Outage Probability Analysis with Rayleigh Faded Cochannel Interferences and Gaussian Noise

Ik Beom Lee and Young Yearl Han

Abstract

In this paper, an outage probability in the presence of Rayleigh faded cochannel interference and Gaussian noise for cellular mobile telephone system is described. Our result is a computational formula that can be applied with or without Gaussian noise in Rayleigh faded cochannel interferences. Without Gaussian noise, the situation degenerates to usual case of the cochannel interferences. The result can be applied also in the presence of Gaussian noise with or without cochannel interferences.

I. Introduction

Efficient spectrum utilization requires the reuse of radio frequencies. Frequency reuse results in cochannel interference which degrades the performance and limits the spectrum efficiency of mobile radio systems. Hence investigating the effects of cochannel interference and Gaussian noise on the performance of digital transmission in mobile radio systems is of paramount importance. Some level of cochannel interference and Gaussian noise is inevitable in cellular systems reusing the frequency. Then outage probability provides a mean of assessing frequency reuse. Outage probability is defined as the probability of failing to achieve adequate signal reception[2]-[6].

Receiver performance is degraded by the multipath fading, cochannel interferences and environmental noise in a cellular mobile radio system. Multipath fading due to the waves reflected from the surrounding buildings and other structures is well represented by a Rayleigh probability density function and this multipath Rayleigh fading can severely degrades the signal transmission performance. Cochannel interference which is generated when two or more radio channels are assigned the same frequency set is inevitable in frequency reuse system. The effect of this component cannot be removed by a bandpass filter or a demodulator. That can be made less by being distant between cells.

Manuscript received November 24, 1997; accepted March 6, 1998.
The authors are with the Department of Electrical Engineering Han-Yang University.

In this paper, a generalized outage probability is studied which includes the effects of both multiple Rayleigh faded interferences and Gaussian noise. The outage probability for single cochannel interference plus nonrandom noise has been represented in [2] and extensive studies on outage probability have been reported for multiple cochannel interferences [4]-[5]. This paper studies a generalized outage probability which takes account of both the multiple interferences and the noise by deriving joint pdf of the m cochannel Rayleigh interferences and the Gaussian noise.

II. Outage Probability Analysis

Cellular radio systems rely on an allocation and reuse of frequency channels throughout a coverage region. Each cellular base station or cell site is allocated a group of radio channels to be used within a geographic area called a cell. The same group of frequency channels are used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits. Interference due to the common use of the same frequency channel is called cochannel interference. Although the real cell is amorphous in nature, a regular cell shape is needed for systematic system design. The hexagonal cell shape shown in Fig.1 is simple model of the radio coverage for each base station, but has been universally adopted in cellular system design since the hexagon permits easy and manageable analysis of a cellular system[1]. The hexagon closely approximates a circular radiation pattern which would occur for an omni-directional base station antenna. The number of cells which use the complete set of available frequencies is called cluster size and typically 7 is used. Due to hexagonal geometry Fig.1 has exactly six equidistant cochannel cells in the first tier and 6 cochannel cells in the second tier. Since the interferences from the cochannel cells in the second tier is negligible we consider only the interferers from the first tier.

Cochannel interference can be experimented both at the cell site and at the mobile units. If the interference power ratio at the mobile unit caused by the interfering cell sits in the down link is on the average the same as the signal-to-interference power ratio received at the cell site by interfering mobile unit[1]. This is called reciprocity theorem in the cellular mobile system. Hence we consider only for the case of the down link.

In a cellular mobile radio system having m cochannel interferences, system is modeled by Fig. 1

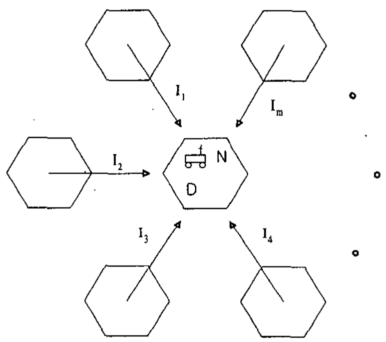


Fig. 1. System modeling with m cochannel interferences

I_i is cochannel interference power and D is desired instantaneous signal power. It is well known that desired signal and undesired interfering signal experience Rayleigh fading. It is also assumed that the received power from interferences are same, and sum of total noise is Gaussian process. Under this assumption, we derive the outage probability in single interference and multiple interferences environment.

