Using Two Ray Multipath Model for Microwave Link Budget Analysis

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Abstract

A two-ray ground multipath deterministic model for worst-case fading-depth prediction in microwave link budget analysis is presented. Simple formulas, providing insight into fading depth as a function of geometrical and electrical parameters, are derived. A detailed analysis shows that, in many cases, the fading depth depends mainly on the path-clearance angle. Comparison with the Olsen-Segal model shows that both models have roughly the same path-clearance-angle factor. To the best of the authors' knowledge, this can be considered the first theoretical justification of the path elevation factor in the Olsen-Segal model.

Keywords: Radio propagation; radio propagation terrain factors; microwave propagation; microwave radio propagation terrain factors; land mobile radio propagation factors; satellite communication; multipath channels; fading channels; link power budget; aircraft communication

1. Introduction

The radio propagation channel is the main contributor to many impairments in a wireless system's performance [1]. Suffice it to say that the signal attenuation in the propagation channel may be as large as 100-150 dB, and this number may vary over short intervals of time, frequency, and space (i.e., fading) by as much as 30-40 dB. While all the other components of a wireless system (i.e., the transmitter, the antennas, the receiver; see Figure 1) are well under the designer's control, virtually nothing can be done about the propagation channel. Consequently, the channel effects have to be compensated for by appropriate design of the rest of the system's components. The propagation-channel characteristics have a profound impact on, among other things, the design of equalizers, modulation/demodulation and coding/decoding schemes [2]. Therefore, the analysis of the propagation channel is a very important step in wireless system design. Specifically, it is considered during the link-power budget calculation [3, 4]:

$$P_R = \frac{P_T G_T G_R}{L_T L_R L_P}, \tag{1}$$

where P_R and P_T are the received and transmitted power, respectively; G_R and G_T are the receiving and transmitting antenna gain, respectively; L_R and L_T are the receiving and transmitting path losses (i.e., cable loss, loss due to aging, antenna misalignment, etc.); and L_P is the propagation-channel loss ($L_R, L_T, L_p > 1$). The propagation loss is usually factored out into three main components [1, 2, 5, 7]:

$$L_P = L_0 L_S L_L, \tag{2}$$

where L_0 is the average path loss (for example, free space loss), L_L is the long-term fading (for example, due to shadowing), and L_S is the short-term fading due to multipath. It should be noted that all the parameters in Equation (1) can be accurately estimated, except for the propagation loss, L_P. Due to the complexity of the propagation channel, its randomness (i.e., a mobile channel, or time variation in the propagation environment), and the lack of accurate characterization data, empirical, semi-empirical, and/or statistical models are used to predict L_P, and are often based on the results of extensive measurements [5-14].

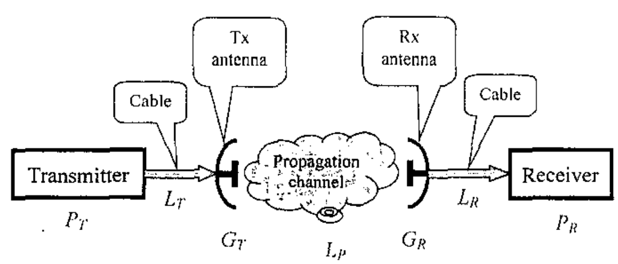

Figure 1. A simplified block diagram of a wireless system.

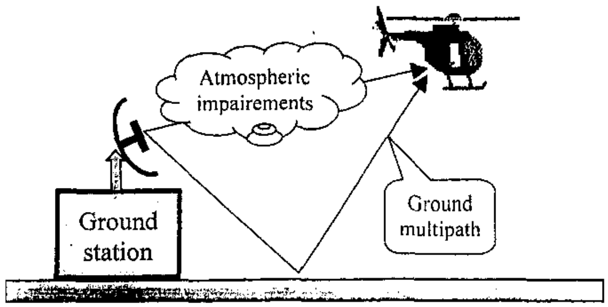

Figure 2. A ground-to-air communication-link scenario.

