JOURNAL OF AEROSPACE COMPUTING, INFORMATION, AND COMMUNICATION
Vol. 3, July 2006

TDMA and CDMA Capacities in Air-Ground Communications

David W. Matolak*
School of Electrical Engineering and Computer Science,
Ohio University, Athens, OH 45701

We evaluate the capacities of code division multiple access (CDMA) and time division multiple access (TDMA) schemes in an aeronautical environment. The model for the environment is a three-dimensional cellular arrangement, analogous to the two-dimensional model used for terrestrial cellular radio. The transmission schemes we consider are based upon those of terrestrial cellular, suitably modified to accommodate the unique requirements of pilot-to-controller communications in civilian air-to-ground communication settings. In accounting for the near free-space propagation of interference, we employ new parameter values required for the estimation of capacities in the aeronautical environment: the TDMA frequency re-use factor and the CDMA outside cell interference factor. Based upon the modified terrestrial cellular schemes and these new parameters, we show that if average interference is considered, CDMA capacity is largest. If worst-case interference is considered, the half-duplex TDMA capacity is comparable to the CDMA capacity when the CDMA system uses rebroadcast of air-ground transmissions in the ground-air link, but if this rebroadcast mode is not used, worst-case CDMA capacity is also larger than worst-case TDMA capacity.

I. Introduction

IN this paper we consider the application of CDMA and TDMA as multiple access techniques for use in the air-ground/ground-air (AG/GA) environment, specifically for voice communication between pilots and air traffic controllers. This paper builds upon previous work in[1,2]. Our investigation focuses on the computation of the capacity of a network of AG/GA voice communication links analogous in form to terrestrial cellular systems. In this network model, base stations (ground sites) are arranged in a fashion similar to that used in typical terrestrial cellular radio studies, i.e., at the centers of a set of tessellating hexagonal cells, and the mobiles (aircraft) move throughout the 3-dimensional (3D) "cells." For the model, we approximate the 3D hexagonal prisms by cylinders—the analog to the 2D approximation of hexagons by circles. In the 3D case, the base stations are centered at one end of the cylinder, i.e., on the earth's surface at the center of the cell. A similar geometric model was employed in.[3] This network model is a reasonable one for the Federal Aviation Administration's (FAA's) current AG/GA network, which is the basis for our study, but it could also be a model for other similar 3D applications. As with terrestrial cellular studies, the model is intended to aid in the comparison of the physical layer and multiple access performance of various alternatives; while actual cells are of course not uniform in size or shape, and actual user (aircraft) spatial distributions must be used for specific network evaluations, the study results do reveal the most important general features and relationships involved in such comparisons, and most significantly, describe the estimation procedure in this environment.

We define capacity in the usual way: the number of channels simultaneously available, with a given performance level, at any given ground radio site, per a given amount of bandwidth. Our results in[1] employed a quasi-2D analysis,

Received 13 December 2005; revision received 18 March 2005 and accepted for publication 12 April 2006.
* Associate Professor, School of Electrical Engineering and Computer Science, Ohio University, Athens, phone: 740.593.1241; fax: 740.593.0007; Email: matolak@ohiou.edu

and showed that the capacity comparison between TDMA and CDMA depended strongly upon several system parameters, even given the relatively simple geometric model. Here we employ the 3D results of[2] to improve the CDMA capacity estimations. The results in[3] favored the use of FDMA over CDMA, but the authors did not employ CDMA power control, which results in pessimistic estimates for CDMA. We also generalize the TDMA analysis to allow for multiple *tiers*[4] of co-channel interferers, whereas in[3] only a single tier of co-channel cells was considered.

The GA link from base to mobile, denoted the *forward channel*, is a point-to-multipoint link, and the AG links from mobiles to base, denoted the *reverse channel*, are multipoint-to-point links. In the AG/GA environment, radio communication is effected via links that are "line-of-sight" for the most part. The AG/GA channel is most accurately characterized as a Rician fading channel, with a time varying Rice factor that is typically large, e.g., 15 dB or more.[5] For simplicity, we approximate this Rician channel as an additive, white Gaussian noise (AWGN) channel. This approximation is a fairly good one for these Rice factors. For example, for a Rice factor of 15 dB, the probability of a fade greater than 3 dB is less than 10^{-2}, and deeper fades are even less likely. In terms of signal-to-noise ratio and error probability performance, for a bit error ratio (BER) of 10^{-3} (more than adequate for voice transmission) with binary phase shift keying (BPSK) modulation, the $K = 15$ dB Rician channel requires approximately only 0.5 dB larger signal-to-noise ratio than that required for this BER on the non-fading AWGN channel. Hence our approximation of the AWGN channel is a good one. In the context of,[5] our study focuses primarily on the "en-route" and "arrival" phases of flight.

We also do not incorporate channel dispersion into our channel model, as this impairment, primarily the result of multipath propagation, is significant mostly for low-elevation-angle links. We reserve incorporation of this channel feature for future work. A channel phenomenon we do account for is the large increase in transmission loss as the radio wave path from transmitter to receiver exceeds the radio line of sight (*RLOS*).[6] From,[6] we can easily deduce that as the distance approaches *RLOS*, the path loss exponent n increases from approximately two, representing essentially free-space propagation, to a very large value, roughly 18 or more. The path loss exponent n is the exponent for distance d in the relationship between received power p_r and transmitted power p_t: $p_r \propto p_t/d^n$. This rapid increase in radio signal attenuation as distance exceeds *RLOS* is approximated in our case as being a near-infinite attenuation. The propagation environment is thus modeled as that of free-space up to *RLOS*; beyond that no propagation occurs.

Just as in the land mobile case, we have a number of air traffic control (ATC) ground sites throughout our region, each of which "covers" a volume in space. As an aircraft moves through these volumes, it establishes communication with the ATC site responsible for the volume in which it is flying. In the current analog system, each ATC site is associated with one or more *frequency protected service volumes* (FPSVs), which can be described as the volume in space allocated, by frequency division, to that ATC site. These FPSVs are also known as *sectors*, and we use this term henceforth. Our "cells" contain multiple sectors.

In the next section we provide a summary of the current system for background purposes, a short discussion of some unique constraints required of any new AG/GA system, and a brief description of the cellular geometry. We also describe the set of system parameters we use for the TDMA and CDMA systems under consideration. In Section III we discuss the CDMA capacity estimation method, and in Section IV we describe the TDMA capacity estimation method. Section V provides some comparison results, and Section VI contains conclusions.

