Outage Probabilities in Mobile Radio Systems
Suffering Cochannel Interference

Kevin W. Sowerby, Member, IEEE, and Allan G. Williamson, Senior Member, IEEE

Abstract—Mobile radio systems are usually designed on the basis of providing adequate reception quality to a specified area. In this paper, outage probability equations are used to determine the quality of radio reception when that quality is limited by a minimum required signal level, interference from a co-channel transmitter, and variability in the received signal levels. Considering Rayleigh fading and lognormal shadowing as joint causes of signal variation, average outage probability expressions are derived for mobile radio systems of a uniform nature. These expressions are used to investigate the influence of various system and propagation characteristics on reception quality.

I. INTRODUCTION

GOOD quality service, efficient spectrum utilization, and cost effectiveness are the fundamental aims of modern mobile radio system design. Cellular radio systems attempt to provide a telephone service to the mobile public with a quality as good as that afforded by conventional landline services. However, the deliberate reuse of radio channels over relatively short distances in cellular radio means that reception quality can be limited by interference.

The problem for the cellular radio system designer is to find the best compromise between performance, efficiency, and cost. Efficiency and cost can be relatively easily measured but the measurement of system quality is more difficult. While the user’s assessment will be purely subjective, the radio system designer needs a more quantitative measure; “outage probability” provides such a measure.

“Outage probability” is a statistical measure that describes the probability of failing to achieve “adequate reception” of a signal at a particular location. To achieve “adequate reception,” the short-term desired signal must be simultaneously greater than both some minimum signal level and the short-term sum of the interfering signal powers by a margin known as the interference protection ratio.

Hence, outage probability can be described mathematically by [1]:

$$P_{\text{out}} = 1 - \int_{\text{min sig}}^{\infty} p(\text{sig}) \cdot \int_{0}^{\text{sig} / r_p} p(\text{int}) \cdot d(\text{sig}) \cdot d(\text{int})$$

where $p(\text{sig})$ is the probability density function (PDF) of the desired signal power, $p(\text{int})$ is the PDF of the resultant interfering signal power, $r_p$ is the signal-to-interference protection ratio, and (min sig) is the minimum required signal power.†

In order to calculate the outage probability at a given location using (1), it is necessary to know the probability density functions of the desired and interfering signals. The most commonly used propagation model is one with three basic components—Rayleigh fading, lognormal shadowing, and a distance-dependent path loss.

In a typical mobile radio environment, the magnitude of the received signal will frequently vary by as much as 20–30 dB over distances as short as a quarter wavelength. This rapid variation of the received signal results from the multipath propagation and is known as fading. In most cases, when measured over distances of a few tens of wavelengths, the received signal envelope has been found to have a Rayleigh probability density function (PDF) [2].

The mean level of the received signal envelope, averaged over many Rayleigh fading cycles, also varies, but much less rapidly than Rayleigh fading. This slower variation is due to the shadowing caused by objects in the path of the radio signal. When measured over distances of several hundred wavelengths, this shadowing has been found to have an approximately lognormal PDF [3] with a standard deviation (typically between 4 and 9 dB) related to the morphostructure in the vicinity of the mobile.

The distance-dependent “path loss” which determines the mean level of the lognormal shadowing can be modeled by a modified “plane earth” propagation model which includes a clutter factor that models the losses dependent largely on the extent of urbanization in the vicinity of the mobile [3].

When several cochannel interferers are involved, the calculation of outage probability by (1) can involve considerable mathematics. The authors have developed outage probability expressions for the multiple-interferer Rayleigh fading plus the lognormal shadowing case [4], [5]. However, less comprehensive analyses are available for restricted cases where only a single type of signal vari-

†In this paper, the term “signal” is used as a synonym for “carrier” since the radio frequency signal, rather than the baseband signal, is being referred to.
ability or just a single interferer is considered [1], [6]–[9]. These analyses are useful for illustrating the effects of various system characteristics such as the variability of the lognormal shadowing or the relative mean strengths of desired and interfering signal envelopes.