In this paper, we concentrate our attention on the signal fading and its impact on reliable digital communication over microwave ground-to-air (airborne) links (see Figure 2). In general, the signal fading is complex in nature, and may arise from different mechanisms: ground reflection multipath, atmospheric reflection or refraction multipath, rainfall, ducting, inverse bending, etc. [4]. Because of this, most models for predicting signal fading that are used in microwave link-budget analyses are mainly empirical in nature, and rely on extensive measured data, e.g., for point-to-point terrestrial line-of-sight (LOS) and satellite links [10-14]. Since they are based on measured data, these models include the aggregate effect of the different fading mechanisms, and do not allow for any insight into the relative importance of these mechanisms. When theoretical models are proposed, – see, for example, [15, 16] – they are often limited to particular fading mechanisms, and are useful when such mechanisms make the main contribution to the total fading level. When the link considered is covered by an existing empirical model, that model is used, and the details of the relative contributions of different fading mechanisms are not important. However, if the link considered is not covered by any existing empirical model, additional analysis of the relative contribution of different fading mechanisms is of large importance. The airborne communication link falls into this latter category and, to the best of our knowledge, there is no any specific fading model for it.

There are three types of fading models that are applied to microwave wireless systems:

1. Cellular-system fading models, e.g., the Rayleigh, Rice, or Nakagami models [5, 6];

2. Point-to-point terrestrial LOS link fading models, e.g., the Olsen-Segal model [10-12];

3. Satellite link fading models, e.g., the ITU-R model [13, 14].

The fading models used for cellular systems are not appropriate for the airborne link because, in the latter case, the richness of multipath is much smaller, and the ground-station antenna may have a high directivity that should be accounted for, as well. The two closest models are, therefore, the Olsen-Segal model and the ITU-R model for satellite links. However, the airborne link scenario has several specific features that do not allow the direct use (or the use with small modifications) of one of the above models. The main source of difference between the airborne link, on the one side, and the terrestrial and satellite links, on the other, is the difference in geometry and antenna parameters.

The specific features of the airborne link are as follows. First, the number of multipath components is small enough – when the airborne antenna is located high enough and the ground antenna clears nearby reflecting objects – that the primary reflection is from the Earth's surface, or from some terrain areas, such as mountains or hills. Second, the ground antenna may or may not "see" the ground, depending on the relationship between the antenna's beamwidth and the path-clearance angle. However, as has been well recognized, the ground reflection gives a substantial contribution to the overall fading level when the elevation angle is small enough so that the antenna "sees" the ground [17]. This is the case for terrestrial point-to-point LOS links, but it may not be the case for the airborne link, depending on the path-clearance angle and the antenna's beamwidth (and thus the need to account for the antenna's pattern). Finally, due to the movement of an air vehicle over large distances, it is very difficult – if possible at all – to analyze the ground multipath component in the same way as for fixed terrestrial point-to-point links. In general, fading in a mobile link is very different from that in a fixed LOS link [4].

Here, we discuss the use of a two-ray ground multipath model, adapted to more or less realistic scenarios of hilly or mountainous terrain, for fading depth prediction. This is for the case when the main contribution is due to the ground reflection, and the contributions of atmospheric multipath and absorption (including rainfall, etc.) may be neglected. This is typically the case if the path elevation (takeoff) angle is higher than few degrees, and the carrier frequency is under 10 GHz [4, 8].

The rest of the paper is organized as follows. First, we briefly discuss the three types of fading models mentioned above. Then, we consider the worst-case two-ray ground multipath model, adapted for the airborne communication scenario. Other possible application areas of the proposed model may include terrestrial LOS systems, mobile satellite systems, and high-altitude platforms.

2. Fading-Depth Prediction Models

All the fading models discussed here are statistical in nature, i.e., they predict fading depth as a function of outage probability (the probability that the given fading depth will be exceeded). The probability-density function can be used for this purpose, as well. Thus, by fixing the outage probability at a certain level (say, $P = 10^{-3}$), one obtains the fading depth, and may further use it in the link-budget calculations.

