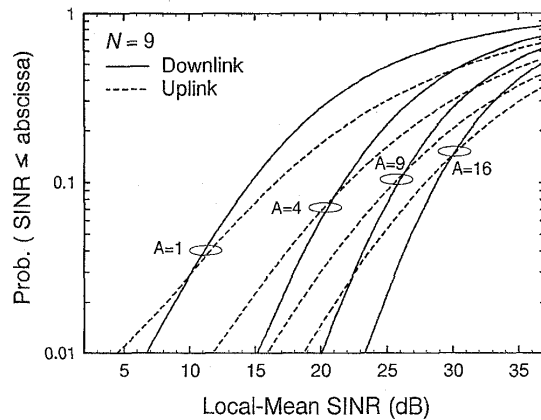


Fig. 3. SINR distribution for $N = 9$ channel sets, $A = 1, 4, 9, 16$ antennas per cell.

SINR gains here are roughly the same as the SIR gains in Section V for portables located in cell corners.

VII. HANDOFF

As a portable moves from one cell to a second cell, a handoff is performed by assigning the portable a channel to the second cell and terminating its channel to the first cell. This section analyzes the number of handoffs performed as a portable moves between distributed antenna cells and the minimum received signal power as the serving cell changes. The initiation of a handoff is determined here by the difference between the received signal powers at the different cells. The parameters of the handoff algorithm can be chosen to make handoffs more or less frequent. It is desirable to minimize the number of handoffs to make it easier for the network to track the portable. Avoiding or delaying handoffs, however, may result in insufficient received signal powers if the portable is not served by the best cell. Simulation results will show that increasing the number of antennas per cell results in better

overall handoff performance, with fewer handoffs and higher received signal power.

A. Distance-Dependent Shadow-Fading Autocorrelation

All handoff calculations in this section express power in dB. The shadow fading is denoted y_k dB. Using (1), the received signal power from antenna k , expressed in dBm, is

$$s_k = 10 \log_{10}(C) - m 10 \log_{10}(d_k) + y_k. \quad (5)$$

With typical link parameters for low power wireless access, it was found that $10 \log_{10}(C) = 20.8$ dBm [18].

For a given portable, the location-specific shadow fading is the same to each antenna k . Thus, the location-specific component has no effect on the relative signal strength to different cells, and it does not effect the handoffs. So for handoff calculations, the shadow fading is modeled by only the sum of the path-specific components. Thus, y_k is zero mean normally distributed with variance $\sigma_P^2 = 8$ dB [17]. It is assumed here that short-term Rayleigh fading is averaged out by the handoff algorithm, so it is ignored.

As a portable moves from one location to another, it experiences different levels of shadow fading. This paper models shadow fading as a location-dependent random process. It is assumed that the autocorrelation of shadow fading between two locations is a function of the distance between the locations. A relatively simple one-pole autoregressive (AR) distance-dependent autocorrelation model is used [21]–[23]. This model is described in detail in Appendix B.

This paper considers multiple distributed antennas per cell. The received signal power is the sum of the signal powers from each antenna, each of which has different shadow fading. Previous work on handoff algorithms [22], [23] considered a single antenna per cell. Ostling [24] considered a simulcast system in which two single antenna cells simultaneously transmit the same frequency for a short time during a handoff. In the single antenna case, the shadow fading between the portable and each antenna is independent because of the large angular separation between the propagation paths. With

multiple-distributed antennas per cell, some propagation paths can have very small angular separation and do not have independent shadow fading. A model was developed for the shadow-fading correlation between different propagation path angles; it is described in Appendix B.

B. Handoff Algorithm

In this paper, the weighted averages of the received signal powers from each cell are compared at each incremental location to determine whether a handoff should occur. A handoff occurs when the weighted average received signal power from the current serving cell is less than that from another cell minus the hysteresis. The weighted average is sometimes referred to as a leaky integrator, or averaging window [22], [23]. This handoff algorithm has recently gained acceptance since it can minimize the number of unnecessary handoffs relative to algorithms that perform handoffs based only on the instantaneous received signal power.

