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3-D Outside Cell Interference Factor for an Air–Ground CDMA "Cellular" System

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***Abstract*—In this paper, we compute the outside-cell interference factor of a code-division multiple-access (CDMA) system for a three-dimensional (3-D) air-to-ground (AG) "cellular-like" network consisting of a set of uniformly distributed ground base stations and airborne mobile users. CDMA capacity is roughly inversely proportional to the outside-cell interference factor. It is shown that for the nearly free-space propagation environment of these systems, the outside-cell interference factor can be larger than that for terrestrial propagation models (as expected) and depends approximately logarithmically upon both the cell height and cell radius.**

***Index Terms*—Aeronautical, capacity, CDMA, cellular, interference.**

I. Introduction

THE SYSTEM under consideration is illustrated in Fig. 1 for the case where base stations are ground sites distributed in a uniform hexagonal cellular pattern on the surface of the earth and the mobiles are aircraft which are assumed uniformly distributed within each cell volume. Hexagonal cells are approximated by cylinders with the same volume $(R_{\text{circle}} = 0.9094R_{\text{hex}})$ for simplicity. While equipower surfaces around the base-station omnidirectional antenna are nearly hemispherical (and so cell shapes could also be nearly hemispherical), we use the cylindrical approximation since these hemispheres would be truncated in the horizontal direction for reasons of link margin (coverage) and in the vertical direction in effect by virtue of a maximum altitude. We are interested in the computation of the (average) outside-cell interference factors f_R for the reverse (mobile-to-base, aircraft-to-ground site) channel and f_F for the forward (base-to-mobile, ground site-to-aircraft) channel. These factors are used in estimating the per-cell capacity of a code-division multiple-access (CDMA) system, as in [1], where the multiuser interference (MUI) contribution of each transmission from an "outside" cell user is multiplied by this propagation-dependent factor to obtain the relative MUI contribution to the aggregate received signal at the desired-cell receiver. We assume power control on the reverse channel and power allocation on the forward channel as is done in terrestrial cellular CDMA (IS-95) [6]. From [1, eq. (1.5)], the capacity estimate is

$$M \approx \frac{W/R}{E_b/I_0} \frac{1}{1+f} \tag{1}$$

where M is the number of active users, W/R is the spreading bandwidth to data rate ratio, E_b/I_0 is the required effective bit-energy-to-noise-density ratio for the desired bit error ratio (BER), and f is the outside-cell interference factor. Equation (1) assumes thermal noise is negligible compared to MUI, and we have also assumed that G_V, the gain due to voice activity, and G_A, the gain due to antenna sectoring, are both equal to unity. When omnidirectional antennas are used, $G_A = 1$. For the forward channel, the situation is somewhat different, since the in-cell transmissions are synchronous, and hence can be made orthogonal, significantly reducing MUI (using, e.g., Walsh–Hadamard codes for distinguishing forward channels). We note that some amount of multipath propagation for low-elevation mobiles will result in some in-cell interference, but this will be minor compared with the outside cell interference, particularly when RAKE receivers are used and additional "scrambling" codes are used to improve the orthogonal sequence cross correlations at nonzero time offsets [7]. Forward channel capacity is thus usually greater than reverse channel capacity, making actual system capacity generally limited by the reverse channel. A formula similar to (1) for forward channel capacity can be used though when enough (asynchronous) outside-cell transmissions are received by any mobile. Instead of the factor $1 + f_R$ in the capacity formula, with orthogonal signals on the forward channel we have only the factor f_F, due to the absence of in-cell MUI. We note that in most references (e.g., [1]) an outside cell interference factor for the forward channel is not explicitly computed. Typically, outage probabilities are computed to determine forward channel capacity. These probabilities make use of statistical averages of system parameters, including outside-cell interference levels. Thus, at least in terms of *average* (and worst case) values for forward channel capacity, use of a forward channel outside cell interference factor in a formula analogous to (1) is reasonable. Strictly speaking, the forward channel capacity would be the minimum of the two values M_s and M_{fa}, where M_s is the number of available orthogonal spreading codes (synchronous), and M_{fa} would be calculated in a manner similar to (1) (when asynchronous outside-cell MUI is significant). We address the computation of M_{fa} in Section II-B.

