Assessment of a Pico-Cellular System Using Propagation Measurements at 1.9 GHz for Indoor Wireless Communications

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***Abstract*—Narrow-band propagation measurements were conducted at two floors of a multi-storied building at 1.9 GHz to study the behavior of the Rice factor and local mean power. To evaluate the influence of the Rice factor on a pico-cellular system, the outage probability is calculated for two different cases: (i) Rician fading for the desired and interfering signals with different Rice factors; (ii) Desired signal with Rician fading and interfering signals with Rayleigh fading with a different local mean power for each interfering signal. Finally, a pico-cellular structure is determined as an illustration.**

I. Introduction

During recent years, a significant interest in indoor wireless communications (IWC) has grown among radio engineers. In order to assist system designers to develop a successful system, a series of propagation measurement results have been reported in the indoor environment [1]–[6]. Whether an IWC system functions using dynamic channel allocation (DCA) or fixed cellular principles, it is essential to evaluate the outage probability for a given carrier to interference ratio.

The present paper investigates the behavior of the outage probability in terms of carrier-to-interference ratio using propagation measurement results of the 23 storyed Electrical Engineering Department Building of the Delft University of Technology, The Netherlands. The propagation measurements were conducted in the rooms on the 19th and 20th floor of the building where the Telecommunications and Traffic Control Systems laboratory is situated. The rooms are located on both sides of a 65 m long, 2 m wide, straight corridor. Each room is 4 m wide, 6 m long, and 2.80 m high. The partitions between the rooms are made of plaster board, rockwool and steel frames. The wall that separates the rooms from the corridor is made of brick. The floor is made of 50 cm reinforced concrete. Above the door at a height of 2.10 m a glass window runs up to the ceiling. On both ends of the corridor an open stairway leads to the upper and lower floors.

This paper has threefold objectives. First, the propagation measurement results are presented and the statistical parameters are obtained using these results. Second, an analytical model is developed to evaluate the outage probability for the desired Rician signal and uncorrelated interfering signals with different Rician factor and equal local mean power. An outage probability expression is also derived for zero Rician factor and different local mean power for each interferer. The outage probability is analytically evaluated using the extracted Rician factor from the propagation measurements. Finally, an illustration is presented to design a cellular structure for the 19th floor. The paper is organized as follows. Section II describes in brief the propagation measurements and presents a typical result for the 19th floor. Outage probability expressions are derived in Section III. Section IV presents the computational results. A short evaluation of a cellular structure is given in Section V. Finally, the conclusions are given in Section VI.

Manuscript received June 21, 1993; revised February 4, 1994.
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IEEE Log Number 9407345.

II. Propagation Measurements

This section first discusses the measurement procedure, then determines the propagation parameters from a typical propagation result and finally extracts the propagation parameters to study the indoor system. Propagation results were obtained for the 19th and 20th the floor. Results for both floors displayed the same general trend. This paper specifically makes use of the results for the 19th floor.

A. Measurement Procedure

The measurement equipment is developed by the Radio communication and EMC department of the PTT Research, Leidschendam, The Netherlands, to plan IWC systems. The equipment consists of a fixed transmitter and a mobile receiver, which operate at a continuous wave frequency of 1.9 GHz. Both transmitter and receiver are equipped with a $\lambda/4$ dipole antenna. The antennas of the transmitter and the receiver are positioned, respectively, at a height of 2.5 m and 1.80 m.

The receiver is operated by an acquisition program that runs on a laptop PC. Before a measurement is done the transmitted power is gauged. The difference in the transmitted and received signal power is digitized and stored in the laptop's memory. The difference is taken because the transmitter is unstable over a long period, which would make a comparison between different measurement results incorrect. The acquisition program measures the signal every traveled cm when it receives an interrupt from the wheel attached to the antenna pole. Localization of the measurement data is done with the help of a graphics tablet which gets the attention of the acquisition program via an interrupt. When for instance a corner is turned, an index will be given. The position of the antenna pole relative to the reference points on the graphics tablet will be stored together with the index