This paper uses outage probability calculations to investigate how the quality of radio reception varies within the base station service area of an idealized mobile radio system. Average outage probabilities within the service area are also calculated since this enables the general quality of reception in the service area to be assessed and compared to the quality of service at the boundary of the service area. In other words, given a certain quality of reception at the boundary of an area, what is the average quality of reception within that boundary? Such a question is important to a mobile radio system designer who needs to consider both the overall quality of service and the quality being provided to the areas on the margin of service.

II. AVERAGE OUTAGE PROBABILITY

Given the probability of outage anywhere within a specified area, the average outage probability can be calculated as follows:

$$P_{\text{outavg}} = \frac{1}{\text{area}} \int_{\text{area}} P_{\text{out(location)}} \cdot d(\text{area})$$

where $P_{\text{outavg}}$ is the average outage probability and $P_{\text{out(location)}}$ is the outage probability at a point within the area being considered.

In this paper, idealized mobile radio systems are considered so that the fundamental effects of different system design and propagation characteristics can be observed. In these idealized systems, the terrain is considered to be flat and the morphostructure constant. Omnidirectional antennas operating without power control have also been assumed. The service area of a base station under such conditions will be circular. Hence, it is convenient to calculate average outage probability using polar coordinates $(r, \theta)$ so that (2) can be written as:

$$P_{\text{outavg}} = \frac{\int_{0}^{2\pi} \int_{0}^{R_c(\theta)} r \cdot P_{\text{out}(r, \theta)} \cdot dr \cdot d\theta}{\int_{0}^{2\pi} \int_{0}^{R_c(\theta)} r \cdot dr \cdot d\theta}$$

where $R_c(\theta)$ is the function which describes the boundary of the area being considered.

III. COVERAGE ONLY

In an idealized mobile radio system with no cochannel interferers present, the calculation of outage probability using (3) is simplified because the function $R_c(\theta)$ is a constant. Hence, the perimeter of the area serviced by a base station is a circle centered on the base station and (3) can thus be written as:

$$P_{\text{outavg}} = \frac{2}{R_c} \int_{0}^{R_c} P_{\text{out}}(r) \cdot r \cdot dr$$

where $R_c$ is the radius of the service area and is defined by a contour of constant outage probability.

A. Rayleigh Fading Only

If only Rayleigh fading is the cause of received signal variation, then the probability of outage is given by [9]:

$$P_{\text{out}} = 1 - \exp \left[ \frac{-\gamma_o}{\Gamma} \right]$$

where $\gamma_o$ is the minimum-required local desired signal power to noise power ratio (SNR) and $\Gamma$ is the local mean SNR which is dependent on the distance from the base station, namely:

$$\Gamma = \frac{1}{\kappa \cdot r^n}$$

where $\kappa$ and $n$ are constants. ($n$ is called the propagation exponent and, typically, has a value between 3 and 4 [2], [3].) Substituting (6) into (5) gives the expression for outage probability as a function of the distance $(r)$ from the base station, namely:

$$P_{\text{out}}(r) = 1 - \exp \left[ -\gamma_o \cdot \kappa \cdot r^n \right].$$

If the outage probability at the boundary of the service area, $P_{\text{out}}(R_c)$, is known, then $\kappa$ can be determined and from (4) and (7) it can be shown that [5]:

$$P_{\text{outavg}} = 1 - \frac{2}{R_c^2} \int_{0}^{R_c} \exp \left[ -\gamma_o \cdot \kappa \cdot r^n \right] \cdot r \cdot dr.$$  

If $n$ is 4 (as it is in the modified plane earth propagation model [3]), the integral in (8) can be evaluated analytically and the average outage probability expression can be written as:

$$P_{\text{outavg}} = 1 - \frac{\sqrt{\pi}}{2} \cdot \frac{\text{erf} \left( \frac{\sqrt{-\ln \left[ 1 - P_{\text{out}}(R_c) \right]} \right)}{\sqrt{-\ln \left[ 1 - P_{\text{out}}(R_c) \right]}}.$$  