As most cellular systems to date are terrestrial, the (reverse channel) outside-cell interference factor has been estimated for propagation path losses that vary according to a $1/d^3$ or $1/d^4$ law, where d is the distance from transmitter to receiver (e.g., in [1]–[4]). In the air-to-ground (AG) environment, propagation path loss varies according to a $1/d^2$ law [5]. Reference [4] does compute f_R for the $1/d^2$ environment, but does so in

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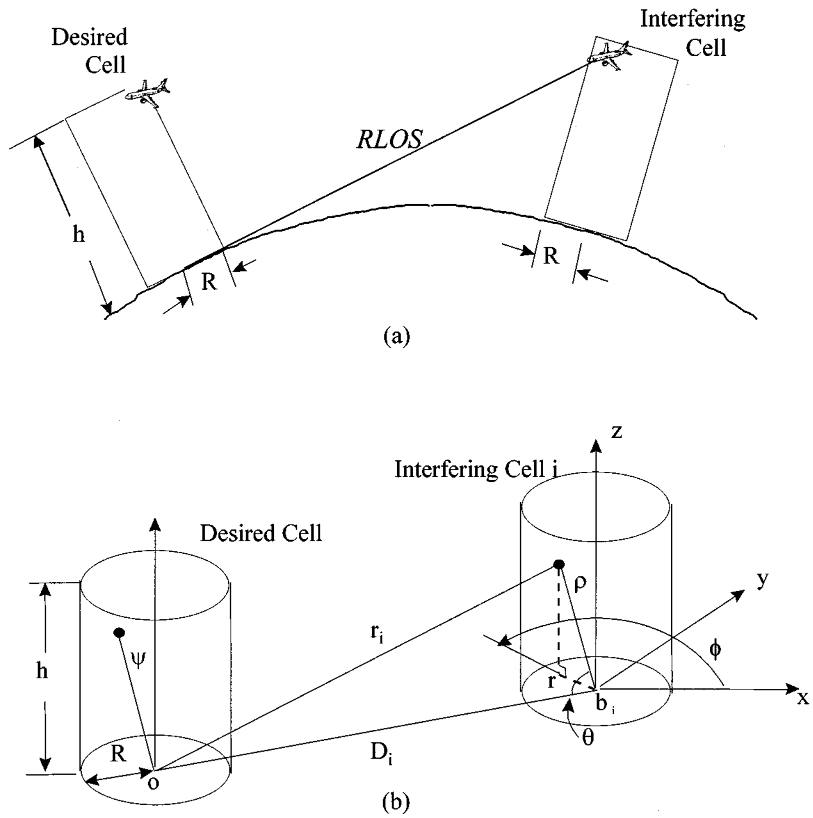

Fig. 1. Illustration of the AG system: (a) cross-sectional view and (b) 3-D view.

a two-dimensional (2-D) environment and for only three surrounding "rings" of cells. [It also appears to contain an error (wrongly correcting a value correctly computed in [3]), which results in an overestimation of f_R.] None of these references addresses the three-dimensional (3-D) AG environment. Thus, this paper attempts to fill this gap by providing the outside-cell interference factor as a function of both cell height h and cell radius R. Solving the integral used to compute f_R in [3] does yield the result that in the 2-D environment with $1/d^2$ propagation, the outside cell interference power increases without bound in a manner proportional to the natural logarithm of the farthest distance considered as more and more outside cells are added. Our results here are in agreement with this, as will be shown.

The method we use can be viewed as an extension of the method in [1] to three dimensions. We also compare with a "quasi-2-D" analysis which computes f_R as a function of RLOS$/R$, where RLOS is the radio line of sight (dependent upon h as $\sqrt{2(4/3)r_e h}$, where r_e is the radius of the earth and the "k factor" of 4/3 accounts for radio refraction in the lower atmosphere). The difference between our 3-D and quasi-2-D analyses and conventional terrestrial analyses arises in accounting for the extremely large signal attenuation which occurs beyond RLOS [5]. We treat this as a step discontinuity in propagation path loss, at RLOS, from the $1/d^2$ function to a near-infinite path loss. Since actual attenuations are in fact quite large beyond RLOS [5], this is a reasonable approximation. We also note that our results are averages and in a sense assume homogeneous cells and environments. Actual results will of course depend upon site-specific parameters (e.g., RLOS taking terrain into account).