Let received signal be $s(t)=i(t)+n(t)$, where $i(t)$ is the interfering signal having Rayleigh probability density and $n(t)$ is the noise which is described by the Gaussian process. We assume that $i(t)$ and $n(t)$ are statistically independent. The expected received power is obtained by

$$E[s^2(t)]=E[(i(t)+n(t))^2]=E[i^2(t)]+E[n^2(t)] \quad \textbf{(1)}$$

$$E[2i(t)n(t)]=0. \quad \textbf{(2)}$$

Outage Probability is defined as the probability that the ratio of instantaneous power of the desired and the interfering signal is less than a parameter known as protection ratio a.

$$P_{out}=Prob\left(\frac{D}{I}<a\right) P_{out}=Prob\left(\frac{D}{I}<a\right) \quad \textbf{(3)}$$

D and I represent the desired and interfering signal power random variables respectively. In a fully equipped hexagonal-shaped cellular system, there are six cochannel interfering cells in the first tier. Eqn.(3) assumed that noise power is small and can be neglected as compared with the interference power.

More general expression of outage probability can be expressed as follows including the effect of noise power

$$P_{out} = Prob\left(\frac{D}{I+N}<a\right)=Prob\left(\frac{D}{U}<a\right) \quad \textbf{(4)}$$

where N is a random variable of instantaneous power due to noise.

1. Outage probability in single interference environment

It is well known that in mobile systems both the desired radio signal and any cochannel interferences experience Rayleigh fading at the mobile receiver. A Rayleigh probability density function for the envelope of the desired signal is given by exponential probability density function for the instantaneous signal power

$$f_D(D)=\frac{1}{2\sigma_d^2}e^{-\frac{D}{2\sigma_d^2}} \quad , \quad D\geq 0 \quad \textbf{(5)}$$

where $2\sigma_d^2$ is the local mean power of the desired signal. Similarly when the envelope of interfering signal due to one interference has a Rayleigh probability density function, the pdf of the instantaneous interference power becomes

$$f_I(I)=\frac{1}{2\sigma_i^2}e^{-\frac{I}{2\sigma_i^2}} \quad , \quad I\geq 0 \quad \textbf{(6)}$$

where $2\sigma_i^2$ is the average power of the undesired signal. Usually noise is Gaussian process with zero mean and variance σ_n^2 and the pdf of the instantaneous noise power is given by

$$f_N(N)=\frac{1}{\sqrt{2\pi N}\,\sigma_n}e^{-\frac{N}{2\sigma_n^2}} \quad , \quad N\geq 0. \quad \textbf{(7)}$$

Assuming that N and I are statistically independent, the pdf of the instantaneous power due to interference and noise can be obtained as follows

$$\begin{aligned} f_{I+N}(U) &= \int_{-\infty}^{\infty} f_N(N) f_I(U-N)\, dN \\ &= \int_0^U f_N(N) f_I(U-N)\, dN \\ &= \int_0^U \frac{1}{\sqrt{2\pi N}\sigma_n} e^{-\frac{N}{2\sigma_n^2}} \cdot \frac{1}{2\sigma_i^2} e^{-\frac{U-N}{2\sigma_i^2}}\, dN. \end{aligned} \quad \textbf{(8)}$$

The pdf of U is given after several manipulations by

$$f(U) = \frac{1}{2\sigma_i^2\sigma_n\sqrt{k}}\, erf\left(\sqrt{\frac{k\cdot U}{2}}\right) e^{-\frac{U}{2\sigma_i^2}} \quad , \quad U \geq 0$$
$$k = \frac{1}{\sigma_n^2} - \frac{1}{\sigma_i^2} \tag{9}$$

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt. \tag{10}$$

As a check on this pdf, we can integrate $f(U)$ from 0 to infinity to obtain 1.