Because the outage probability will be lower at locations closer to the base station, it may be of interest to know not only the average outage probability within the service area of a base station as a whole, but also the average outage probability within a fraction of that service area. The average outage probability in the best fraction, $f$, of a service area (namely in an area where $r \leq R_c \cdot \sqrt{f}$) is given by:

$$P_{\text{outavg}} = 1 - \frac{\sqrt{\pi}}{2} \cdot \frac{\text{erf} \left( f \cdot \sqrt{-\ln \left[ 1 - P_{\text{out}}(R_c) \right]} \right)}{f \cdot \sqrt{-\ln \left[ 1 - P_{\text{out}}(R_c) \right]}}.$$  

(10)
B. Lognormal Shadowing Only

Expressions similar to (9) and (10) can be obtained for the case where signal variation is due to lognormal shadowing only. For this case, the average outage probability within a radius \( R_c \) has been shown (using the method given in [2]) to be:

\[
P_{\text{out,avg}} = P_{\text{out}}(R_c) - \frac{1}{2} \cdot \exp \left[ b \cdot (2a + b) \right] \cdot \text{erfc} \left[ a + b \right]
\]

where

\[
a = \frac{\alpha(R_c)}{\sqrt{2} \sigma}, \quad b = \frac{\sqrt{2} \sigma \ln (10)}{10n}
\]

and \( \alpha(R_c) \) is the margin (in dB) by which the median of the received signal power at the boundary exceeds the minimum required signal power. The term \( \alpha(R_c) \) is directly related to \( P_{\text{out}}(R_c) \), namely:

\[
P_{\text{out}}(R_c) = \frac{1}{2} \cdot \text{erfc} \left[ \frac{\alpha(R_c)}{\sqrt{2} \sigma} \right].
\]

The average outage probability within a fraction \( f \) of the area within radius \( R_c \) of the base station is found by replacing \( \alpha(R_c) \) in (12) with \( \alpha(r_f) \), where:

\[
\alpha(r_f) = \alpha(R_c) - \frac{10n}{2} \cdot \log_{10}(f).
\]

C. Rayleigh Fading and Lognormal Shadowing

In the general situation where signals suffer both Rayleigh fading and lognormal shadowing simultaneously, the outage probability at a specific location is given by [6]:

\[
P_{\text{out}} = 1 - \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp \left( -y^2 \right)
\]

\[
\cdot \exp \left[ -\frac{\pi}{4} 10^{\left[ -\alpha + \sqrt{2} \sigma y \right] / 10} \right] dy
\]

where \( \alpha \) is the margin, in dB, between the median of the lognormal shadowing component of the received signal and the minimum required signal level.

Equation (14) can be rewritten as a function of the distance \( r \) between the mobile and the base station, namely:

\[
P_{\text{out}}(r) = 1 - \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp \left( -y^2 \right)
\]

\[
\cdot \exp \left[ -\frac{\pi}{4} \frac{r}{R_c} 10^{\left[ -\alpha(R_c) - \sqrt{2} \sigma y \right] / 10} \right] dy.
\]

The average outage probability within radius \( R_c \) of the base station is found by substituting (15) into (4). For example, if the propagation exponent \( (n) \) is 4, then the average outage probability expression can be written as:

\[
P_{\text{out,avg}} = 1 - \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp \left( -y^2 \right)
\]

\[
\cdot \exp \left[ \frac{\sqrt{\pi} \alpha(y)}{2} \right]
\]

\[
dy
\]

where

\[
\alpha(y) = 10^{\left[ 1 - \alpha(R_c) - \sqrt{2} \sigma y \right] / 10}.
\]

The average outage probability within a fraction \( f \) of the area within radius \( R_c \) of the base station can be found by the same method that is used for the "shadowing only" situation, namely by replacing \( \alpha(R_c) \) in (16) with \( \alpha(r_f) \) [where \( \alpha(r_f) \) is given by (13)].