II. Results

A. Reverse Channel

For the reverse channel, the outside-cell interference factor f_R is essentially the ratio of the per-user interference power received at the base from mobile users in an outside cell to the desired power received at the base from any mobile within the cell. In Fig. 1(b), our desired base is at point o, and the interfering mobile in the ith interfering cell is at cylindrical coordinates (r, ϕ, z) with respect to its base station at location b_i. With a traditional hexagonal cell layout on the earth's surface, we compute the average contribution f_{Ri} of outside cell i as the integral of the spatial density function of users multiplied by the distance ratio ρ/r_i raised to the nth power, where n is the propagation path loss exponent, equal to two in our case. This computation is simply the expectation of the function $(\rho/r_i)^n$ and assumes that mobile users within a cell are power controlled by that cell's base station. The distance ρ is the distance from any user in an outside cell to its base station, and r_i is the distance from this interfering user to the desired base station [Fig. 1(b)]. We augment the integrand by multiplying by $I(\text{RLOS} - r_i)$, the *indicator function*, which accounts for propagation up to RLOS only (as mentioned in the previous section). The contribution for cell i is

$$f_{Ri}(h, R) = \iiint_{Vi} (\rho/r_i)^n I(\text{RLOS} - r_i) \times p(r, \phi, z) r\, dr\, d\phi\, dz \qquad (2)$$

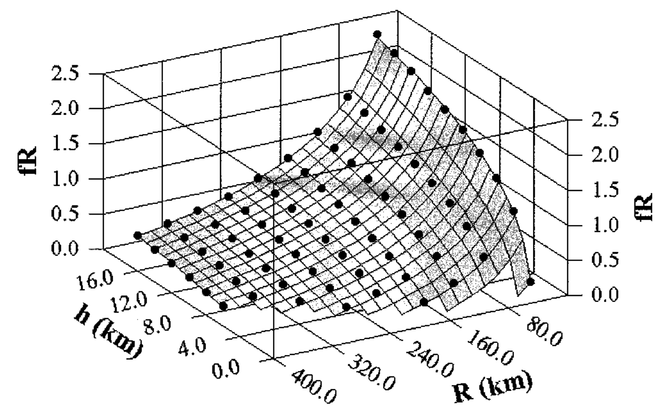

Fig. 2. Plot of f_R versus cell height h and cell radius R, both in kilometers. Points are computed data, and surface is the curve fit.

where $p(r,\phi,z)$, the spatial user density, is $1/(cell\ volume) = 1/V_i = 1/(\pi R^2 h)$. Referring to Fig. 1(b), the variable r_i is equal to $\sqrt{D_i^2 + r^2 - 2r(x_i\cos\phi + y_i\sin\phi)}$, where D_i is the distance from the desired base station at the coordinate origin to the ith base station, at coordinates (x_i, y_i). The angle ϕ is the polar angle in the x-y plane referred to a coordinate system centered on b_i, and r is the polar radius variable. The distance ρ is equal to $\sqrt{r^2+z^2}$. For a system with a nonuniform user spatial density, the same type of computation can be used, with the appropriate user spatial density $p(r,\phi,z)$. We count up to seven "rings" of cells surrounding our desired cell, for a total of 168 interfering cells. The value of f_R is then equal to the sum over i of the f_{Ri}. For convenience, we computed f_R for a grid of 100 points [pairs (h, R)]: a set of values of h from 0.3 to 18.3 km in steps of 2 km and values of R from 6 to 372 km in steps of approximately 40.6 km. Some of these points define cell sizes that are not realistic. In particular, the 6-km radius cell sizes are unrealistically small. If we omit these data points and all those for which $R >$ RLOS (since it makes no sense to have aircraft at height h and radius R if $R >$ RLOS), we have 72 data points, a least-squares curve fit for which is

$$\begin{aligned} f_R(h,R) &= c_0 + c_1\ln(h) + c_2\ln(R) + c_3[\ln(h)]^2 \\ &\quad + c_4[\ln(R)]^2 + c_5\ln(h)\ln(R) \end{aligned} \tag{3}$$

with coefficients $c_0 = 6.1226$, $c_1 = 1.0856$, $c_2 = -1.99$, $c_3 = 0.0482$, $c_4 = 0.1517$, and $c_5 = -0.1724$, and h and R are in kilometers. Fig. 2 shows a plot of the computed values (points) and the curve fit (surface). For much of the plot, specifically for the smaller values of R and larger values of h, the 3-D f_R is larger than that found for typical terrestrial propagation models, where for path-loss exponents of $n = 3$ and $n = 4$, f_R is approximately 0.77 and 0.44, respectively [1].