2.1 Fading Models for Cellular Systems

In a mobile cellular scenario, the Rayleigh, Rice, and/or Nakagami models are used. The main idea behind the Rayleigh model is that there is a large number (ideally, an infinite number) of multipath components of approximately the same amplitude, and with random, independent phases. This model is usually used in non-LOS conditions, and has the following form [1, 18]:

$$P\left(F_a > F\right) = 1 - \exp\left(-F^{-1}\right), \tag{3}$$

where $P\left(F_a > F\right)$ is the probability that the actual fading depth, F_a, exceeds a specific level, F. The fading depth is defined here as

$$F = \frac{\overline{s}}{s}, \tag{4}$$

where $\overline{s}$ is the average signal power (averaged over short-term fading), and s is the instantaneous signal power. In fact, $F = L_s$, because the Rayleigh model describes the short-term fading. The log-normal distribution is usually used to characterize the long-term fading [1, 18]. Note that for a high fading depth, $F \gg 1$, Equation (3) can be reduced to

$$P(F_a > F) \approx F^{-1}. \tag{5}$$

Thus, for example, a 10^{-3} outage probability corresponds to a 30 dB fading depth. The slope of the Rayleigh model in this region is 10 dB/decade. When there is a dominant LOS ("unfaded") component, the Rayleigh model is not accurate, and the Rice model should be used, in this case [1, 18]. The Nakagami distribution has been obtained from data measured on rapidly fading HF long-distance propagation [18]. While this empirical model is more complex than the Rayleigh or Rice models, it has been found to be useful for the analysis of wireless links. The Nakagami model describes the fading of clusters of multipath signals, so that within each cluster, the signals' phases are random and have similar delay times, with the delay spreads of different clusters being relatively large.

2.2 Point-to-Point Terrestrial-LOS-Link Fading Models

For terrestrial point-to-point LOS links, the Olsen-Segal model, which has been approved by ITU-R [12], is used [10, 11]. In fact, this model is an empirical generalization of the Barnett's well-known model [19], and is based on extensive measured data available world-wide (for over 240 links in 23 countries). A systematic development of this model and a comparison with measured data are presented in [10-12], and will not be repeated here. The model takes into account both the atmospheric impairments as well as the ground reflection. The outage probability for this model is given by

$$P = Kd^{3.6} f^{0.89} \left(1 + 10^3 |\varepsilon|\right)^{-1.4} F^{-1}, \tag{6}$$

where K is the geoclimatic factor, d is the distance (km), f is the carrier frequency (GHz), and ε is the path elevation angle (radians). P can also be considered to be the percentage of time in the average worst month when the actual fading depth exceeds F. For this model, $F = L_L L_S$. Note that Equation (6) is valid for high fading depths: $F \geq 15 - 20$ dB. For shallow fading depths, the interpolation procedure described in [10, 12] must be implemented. The other limitations of this model are:

1. $120\text{ MHz} \leq f \leq 37\text{ GHz}$; however, the minimum frequency depends strongly on the path length and the minimum path clearance (see [10-12] for more detail);

2. $10\text{ km} \leq d \leq 140\text{ km}$;

3. $\varepsilon < 2°$.

Note that the method of calculating the geoclimatic factor worldwide is available as well [11, 12]. Comparing Equation (6) with Equation (5), one may conclude that the Olsen-Segal model is a modification of the Rayleigh model, accounting for frequency, distance, path elevation, and geoclimatic conditions. This model predicts fading depth as a function of elevation angle, which is of great importance for analysis of the airborne link. However, this model is valid when the elevation angle is less than few degrees, but the elevation angle for the airborne link may be much higher, and it does not account explicitly for antenna pattern. Thus, some method is required to predict fade depth for higher elevation angles, and to account for the antenna pattern in an explicit way.

2.3 Satellite-Link Fading Models

The ITU-R model is usually used for fading-depth predictions on satellite links [13, 14]. This model accounts for electrical and geoclimatic parameters. In general, there are many atmospheric factors that have a profound impact on radiowave propagation above 10 GHz (a range which is typical for satellite frequencies), including atmospheric gas absorption, rain, clouds, fog, and depolarization. However, these factors are usually not important at frequencies below 10 GHz. The main phenomenon of interest below 10 GHz – which can be important for the airborne link, as well – is tropospheric scintillation, caused by refractive index fluctuations in the first few kilometers of altitude [13]. However, one cannot directly employ the satellite-link model for the airborne link, because (1) satellite antennas usually have very narrow beams (a few degrees and smaller), while the antenna beamwidth for the airborne scenario may be as large as 10°-20°; and (2) satellite links go through the entire troposphere, while the airborne link goes through only a part of the troposphere, which can result in smaller tropospheric fading.