II. Background

Because of the unique nature of the AG/GA communication environment, we provide in this section some background descriptions of the current analog communication system and some of the unique requirements of the AG/GA setting. We also briefly describe the model geometry we use; additional detail on this model is given in.[2]

A. Current Analog FDMA System

The current system for civilian AG/GA voice communications is based on frequency division of the 118 to 137 MHz VHF aeronautical communications band into 25 kHz channels. Each channel may be assigned to AG/GA "two-way voice," or to ground-to-air broadcast. The two-way voice mode is half-duplex, since a single FDM channel is used, with communication only in one direction at a time. In some references (e.g.,[3]), this is termed "simplex," which strictly means communication in one direction *only*.[9] There are 760 total channels in this band; of these, 530 are available for air traffic control in the United States. Each sector is assigned a unique 25 kHz frequency channel, which allows for the roughly 6 kHz analog AM signal plus substantial guard bands to account for frequency offsets and Doppler shifts, and to reduce adjacent channel interference.† Each sector is most often controlled by a single air traffic controller, thus in a sense limiting the maximum number of aircraft contained within a sector. Aircraft are *not* prevented by the communication system from entering a sector at any time—the sectors are designed, based on flight routes, to yield peak aircraft numbers per sector on the order of 20.

We also note that there can be more than one sector per controller, for example during late-night hours when sectors are combined, and also more than one controller per sector, for example during peak traffic hours, but the 1-sector/1-controller situation is most common. One channel is reserved as a continental United States (CONUS)-wide emergency channel. Most channels are used more than once within CONUS, with geographic separation providing isolation between the voice channels that share it, just as frequency re-use is applied in terrestrial cellular. The sectors are engineered to yield channels that are susceptible to a minimal amount of interference from other sectors. The minimum required signal-to-interference ratio (SIR) of this analog waveform is 14 dB.[3]

B. New System Considerations

In comparison to terrestrial cellular systems, the market for aeronautical radios is small. Because of this constraint, any new aeronautical system that is deployed will have to be very cost effective. For this reason, we base our analysis upon terrestrial cellular standards, for which a large technology base exists. This existing technology, suitably modified for the aeronautical application, would be economically attractive. As an ancillary benefit of this choice, we can make use of the large amount of research done on terrestrial cellular systems for our analysis.

The single most unique requirement of the AG/GA communication system is the requirement for “party line” communication within a sector. This requirement means that all aircraft within a sector must be able to hear each others’ transmissions, so aircraft transmissions can be viewed as both AG and peer-to-peer broadcast AA. There are two related operational reasons for this requirement: (1) the need for communicators to know when a circuit (channel) is “busy” since there is most often only a single controller per sector; and, (2) the desire for pilots to maintain “situational awareness”.[7] In the current half-duplex analog system, and the proposed half-duplex TDMA system,[8] this is achieved by assigning a single frequency channel (and time slot for TDMA) to a sector, over which all communication will occur. Pilots will “tune” their radios, both transmitters and receivers, to this frequency/time slot, and operate in a “listen before push-to-talk” (LBPTT) mode. For a given frequency/time slot then, the multiple access protocol is similar to the network protocol *carrier sense multiple access* (CSMA).[9] Within the LBPTT framework, a number of aircraft time-share the available channel, so only one of these users is occupying a channel at any given time. The number of actual aircraft within a sector is thus greater than the number of channels provided to that sector, since there are several aircraft—usually no greater than 20—sharing a single channel within a sector. Any new system must allow the LBPTT operation mode.

For economic reasons, any CDMA scheme would likely be based upon those employed for cellular radio, i.e., the IS-95 standard,[10] and as such, would likely use frequency division for the uplink and downlink channels. Given this constraint, to achieve the party-line operation, we presume that AG transmissions will be *re*broadcast from the ground site transmitter to its assigned sector. This method has the effect of increasing the forward link traffic, and will prove to be a limiting factor in some situations. In order to ensure timely “situational awareness,” the delay of this rebroadcast must be minimal. Discussion of this delay issue is outside the scope of this work. We also presume that the CDMA system will also operate on a sector basis, in which each sector is assigned a unique code, analogous to the unique frequency/time slot assignments of the other schemes. Similar to the other schemes, we refer to a channel and circuit interchangeably, and for CDMA, a channel is a unique signature sequence, or spreading code.

An alternative method to rebroadcast for achieving the party-line connectivity is the use of additional aircraft receiver hardware. In this approach, aircraft would be equipped with transmitters for the downlink, and receivers capable of detecting both downlink and uplink transmissions simultaneously. This approach avoids any rebroadcast delays, but requires that the cost of this functionality reside in the aircraft avionics instead of the ground site. We focus on the rebroadcast method for this reason.

† In some regions, e.g., Europe, the channelization has recently been altered by division of the 25 kHz channels into three 8.33 kHz channels.

We treat the party line connectivity as a requirement, satisfied by the half-duplex mode in the TDMA systems, and via re-broadcast from the ground sites in the frequency-division duplex CDMA system. The systems are "interference limited," not power limited; for a good discussion of signal-to-interference requirements—both co- and adjacent-channel—see.[3] We also presume a "listen-before-push-to-talk" protocol on any given shared channel—either a TDMA time slot or CDMA spreading code. This follows the current FAA network example, where short messages—most less than 5 seconds in duration—form the vast majority of the communication traffic and a spatial group of users time-shares any channel.

C. System Geometry

A cross-sectional diagram of the basic geometric model is shown in Figure 1(a), where altitudes are exaggerated for illustration. In this figure, aircraft are shown at the edges of their respective cells. Figure 1(b) shows the plan view for the two cells. The *RLOS* indicated in Figure 1(a) applies to a half-duplex system where air-to-air interference can exist; for the full-duplex case the relevant *RLOS* is that between a different-cell base and mobile.

As noted, in the AG/GA environment, radio communication is accomplished primarily via LOS links, and for simplicity, we approximate the channel as an AWGN channel. The propagation model is that of free-space, so the propagation path loss exponent is two. Also for ease of analysis, we model the AG/GA system as a 3D "cellular" system. The standard cellular layout is shown in Figure 2. This figure is a plan view, which suppresses the vertical dimension. It shows the reference cell at the center, and six surrounding "rings" of "outside" cells. We take the vertical dimension into account by making our analysis parametric in *RLOS*. For a link between antennas at altitudes h_1 and h_2, simple trigonometry yields

$$RLOS \cong \sqrt{2kr_e}\left(\sqrt{h_1} + \sqrt{h_2}\right) \tag{1}$$

where r_e is the radius of the earth and k is a constant, typically equal to $4/3$, that accounts for refraction in the lower atmosphere. Equation (1) is a simple extension of equation (1) in.[3] The circle of radius $RLOS = 5R$ in Figure 2 shows the area "visible" to an aircraft directly above the center of the reference cell. Altitudes are typically much smaller than *RLOS* values, so viewing the environment in two dimensions is quite reasonable, but has the effect of slightly overestimating outside-cell interference propagation; as noted in,[2] this is because the *RLOS* acts to "cut off" a low-altitude portion of the cylinder along the earth's surface and farthest from the interfered-with receiver. Note also that Figure 2 highlights an additional tier of co-channel interferers; these additional tiers of co-channel cells are typically neglectable in terrestrial communications where path loss exponents are larger ($n = 3$ or 4), but the effects of these tiers are not neglectable in the aeronautical environment.