We note that we are comparing with the "hard-handoff" values in [1], since in an aeronautical environment where the communication messages are typically of short duration, use of "soft-handoff" techniques seems less necessary. Hard handoff represents a more likely mode of operation for pilot to controller communication. Typical messages between pilots and air traffic controllers in commercial aviation are of short duration, e.g., 5 s. This is much shorter than the average cellular phone conversation. In addition, different cells are most often assigned to different controllers, so there is no attempt to maintain communication when crossing cell boundaries. Finally, with accurate power control (say, $\sigma < 3$ dB), which is very feasible in near-line-of-sight propagation environments, the difference in the outside cell interference factor between the hard- and soft-handoff cases will be negligible (see [1, Tables 6.1–6.3]). For passenger communication, soft handoff will be applicable; yet with accurate power control the difference between the soft- and hard-handoff outside-cell interference factors is small, as noted. In addition, we have separated the outside-cell interference factor from the term that takes into account the power control "imperfections." In [1], in the hard-handoff case this power control imperfection term simply multiplies the outside-cell interference factor and thus can be used in a similar way with (3), that is, the outside-cell interference factor and the power control contribution are "separable" in the hard-handoff case.

B. Forward Channel

In the forward channel case, the outside-cell interference factor is computed somewhat differently. We begin with the equation for the effective E_b/N_0 for the mth user in the desired (0th) cell [1, eq. (6.79)] and arrive at an expression analogous to (1), solved for the effective E_b/N_0. The effective E_b/N_0 expression from [1] is

$$\left(\frac{E_b}{N_0}\right)_{\text{eff},m} = \frac{\beta\phi_m S_{0m}/R_b}{\left(\sum_{i=1}^{J} S_{im} + N_0 W\right)/W} \tag{4}$$

where β is the fraction of the total base transmit power devoted to user (traffic) channels, ϕ_m is the fraction of the user channel power allocated to user m, S_{0m} is the power received by user m from its base station (base 0), R_b is the data rate, S_{im} is the power received by user m from interfering base station i, N_0 is the thermal noise spectral density, and W is the bandwidth (equal approximately to R_c, the chip rate). A total of J interfering bases are counted. The numerator of (4) is simply the energy-per-bit for user m, $E_{b,0m}$. If we substitute $E_{b,im}R_b$ for S_{im} in the denominator (assuming all users transmit/receive at a common data rate R_b) and divide both the numerator and denominator of (4) by N_0, we obtain

$$\begin{aligned} \left(\frac{E_b}{N_0}\right)_{\text{eff},m} &= \frac{E_{b,0m}/N_0}{1 + \frac{1}{\text{PG}}\sum_{i=1}^{J}\frac{E_{b,im}}{N_0}} \\ &= \frac{\gamma_{0m}}{1 + \frac{1}{\text{PG}}\sum_{i=1}^{J}\sum_{k=1}^{M} E_{b,im}^{(k)}/N_0} \\ &\cong \frac{\text{PG}\gamma_{0m}}{\sum_{i=1}^{J}\sum_{k=1}^{M} E_{b,im}^{(k)}/N_0} \\ &= \frac{\text{PG}\gamma_0}{I_{0,m}/N_0} \end{aligned} \tag{5}$$

where we have defined $\gamma_{0m} = E_{b,0m}/N_0$ and the processing gain $\text{PG} = W/R_b$. The approximation applies when the system is interference limited, not thermal noise limited. The term $E_{b,im}^{(k)}$ is the interference energy-per-bit received by user m in cell 0, due to the power transmitted by base station i to its kth user. We assume M users in each cell. For simplicity, we compute an average $(E_b/N_0)_{\text{eff}}$, which is assumed the same for all users (giving them all the same BER). Also, for simplicity we assume $\gamma_{0m} = \gamma_0$ is the same for all users. Thus, $E_{b,im}^{(k)}/N_0$ is equal to γ_0 times the ratio of propagation path losses: $E_{b,im}^{(k)}/N_0 = \gamma_0(\psi_{ik}/r_{mi})^2$, where ψ_{ik} is the distance from the ith interfering base to its kth user and r_{mi} is the distance from the ith interfering base to user m in cell 0. This results from the forward channel power allocation assumption, wherein each mobile is allocated only enough power to satisfy its $(E_b/N_0)_{\text{eff}}$ (hence BER) requirement. Referring to Fig. 1(b), if we interchange the labels of the desired and interfering cells (and their base coordinates, points o and b_i), r_i in the figure becomes r_{mi}. The denominator of the last expression in (5) is the ratio of MUI to N_0 for user m