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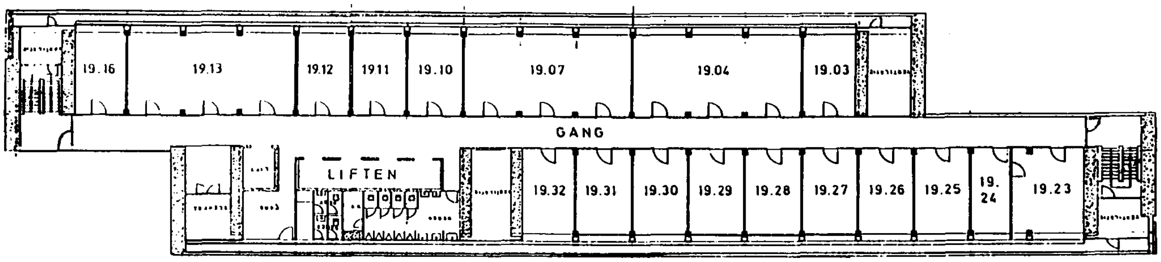

Fig. 1. 19th floor.

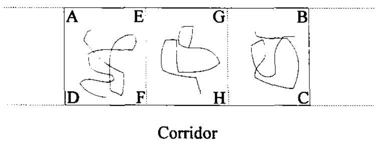

Fig. 2. The measurement method for the large rooms.

number and the corresponding measured signal. The location of the measurement data between two such indexes can be determined provided the measurement route is a straight line between the index points. When the PC is not engaged with the interrupts of the wheel or the graphics tablet, the acquisition program writes the measurement results to the screen to inform the user. The system makes it possible to measure the received power within 1 dB accuracy over a range of -110 to 5 dBm.

Fig. 1 shows the 19th floor. The transmitter is positioned in room 19.28 about 1 m from the common wall with room 19.29 and 3 m from the window. This is the only position used during the measurements due to time limitations. Data are obtained by randomly driving the receiver around in a room over a distance of about 20 m. The large rooms are split up into three separate fictional rooms to simplify the illustration of a cellular structure in Section V. Fig. 2 illustrates that the large room ABCD is divided in to three separate fictional rooms, namely, AEFD, EGHF, and GBCH. During the measurements, the receiver was driven within each fictional room as shown in Fig. 2.

B. Propagation Parameters

Fig. 3 is a typical propagation result attained from room 19.23, which shows the received instantaneous power versus the traveled distance. The fast variation of the instantaneous power is called multipath fading. The fast varying amplitude is described by the Rician distribution

$$f(A) = \frac{A}{\sigma^2} \exp\left(-\frac{A^2 + s^2}{2\sigma^2}\right) I_0\left(\frac{As}{\sigma^2}\right) \quad 0 \leq A < \infty \quad (1)$$

where A is the signal amplitude, σ^2 is the average fading power, s is the peak amplitude of the dominant received multipath component and $I_n(\cdot)$ is the modified Bessel function of the first kind and nth order. From (1) the probability density function (pdf) of the fast varying instantaneous power,

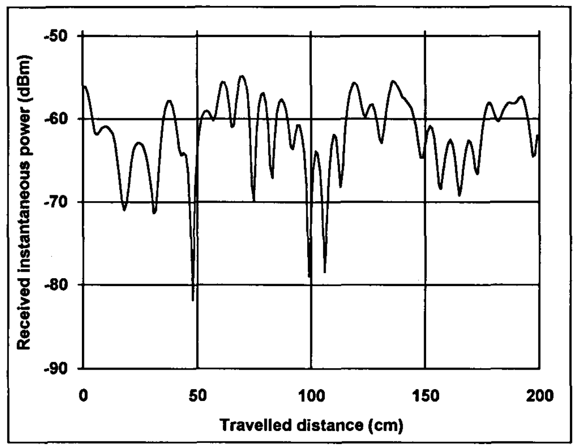

Fig. 3. The received instantaneous signal power versus the traveled distance.