Fig. 1 shows the average outage probability (dotted lines) over a fraction of an area bounded by a constant outage probability contour (20%, 10%, and 5%). Also shown is the outage probability (solid lines) at the boundary of the fractional area. The received signal has been assumed to suffer both Rayleigh fading and lognormal shadowing. Fig. 1(a) is for the case where \( \sigma = 6 \) dB and (b) is for \( \sigma = 12 \) dB. The results illustrate that the parameter \( \sigma \) has a significant effect on the average outage probability and that knowledge of the outage probability at the very edge of a service area does not provide complete knowledge of the distribution of outage probability within that service area.

IV. INTERFERENCE ONLY

In a mobile radio system with no cochannel interferers, outage occurs when the short-term received signal power is lower than the minimum power level required by the receiver. When cochannel interfering transmissions are present, outage will also occur when the short-term level of the desired signal power is not sufficiently greater than the short-term sum of the interfering signal powers. Depending on the design of a mobile radio system, it is possible for one, or other, of these two causes of outage to dominate the system. In a situation where the transmitter powers are relatively weak and/or any cochannel stations are widely separated, the radio system is likely to be limited by outage due to a failure to meet the "coverage condition." Such a system is said to be "coverage limited." Conversely, in a situation where the transmitter powers are strong and cochannel stations are relatively close, then the system is likely to be limited by cochannel interference. Such a system is said to be "interference limited."

In the previous section, average outage probabilities were found for coverage-limited systems (that is, no cochannel interferers were considered). A constant outage probability contour in such an idealized system is a circle and is centered on the base station. When a totally interference-limited system with a single cochannel interferer is examined, it is found that a constant outage probability contour is, again, a circle [10]. However, this contour is
not centered on the desired base station but is offset in the direction away from the cochannel interfering station.

If \( d_0 \) is the distance from a mobile receiver to the desired base station and \( d_i \) is the distance from the mobile to the interfering base station then, in an idealized "interference-limited" mobile radio system, constant outage probability occurs along a contour where the ratio \( d_i/d_0 \) (\( = k \)) is constant, that is where the relative mean levels of the received signal powers remain constant.

In order to calculate the average outage probability within a constant outage probability contour, an expression for the distance between the base station and the contour, \( R_0(\theta) \), is necessary. If the distance between the two base stations is normalized to unity, then this relationship is given by:

\[
d_d = -\cos(\theta) + \frac{\sqrt{k^2 - \sin^2(\theta)}}{k^2 - 1}.
\]  

(17)

As illustrated in Fig. 2, (17) is the equation of a circle with a radius of \( [k/(k^2 - 1)] \), centered on the point (0, \((-1/k^2 - 1)) \). The area inside this circle is equal to \([\pi k^2/(k^2 - 1)^2]\).

A. Rayleigh Fading Only

If Rayleigh fading is the only cause of signal variation and if outage is due only to a single cochannel interferer, then the expression for outage probability is [9]:

\[
P_\text{out}^1 = \frac{1}{1 + \Lambda/r_p^*}
\]

(18)

where \( \Lambda \) is mean signal to mean interference ratio, and \( r_p \) is the interference protection ratio. The superscript '1' in \( P_\text{out}^1 \) indicates that one cochannel interferer is being considered.

An average outage probability expression for the "interference-only" situation can be derived by first expressing (18) as a function of the distance \( r \) from the desired base station and then substituting the resulting expression into (3). If the propagation exponent \( n \) is 4 and the outage probability at the boundary is \( P_\text{out}^1(R_0(\theta)) \), then the average outage probability within the boundary can be shown to be:

\[
P_\text{out}^1 = \frac{2 \cdot (k^2 - 1)^2}{\pi k^2} \cdot \int_0^{\pi} \int_0^{d_0} \frac{r^5}{r^4 + (1 + r^2 - 2 \cdot r \cdot \cos(\theta))^2} \cdot dr \cdot d\theta
\]

(19)

where \( d_d \) is given by (17), and

\[
k = \left[ r_p \left( \frac{1}{P_\text{out}^1} - 1 \right) \right]^{1/4} \left( = \frac{d_d}{d_0} \right).
\]

B. Lognormal Shadowing

When the effects of Rayleigh fading are ignored and only the signal variation caused by lognormal shadowing is considered, then the "interference-only" outage probability expression is [2]:

\[
P_\text{out}^1 = \frac{1}{2} \cdot \text{erfc} \left( \frac{\tau}{2\sigma} \right)
\]