The outage probability can be expressed as follows [6]

$$P_{out} = Prob\left(\frac{D}{U} < \alpha\right)$$
$$= \int_0^\infty \int_0^{\alpha\cdot U} f(D)dDf(U)dU \tag{11}$$
$$= \int_0^\infty \left(1 - e^{-\frac{\alpha\cdot U}{2\sigma_d^2}}\right)\cdot \frac{1}{2\sigma_i^2\sigma_n\sqrt{k}} \cdot erf\left(\sqrt{\frac{k\cdot U}{2}}\right)\cdot e^{-\frac{U}{2\sigma_i^2}}dU.$$

To integrate eqn. (11), we use following relation

$$\int_0^\infty erf(\sqrt{q\cdot x})\cdot e^{-p\cdot x}dx = \sqrt{\frac{q}{p+q}}\cdot\frac{1}{p}. \tag{12}$$

Using eqn. (12), the outage probability simplifies to

$$P_{out} = 1 - \frac{\sigma_d^2/\sigma_i^2}{\sigma_d^2/\sigma_i^2 + \alpha}\cdot\sqrt{\frac{\sigma_d^2/\sigma_n^2}{\sigma_d^2/\sigma_n^2+\alpha}}$$
$$= 1 - \frac{\gamma_i}{\gamma_i + \alpha}\cdot\sqrt{\frac{\gamma_n}{\gamma_n+\alpha}} \tag{13}$$

where signal-to-noise and interference ratio γ is defined as

$$\gamma = \frac{\sigma_d^2}{\sigma_n^2+\sigma_i^2} = \left(\left(\frac{\sigma_d^2}{\sigma_n^2}\right)^{-1} + \left(\frac{\sigma_d^2}{\sigma_i^2}\right)^{-1}\right)^{-1}$$
$$= (\gamma_n^{-1} + \gamma_i^{-1})^{-1} \tag{14}$$

where

$\gamma_n = \frac{\sigma_d^2}{\sigma_n^2}$; signal to noise ratio,

$\gamma_i = \frac{\sigma_d^2}{\sigma_i^2}$; signal to interference ratio.

In the event of Rayleigh fading only (i.e., $\sigma_n^2 = 0$), the outage probability becomes

$$P_{out} = P\left(\frac{D}{I} < \alpha\right) = 1 - \frac{\gamma_i}{\gamma_i+\alpha}. \tag{15}$$

In the event of no cochannel interference being transmitted (i.e., $\sigma_i^2 = 0$), the outage probability can be expressed as

$$P_{out} = P\left(\frac{D}{N} < \alpha\right) = 1 - \sqrt{\frac{\gamma_n}{\gamma_n+\alpha}}. \tag{16}$$

Fig.2 and Fig.3 show the numerical results of eqn.(13). Figures illustrate outage probability as a function of SIR (signal-to-interference ratio) for several values of SNR (signal to noise ratio) in single interference environment with $\alpha = 6$dB and $\alpha = 18$dB. 18dB is system design parameter used in most cellular mobile system. Signal-to-interference power ratio of 18dB is measured by the acceptance of voice quality from the present cellular mobile receivers, this acceptance implies that both mobile radio multipath fading and cochannel interference power ratio become 63.1. We choose 6dB as used in the other literatures for comparison. 6dB implies that the signal-to-interference power ratio is 4. At 6dB cochannel interference reduction factor $q = D/R$ becomes half of that of 18dB. R is the coverage radius of the cell and D is the distance from the center of the cell to the center of the interfering cell. From Fig.2 and Fig.3 we can notice that as the SNR increases, i.e. as the influence of noise decreases, outage probability decreases and as the protection ratio α increases, outage probability increases. It is observed that for SIR $\leq$ 20dB the cochannel interference dominates as the major source of outage probability at low values of SNR.