Denote the instantaneous received signal power, in dB, from cell i when the portable is at location x as $S_i(x)$. The total received signal power is the sum of the A signal powers, which is expressed in dBm as

$$S_i(x) = 10 \log_{10} \left[\sum_{k=1}^A 10^{s_k/10} \right]$$

with s_k given in (5). Note that the received signal power is the same on the up link as on the down link, assuming the transmit powers are the same, so the results here hold for both the up link and down link. An exponentially windowed weighted average is used here, so the weighted average of the received signal power from cell one is

$$\hat{S}_1(x) = \frac{1}{D_{\text{avg}}} \int_0^x e^{-a/D_{\text{avg}}} S_1(x-a) da$$

where D_{avg} determines the length of the averaging window. Higher values of D_{avg} give more averaging. The weighted average of the received signal power from cell two, $\hat{S}_2(x)$, is defined similarly. It was shown by Goldsmith *et al.* [25], that averaging with this exponential window is a little more accurate than with a rectangular window.

The weighted averages are updated at discrete points. So only discrete points spaced a small increment, δ , apart are considered. Then the integral in the equation for $\hat{S}_1(x)$ becomes

$$\hat{S}_1(k\delta) = \frac{\delta}{D_{\text{avg}}} \sum_{i=0}^k S_1((k-i)\delta) e^{-i\delta/D_{\text{avg}}}.$$

This can be written recursively as

$$\hat{S}_1(k\delta) = \frac{\delta}{D_{\text{avg}}} S_1(k\delta) + \hat{S}_1((k-1)\delta) e^{-\delta/D_{\text{avg}}}.$$

Initially, cell one is the serving cell. The position, x , moves along a straight line between cells one and two, with $x > 0$. As the portable moves toward cell two, a handoff is performed at position x if $\hat{S}_1(x) < \hat{S}_2(x) - T$. Then, a handoff back to cell one is performed if $\hat{S}_2(x) < \hat{S}_1(x) - T$, etc. Here, T is called the hysteresis; it provides inertia and lowers the

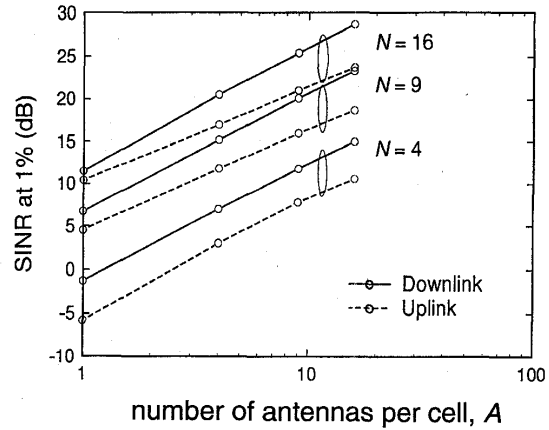


Fig. 5. SINR at 1%, dB. $\Pr(\text{SINR} \leq \text{SINR at 1\%}) = 0.01$.

number of unnecessary handoffs. For any reasonable value of D_{avg} , T can be chosen to minimize the number of handoffs while maintaining a high signal strength. A careful joint choice of D_{avg} and T , however, is necessary to provide robustness to changes in the propagation environment. This joint choice was analyzed extensively by Vijayan and Holtzman [23] for single-antenna cells.

C. Handoff Simulations

A square grid of $A = 1, 4, 9, 16, 25$ antennas occupies each square cell. The portable's x coordinate moves between the center of cell one to the center of horizontally adjacent cell two, as shown in Fig. 6. The y coordinate is fixed and equals the center of the cell unless $\sqrt{A}$ is an odd number ≥ 3 , in which case the portable's y coordinate is positioned so that it is in the center of the antennas that are closest to the center of the cell. Since the portable is centered between the antennas, it has a worst-case type of positioning.