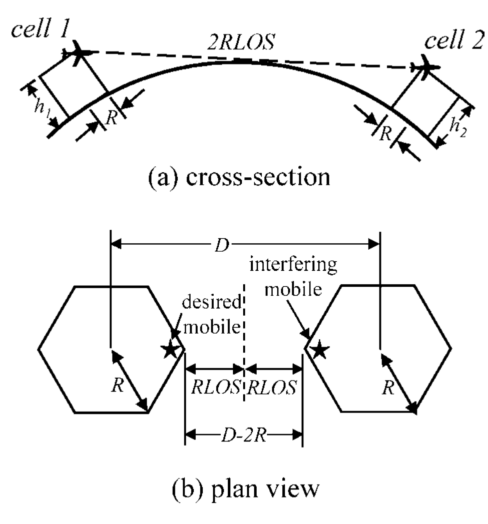

Fig. 1 *RLOS* & cell dimensions for half-duplex communication system (a) cross-section, (b) plan view.

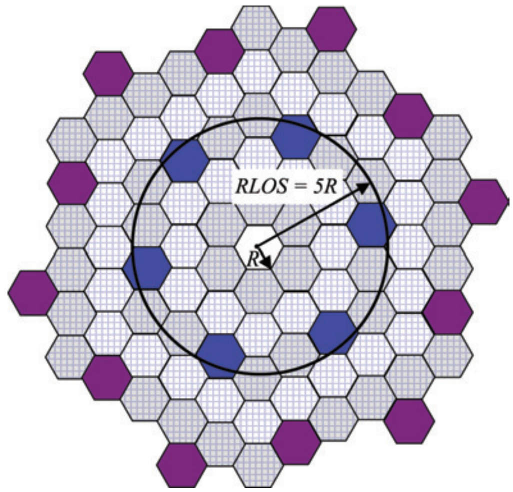

Fig. 2 Canonical uniform cellular system geometry. *RLOS* = 5 *R* circle shown. First two tiers of co-channel cells for re-use $f_{RU} = 7$ shown darkened.

Hexagonal prism cells are approximated by cylinders with the same volume ($R_{circle} \cong 0.9094\ R_{hex}$). Although equi-received-power surfaces around the base station's typically 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, and in the vertical direction in effect by virtue of a maximum aircraft altitude.

In Sections III and IV we discuss computation of key parameters required for capacity computation—the frequency re-use factor f_{RU} for TDMA, and the outside cell interference factor f for CDMA. We have only 2D—actually quasi 2D—values for the re-use factor f_{RU} for TDMA, whereas for CDMA we have quasi-2D, and 3D values for the outside-cell interference factor f. Because of this, the capacity comparisons in Section V are quasi-2D. For completeness and clarity, we define these terms:

- 2D pertains when the entire model assumes a 2D environment, like the plan view of the typical hexagonal cellular layout in Figure 2. No altitude dimension is considered. This is what is used in the cellular case, e.g., in.[13]
- quasi-2D pertains when the cell altitude is taken into account, but is done parametrically. Here, and in[3] this is done through the use of $RLOS/R$, since $RLOS$ is related to altitude. All the capacity comparisons here use the quasi-2D factors.
- 3D pertains when the altitude is left as an independent variable, as in[2] and in the CDMA capacity plot here in Section V.

D. Key System Parameters

Both candidate digital systems considered are based upon a terrestrial cellular counterpart. For TDMA, we consider a system based upon the cellular IS-136 standard,[11] which uses $\pi/4$-DQPSK modulation and a 30 kHz channel separation. We analyze both full and half-duplex TDMA versions. The voice bit rates available for the TDMA systems are 8 and 4 kbps, corresponding to 3 and 6 time slots per RF channel, respectively. Based upon this modulation and the IS-136 FEC coding scheme on an AWGN channel, including implementation loss of 1 dB, we use a required E_b/N_0 of 5 dB for the TDMA system for a target $BER = 10^{-3}$. The required value of 5 dB for the E_b/N_0 was obtained as follows: for the rate-1/2, constraint-length-6 code used, AWGN channel performance can be estimated using well-known techniques such as the transfer function bound,[16] or from plots obtained from this approach. The E_b/N_0 value for $BER = 10^{-3}$ is approximately 3 dB, which applies for coherent detection. We then add 1 dB for the differential detection,[4] and another 1 dB of implementation loss to yield the required value of 5 dB.

For CDMA, we consider an IS-95 based system,[10] with bit rate of 4.8 kbps. The bandwidth and FEC for the CDMA system are the same as that of IS-95. We also assume a voice activity factor of α (<0.5) for the CDMA reverse channel, and twice this value for the forward channel due to the rebroadcast function used to support party-line connectivity.

The required E_b/N_0 for the IS-95-based system for the target $BER = 10^{-3}$ is 5.5 dB for the reverse channel and 3.2 dB for the forward channel, again based upon the AWGN channel modulation and FEC performance, and including 1 dB of implementation loss, as in the TDMA case. For the coherently-detected forward channel E_b/N_0, the rate-1/2, constraint-length-9 code requires approximately 2.2 dB for $BER = 10^{-3}$.[16] Adding 1 dB of implementation loss yields the 3.2 dB value we use.

In the case of the reverse channel, the analysis is slightly more involved, but straightforward. The reverse-channel modulation is 64-ary orthogonal, and detection is noncoherent. From a typical text (e.g.,[16]), we can find the symbol error probability for this scheme as a function of the symbol energy to noise density ratio E_s/N_0. These 64-ary code symbols are translated to 6-bit words, and in orthogonal modulation, the probability of bit error is approximately one-half the probability of a symbol error. The bits from these demodulated 6-bit words are the code symbols into the FEC decoder. Given the code rate of 1/3, and its AWGN performance (via transfer function bound or plots, e.g., from[16]), we can easily determine that for a decoder output $BER = 10^{-3}$, the code symbol input error probability $P_s \cong 0.16$, and for this value of code symbol error rate, we find that the required code symbol energy to noise density ratio E_s/N_0 is approximately −0.2 dB. Since there are three code symbols per decoded information bit, the bit energy to noise density ratio is $10\log(3)$ dB larger than this, or approximately 4.5 dB. Adding 1 dB of implementation loss gives the 5.5 dB required E_b/N_0.