$$\frac{I_{0,m}}{N_0} = \gamma_0 \sum_{i=1}^{J} \sum_{k=1}^{M} \left(\frac{\psi_{ik}}{r_{im}}\right)^2. \tag{6}$$

For an average value of this quantity, we take an expectation, so

$$\begin{aligned}\left(\frac{I_{0,m}}{N_0}\right)_{\text{avg}} &= \gamma_0 E \sum_{i=1}^{J} \sum_{k=1}^{M} \left(\frac{\psi_{ik}}{r_{im}}\right)^2 \\ &= \gamma_0 \sum_{i=1}^{J} E\left(1/r_{im}^2\right) \sum_{k=1}^{M} E\left(\psi_{ik}^2\right) \\ &= \gamma_0 \sum_{i=1}^{J} E\left(1/r_{im}^2\right) M E\left(\psi_{ik}^2\right) \\ &= \gamma_0 M \sum_{i=1}^{J} \mu_i \end{aligned} \tag{7}$$

where the third line follows since the expectation of ψ_{ik}^2 is the same for all k and $\mu_i = E(1/r_{im}^2)E(\psi_{ik}^2)$. The term $M\Sigma\mu_i$ is essentially M times the forward channel outside-cell interference factor f_F. We can see this, via comparison with (1), as follows: if we substitute (7) into (5), divide out γ_0, then solve for M, we obtain

$$M = \frac{\text{PG}}{\left(\frac{E_b}{N_0}\right)_{\text{eff,avg}} \sum_{i=1}^{J} \mu_i} \tag{8}$$

which is the same as (1) with $1 + f$ replaced by $f_F = \sum \mu_i$ (again assuming no voice activity gain and omnidirectional antennas—both of which affect (1) and (8) in the same way). Strictly speaking, when taking expectation of the last expression in (5), Jensen's equality yields

$$\left(\frac{E_b}{N_0}\right)_{\text{eff,avg}} \geq \frac{\text{PG}_{\gamma_0}}{E\left(\frac{I_{0,m}}{N_0}\right)} \tag{9}$$

thus our result is an *approximate* lower bound.

As indicated by (7), we perform the averaging in two steps, over first the interfering cell (averaging over the user positions in that cell, essentially determining an average per-user interfering base transmit power) and then over the cell containing the desired user (averaging over the "victim" user position). [We note that, strictly speaking, since the control channels used in the forward channel (i.e., the "pilot," "sync," and "paging" channels in IS-95) must be broadcast with sufficient power to reach the cell edges, at distance $D_{\max} = \sqrt{R^2 + h^2}$, a few of the ψ_{ik} values are always equal to $D_{\max}$. This has only a minor effect on the final answer when $M > 20$ or so, hence, we ignore this effect here.] For the ith interfering cell, we first compute the expected value of ψ_{ik}^2. This is equal to the integral, over the volume of the ith cell, of the spatial user density times ψ_{ik}^2. With a uniform spatial user density $(1/(\pi R^2 h))$, the result of this integration is $(R^2/2 + h^2/3)$. Thus, $E[\psi_{ik}^2]$ becomes $(R^2/2 + h^2/3)$. We then take the expectation of r_{mi}^{-2}, times the indicator function $I(\text{RLOS} - r_{mi})$ and the user spatial density, over the desired user position in cell 0, to obtain f_{Fi}, the contribution of the ith cell to f_F. The total forward channel outside-cell interference factor f_F is then equal to the sum over the J interfering cells of the f_{Fi}. The expression for f_{Fi} is

$$\begin{aligned} f_{Fi}(h,R) &= \left(\frac{R^2}{2} + \frac{h^2}{3}\right) \frac{1}{\pi R^2 h} \iiint\limits_{V_0} \frac{I(\text{RLOS} - r_{mi})}{r_{mi}^2} r\, dr\, d\phi\, dz. \end{aligned} \tag{10}$$