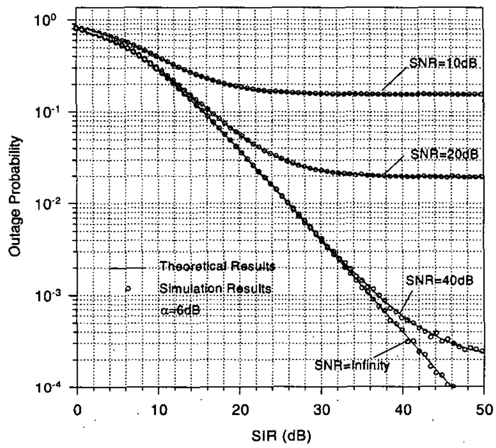


Fig. 2. Outage probability for single interference case α = 6dB, SNR = 10, 20, 40, Infinity

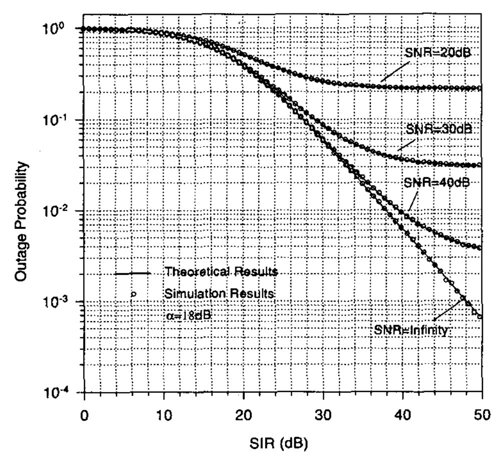


Fig. 3. Outage probability for single interference case α = 18dB, SNR = 20, 30, 40, Infinity

2. *Outage probability in multiple interference environment with same mean power*

The outage probability in a cellular mobile radio system with m-cochannel interferences and background noise is calculated. As mentioned above, cochannel interferences experience Rayleigh fading and it is assumed that each interference has the same mean power $2\sigma_i^2$. The joint probability density function of m exponential distributed interfering power is given by [5].

$$f_I(I) = \frac{I^{m-1}}{(m-1)!\,(2\sigma_i^2)^m} e^{-\frac{I}{2\sigma_i^2}} \quad I \ge 0$$
$$I = I_1 + I_2 + \cdots + I_m . \tag{17}$$

Assuming that sum of the m-cochannel instantaneous interference power I and the noise power N are statistically independent, the joint pdf of the I and the N can be obtained by convolution. It can be derived as follows

$$f(U) = \frac{1}{\sqrt{2}\,\sigma_n 2^m (\sigma_i^2)^m \Gamma\left(m+\frac{1}{2}\right)} e^{-\frac{U}{2\sigma_i^2}} U^{m-\frac{1}{2}} {}_1F_1\left(\frac{1}{2}; m+\frac{1}{2}; -\frac{k}{2}U\right)$$
$$U = N + I_1 + I_2 + \cdots + I_m = N + I \ge 0 \tag{18}$$
$$k = \frac{1}{\sigma_n^2} - \frac{1}{\sigma_i^2}$$

$${}_mF_n(\alpha_1, \cdots, \alpha_m;\ \beta_1, \cdots, \beta_n;\ x) = \sum_{j=0}^{\infty} \frac{(\alpha_1)_j \cdot (\alpha_2)_j \cdots (\alpha_m)_j}{(\beta_1)_j \cdot (\beta_2)_j \cdots (\beta_m)_j} \frac{x^j}{j!} \tag{19}$$

$$(\alpha)_j = \frac{\Gamma(\alpha + j)}{\Gamma(\alpha)} \tag{20}$$

where ${}_mF_n(\alpha_1 \cdots \alpha_m ;\ \beta_1 \cdots \beta_n ;\ x)$ is hypergeometric function [8, pp.1045]. $\Gamma(\cdot)$ is gamma function. To obtain outage probability, we use eqn. (5), eqn. (18) and eqn. (8).