Although the GSM cellular system is much more widely used than either of these systems, its performance should be quite comparable to that of an IS-136-like TDMA system. In the terrestrial cellular environment, the IS-136 type systems have even been reported to yield larger capacities than GSM.[12] Many of the key waveform parameters for the two systems are listed in Table 1. Additional explanation is given in subsequent sections.

Lastly, we note that for both systems, *hard handoff* is assumed because it represents the most 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 seconds.[7] 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.

Table 1 Key waveform parameters for CDMA and TDMA systems.

CDMA System		TDMA System	
Forward channel modulation	BPSK data, QPSK spreading, 64 orthogonal spreading codes (1/user)	Forward channel modulation	DQPSK
Reverse channel modulation	BPSK data QPSK spreading (1 code shift/user), 64-ary orthogonal symbols,	Reverse channel modulation	DQPSK
Duplex method	Full duplex (frequency-division)	Duplex method	Half duplex
Total bandwidth B_T	2.5 MHz	Total bandwidth B_T	2.5 MHz
Chip rate R_c	1.2288 Mcps	Voice bit rate R_b	4 and 8 kbps
Voice bit rate R_b	4.8 kbps	# Timeslots N_s	6 and 3
Processing gain PG ($=R_c/R_b$)	256	Channel bandwidth B_c	30 kHz
FWD channel # codes P_{HF}	64	Channel symbol rate R_s	24 ksps
Forward Error Correction	$K = 9$ convolutional; $r = 1/2$ (forward), $r = 1/3$ (reverse)	Forward Error Correction	$K = 6$ convolutional $r = 1/2$
Target BER	10^{-3}	Target BER	10^{-3}
Baseline SNIR $\gamma_{eff,req}$	5.5 dB reverse, 3.2 dB forward	Baseline SNIR $\gamma_{eff,req}$	5 dB

III. CDMA Capacity

A. Capacity Formulas

The forward CDMA channel is synchronous, and the reverse channel asynchronous, just as in cellular applications.[13] The CDMA capacity is thus the minimum of the forward and reverse channel capacities. In contrast to terrestrial cellular systems, in the AG/GA environment CDMA can easily be forward channel limited. This is due to the larger value of "outside-cell" multiuser interference (MUI) that arises from the near free-space propagation environment—co-channel interference is not attenuated with distance as rapidly as in non-LOS terrestrial environments, so in worst-case locations, forward channel interference can be much larger than in the terrestrial case. In,[14] the authors estimated forward channel capacity via a quasi-analytical technique that required computer simulation due to the ranked lognormal fading random variables involved in estimating forward channel interference; in the non-fading AG/GA case the average forward channel interference can be obtained analytically.[2]

The asynchronous reverse channel capacity formula, for a cell with no antenna sectoring, i.e., omni-directional base station transmit antenna patterns, is given by

$$M_R = \frac{PG\beta}{\gamma_{eff}\,\alpha_R(1+f_R)10^{1.15[(\sigma_R/10)^2]}} \tag{2}$$

where $PG = R_c/R_b$ is the processing gain, with R_c the chip rate and R_b the bit rate, γ_{eff} is the required target E_b/N_0 (equal to $E_b/(N_0 + I_0)$, with I_0 the *MUI* energy) for a given BER, α_R is the reverse channel voice activity factor, f_R is the reverse channel outside-cell interference factor, and σ_R is the reverse channel power control standard deviation, in dB. We do not include the effect of directional antennas first for simplicity, and second, because at least in initial deployments, the economic constraints could prohibit their use, particularly if 3-dimensional sectoring were required.

The formula in (2) is identical to the formula of Viterbi,[13] (eq. (1.5)), with the inclusion of the non-ideal power control term that is a function of σ_R, and the inclusion of the factor β. The parameter $\beta = 1 - \gamma_{eff}/\gamma = I_0/(N_0 + I_0)$, where γ is the *thermal* E_b/N_0; β is usually close to unity except in power limited systems (e.g., satellites). The formula in (2) is also easily and directly derived from the E_b/I_0 formula of[13] (eq. (2.35)) as follows: multiply the *MUI* term I_0 in that formula by the voice activity factor α_R, the outside-cell interference term $1 + f_R$, and the factor involving σ_R, then solve the E_b/I_0 formula for M_R. (This is how eq. (1.5) of[13] is obtained.) Equation (2) also allows for an access channel; that is, if the access channel were counted as a traffic channel, we must add one to (2). The power control term involving σ_R is the mean value of the random variable which multiplies the target *effective* E_b/N_0—see,[13] (eq. (6.57))—and assumes a log-normal distribution for the received *effective* E_b/N_0. This is a reasonable model for the reverse channel power control effect on E_b/N_0, where power adjust commands from the base are in dB units.

The forward channel is synchronous, and for a single cell, with orthogonal sequences for all users, the capacity is limited by the number of sequences, not by *MUI*. In a multiple-cell case, as the number of users increases, the asynchronous outside-cell interference becomes non-negligible, so the forward channel must be treated as an asynchronous channel. The forward channel capacity is thus given by

$$M_F = \min\left\{P_{HF} - 3,\ \frac{PG\beta}{\gamma_{eff}\,\alpha_F f_F} - 2\right\}, \tag{3}$$

where P_{HF} is equal to the number of available Walsh–Hadamard sequences on the forward channel (64 in IS-95), and PG, β, γ_{eff}, α_F, and f_F are as defined for the reverse channel. We assume accurate power allocation on the forward channel. We also subtract out the "pilot," "sync," and "paging" channels used by the aircraft for acquisition, addressing, and the gathering of system parameters needed for transmission and reception, which accounts for the "−3" and "−2" factors in (3). The usable CDMA system capacity is the minimum of (2) and (3), i.e.,

$$M_{CDMA} = \min\left\{\frac{PG_R\beta_R}{\gamma_{eff,\,R}\,\alpha_R(1+f_R)10^{1.15(\sigma_R/10)^2}},\ \min\left[P_{HF} - 3,\ \frac{PG_F\beta_F}{\gamma_{eff,\,F}\,\alpha_F f_F} - 2\right]\right\}. \tag{4}$$

B. Outside Cell Interference Factor

Most of the parameters in (2) and (3) are either given, or assumed or estimated for the environment under consideration. In addition to the parameters previously described, we assume $\beta \cong 1$ (implying each link has sufficient transmit power so that thermal noise is negligible in comparison with multi-user interference). We evaluate capacity versus cell size, relative to *RLOS*. This relation is predominantly embodied in the parameter *f*, which is the ratio of per-user outside-cell interference power to (desired) per-user in-cell power (see (2) and (3)). As cell size increases, *RLOS* increases, and more outside cells are "in view." This has the effect of increasing *f*. We normalize *RLOS* by cell radius *R*, and consider both average and worst-case values for f versus $RLOS/R$.