We have computed f_F for the same grid of points (h, R) as used for the reverse channel, resulting in a set of 72 valid data points, a least-squares curve fit for which was found to be of the *same* form as that for the reverse channel [see (3)], with slightly different coefficients: $c_0 = 6.034$, $c_1 = 1.1126$, $c_2 = -1.9989$, $c_3 = 0.0466$, $c_4 = 0.1553$, and $c_5 = -0.179$. As seen by comparing the coefficients, the average value of f_F is very nearly the same as that of f_R.

C. Quasi-2-D Approach

For most true aeronautical (i.e., nonsatellite) cases of interest, aircraft altitudes are generally *much* smaller than RLOS: for aircraft altitudes from 1000 to 60 000 ft (0.3–18.3 km), RLOS ranges from approximately 44 to 345 mi (71–558 km); thus, the approximation $h \ll$ RLOS is reasonable. What this means is that, to first order at least, the problem can be approximated as a quasi-2-D one, just as in the terrestrial case.

In the quasi-2-D case, we use the same method, but compute f_R as an integral over the interfering cell area (as in [1]–[4]) and do this as a function of RLOS$/R$. For a fixed cell radius R, varying RLOS$/R$ corresponds to varying the maximum aircraft altitude; for a fixed value of RLOS (corresponding to a fixed maximum aircraft altitude), varying RLOS$/R$ corresponds to varying the cell radius R. The integral for any given cell is the same as that given, for example, in [1], augmented by the indicator function $I(\text{RLOS} - r_i)$. In the quasi-2-D case, we also compute the average outside-cell interference factor for a case where the CDMA system uses a 1/3 frequency reuse pattern and the worst case forward channel outside-cell interference factor for full reuse. The worst case forward channel factor applies to mobiles residing at the corners of hexagonal cells and thus provides an upper bound. In the quasi-2-D case, we have also found that the average forward channel outside cell interference factor f_F is very nearly the same as the average f_R when the path-loss exponent is $n = 2$. For path-loss exponents of three and four, f_F was found to be at least 87% and 76% of f_R, respectively.

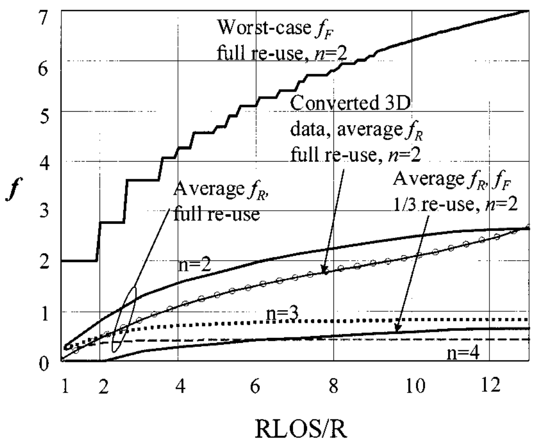

Fig. 3. Outside-cell interference factors versus RLOS$/R$ for the quasi-2-D analysis and converted 3-D data (circles). Average values shown for propagation path-loss exponents $n = 2, 3$, and 4 for full frequency reuse and for $n = 2$ and 1/3 frequency reuse. Worst case forward channel value shown for $n = 2$ and full frequency reuse.