(20)
where $\sigma$ is the standard deviation, in dB, of the desired and the interfering signals (expressed in logarithmic units), and $\tau$ is the margin, in dB, by which the mean of the desired signal exceeds the mean of the interfering signal and the protection ratio. $\tau$ can also be expressed in terms of the parameters $r$ and $\theta$, namely:

$$
\tau = 10 \cdot n \cdot \log_{10} \left[ \sqrt{r^2 + 1 - 2 \cdot r \cdot \cos(\theta)} \right] / r \\
\sim 10 \log_{10} (r_p).
$$

(21)

Hence, the expression for the average outage probability within an area defined by a constant outage probability contour with the value $P_{\text{out}}(R, \theta)$ can be shown to be:

$$
P_{\text{out,avg}} = \frac{2 \cdot (k^2 - 1)^2}{\pi k^2} \cdot \int_0^{\infty} \int_0^{\frac{\pi}{2}} \int_0^{\infty} \frac{r}{2} \cdot \text{erfc} \left( \frac{\tau(r, \theta)}{2 \cdot \sigma} \right) \cdot dr \cdot d\theta \\
\text{where } d_j \text{ is given by (17), and } \\
k = \sqrt{r_p} \cdot 10^{(\sigma/20)} \cdot \text{erf} \left( \frac{1}{\sqrt{2}} \cdot P_{\text{out}}(R, \theta) \right) \left( = \frac{d_j}{d_{\text{avg}}} \right).
$$

(22)

C. Rayleigh Fading and Lognormal Shadowing

An average outage probability expression which is similar to (22) can be found for the general mobile radio situation where signals suffer both Rayleigh fading and lognormal shadowing simultaneously, namely:

$$
P_{\text{out,avg}} = \frac{2 \cdot (k^2 - 1)^2}{\pi k^2} \cdot \int_0^{\infty} \int_0^{\frac{\pi}{2}} \int_0^{\infty} \frac{r}{2} \cdot \text{erfc} \left( \frac{\tau(r, \theta)}{2 \cdot \sigma} \right) \cdot dr \cdot d\theta.
$$

(23)

For the single-interferer situation where the variabilities of the desired and interfering signals are the same, the “interference-only” outage probability is [6]:

$$
P_{\text{out}}^1 = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp \left( -x^2 \right)}{1 + 10^{(\sigma/20)}} \cdot dx
$$

(24)

where $\tau$ is the same parameter that was used in (20) and is expressed in terms of the parameters $r$ and $\theta$ in (21).

Given the outage probability at the boundary of an area (namely $P_{\text{out}}(R, \theta)$), the distance ratio $k$ in (23) must be calculated numerically because the relationship between $k$ and $P_{\text{out}}^1(R, \theta)$ is:

$$
P_{\text{out}}^1(R, \theta) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp \left( -x^2 \right) \cdot \left[ \frac{10^{-\tau^2/R_p^2}}{k^{\theta}} \right] \cdot dx.
$$

(25)

Equations (20)-(25) are functions of $\sigma$, $r_p$, and $k$. This implies that in interference-limited systems, outage probability depends on the signal variability, the interference protection ratio, and the relative (not absolute) distances of the desired and interfering transmitters from the mobile. Absolute transmitter power levels are not important in interference-limited systems, unlike those in coverage-limited systems.

Fig. 3 shows the average outage probability (dotted lines) in a fraction of the area bounded by a constant outage probability contour for the general fading and shadowing situation for an interference protection ratio of 6 dB, a propagation exponent ($n$) of 4, and $\sigma = 6$ dB. Fig. 3 also shows the outage probability (solid lines) at the boundary of the fractional area. Together, the outage probabilities and the average outage probabilities give an indication of the distribution of reception reliability throughout the service area of the base station.

Similar results for different signal variabilities are presented in [5] and these results indicate that the nature of the signal variation has a significant effect on the distribution of the quality of signal reception within an area with a particular reception quality at its boundary. In general, it is found that average outage probabilities are higher in systems with greater variation in received signal levels.