$p = A^2/2$, is found as

$$f(p) = \frac{K+1}{p_0} \exp\left(-\frac{K+1}{p_0} p - K\right) \times I_0\left(2\sqrt{\frac{K^2+K}{p_0} p}\right) \quad 0 \leq p < \infty \quad (2)$$

where $p_0 = (s^2 + 2\sigma^2)/2$, is the local mean power and K the Rice factor, which is defined as the ratio of the average power of the dominant multipath component and the average fading power received over the non-dominant paths

$$K = \frac{s^2}{2\sigma^2}. \quad (3)$$

Equation (2) shows that the modeling parameters are K and p_0. These parameters are to be extracted from the received signal. The local mean power is extracted by averaging the instantaneous signal power over one meter (100 samples). In [7] it is shown that this results in a 95% reliability interval for the local mean power.

The Rice factor is extracted from the received signal using the following expression (Appendix A):

$$\frac{E[A]}{\sqrt{E[A^2]}} = \sqrt{\frac{\pi}{4(K+1)}} \exp\left(-\frac{K}{2}\right) \times \left[(K+1) I_0\left(\frac{K}{2}\right) + K I_1\left(\frac{K}{2}\right)\right] \quad (4)$$

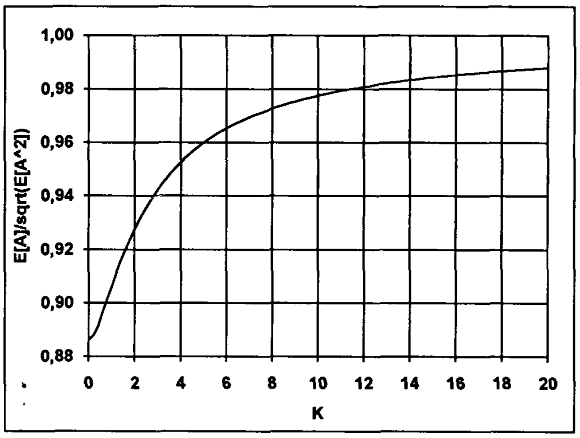

Fig. 4. The relationship between the statistics of the received amplitude and the Rice factor.

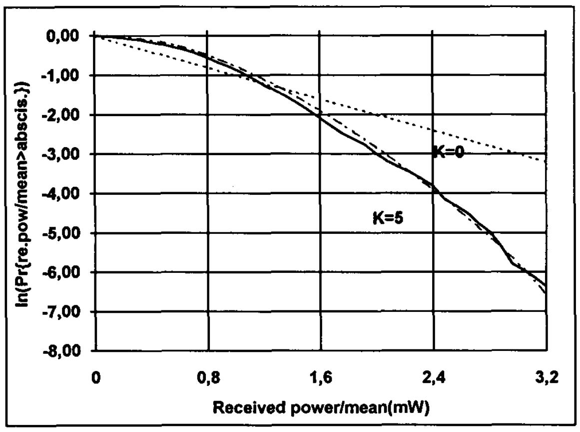

Fig. 5. A typical example of the CDF plot due to the measured data and (2) and (4). ··· correspond to $K = 0$; - - - corresponds to distribution via (2) and (4); and — corresponds to distribution which results from dividing the number of equal samples by the total sample size.

where $E[A]$ is the average amplitude and $E[A^2]$ the average of the squared amplitude. Fig. 4 shows (4) graphically.

The K value that is generated by (4) is checked by plotting the cumulative distribution function (CDF) obtained using the measured data, and the CDF obtained using (2) and (4). The Kolmogorov–Smirnov test is used for the best fit test [8]. This test generates a reliability interval around the CDF of the received signal power normalized on its local mean power. Plots using many different measurements showed that (4) is a reliable tool in the determination of K. An example of a typical plot is shown in Fig. 5. $K = 0$ is used as a reference. It equals the exponential distribution and therefore becomes a straight line in a log-normal scaled graph. The CDF that was obtained using (2) and (4), corresponds to $K = 5$. It is seen that when $K \geq 0$ a clear deviation occurs from the exponential distribution at the lower probabilities.