3. Fading-Depth Predictions Using the Two-Ray Ground Multipath Model

In this section, we consider the classical two-ray ground multipath model for fading-depth prediction on the airborne link, when the main mechanism of fading is ground multipath and the atmospheric contribution may be neglected. This is the case for frequencies lower than 10 GHz and for elevation angles above a few degrees. In all the considerations below, we adopt the Geometrical Optics approximation. We consider single specular reflection, assuming that the size of the reflective area is large enough to cover the first Fresnel zone, which constitutes the worst-case fading estimation. Figure 3 depicts the scenario considered.

Furthermore, we consider – without loss of generality – that Antenna 1 (the ground antenna) is transmitting, and Antenna 2 (the airborne antenna) is receiving. The total field at Antenna 2 is

$$E_{total} = E_D + E_R e^{j\Delta\varphi}, \tag{7}$$

where E_D and E_R are the amplitudes of the direct (LOS) and reflected rays, respectively, and $\Delta\varphi$ is their phase difference. The minimum received signal level is $E_{\min} = E_D - E_R$ when the phase difference $\Delta\varphi = \pi$. Consequently, the fading depth, F, is

$$F = \left(\frac{E_D}{E_{\min}}\right)^2 = \left(1 - \frac{E_R}{E_D}\right)^{-2}. \tag{8}$$

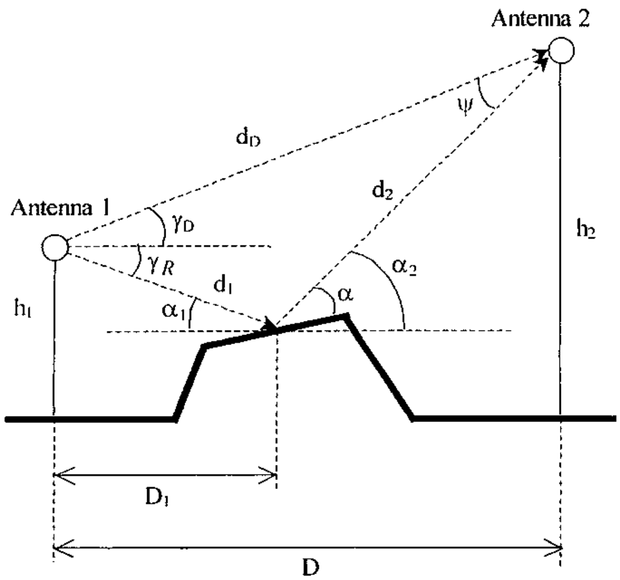

Figure 3. A two-ray multipath propagation scenario for hilly or mountainous terrain.

Using the Geometrical Optics approximation, Equation (8) can be presented in the following form:

$$F = \left[1 - \Gamma \frac{d_D}{d_1 + d_2} G_1(\gamma) G_2(\psi)\right]^{-2}, \tag{9}$$

where Γ is the magnitude of the reflection coefficient, $G_1(\gamma)$ is the normalized pattern in the direction of the reflected ray for the ground antenna, $G_2(\psi)$ is the normalized pattern of the airborne antenna, $\gamma = \gamma_D + \gamma_R$ is the path-clearance angle, d_D is the LOS path length, and $d_1 + d_2$ is the reflected path distance. We assume that the ground antenna, Antenna 1, is steered exactly to the airborne antenna, Antenna 2, i.e., $G_1(0) = 1$ and vice versa, i.e. $G_2(0) = 1$. The magnitude of the reflection coefficient may be estimated using the classic equations [20]

$$\Gamma_V = \frac{-\varepsilon_r \sin(\alpha) + \sqrt{\varepsilon_r - \cos^2(\alpha)}}{\varepsilon_r \sin(\alpha) + \sqrt{\varepsilon_r - \cos^2(\alpha)}},$$

$$\Gamma_H = \frac{-\sin(\alpha) + \sqrt{\varepsilon_r - \cos^2(\alpha)}}{\sin(\alpha) + \sqrt{\varepsilon_r - \cos^2(\alpha)}}, \tag{10}$$

where V and H stand for vertical and horizontal polarization, respectively; ε_r is the relative ground permittivity; and α is the local incidence/reflection angle at the reflection point. Note that Equations (9) and (10) are general enough to account for the geometry of the problem, the antenna patterns, and the ground permittivity. No detailed path profile is required for this method.