$$P_{out} = \int_0^{\infty} \int_0^{\alpha \cdot U} f(D)\, dD f(U)\, dU$$
$$= \int_0^{\infty} \left(1 - e^{-\frac{\alpha \cdot U}{2\sigma_i^2}}\right) \cdot f(U)\, dU \tag{21}$$

To integrate eqn.(21), we use following relation[8, pp.851].

$$\int_0^{\infty} e^{-\mu x} x^{\nu - 1} {}_1F_1(\alpha; \beta; \lambda x)\, dx$$
$$= \Gamma(\nu) \mu^{-\nu} {}_2F_1\left(\alpha, \nu; \beta; \frac{\lambda}{\mu}\right), \quad \mu > 0,\ \nu > 0. \tag{22}$$

$${}_2F_1(\alpha,\ \beta;\ \beta;\ x) = (1 - x)^{-\alpha}, \quad \text{arbitrary } \beta. \tag{23}$$

Using eqn.(22), eqn.(23) and eqn.(21), the outage probability is shown as follows

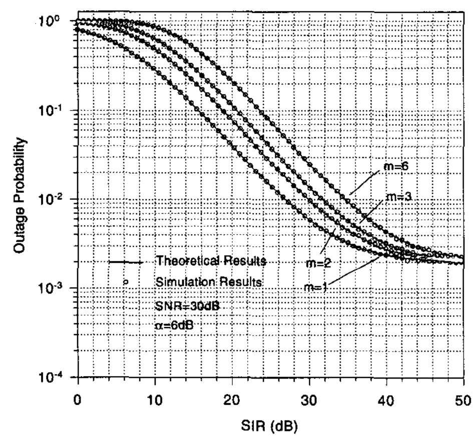
$$P_{out} = 1 - \left[\frac{\gamma_i}{\gamma_i + \alpha}\right]^m \cdot \sqrt{\frac{\gamma_n}{\gamma_n + \alpha}} . \tag{24}$$

In the case of m is 1 in eqn. (24), the outage probability results in the eqn. (13) due to single interference. In the event of Rayleigh fading only (i.e. $\sigma_n^2 = 0$), the outage probability becomes

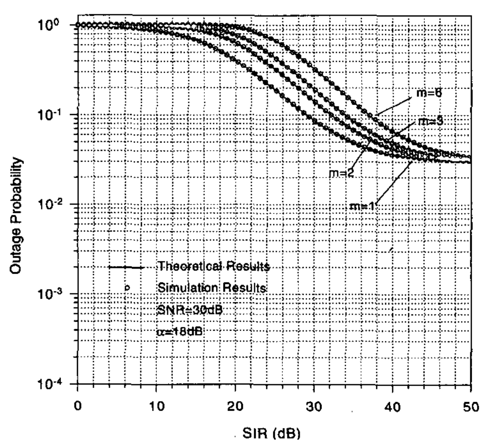
$$P_{out} = 1 - \left[\frac{\gamma_i}{\gamma_i + \alpha}\right]^m . \tag{25}$$

In the event of no cochannel interferences being transmitted (i.e. $\sigma_i^2 = 0$), the outage probability reduces to eqn.(16).