C. Extracted Results

In this section the measured propagation parameters are presented. Some remarks are made to explain the resulting numerical values. In Table I the measurement results of the 19th floor are displayed. In Fig. 6 a more useful overview is given.

TABLE I
THE MEASURED PROPAGATION PARAMETERS OF THE 19TH FLOOR

Room number 19th floor	Rice factor K	$-P_0$ (dBm)	Standard deviation of P_0(dB)
03	1	67.2	3.0
04	1.4	57.5	5.7
05	0.8	66.0	2.3
06	0.6	68.1	1.4
07	1.4	72.3	2.1
08	0	74.2	1.1
09	0	76.8	1.2
10	0.8	81.3	1.6
11	1	87.4	1.8
12	0.6	90.8	1.6
13	0	95.2	1.0
14	0	97.0	1.6
15	0	98.0	1.1
16	0.4	99.5	1.9
23	1.2	69.4	2.1
24	0.8	67.7	1.5
25	0.8	65.0	1.5
26	0.8	61.3	1.5
27	0	50.0	1.5
28 *	5.8	37.3	2.9
29	6.6	43.2	2.6
30	1.8	51.6	2.6
31	1.4	58.0	4.3
32	2.4	63.5	3.4

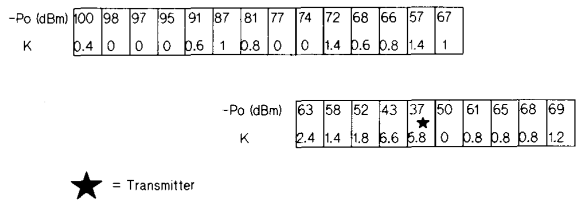

Fig. 6. An overview of the measured propagation parameters, K and P_0, on the19th floor.

The remarks are concerned with the behavior of the Rice factor. Fig. 6 shows that $K \neq 0$ in areas where no line-of-sight (LOS) is present. The corridor acts as a sort of wave guide which results in a dominant multipath component in the rooms out of sight of the transmitter. The Rice factor varies between 0 and 2.4 for the rooms more than one room distant from the transmitter. However, in the transmitter room and its two neighbors K varies between 0 and 6.6. The high K value in the transmitter room is to be expected because of the LOS in that room. The large difference between the K value found in room 19.29 of 6.6 and the zero K value in room 19.27 is not expected. An explanation could be that the transmitter is positioned closer to room 19.29, which causes a large component through the wall bordering 19.29 and a scattered one through the wall bordering 19.27.

The measured local mean power is used for the computational results in Section III and for the evaluation of the pico-cellular system in Section V.

III. FORMULATION OF COCHANNEL INTERFERENCE PROBABILITY

The cellular concept has been described in numerous papers, e.g., [9]. In order to investigate the reuse distance of a cellular system, it is necessary to determine the cochannel interference probability [10], [11], defined as

$$F(\mathrm{CI}) \triangleq \sum_{n} F(\mathrm{CI} \mid n) F_n(n). \quad (5)$$

Here $F_n(n)$ is the probability of n cochannel interferers being active. $F(\mathrm{CI} \mid n)$ is the corresponding conditional cochannel interference probability,

$$F(\mathrm{CI} \mid n) \triangleq \mathrm{prob}\left\{\frac{p_d}{p_n} < \alpha\right\} \quad (6)$$

where p_d is the instantaneous power of the desired signal, p_n is the joint interference power from n active channels and α is the specified cochannel protection ratio.