Distances are in feet. The side of each square cell is 2000 feet long, so in moving from the center of cell one to the center of adjacent cell two, the portable moves 2000 feet. Statistics are updated each $\delta = 2$ feet, for a total of 1000 positions for each motion. For each combination of different parameters, 10 000 motions are simulated to get accurate statistics.

By averaging the values used by Gudmundson [21], Vijayan [22], and Goldsmith [25], a typical value for the shadow-fading autocorrelation constant was determined: $\lambda = 50$ feet. This makes the shadow fading autocorrelation coefficient, ρ , equal to 0.1 at 115-foot separation. Recall that the path loss exponent is $m = 4$, and shadow-fading standard deviation is $\sigma_P^2 = 8$ dB.

The hysteresis, T , can be chosen to determine the rate of handoffs. Large hysteresis results in few unnecessary handoffs, but it also delays legitimate handoffs and degrades the received signal power since the serving cell may not be the best one. The choice of the amount of averaging, D_{avg} is more involved. Similar to the hysteresis, large averaging results in few handoffs but lower received signal power. Large averaging has other effects: it gives good robust performance with

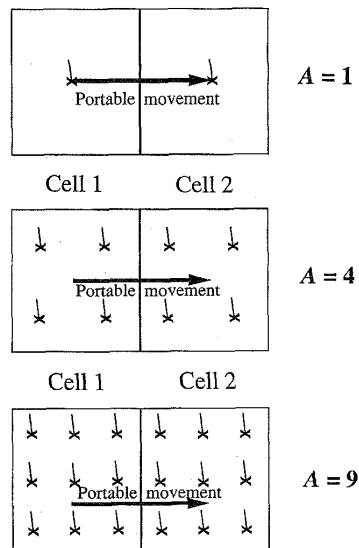


Fig. 6. The movement of a portable between two cells in handoff simulations.

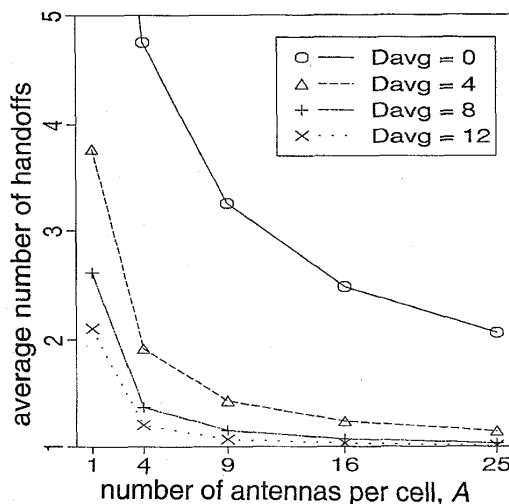


Fig. 7. Average number of handoffs as a function of the number of antennas, A , per cell, and the averaging, D_{avg} . Handoff hysteresis, $T = 2.5$ dB.

changes in the shadow-fading standard deviation, σ_P , but it gives poor performance during the "street corner" effect when the received signal power changes rapidly [23]. By analyzing prior research for $A = 1$ antenna per cell, and from preliminary simulation results, it was decided to simulate the values $D_{avg} = 0, 4, 8, 12$ dB, and $T = 1.5, 2.5, 3.5$ dB. A value of $D_{avg} = 0$ means that there is no averaging, and handoffs are performed based on the instantaneous received signal powers.

For each combination of A , D_{avg} , and T , two statistics were culled from the simulations: the average number of handoffs