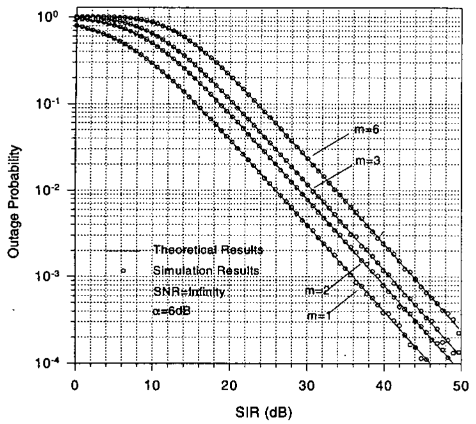
Fig. 4, Fig. 5 show the influence of multiple cochannel interferences on the outage probability as a function of SIR (signal-to-interference ratio) with fixed protection ratios and SNR's. Note that in Fig.4 SIR is defined as σ_d^2/σ_i^2. In each case, outage probability curves are presented for different values of α and SNR. Fig.5 shows the outage probability with respect to total interference power by defining SIR as $\sigma_d^2/m\sigma_i^2$. Assuming that the total interference power is I, little or no difference in outage probabilities were observed for single ($I_1 = I$) and multiple interferences ($I_1 = I_2 = \cdots I_m = I/m$) cases. This implies that the outage probability is influenced by the total interference power, not by the number of interferences.



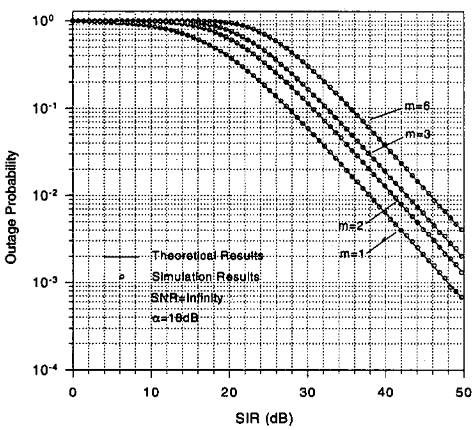
(a) SNR = 30dB, α = 6



(b) SNR = 30dB, α = 18



(c) SNR = infinity, α = 6



(d) SNR = infinity, α = 18

Fig. 4. Outage probability for multiple interferences case SIR = σ_d^2/σ_i^2, m = number of interferences

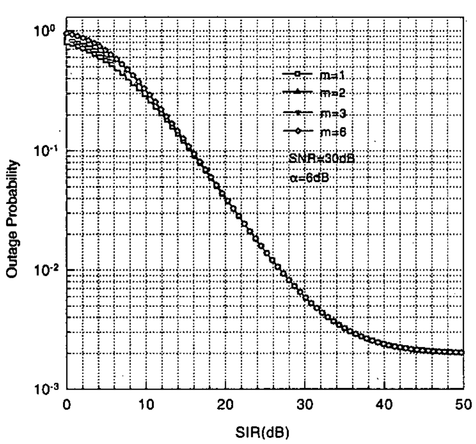


Fig. 5. Outage probability for multiple interferences case α = 6dB, SNR = 30dB, SIR = $\sigma_d^2/m\sigma_i^2$, m = number of interferences

3. Outage probability in multiple interference environment with different mean power

The joint probability density function of L exponential distributed interfering instantaneous power with different mean power is given by [5].

$$f_I(I) = \sum_{k=1}^{L} \frac{(2\sigma_{ik}^2)^{L-2}}{\prod\limits_{\substack{1\le l\le L\\ l\ne k}} (2\sigma_{ik}^2 - 2\sigma_{il}^2)} e^{\frac{-I}{2\sigma_{ik}^2}} \quad I \ge 0. \tag{26}$$

where $2\sigma_{ik}^2$ and $2\sigma_{il}^2$ are the kth and the lth average interfering signal powers respectively.

Assuming that sum of the L cochannel instantaneous interference power I and the noise power N are statistically independent, the pdf of sum of the I and the N can be obtained by convolution.

$$\begin{aligned} f_{I+N}(U) &= \int_0^U f_N(N) f_I(U-N)dN \\ &= \int_0^U \frac{1}{\sqrt{2\pi N}\sigma_n} e^{-\frac{N}{2\sigma_n^2}} \cdot \sum_{m=1}^{L} b_m e^{\frac{-(U-N)}{2\sigma_{im}^2}} dN \\ &= \sum_{m=1}^{L} \frac{b_m}{\sqrt{k_m}\sigma_n} e^{\frac{-U}{2\sigma_{im}^2}} erf\left(\sqrt{\frac{k_m U}{2}}\right) \end{aligned} \tag{27}$$

where $\quad b_m = \frac{(2\sigma_{im}^2)^{L-2}}{\prod\limits_{\substack{1\le l\le L\\ l\ne m}} (2\sigma_{im}^2 - 2\sigma_{il}^2)}, \quad k_m = \frac{1}{\sigma_n^2} - \frac{1}{\sigma_{im}^2}.$