The measurement results show that the fast amplitude fluctuations of a mobile radio signal are described by a Rician density function with a Rice factor varying between 0 and 6.6. This means that the desired and the interfering signals are described by a Rician density function. The probability density function (pdf) for the joint interference power p_n is obtained by convolving (2) n times [15], (Appendix B)

$$f_{p_n}(p_n) = \left(\frac{K_i+1}{p_{0i}}\right)^{\frac{n+1}{2}} \left(\frac{p_n}{nK_i}\right)^{\frac{n-1}{2}} \times \exp\left(-\frac{K_i+1}{p_{0i}} p_n - nK_i\right) \times I_{n-1}\left(\sqrt{\frac{4n(K_i^2+K_i)}{p_{0i}} p_n}\right) \quad (7)$$

where p_{0i} is the local mean power of each interfering signal, K_i is the Rice factor of each interfering signal and n is the number of cochannel interferers. The conditional cochannel interference probability can be derived using (2), (5)–(7)

$$F(\mathrm{CI}|n) = 1 - (2nK_i)^{\frac{1-n}{2}} e^{-nK_i} \int_0^{\infty} Q \times \left(\sqrt{2K_d}, \sqrt{\frac{K_d+1}{K_i+1} \frac{\alpha p_{0i}}{p_{0d}}} x^2\right) \times I_{n-1}\left(\sqrt{2nK_i x^2}\right) dx \quad (8)$$

where K_d is the Rice factor of the desired signal, p_{0d} is the local mean power of the desired signal and $Q(a,b)$ is Marqum's Q-function [12]. A heavy restriction on the applicability of (8) in practice is the assumption that the local mean power is equal for each interfering signal. Table I shows that this is not the case in a real environment.

When K_i is taken as zero, it is possible to calculate the conditional cochannel interference probability with a different local mean power p_{0i} for each interferer (Appendix C)

$$F(\mathrm{CI} \mid n) = \sum_{i=1}^{n} \frac{1}{1 + \frac{\mathrm{SI}_i}{(K_d+1)\alpha}} \times \exp\left(-\frac{K_d}{\frac{(K_d+1)\alpha}{\mathrm{SI}_i} + 1}\right) \prod_{j=1 \wedge j \neq i}^{n} \frac{1}{1 - \frac{p_{oj}}{p_{0i}}} \quad (9)$$

where SI_i is $p_{0d}/p_{0i}, p_{0d}$ and p_{0i} are the local mean power of the desired and of the ith interfering signals, respectively.

In Section IV it will be shown that, given some practical system requirements and the measured propagation parameters, (9) does not significantly differ from (8). The simplicity of (9) and its flexibility concerning p_{0i} promises new possibilities for the evaluation of an IWC system, which uses dynamic channel allocation.

IV. Computational Results

This section shows that the Rice factor of the interfering signals has no significant influence on the reuse distance in the measured environment. First, it is necessary to specify the system requirements, namely, the maximum allowed cochannel interference probability and the protection ratio

- $F(\mathrm{CI} \mid n) \leq 10\%$
- $\alpha = 10$ dB [13]
  $F(\mathrm{CI} \mid n)$ will be evaluated using the ratio of desired and total interfering local mean power SI_t. A base station is placed in every room because this promises to be the most efficient cell size concerning the spectrum efficiency [14]. This means that the propagation parameters of the desired and interfering signals have the following values or bounds:
- $K_d = 5.8, P_{0d} = -37$ dBm
- $0 \leq K_i \leq 6.6, -100 \leq P_{0i} \leq -43$ dBm
  Fig. 7 depicts $F(\mathrm{CI} \mid n)$ versus SI_t for $K_d = 5.8$, $n = 1, K_i = 0$ and 6.6. When $F(\mathrm{CI} \mid n) \approx 0.01$, the largest difference in allowed SI_t occurs, namely, 2 dB in favor of $K_i = 0$. This may be unacceptable, however, Fig. 7 shows that the minimum allowed $\mathrm{SI}_t = 14$ dB and the combination of $K_i = 6.6$ and $\mathrm{SI}_t \geq 14$ dB does not occur in the measured environment as can be seen from Fig. 6. This means that the bounds on the interfering signal's propagation parameters alter to
- $0 \leq K_i \leq 2.4, -100 \leq P_{0i} \leq -52$ dBm
  Fig. 8 depicts $F(\mathrm{CI} \mid n)$ versus SI_t for $K_i = 0$ and 2.4. There is no significant difference in the allowed SI_t for $K_i = 0$ and 2.4. This means that the Rice factor of the interfering signals can be taken zero without loss of accuracy in the determination of the reuse distance. (9) can therefore be used in the measured environment given the specified system requirements.