In evaluating f in,[2] we counted up to seven rings of cells surrounding the reference cell (see Fig. 2), which corresponds to a maximum value of $RLOS/R$ of approximately 12, and 168 total interfering cells. As found there, the average forward channel outside cell interference factor f_F is very nearly the same as the average reverse channel factor f_R.

The results for average f as a function of cell height h and radius R are given by[2]

$$f(h, R) = c_0 + c_1 \ln(h) + c_2 \ln(R) + c_3[\ln(h)]^2 + c_4[\ln(R)]^2 + c_5 \ln(h)\ln(R), \tag{5}$$

with coefficients $c_0 = 6.1226$, $c_1 = 1.0856$, $c_2 = -1.99$, $c_3 = 0.0482$, $c_4 = 0.1517$, and $c_5 = -0.1724$, for the reverse channel; and $c_0 = 6.034$, $c_1 = 1.1126$, $c_2 = -1.9989$, $c_3 = 0.0466$, $c_4 = 0.1553$, $c_5 = -0.179$, for the forward channel. In (5), h and R are in km. Equation (5) is a full 3-dimensional average outside-cell interference factor. Since for the TDMA case we have only quasi-2D reuse factors, for the purpose of fair capacity comparisons, we can't employ (5), but must use its quasi-2D equivalent. From,[2] for the average case, this is given by

$$f(RLOS/R) = \ln(RLOS/R) + 0.16. \tag{5a}$$

To compute the worst-case value of f_F, the procedure is simple: from the perspective of a mobile at a cell corner or edge, we sum the contributions f_{Fi}, where f_{Fi} is the interference-to-desired power ratio due to the i^{th} interfering base. Here $f_{Fi} = (R/r_i)^2$, where R is the cell radius, since the mobile is at the cell corner, and r_i is the distance to the i^{th} interfering base. A worst-case value of f_R is less clearly definable–clustering all aircraft in all outside cells at their cell edges closest to a desired cell is unrealistic.

In[2] we showed the actual worst-case f_F, for which a least-squares fit as a function of $RLOS/R$ is $f_F = 2.3\ln(RLOS/R) + 1$. We also note that the quasi-2D computation of f_R (5a) applied in[1] overestimates the actual 3D f_R by a fairly substantial percentage for small values of $RLOS/R$, but the difference between the 3D and quasi-2D values is always less than 0.5. These interference factor values are all for the case of hard handoff; even if soft handoff were to be considered, with accurate power control, feasible in near-line-of-sight propagation environments, the difference in the outside cell interference factor between the hard and soft handoff cases is negligible (see,[13] Tables 6.1, 6.2 and 6.3).

IV. TDMA Capacity

A. Capacity Formula

In the TDMA case, the capacity formula is substantially simpler. For our half-duplex case we have, from[4] (Chapter 1),

$$M_{TDMA} = \frac{B_T N_s}{B_c f_{RU}}, \tag{6}$$

where B_T is the total system bandwidth, B_c is the bandwidth per channel, and N_s is the number of time slots per channel. The full-duplex (frequency division) formula is the same as the above but with B_c replaced by $2B_c$. The parameter f_{RU} is the frequency re-use factor, equal to the number of subsets into which the total bandwidth must be divided to ensure adequately small co-channel interference (CCI) when frequency channels are allocated to cells. Valid values for f_{RU} in a regular hexagonal tessellation are given by $f_{RU} = i^2 + j^2 + ij$, with *i, j* nonnegative integers.[4] For land mobile cellular systems, f_{RU} is typically 7.[11] In the AG channel, because we have near free-space propagation, the value of f_{RU} can be *significantly* larger, and it is the determination of this factor as a function of required S/I that is key to TDMA capacity estimation, analogous to the determination of f_R and f_F in CDMA. Our computation of f_{RU} is also parametric in $RLOS/R$.

B. Frequency Re-use Factor

The derivation of the required value of f_{RU} as a function of $RLOS/R$ amounts to accounting for two conditions: (1) either f_{RU} must be large enough to keep all co-channel interferers beyond $RLOS$, so that CCI does not propagate to co-channel cells at all, or (2) it must be large enough to ensure satisfaction of the target S/I value when all interferers within $RLOS$ are accounted for. We discuss the two conditions and their corresponding equations, then summarize the computation procedure.

For small values of $RLOS/R$, only the first "ring" of surrounding cells is visible, so $f_{RU} = 7$ is sufficient for full-duplex, and $f_{RU} = 3$ for full-duplex. As $RLOS/R$ increases, additional "rings" of surrounding cells become visible. Hence, in the half-duplex case, as in Figure 1(b), to keep co-channel cells *beyond RLOS*, we require that

$$RLOS \leq (D - 2R)/2 \tag{7}$$

where D is equal to the distance between co-channel cell centers. From,[15] we have

$$D = R\sqrt{3 f_{RU}} \tag{8}$$

for a regular hexagonal cellular arrangement, so combining these two equations, we obtain the following inequality for the value of f_{RU} required to keep all co-channel cells beyond $RLOS$:

$$f_{RU} \geq \frac{4(RLOS/R + 1)^2}{3}. \tag{9}$$

Equation (9) applies to the half-duplex case; the full duplex case is obtained by replacing the "4" by "1," since the requirement in that case is $RLOS \leq D - R$ for base-to-mobile or mobile-to-base interference. For a large enough value of f_{RU}, co-channel cells will be sufficiently separated to allow the S/I criterion to be met. In the regular tessellation, the m^{th} "tier" of interfering cells contains $6\,m$ co-channel cells[15] (see Fig. 2). For most of the values of $RLOS/R$, only the first tier needs to be considered, since higher-level tiers are at distances on the order of *2D*; when these tiers are visible, the S/I is calculated and an appropriate f_{RU} computed numerically. Assuming that all mobiles use the same transmit power when at their respective cell edges, when the 6 co-channel cells in the first tier each contain an interferer at distance D_I, we have

$$S/I = D_I^2/(6R^2). \tag{10}$$

At the point where $RLOS$ is just large enough for the interfering transmissions to reach a desired user, in the half-duplex case we have from Figure 1 that $D_I = D - 2R = 2RLOS$. Using $D - 2R$ for D_I in (10), employing (8), and using values in dB, setting $(S/I)_{dB} \geq (S/I)_{\min,dB}$, we can again solve for f_{RU} to allow the S/I criterion to be met with the six first-tier co-channel interferers

$$f_{RU} \geq \frac{1}{3}\left[(\sqrt{6})10^{(S/I)_{\min,dB}/20} + 2\right]^2. \tag{11}$$