Further, we develop simple approximate formulas for practically important cases, which may provide some insight and help to estimate the fading depth in a simple and fast way, although still accurately enough for many practically important problems in system-level design. We adopt the following assumptions, which hold in many cases: $D \gg h_1, h_2$; $h_2 \gg h_1$; $D_1 \ll D$. We also assume that the ground antenna "sees" the ground (i.e., $G_1(\gamma) = 1$), i.e., we neglect the ground antenna's pattern. The beamwidths of airborne antennas are usually large enough so that $G_2(\psi) = 1$ (note that under the assumptions above, ψ will be very small, typically smaller than a degree). Under the assumptions above, $\gamma_D \approx \alpha_2$, and, consequently,

$$\alpha = \frac{\alpha_1 + \alpha_2}{2} \approx \frac{\gamma}{2}. \tag{11}$$

Note that $\gamma \ll 1$, and for a typical ground, $\varepsilon_r \gg 1$ (for example, for the average ground, $\varepsilon_r \approx 15$). Thus, Equation (10) reduces to

$$\Gamma_V \approx 1 - 2\alpha\sqrt{\varepsilon_r},$$

$$\Gamma_H \approx 1 - \frac{2\alpha}{\sqrt{\varepsilon_r}}. \tag{12}$$

A detailed analysis shows that the path-length-difference effect on the signals' amplitudes can usually be neglected in Equation (9), i.e. $d_D \approx d_1 + d_2$ (its effect is approximately two to three orders of magnitude smaller than the reflection-coefficient effect). Combining Equations (9), (11), and (12), the fading depth can be estimated by remarkably simple formulas:

$$F_V \approx \frac{1}{\gamma^2 \varepsilon_r},$$

$$F_H \approx \frac{\varepsilon_r}{\gamma^2}. \tag{13}$$

Note that in deriving these formulas, we assumed that $\gamma > 0$; otherwise, the LOS path would be obstructed. Equation (13) may be used provided that $\gamma^2 \varepsilon_r \ll 1$ (for vertical polarization) and $\gamma^2 \ll \varepsilon_r$ (for horizontal polarization).

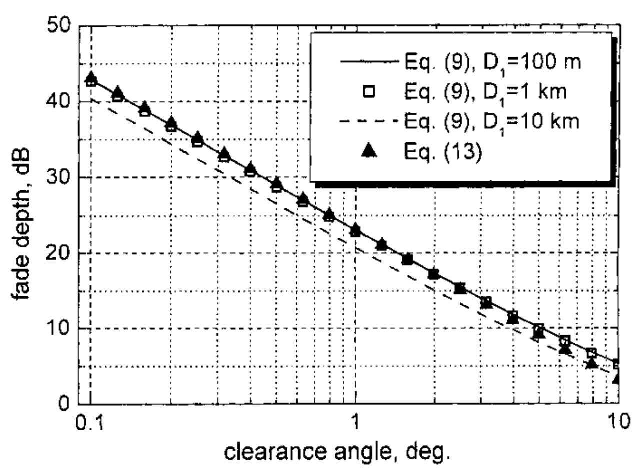

Figure 4. The fading depth as a function of clearance angle for vertical polarization, computed from Equations (9) and (13): $D = 40\,\text{km}$, $h_1 = 10\,\text{m}$, $\gamma_D = 10°$, **and** $\varepsilon_r = 16$.