To obtain eqn.(27) we used following relationship

$$\int_0^U \frac{e^{-qx}}{\sqrt{qx}} dx = \frac{\sqrt{\pi}}{q} erf(\sqrt{qU}). \tag{28}$$

We show eqn.(27) becomes 1 as follows

$$\begin{aligned} &\int_0^\infty \sum_{m=1}^{L} \frac{b_m}{\sqrt{k_m}\sigma_n} e^{\frac{-U}{2\sigma_{im}^2}} erf\left(\sqrt{\frac{k_m U}{2}}\right) du \\ &= \sum_{m=1}^{L} \frac{(2\sigma_{im}^2)^{L-1}}{\prod\limits_{\substack{1\le l\le L\\ l\ne m}} (2\sigma_{im}^2 - 2\sigma_{il}^2)} \\ &= \frac{(2\sigma_{i1}^2)^{L-1}\Phi_1 + (-1)\,(2\sigma_{i2}^2)^{L-1}\Phi_2 + \cdots\cdots + (-1)^{L-1}\,(2\sigma_{iL}^2)^{L-1}\Phi_L}{\Phi} \\ &= \frac{\Phi}{\Phi} = 1 \end{aligned} \tag{29}$$

where

$$\Phi = \begin{vmatrix} 1 & 1 & \cdots & 1 \\ 2\sigma_1^2 & 2\sigma_2^2 & \cdots & 2\sigma_L^2 \\ \vdots & \vdots & & \vdots \\ (2\sigma_1^2)^{L-1} & (2\sigma_2^2)^{L-1} & \cdots & (2\sigma_L^2)^{L-1} \end{vmatrix} \tag{30}$$

$$\Phi_i = \begin{vmatrix} 1 & 1 & \cdots & 1 & 1 & \cdots & 1 \\ 2\sigma_1^2 & 2\sigma_2^2 & \cdots & 2\sigma_{i-1}^2 & 2\sigma_{i+1}^2 & \cdots & 2\sigma_L^2 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ (2\sigma_1^2)^{L-2} & (2\sigma_2^2)^{L-2} & \cdots & (2\sigma_{i-1}^2)^{L-2} & (2\sigma_{i+1}^2)^{L-2} & \cdots & (2\sigma_L^2)^{L-2} \end{vmatrix}. \tag{31}$$

$i = 1, 2, 3, \cdots, L.$

Finally, to obtain outage probability, we use eqn.(5), eqn.(12) and eqn.(27)

$$
\begin{aligned}
P_{out} &= \int_0^{\infty}\int_0^{a\cdot U} f(D)f(U)dDdU \\
&= \int_0^{\infty}\left(1-e^{\frac{-a\cdot U}{2\sigma_d^2}}\right)\cdot f(U)dU \\
&= 1-\frac{\sqrt{\frac{\sigma_d^2}{\sigma_n^2}}}{\sqrt{a+\frac{\sigma_d^2}{\sigma_n^2}}}\sum_{m=1}^{L}\frac{\frac{\sigma_d^2}{\sigma_{im}^2}\cdot b_m\cdot 2\sigma_{im}^2}{a+\frac{\sigma_d^2}{\sigma_{im}^2}} \\
&= 1-\sqrt{\frac{\gamma_n}{\gamma_n+a}}\cdot\frac{\gamma_{i1}\cdot\gamma_{i2}\cdot\gamma_{i3}\cdots\gamma_{iL}}{(a+\gamma_{i1})\cdot(a+\gamma_{i2})\cdots\cdot(a+\gamma_{iL})}
\end{aligned}
\qquad (32)
$$

where

$$\gamma_n = \frac{\sigma_d^2}{\sigma_n^2},\quad \gamma_{im} = \frac{\sigma_d^2}{\sigma_{im}^2}.$$

When γ_{im}'s, $m = 1, 2, \cdots, L$ are the same we obtain eqn.(24).