The corresponding full-duplex equation is $f_{RU} \geq \frac{1}{3}[(\sqrt{6})10^{(S/I)_{\min,dB}/20} + 1]^2$. If only k out of the 6 co-channel cells contain users who are both within $RLOS$ and active at the same time as our desired user, $\sqrt{6}$ becomes $\sqrt{k}$ in (11). We consider the cases where $k = 1$ and $k = 6$, and denote these as single-interferer-per-tier, and worst-case, respectively. We also compute f_{RU} for a value of $k = 2.4$, corresponding to the 40% voice activity factor used in CDMA. We note that the "average" naming convention is not in general accurate—an actual average value for k would be calculated based upon an actual voice activity factor as well as an average number of co-channel users.

An additional modification to (11) is worth discussion. If the reference user is not at the cell edge, but is at radius aR, where $0 \leq a \leq 1$, (11) becomes for our half-duplex case

$$f_{RU} \geq \frac{1}{3}\left[\sqrt{k}10^{(S/I)_{\min,dB}/20} + 1 + a\right]^2, \tag{12}$$

The corresponding full-duplex equation, with the airborne reference user at aR, is $f_{RU} \geq \frac{1}{3}[(\sqrt{k})10^{(S/I)_{\min,dB}/20} + a]^2$. The use of the factors k and a allow for the development of "average" re-use factors, analogous to the average interference factors of CDMA. While system performance in this AG/GA system is likely to be based upon worst-case and not average values, the general procedure is still of interest.

To account for additional tiers of co-channel interferers, we use the equation

$$(S/I)_{\min} = \frac{1}{\sum_{m=1}^{N_t} \sum_{n=1}^{6m} R^2/D_{nm}^2} \cong \frac{1}{\sum_{m=1}^{N_t} g(k,m)/[h(m,\, f_{RU})]^2} \tag{13}$$

where N_t is the number of tiers considered, and D_{nm} is the distance between the n^{th} interferer of the m^{th} tier to the reference user at the cell edge R. The approximation occurs in the estimation of the distance D_{nm}: we assume all users in a given tier have a common distance D_m, and that this common distance is equal to the minimum possible distance of any user in any cell of the given m^{th} tier. The function $g(k, m)$ is equal to km, where $k \in \{0, 1, \ldots, 6\}$ is the number of interferers per 6 possible, and m is the tier index. The distance function $h(m,\, f_{RU})$, which is equal to (D_m/R), is easily found from the hexagonal geometry as

$$h(m,\, f_{RU}) = \begin{cases} \sqrt{3 f_{RU}(m^2 - m + 1)} - 2, & \text{half-duplex} \\ \sqrt{3 f_{RU}(m^2 - m + 1)} - 1, & \text{full-duplex} \end{cases} \tag{14}$$

which is applicable for $m \le 4$, which encompasses all of our results.

When (14) and (13) are used with $N_t > 1$, f_{RU} must be found numerically. Using Figure 1(b) and the distance approximation used in (14), we determine that the m^{th} tier is within $RLOS$ when

$$RLOS/R = \eta\sqrt{3 f_{RU}(m^2 - m + 1)} - 1,\ \eta = \begin{cases} 1/2, & \text{half-duplex} \\ 1, & \text{full-duplex.} \end{cases} \tag{15}$$

The procedure used for finding the required f_{RU} is summarized as follows, for the half-duplex case. The full-duplex procedure is directly analogous, with the appropriate full-duplex formulas replacing their half-duplex counterparts.

1. The minimum value of $RLOS/R$ is 1. Beginning with $RLOS/R = 1$, compute f_{RU} vs. $RLOS/R$ using (9), rounded up to the next valid value ($f_{RU} = i^2 + j^2 + ij$, with i, j nonnegative integers) if needed.
2. Increase $RLOS/R$ and continue using (9), rounding up, until f_{RU} reaches the value given by (12) for the desired minimum value of S/I. In (12), use $a = 1$ for the worst-case condition. This value of f_{RU} is sufficient to yield the minimum value of S/I with a single tier of co-channel interferers, and is valid for $RLOS/R$ up to the value where the second tier of co-channel interferers becomes visible.
3. For the value of f_{RU} found from (12) in step #2, use (15) to determine the value of $RLOS/R$ where the second tier becomes visible with this value of f_{RU}.
4. Solve (13) numerically with $N_t = 2$ to find the next required value of f_{RU}. This value is then sufficient until the 3rd tier becomes visible (the $RLOS/R$ for this is found using (15) again), at which point we use (13) again with $N_t = 3$, and so on.

Values for f_{RU} for the half-duplex and full-duplex cases were computed using this procedure, and are plotted versus $RLOS/R$ in Figure 3 for several values of the parameter k and a required S/I of 5 dB. For comparison, in Figure 4, we plot the half-duplex f_{RU} versus $RLOS/R$ for two different S/I values, $(S/I)_{\min} = 16$ dB and 7 dB, and with $k = 6$, 2.4, and 1 co-channel interferer (out of $6k$ possible per tier). In this figure, the curved portion, corresponding to (12), represents a lower bound to f_{RU}.

To point out the effect of considering multiple tiers of interfering cells, consider the worst-case half-duplex plot in Figure 3, which is the solid line with the largest values, labeled "*HD*, $k = 6$." With $f_{RU} = 16$ for $2.46 \le RLOS/R \le 5.5$, the second tier becomes visible at $RLOS/R = 5.5$, at which point we must solve (13) with $N_t = 2$ to find the next valid value of f_{RU}, equal to 19. Similarly, with $f_{RU} = 19$, the 3rd tier becomes visible at $RLOS/R = 9.5$, at which point we solve (13) again. Hence, the effect of multiple tiers directly causes f_{RU} to increase as $RLOS/R$ increases.