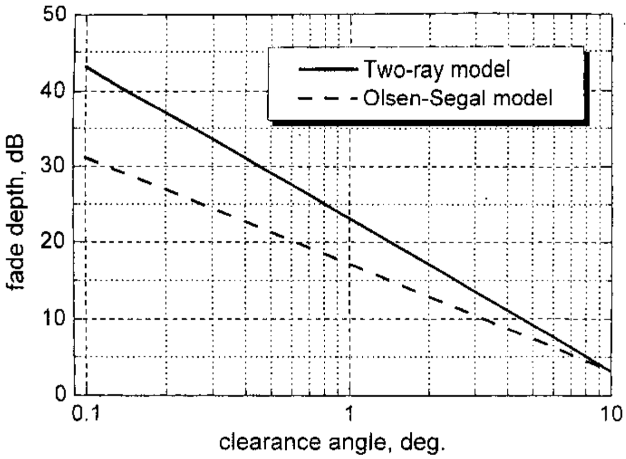

Figure 5. A comparison of the fading depth as a function of clearance angle for the two-ray model and the Olsen-Segal model. The same fading depth is assumed at 10°.

Figure 4 compares the fading depth computed by Equations (9) and (13). As one may see from this figure, Equation (13) provides quite a good approximation to Equation (9) for a wide range of D_1 values. A more detailed analysis shows that the fading depth depends mainly on the clearance angle. Its dependence on the LOS path elevation and on the distance to the reflection point is much smaller (provided the clearance angle is fixed). It is interesting to note that if the spherical Earth profile is taken into account, the results do not change substantially, provided that the angles are used as independent variables (as in Figure 4).

The two-ray model above and the flight-dynamics parameters were further used to propose a time-varying dispersive-channel model for an airborne communication system [21]. A channel emulator, programmed accordingly, was then used to simulate the airborne communication system, and to obtain parametric performance results.

4. Comparison of the Present Model and the Olsen-Segal Model

Let us now compare this result with the Olsen-Segal model (see Equation (6)). For LOS terrestrial links, the path elevation angle and the clearance angle are approximately the same (because the reflection point is usually far away from both antennas): $\varepsilon \approx \gamma$. Hence, for γ larger than few milliradians, one obtains from Equation (6)

$$F \approx C\gamma^{-1.4}, \tag{14}$$

where C is a constant. Comparing Equation (14) to Equation (13), we see that they give approximately the same dependence of F on γ. The difference in the power value [the value of the exponent of γ] may be attributed to the ground roughness and the antenna pattern (which are unaccounted for in Equation (13)), and to the atmospheric-fading contribution (however, more studies are required to draw a final conclusion, and to accurately estimate these effects). Thus, from these considerations, we may speculate that a substantial contribution to fading in Equation (6) is due to ground or atmospheric reflection. This may be – to the best of the authors' knowledge, for the first time – a theoretical justification (not a proof) of the path elevation factor in the Olsen-Segal model.

Another interesting issue is how strongly the fading depth depends on the power value [the value of the exponent of γ] in Equation (13). However, this sensitivity analysis is not simple to do. The basic problem relates to whether we need to modify only the value of the exponent, or the rest of the formula as well: for example, to modify the dielectric-constant factor, or to add some additional factor. Another way to do this analysis is to compare the Olsen-Segal and the two-ray multipath models directly. In Figure 5, we compare the fading depths given by Equations (13) and (14). We set the constant in Equation (14) in such a way that both models give the same prediction for $\gamma = 10°$. The reason for this particular choice of γ is that the fading depth is usually a few dBs and smaller for elevations higher than roughly 10°, and any reasonable model should predict this. Hence, we set C in such a way as to satisfy this requirement. Using this particular choice of C also has the advantage that one may see the difference in Equations (13) and (14) due to the angle's power value [exponent] only, separated from other possible differences. The agreement between Equations (13) and (14) is quite good, taking into account the fact that the two-ray model is a rough model, and it does not take into account many factors (i.e., surface roughness, atmospheric contribution, etc.).

5. Conclusions

Fading-depth prediction for power-budget analysis of airborne communication links has been discussed in this paper. At the moment, there is no fading model for this particular scenario. The two closest models are the Olsen-Segal model and the ITU-R model for satellite links. However, they cannot be directly applied to the airborne link scenario. The two-ray ground multipath model, adapted to a realistic scenario of hilly or mountainous terrain, has been used for fading-depth prediction on airborne links in this paper. The model applies to elevation angles higher than a few degrees and frequencies lower than 10 GHz, when the contribution of the ground multipath component is dominant. The comparison of the two-ray model with the Olsen-Segal model shows that they predict roughly the same fading-depth dependence on the elevation angle. This may be considered – to the best of our knowledge, for the first time – as a theoretical justification of the path elevation factor in the Olsen-Segal model. However, more studies are required to draw a final conclusion.