For the “fading and shadowing” situation where $\sigma = 6$ dB, the average outage probability is higher for the “interference-only” situation shown in Fig. 3 than for the “coverage-only” situation shown in Fig. 1(a). This difference is primarily attributable to the position of the outage probability contour that defines the boundary of the area being considered. For the “interference-only” situation, the circular boundary contour is not centered on the desired base station and consequently there is a larger area in which high outage probabilities occur than there is for the “coverage-only” situation.

V. COVERAGE AND INTERFERENCE

For the idealized radio systems considered in this paper, the area bounded by a constant outage probability contour is a circle for both coverage-limited and interference-limited (single interferer) systems. However, the service area (defined by a constant outage probability contour) for a case where outage is due to both interference and a failure to meet the “coverage condition” is not a circle (although it is generally circular). This is illustrated by Fig. 4, in which (for the general “fading and shadowing” situation and for $\sigma = 6$ dB) the 10% outage probability contours are drawn for three cases: coverage only, interference only (single interferer), and coverage and interference considered jointly. For Fig. 4(a) and (b), the desired base station and the interfering base station transmitters are assumed to be identical and separated by a distance of 13.75 km. The base stations have an EIRP sufficient to give 10% outage probability at a distance of 3 km in the absence of interference.\footnote{As an example, 10% outage probability in the presence of fading and shadowing ($\sigma = 6$ dB) will occur at a distance of 3 km for the following system parameters: base station EIRP: 63.5 dBm minimum required signal: -97 dBm cluster factor: -15 dB base station antenna height: 30 m mobile antenna gain: 0 dB}

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
System & EIRP & Minimum Required Signal & Cluster Factor & Base Station Antenna Height & Mobile Antenna Gain \\
\hline
Coverage Only & 63.5 dBm & -97 dBm & -15 dB & 30 m & 0 dB \\
\hline
Interference Only & 63.5 dBm & -97 dBm & -15 dB & 30 m & 0 dB \\
\hline
Coverage and Interference & 63.5 dBm & -97 dBm & -15 dB & 30 m & 0 dB \\
\hline
\end{tabular}
\end{table}
distance (namely 13.75 km) is that used in a seven-cell-repeat cellular mobile radio system where the cell radius is 3 km [11].

For Fig. 4(a), the interference protection ratio has been taken as 6 dB and, for this situation, the 10% "coverage only" outage probability contour lies entirely within the 10% "interference only" outage probability contour. Even so, the 10% outage probability contour for the general "coverage and interference" situation is significantly smaller than the "coverage only" contour. This illustrates that, in general, both the minimum signal requirement and the effects of interference need to be considered jointly.

For Fig. 4(b), the interference protection ratio has been taken as 10 dB and, for this situation, the 10% "coverage only" outage probability contour and the 10% "interference only" outage probability contour cross each other. The combined "coverage and interference" 10% outage probability contour is coverage-limited for most of its length but in the region nearest the interfering transmitter the contour is limited by cochannel interference.

Because the general "coverage and interference" outage probability contour is not a circle, it is not possible to give a simple analytical description of a particular outage probability contour, $R_0(\theta)$. This makes the analytical evaluation of (3) impossible and the average outage probability within an outage probability contour must be calculated numerically. Of course, in practice a constant outage probability contour will not usually define the area that a base station is intended to service. In an "idealized" mobile radio system with omnidirectional antennas, the intended area of service is essentially circular and centered on the desired base station. Therefore, the radio system designer may be more interested to know the average outage probability within a particular radius of a base station rather than within a constant outage probability contour.

In mobile radio systems which suffer from both noise and interference, average outage probability is more easily calculated when $R_0(\theta)$ in (3) is a constant rather than a nonconstant function. For the mobile radio system configuration that was described for Fig. 4, the outage probability (solid lines) at a 3 km radius of the desired base station and the average outage probability within that boundary is plotted in Fig. 5. Three transmitter power levels have been considered, these being sufficient to give outage probabilities of 20%, 10%, and 5% at a distance of 3 km in the absence of cochannel interference.