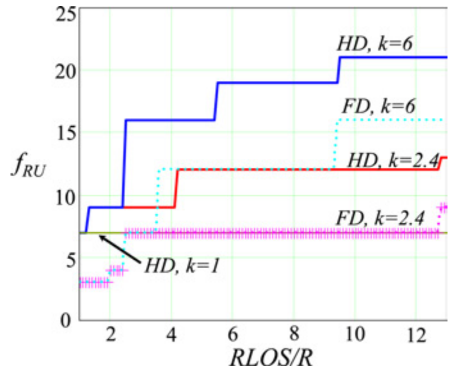

Fig. 3 Frequency re-use factors vs. $RLOS/R$ for the TDMA system, for required $S/I = 5$ dB; $k =$ # co-channel interferers within $RLOS$ out of 6 possible, per tier.

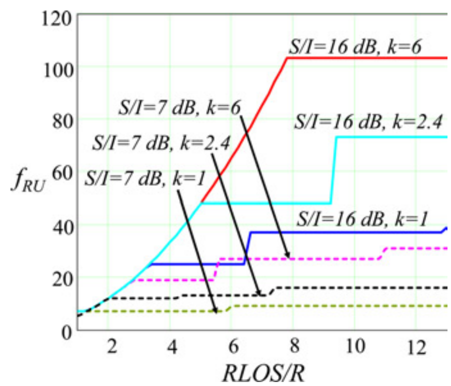

Fig. 4 Required values of re-use factor f_{RU} versus $RLOS/R$ for the half-duplex case, for required S/I values of 16 dB and 7 dB, and $k = 6, 2.4$, and 1 co-channel interfering users per 6 possible co-channel interfering users per tier.

V. Capacity Results

To illustrate the effect of the outside-cell interference factor upon CDMA capacity in this 3D environment, we show in Figure 5 a plot of M_{CDMA} vs. cell height h and cell radius R, both in km. The CDMA system parameters are those given in Table 1, and the 3D f is computed using (5). The reverse-channel voice activity factor is $\alpha_R = 0.4$ (and $\alpha_F = 2\alpha_R = 0.8$), and the power control standard deviation is $\sigma = 2$ dB. The maximum value of capacity for this example is 61, which is the forward channel sequence limit of 64 Walsh–Hadamard sequences minus the three signaling channels. As shown, for a fixed value of R, as h increases, $RLOS$ increases, and additional interference from outside cells decreases capacity. Equivalently, for a fixed value of h, as R decreases, $RLOS/R$ increases and additional interference from outside cells again decreases capacity. Since R must be less than $RLOS$, e.g., for $h = 5$ km, $R_{\max} = RLOS(h) \cong 300$ km, the capacity plot is "zeroed" for large R and small h where the (h, R) combination does not make physical sense (i.e., for $R > RLOS$).

Figure 6 shows plots of capacity versus $RLOS/R$ for the CDMA and TDMA systems, for average values of f_R, f_F, and f_{RU}, for a 2.5 MHz total bandwidth. This plot, and Figure 7, use the quasi-2D values of the interference and re-use factors, since as noted, that is all we have for the TDMA case. Along with the parameters given in Table 1, equations (4) and (5a) were used for CDMA, and equation (6) and the appropriate $(k = 2.4)$ curves from Figure 3 were used for TDMA. The behavior of capacity vs. $RLOS/R$ is dominated by the behavior of the re-use or outside-cell interference factors. Specifically, capacity is roughly inversely proportional to these factors. As seen from this figure, except for the smallest values of $RLOS/R$, the capacity of the CDMA system is largest. Also, CDMA is forward channel limited at $M = 64$ for this average-f case, for $RLOS/R < 4$, and reverse-channel limited for $RLOS/R > 4$. The capacity of

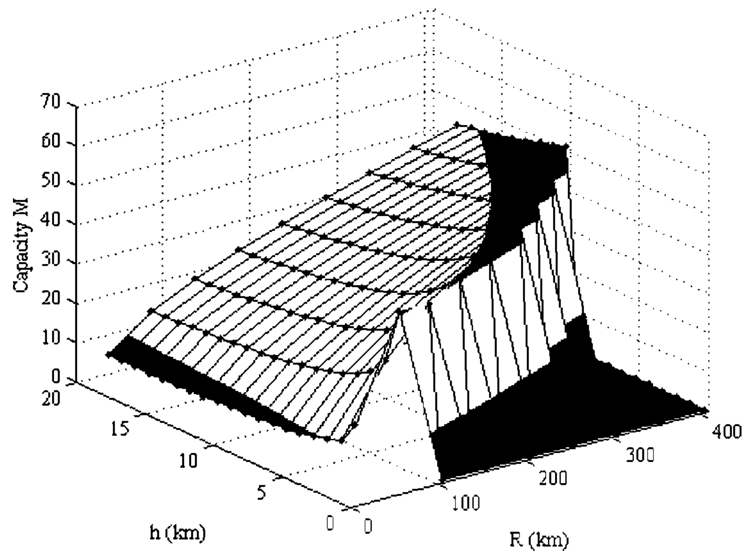

Fig. 5 Plot of M_{CDMA} vs. cell height *h* and radius *R*, with both *h, R* in km.

the HD TDMA system with the "half-rate" data rate (4 kbps) is second-largest. A hybrid FDMA/CDMA system, with frequency re-use of 1/3 was also considered. This frequency re-use of 1/3 degrades CDMA capacity. For the TDMA system, full-duplex capacity is superior to half-duplex capacity only at the lower values of $RLOS/R$ (larger cells) (note that FD TDMA does *not* directly satisfy the party-line requirement unless aircraft have both forward and reverse channel receivers).

Figure 7 shows similar results for the worst-case values of f_F and f_{RU}, where as noted for CDMA, only the forward channel has a worst case interference condition. In this worst-case interference condition, CDMA and HD TDMA capacity are comparable. We have also plotted the CDMA capacity with*out* using the rebroadcast mode. In this case, where aircraft would require two receivers to receive both the GA and AG transmissions, CDMA capacity is superior. In any case, given the strict integrity requirements of pilot-controller communication, the conservative worst-case conditions are most likely to be used (as in[3]).

For the system parameter values we used here, the IS-136 TDMA capacity is smaller than IS-95 CDMA capacity when the average f's are used. When worst-case f's are used, the capacity of the HD TDMA and CDMA are comparable, at least for the CDMA with rebroadcast. We also note that the voice activity factor of 0.4 for CDMA is

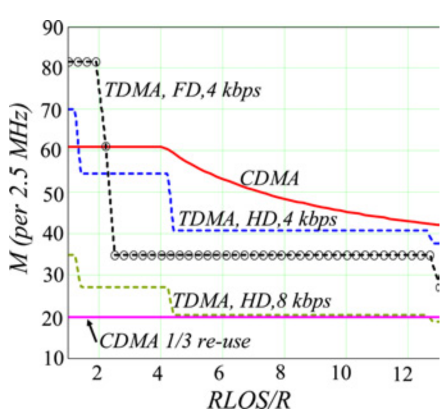

Fig. 6 Capacities/cell/2.5 MHz vs. *RLOS/R* for the two systems with *average f*'s. CDMA capacities are solid lines, TDMA capacities are dashed lines. *HD* = half duplex, *FD* = full duplex (circles).