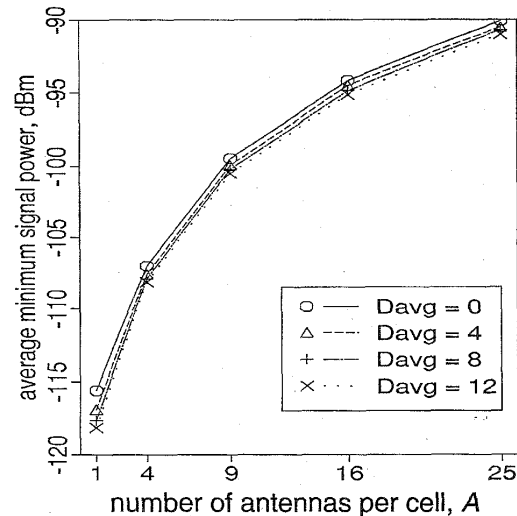


Fig. 8. Average minimum received signal power as a function of the number of antennas, A , per cell, and the averaging, D_{avg} . Handoff hysteresis, $T = 2.5$ dB.

and the average minimum received signal power. The number of handoffs performed at each simulated motion were averaged to get the average number of handoffs. The received signal power from the serving cell was tracked, its minimum value was found for each simulated motion and averaged to get the average minimum received signal power.

Results are shown in Figs. 7–11. Figs. 7–11 show that changing D_{avg} and T changes the average number of handoffs sharply but changes the average minimum received signal power only by 1 or 2 dB. The biggest effect is caused by the number of antennas per cell, A . Higher numbers of antennas, A , per cell result in better overall handoff performance, with fewer handoffs and higher received signal power.

Fig. 11 shows the trade-off between the average number of handoffs and the average minimum received signal power. All simulated pairs of D_{avg} and T are plotted as points in Fig. 11. Again, A has the greatest effect. As the number of antennas per cell A increases, the received signal power increases and allows relatively high values of D_{avg} and T . This usually results in one handoff per motion, practically eliminating unnecessary handoffs. This comes with a loss in received signal power of only 1 dB or so, compared with low values of D_{avg} and T , and a gain in received signal power compared with one antenna per cell ($A = 1$).

VIII. DISCUSSION

This paper analyzed a method for providing radio access by broadcasting the same signal on multiple antennas geographically dispersed throughout a cell. It is assumed here that all cells have the same size, and as multiple antennas are added to each cell, the spacing between the antennas decreases. It is not surprising that blanketing a cell with distributed antennas increases the SIR. This paper quantified that increase

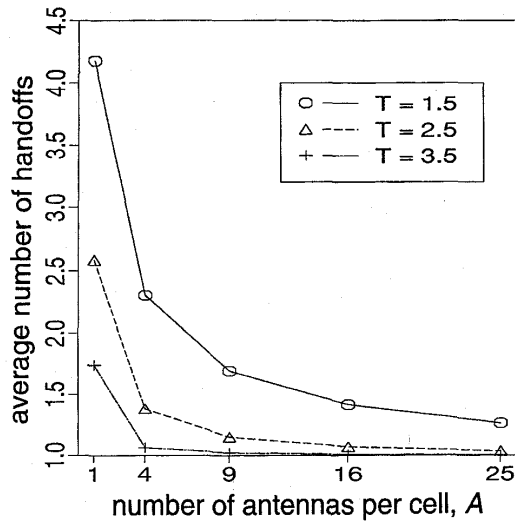


Fig. 9. Average number of handoffs as a function of the number of antennas, A , per cell, and the handoff hysteresis, $T.D_{avg} = 8$.

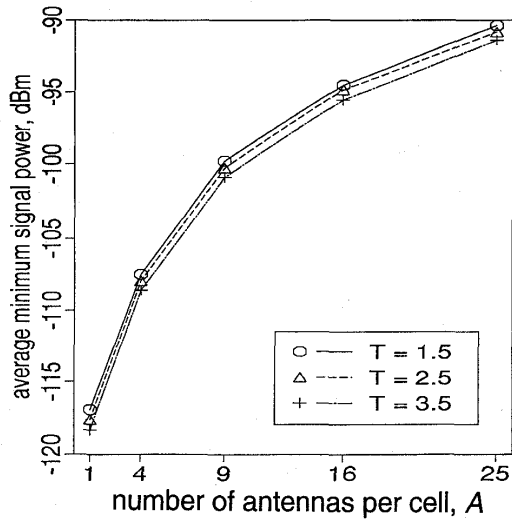


Fig. 10. Average minimum received signal power as a function of the number of antennas, A , per cell, and the handoff hysteresis, $T.D_{avg} = 8$.

by calculating both the gain in SIR and the gain in handoff performance.