III. Conclusion

A generalized outage probability including the effects of both m cochannel Rayleigh faded interferences and additive white Gaussian noise have been investigated in the cellular mobile radio system. The derived result is a computational formula that can be applied with or without Gaussian noise in Rayleigh faded cochannel interferences. In the case of neglecting Gaussian noise, the situation degenerates to usual case of interferences only. The desired outage probability formula is obtained by deriving the probability density function of sum of interference and noise.

References

[1] W.C.Y. Lee, "Mobile Telecommunications Systems," McGraw-Hill, 1990.

[2] H.D.M. Gurr, "Generalized Outage Probability and BER Estimation Using Dual Protection Margins," 1993 Vehicular Technology Conference, pp.1440-1444, June 1993.

[3] Y.D. Yao, "Investigations into Cochannel Interference in Microcellular Mobile Radio System," IEEE Trans. Veh. Techno., Vol. VT-41, pp.114-123, May 1992.

[4] K.W. Sowerby, "Outage Probability Calculations for a Mobile Radio System having Multiple Rayleigh Interferers," Electronic Letters vol.23 No.11 pp.600-601, May 1987.

[5] Y.D. Yao, "Outage Probability Analysis for Microcell Mobile Radio Systems with Cochannel Interferences in Rician/Rayleigh Fading Environment," Electronic Letters vol.26 No.13 pp.864-866, June 1990.

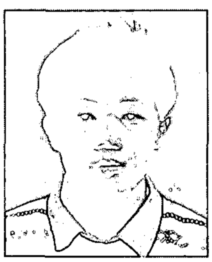
[6] R. Prasad, "Near-Far Effects on Performance of DS/SS CDMA Systems for Personal Communication Networks," 1993 Vehicular Technology Conference, pp.710-713, May 1997.

[7] A. L. Mood, "Introduction to the Theory of Statistics", McGraw-Hill, Inc., 1982.

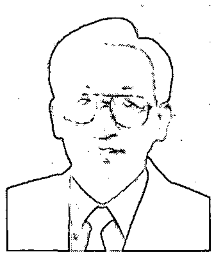
[8] I.S. Gradshteyn and I.M. Ryzhik, "Table of Integrals, Series, and Products", Academic Press, Inc., 1980.

[9] A.A. Abu-Dayya and N.C. Beaulieu, "Outage Probability of Cellular Mobile Radio Systems with Multiple Nakagami Interferers," IEEE Trans. Veh. Techno., Vol. 40, pp.757-768, Nov. 1991.

[10] R. Prasad, B.V. Lieshout, "Performance of indoor and Outdoor Radio Communications in Millimeric Wavelength", PIMRC'93 pp.20-24, 1993.



Ik Beom Lee received the B.S. nde M.S. degree from the Hanyang University, Seoul, Korea in 1996 in electronic communication engineering. He is working for Telecommunitation R&D Center of Hyundai Electronics.



Young Yearl Han received the B.S. degree from the Seoul National University, Seoul, Korea in 1960, the M.S. and Ph.D. degree from the University of Missouri-Rolla in 1976 and 1979, respectively, all in electrical engineering. Currently he is a professor at the Hanyang University, Seoul, Korea. Dr. Han received National Order of Merits and Presidential Citation from the Government of Korea, and Achievement Award from the Korea Insititute of Communication theory as applied to analysis and evaluation of digital communication systems, with a current emphasis on mobile and wireless communications. He was Vice-president of KICS from 1990 to 1995. He is a member of Sigma χ ι.