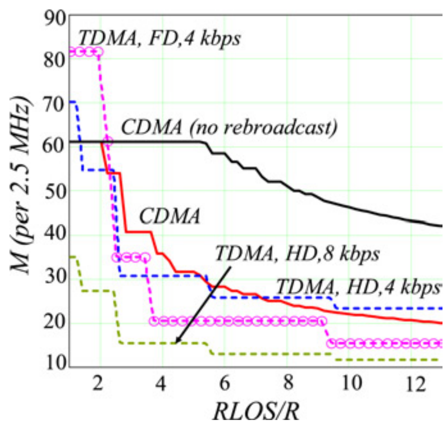

Fig. 7 Capacities/cell/2.5 MHz vs. *RLOS/R* for the two systems with *worst-case f*'s. CDMA capacities are solid lines, TDMA capacities are dashed lines.

likely large for this environment (where messages are generally brief), and the power control standard deviation of $\sigma = 2$ dB may be larger than is achievable in this environment (a value of $\sigma = 2$ dB is typically cited for the more difficult dispersive cellular channel[13] (pp. 183). Modifying these accordingly would increase the CDMA capacity estimates.

VI. Conclusions

In this paper we have obtained capacity estimates for cellular-like systems applied to the AG/GA environment. We considered a TDMA system based upon the land mobile cellular standard IS-136 and a CDMA system based upon the land mobile standard IS-95. Our results required a 3-dimensional extension to the conventional terrestrial cellular geometry, and show that the predominant difference between the terrestrial and aeronautical cases is the increase in the "outside-cell" interference that results from the near free-space AG/GA propagation environment. The final results depend upon assumed system parameters, but the analysis accounts for all pertinent terms that affect system capacity. For the system parameters used, CDMA capacity is superior when average interference conditions are assumed, but half-duplex TDMA and CDMA capacity are comparable when worst-case interference conditions prevail and the CDMA system uses re-broadcast of all the AG transmissions on the GA link. If the CDMA system does not use rebroadcast to achieve the "party-line" functionality, the CDMA worst-case capacity is larger than that of the worst-case TDMA capacity.

Future work would include better estimation of the numerous parameters involved, the voice activity factors and power control standard deviations for CDMA, in particular. For TDMA, a full 3D computation of the re-use factor would be advantageous, so that the capacity comparisons could be done using the 3D parameters for both systems. Newer terrestrial system waveforms, e.g., multicarrier CDMA, or orthogonal frequency division multiplexing, could also be considered. In addition, other beneficial future work would focus on a more accurate spatial characterization of the physical environment, with overlapping cells, non-uniform cell sizes, and a realistic distribution of aircraft within cells. Given the non-homogeneity of the existing AG/GA cells, this would be mostly site-specific. The use of more accurate channel models, which would require some specification of fading and dispersion mitigation techniques for both MA schemes, would also be desirable. The analytical estimation procedure described here—suitably modified to take into account the factors noted—would still form the basis for comparison.

References

[1]Matolak, D. W. and Smith, S. L., "Estimation of TDMA and CDMA Capacities for an Air-to-Ground Communication System," *Proc. Milcom 97*, Session 11, Monterey, CA, November 2–5, 1997.

[2]Matolak, D. W. "3D Outside Cell Interference Factor for an Air-Ground CDMA 'Cellular' System," *IEEE Trans. Vehicular Tech.*, vol. 49, no. 3, pp. 706–710, May 2000.

[3]Elnoubi, S. M., "Capacities of Mobile Air/Ground Radio Communication Systems Employing Cylindrical Cells," *IEEE Trans. Aerospace Elec. Sys*., vol. 34, no. 1, pp. 247–256, January 1998.

[4]Stuber, G., *Principles of Mobile Communication*, 2nd ed., Kluwer Academic Press, Boston, MA, 2001.

[5]Haas, E., "Aeronautical Channel Modeling," *IEEE Trans. Vehicular Tech.*, vol. 51, no. 2, pp. 254–264, March 2002.

[6]Johnson, M. E., and Gierhart, G. D., "An Atlas of Basic Transmission Loss (0.125, 0.3, 1.2, 5.1, 9.4, 15.5 GHz)" DOT-Rep. FAA-RD-80-1, NTIS Accession No. ADA 088153. National Technical Information Service, Springfield, VA., 22161, USA, 1980.

[7]Pritchett, A. R., and Hansman, R. J., "Variations Among Pilots from Different Flight Operations in Party Line Information Requirements for Situation Awareness," *Air Traffic Control Quarterly*, vol. 4, no. 1, pp. 29–50, 1996.

[8]Dept. of Transportation, Federal Aviation Administration, "Subsystem Specification: Multimode Digital Radio (MDR) Supporting Programmable VHF Multi-Mode Communication Equipment Operating within the Frequency Range of 112.000-137.000 MHz," DRAFT Version 20d, March 31, 2000.

[9]Stallings, W., *Data and Computer Communications*, 2nd ed., Macmillan, New York, NY, 1988.

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

[11]Electronic Industries Association, "Mobile-Standard Land Station Compatibility Specification," *American National Standard EIA/TIA 553–1989*, April 1989.

[12]Raith, K., and Uddenfeldt, J., "Capacity of Digital Cellular TDMA Systems," *IEEE Trans. Vehicular Tech.*, vol. 40, no. 2, pp. 323–331, May 1991.

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

[14]Gilhousen, K. S., Jacobs, I. M., Padovani, R., Viterbi, A. J., Weaver, L. A. Jr., and Wheatley, C. E. III, "On the Capacity of a Cellular CDMA System," *IEEE Trans. Vehicular Tech*., vol. 40, no. 2, pp. 303–311, May 1991.

[15]Jakes, W. C., *Microwave Mobile Communications*, IEEE Press, IEEE, New York, NY, 1994.

[16]Ziemer, R. E., and Peterson, R. L., *Introduction to Digital Communications*, 2nd ed., Prentice-Hall, Upper Saddle River, NJ, 2001.

Reinaldo Perez
Associate Editor