The calculations presented in this paper show the gain in SIR from using distributed antennas per cell ($A > 1$) instead of using a single antenna per cell ($A = 1$). It was shown here that the use of distributed antennas can increase the SIR at 1% by more than 12 dB. This increase in SIR is attained with no increase in bandwidth, but deploying distributed antennas may increase the cost.

Increasing the number of antennas per cell (distributed antennas) was compared with increasing the number of cells (called cell splitting in cellular systems). Increasing the number

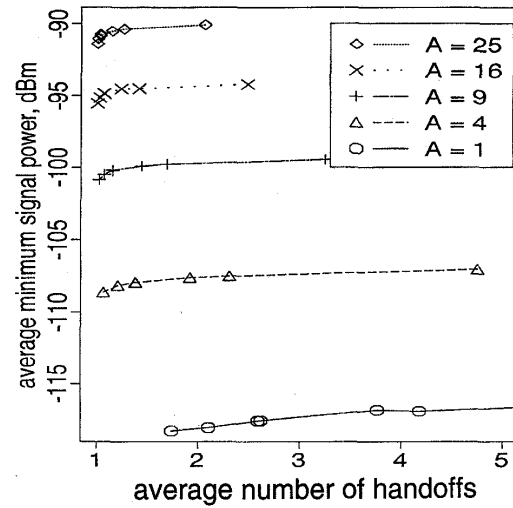


Fig. 11. Trade-off curves, average minimum received signal power versus average number of handoffs for different number of antennas, A , per cell.

of cells increases the amount of traffic that can be served, but it does not increase the SIR. Increasing the number of antennas per cell increases the SIR, but the amount of traffic that can be served is only increased as a secondary benefit of the increase in SIR. Increasing the number of antennas per cell increases the SNR less than increasing the number of cells does.

It was shown that unnecessary handoffs can almost be eliminated by using distributed antennas. This is highly desirable for low power wireless PCS access, which carries a heavy burden for tracking users. At the onset of this work, an overlapping architecture was conceived that had the antennas on the borders of adjacent distributed antenna cells transmitting frequencies for both cells simultaneously. It was thought that this overlap would minimize the number of unnecessary handoffs. The handoff results reported here showed that simply using distributed antennas decreased the number of unnecessary handoffs to a satisfactory level, so overlapping the cells is not necessary.

This paper presents a systematic study of the performance benefits of simulcasting with distributed antennas. This is an initial study, however, and there are many system and implementation details not addressed here that could significantly affect the use of distributed antennas.

APPENDIX A SUMS OF RAYLEIGH-FADING SIGNALS

A signal with a Rayleigh-distributed envelope and uniformly distributed phase also has a complex Gaussian distribution, (see Blahut [26], pp. 100–102). That is, if the signal on the i th antenna is

$$r_i(t) = \alpha_i(t)e^{-j\theta_i(t)}$$

with $\alpha_i(t)$ Rayleigh distributed and $\theta_i(t)$ uniformly distributed between 0 and 2π , then $r_i(t) = x_i(t) + jy_i(t)$ with $x_i(t)$ and $y_i(t)$ independent and Gaussian distributed, each with zero

mean and variance σ_i^2 . Each cell has A antennas. The sum of all A signals from all antennas, $r(t)$, is

$$r(t) = \sum_{i=1}^A r_i(t) = \sum_{i=1}^A x_i(t) + j \sum_{i=1}^A y_i(t).$$

Sums of Gaussian-distributed random variables are Gaussian distributed, and $r(t) = x(t) + jy(t)$ with $x(t)$ and $y(t)$ independent and Gaussian distributed, each with zero mean and variance $\sum_{i=1}^A \sigma_i^2$. Thus [12], [26]

$$r(t) = \alpha(t)e^{-j\theta(t)}$$

with $\alpha(t)$ Rayleigh distributed and $\theta(t)$ uniformly distributed between 0 and 2π . This equation proves the assertion that a sum of signals with Rayleigh-distributed envelopes and uniformly distributed phases also has a Rayleigh-distributed envelope and uniformly distributed phase.