For the worst case value of f_F, the procedure is simple: from the perspective of a mobile at a cell corner, we sum the contributions f_{Fi}, where f_{Fi} is due to the ith interfering base. Here $f_{Fi} = (\rho/r_i)^2 = (r/r_i)^2$, where r is the cell radius, since the mobile is at the cell corner, and r_i is the distance to the ith interfering base. A worst case value of f_R is less clearly definable—clustering all aircraft in all cells at their cell edges closest to a desired cell seems unrealistic. The quasi-2-D average values of f_R and the worst case value of f_F are plotted in Fig. 3 versus RLOS$/R$. For the same number of outside cells counted, the results in Fig. 3 agree with those presented in [1] and [2]. A least-squares fit to the average $n = 2$ values yields $f(\text{RLOS}/R) = \ln(\text{RLOS}/R) + 0.16$, where f is both f_R and f_F. A least-squares fit to the worst case forward channel f_F for $n = 2$ is $f_F = 2.3 \ln(\text{RLOS}/R) + 1$. The quasi-2-D computation overestimates the actual 3-D f_R by a fairly substantial percentage for small values of RLOS$/R$; for values of RLOS$/R$ larger than six, the quasi-2-D estimate is less than 30% larger than the 3-D value. The difference between the $(n = 2)$ 3-D and quasi-2-D values is always less than 0.5. This overestimation occurs because in the quasi-2-D model, portions of cell "volumes" that are below RLOS [see Fig. 1(a)] are incorrectly counted in the integral via the use of the indicator function. Nonetheless, the simple formula afforded by the quasi-2-D approach may be attractive.

III. Conclusion

In this paper, we have computed the outside-cell interference factor for an AG CDMA "cellular" like system. The outside-cell interference factor is used in the estimation of CDMA system capacity and applies for the case where the network of base stations is ground-based and the airborne spatial user distribution is uniform. We showed that the outside-cell interference factor for the nearly free-space propagation environment can be larger than that for typical terrestrial propagation models and can be approximated as a logarithmic function of both the cell height and radius. We also showed that a reasonable approximation to the 3-D outside-cell interference factor can be obtained using a quasi-2-D analysis. Using the quasi-2-D approach, we also computed the outside-cell interference factor for a 1/3 frequency reuse system and the worst case value for the forward (base-to-mobile) channel, corresponding to a user situated at a cell corner.

References

[1] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communication*. Reading, MA: Addison-Wesley, 1995.

[2] P. Newson and M. R. Heath, "The capacity of a spread spectrum CDMA system for cellular mobile radio with consideration of system imperfections," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 673–684, May 1994.

[3] G. R. Cooper and R. W. Nettleton, "A spread spectrum technique for high-capacity mobile communications," *IEEE Trans. Veh. Technol.*, vol. VT-27, pp. 264–275, Nov. 1978.

[4] J. Wang and L. B. Milstein, "CDMA overlay situations for microcellular mobile communications," *IEEE Trans. Commun.*, vol. 43, pp. 603–614, Feb./Mar./Apr. 1995.

[5] M. E. Johnson and G. D. Gierhart, "An atlas of basic transmission loss (0.125, 0.3, 1.2, 5.1, 9.4, 15.5 GHz)," National Technical Information Service, DOT Rep. FAA-RD-80-1, Springfield, VA, 1980.

[6] *Mobile Station–Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System*, TIA/EIA/IS-95-A, 1995.

[7] M. Schnell, "Hadamard codewords as orthogonal spreading sequences in synchronous DS CDMA systems for mobile radio channels," in *Proc. 3rd IEEE Int. Symp. Spread Spectrum Techniques & Applications, ISSTA '94*, Oulu, Finland, 1994, pp. 505–509.

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He was with the Rural Electrification Administration, Washington, DC, from 1983 to 1985, working on upgrading of specialized rural telecommunication systems. From 1985 to 1986, he was with the UMass LAMMDA Laboratory, where he worked on the full-wave analysis, design, fabrication, and testing of planar microwave transmission lines and antennas. From 1986 to 1989, he was with the Microwave Radio Systems Development Department, AT&T Bell Laboratories, North Andover, MA, where he worked on the analytical and empirical characterization of nonlinearities and their effect on QAM transmission. In 1990, he joined the University of Virginia's Communication Systems Laboratory, where his work focused on analysis of trellis coding and equalization for TDMA mobile radio systems, with additional study of CDMA. From 1994 to 1996, he was with Lockheed Martin Tactical Communication Systems, Salt Lake City, UT, where he was the Lead System Engineer on the development of a wireless local loop synchronous CDMA communication system. From 1996 to 1998, he was with MITRE Corporation, McLean, VA, where he worked on the analysis and modeling of various digital radio communication systems. He was with Lockheed Martin Global Telecommunications, Reston, VA, working on mobile satellite communication system analysis and design. He is now an Assistant Professor at the School of Electrical Engineering and Computer Science, Ohio University, Athens. His research interests are communication over fading channels, radio channel modeling, trellis coding, and CDMA.