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7. References

1. D. Parson, *The Mobile Radio Propagation Channel*, UK, Pentech, 1992.

2. J. B. Andersen, T. S. Rappaport, S. Yoshida, "Propagation Measurements and Models for Wireless Communications Chan-

nels," *IEEE Communications Magazine*, **33**, 1, January 1995, pp. 42-49.

3. D. R. Smith, *Digital Transmission Systems*, New York, Van Nostrand Reinhold, 1993.

4. R. L. Freeman, *Radio System Design for Telecommunications*, New York, John Wiley & Sons, 1997.

5. B. Sklar, "Rayleigh Fading Channels in Mobile Digital Communication Systems, Part I: Characterization," *IEEE Communications Magazine*, **35**, 9, September 1997, pp. 136-146.

6. B. Sklar, "Rayleigh Fading Channels in Mobile Digital Communication Systems, Part II: Mitigation," *IEEE Communications Magazine*, **35**, 9, September 1997, pp. 148-155.

7. B. H. Fleury, P. E. Leuthold, "Radiowave Propagation in Mobile Communications: An Overview of European Research," *IEEE Communications Magazine*, **34**, 2, February 1996, pp. 70-81.

8. G. Feldhake, "Estimating the Attenuation due to Combined Atmospheric Effects on Modern Earth-Space Paths," *IEEE Antennas and Propagation Magazine*, **39**, 4, August 1997, pp. 26-34.

9. J. Goldhirsh, W. J. Vogel, *Handbook of Propagation Effects for Vehicular and Personal Mobile Satellite Systems*, NASA Reference Publication 1274 (Second Edition), 1999.

10. R. L. Olsen, B. Segal, "New Techniques for Predicting the Multipath Fading Distribution on VHF/UHF/SHF Terrestrial Line-of-Sight Links in Canada," *Canadian Journal of Electrical and Computer Engineering*, **17**, 1, 1992, pp. 11-23.

11. R. L. Olsen, T. Tjelta, "Worldwide Techniques for Predicting the Multipath Fading Distribution on Terrestrial LOS Links: Background and Results of Tests," *IEEE Transactions on Antennas and Propagation*, **AP-47**, 1, January 1999, pp. 157-170.

12. ITU-R Recommendation P.530.5, "Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems," Geneva, Switzerland, 1999.

13. L. J. Ippolito Jr., "Satellite Transmission Impairments," in J. D. Gibson (ed.), *Communications Handbook*, Boca Raton, FL, CRC Press, 1997.

14. ITU-R Recommendation P.618-6, "Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems," Geneva, Switzerland, 1999.

15. C. L. Ruthroff, "Multiple-Path Fading on Line-of-Sight Microwave Radio Systems as a Function of Path Length and Frequency," *The Bell System Technical Journal*, **50**, 7, September 1971, pp. 2375-2398.

16. S. H. Lin, "Statistical Behavior of a Fading Signal," *The Bell System Technical Journal*, **50**, 10, December 1971, pp. 3211-3270.

17. R. L. Olsen, L. Martin, T. Tjelta, "A Review of the Role of Surface Reflection in Multipath Propagation Over Terrestrial Microwave Links," in the *Proceedings of NATO/AGARD Conference on Terrestrial Propagation Characteristics in Modern Systems of Communications, Surveillance, Guidance and Control*, (November 1987), (N. CP-407), pp. 2/1-1/23.

18. M. D. Yacoub, "Fading Distributions and Co-Channel Interference in Wireless Systems," *IEEE Antennas and Propagation Magazine*, **42**, 1, February 2000, pp. 150-159.

19. W. T. Barnett, "Multipath Propagation at 4, 6, and 11 GHz," *The Bell System Technical Journal*, **51**, 2, February 1972, pp. 321-361.

20. L. Boithias, *Propagation of Radio Waves*, New York, McGraw Hill, 1987.

21. A. Kouki et al., "Airborne Communication Node Study," Technical Report Ecole de Technologie Superieure, Montreal, July 2000.

Introducing the Feature Article Authors

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