APPENDIX B SHADOW-FADING AUTOCORRELATION MODEL FOR DISTRIBUTED ANTENNAS

A one-pole autoregressive (AR) distance-dependent shadow-fading autocorrelation model is used here. This model was found by Gudmundson [21] to be a good fit to experimental data; it has been analyzed extensively by Vijayan [22], [23].

Consider two locations separated by D feet, with $D \geq 0$. Then the autocorrelation of the shadow fading at the two locations is $\rho = e^{-D/\lambda}$, where $\lambda > 0$ determines the rate of change of shadow fading. Therefore, the shadow fading at location 1, $y(1)$, and the shadow fading at location 2, $y(2)$, separated by D feet, has autocorrelation

$$E[y(1)y(2)] = \sigma_P^2 \rho = \sigma_P^2 e^{-D/\lambda}.$$

The simulations in this paper use a grid of equally spaced discrete points. To discretize, let $D = j\delta$, with δ a small positive increment and j an integer. Then the shadow fading autocorrelation coefficient, ρ , can be expressed as a function of j ,

$$\rho(j) = e^{-|j|\delta/\lambda} = \alpha^{|j|}$$

with $\alpha = e^{-\delta/\lambda}$. To find the AR process that generates the shadow-fading random process y , the z -transform, $R(z)$, of ρ is taken (Roberts and Mullis [27], p. 61)

$$R(z) = \frac{1 - \alpha^2}{(1 - \alpha z)(1 - \alpha z^{-1})}.$$

Let $U(z)$ be the z -transform of a white-noise process, and let $Y(z)$ be the z -transform of the shadow-fading process. Define $H(z)$ to be the z -transform of the transfer function, so that $Y(z) = H(z)U(z)$. Then (Roberts and Mullis [27], pp. 486–487) $R(z) = H(z)H(z^{-1})$, so

$$H(z) = \frac{\sqrt{1 - \alpha^2}}{1 - \alpha z^{-1}}.$$

Taking the inverse z -transform, it is seen that

$$y_j = \sqrt{1 - \alpha^2} u_j + \alpha y_{j-1}. \quad (6)$$

Equation (6) shows how to simulate the shadow-fading random process. The portable moves a small distance δ at each iteration, j . An independent normal-distributed random variable, u_j , is generated with variance σ_P^2 and zero mean. Then, using the previous value, y_{j-1} , the new value y_j is found with (6). Recall that all values here are in dB.

There is no published data on the correlation of shadow fading as a function of the angular separation of different propagation paths. The following model is used for this paper. As the portable moves, four independent shadow-fading random variables are each generated as described by (6). Each shadow-fading process corresponds to a direction: north, east, south, or west. Viewed from the portable, the propagation path to each antenna is located in a particular direction. The shadow fading between the portable and the antenna is the weighted sum of the two shadow-fading processes (north and east, east and south, south and west, or west and north) that are closest to the direction of the propagation path. The weight is given by the cosine of the angle between the propagation path and the north, east, south, or west direction. For example, if the antenna is located in the first quadrant when viewed from the portable, then the propagation path has direction angle θ , with $0^\circ \leq \theta \leq 90^\circ$. The shadow fading to that antenna is $\cos(\theta)$ times the east shadow-fading process plus $\cos(90^\circ - \theta) = \sin(\theta)$ times the north shadow-fading process. Since $\cos^2(\theta) + \sin^2(\theta) = 1$, the variance of the total shadow-fading process to each antenna is still σ_P^2 . This model assures that propagation paths with little angular separation have highly correlated shadow fading and that propagation paths with large angular separation have nearly uncorrelated shadow fading.

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