In Fig. 5, the interference protection ratio is the abscissa and serves as a means of quantifying the vulnerability of reception quality to cochannel interference. If "adequate" reception of the received signal requires that the mean level of the desired signal is considerably higher than the mean level of the interfering signal, then a high protection ratio is appropriate. Conversely, if just a small difference between the desired and interfering signals is sufficient to give "adequate" reception then a low interference protection ratio is sufficient.
Fig. 5. Outage probability (solid lines) at a 3 km radius from the desired base station and the average outage probability (dotted line) within 3 km radius as a function of the interference protection ratio. For the single cochannel interferer mobile radio system described for Fig. 4 and for the "coverage and interference" situation. Outage probability at 3 km from the desired base station in the absence of cochannel interference is: a and d: 20% b and e: 10% c and f: 5%.

If the interference protection ratio is small, the mobile radio system considered for Fig. 5 is essentially coverage-limited and the outage probabilities shown are only slightly higher than those given by Fig. 1(a) (for 100% of the area). However, if the protection ratio is large (that is, if radio communications are vulnerable to the effects of interference) the radio system is essentially interference-limited and the outage probability and the average outage probability are very dependent upon the protection ratio.

VI. CONCLUSIONS

Average outage probability equations have been formulated for mobile radio systems in which the quality of reception is dependent upon the margin between the mean of the desired signal and the minimum required signal, the margin between the mean of the desired signal and the interfering signal, and the variation of the received signals. Signal variation due to both Rayleigh fading and lognormal shadowing has been considered and the effect of a cochannel interferer on the quality of radio reception has been investigated.

It has been shown that the quality of radio reception at the boundary of an area is not in itself sufficient to describe the distribution of reception reliability within that area. The characteristics of radio propagation in a mobile radio system, such as the variability of the received signals, affect the average quality of reception within an area bounded by a particular outage probability contour.

The presence of cochannel interference in a mobile radio system degrades the quality of reception. The extent of this degradation is dependent upon both the absolute and relative strengths of the desired and interfering signals. Mobile radio systems can be "coverage limited" or "interference limited" depending upon the arrangement and strength of the transmitters and on such parameters as the signal-to-interference protection ratio.

The equations developed in this paper provide a basis for assessing the sensitivity of the reliability of reception to variations in system parameters such as $\sigma$, the propagation exponent, and the interference protection ratio. Although only the single-interferer situation has been considered in this paper, the authors have found that the same trends also occur in multiple interferer situations.

REFERENCES


Kevin W. Sowerby (S’86-M’90) was born in Hamilton, New Zealand, in September 1964. He received the B.E. and Ph.D. degrees in electrical and electronic engineering at the University of Auckland, Auckland, New Zealand, in 1986 and 1989, respectively.

During 1989 and 1990, he was a Leverhulme Visiting Fellow at the University of Liverpool, Liverpool, UK, in the Department of Electrical Engineering and Electronics. In 1990, he returned to the University of Auckland to take up a lectureship in the Department of Electrical and Electronic Engineering. His research interests are primarily in the area of mobile radio systems and, in particular, methods for determining communications reliability.

Allan G. Williamson (M’78-SM’83) received the B.E. and Ph.D. degrees from the University of Auckland, Auckland, New Zealand.

Following a brief period with the New Zealand Broadcasting Corporation, he joined the Department of Electrical and Electronic Engineering at the University of Auckland as a Lecturer in 1975, being promoted to Senior Lecturer in 1979 and Associate Professor and Leader of the Radio Systems Group in 1985. He was appointed Professor of Telecommunications in 1988 and Department Head in 1989. His early research was concerned with the analysis and modeling of waveguide circuit problems while more recently he has been involved with mobile radio research, now largely centered on issues closely related to cellular radio. In 1980, he was a Royal Society/Nuffield Foundation Scholar at the University of Birmingham, Birmingham, UK. From 1984 to 1985, he was a Leverhulme Visiting Fellow at the University of Liverpool, Liverpool, England. He has served as Chairman of both the IEEE New Zealand North Section and the IEEE New Zealand Council.