V. An Illustration to Evaluate a Pico-Cell

An IWC system, which uses a fixed cellular structure, has been determined for the 19th floor of the building. The objective is to have as many cochannel users as possible on the floor. This means that the reuse distance has to be very small. When the pathloss of the desired signal is kept low, the cochannel users are allowed close to each other because the reuse distance is dependent on SI_t. For this reason we

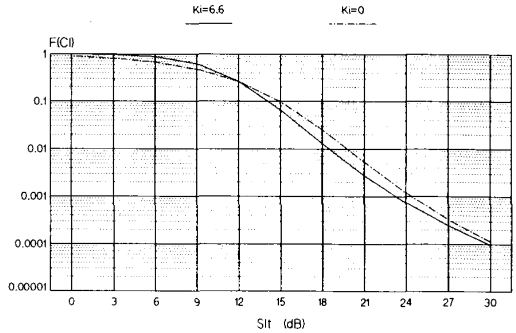

Fig. 7. The conditional cochannel interference probability $F(\mathrm{CI} \mid n)$ versus the ratio of the desired and the total interfering local mean power SI_t ($n = 1$, $\alpha = 10$dB, $K_d = 5.8$, $K_i = 0$, and 6.6).

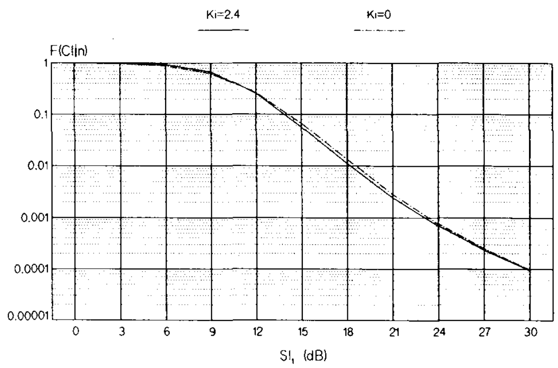

Fig. 8. The conditional cochannel interference probability $F(\mathrm{CI} \mid n)$ versus the ratio of the desired and the total interfering local mean power SI_t ($n = 4$, $\alpha = 10$ dB, $K_d = 5.8$, $K_i = 0$, and 2.4).

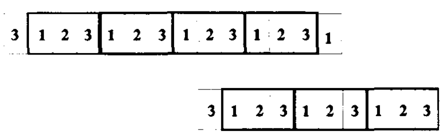

Fig. 9. The resulting cellular structure for the 19th floor.

chose a cell size of one room (see also [14]). The propagation results of Table I and the Rayleigh interferers approximation (9) are used. Fig. 9 shows the resulting cellular structure for the 19th floor. The structure covers the whole floor with eight clusters of three cells with a maximum cochannel interference probability of 1.46%.

VI. Conclusion

This paper has presented measurement results that were conducted in an office environment. The measured propagation parameters, namely, the Rice factor and the local mean power, are presented in tables. An analytical expression has been derived from which the relationship between the statistics of the received signal and the Rice factor becomes clear.

It is found that the Rice factor is not necessarily dependent on a line-of-sight to the transmitter. An explanation is that dominant multipath components are generated by wave guiding of the corridor. The numerical values of the measured Rice factor vary between 0 and 6.6. High Rice factors are measured only in rooms close to the transmitter. More than one room away from the transmitter, the Rice factors vary between 0 and 2.4.

An analytical expression has been found for the cochannel interference probability for a Rician desired signal and n Rayleigh interfering signals. Each interfering signal introduces its own local mean power to the expression. This possibility offers a degree of freedom which was not present in earlier calculations. The Rayleigh approximation can be made because the Rice factor of the interfering signals does not influence the use distance significantly given the measured propagation parameters and the specified system requirements. The expression promises to be useful in capacity calculations for DCA IWC systems, because of its simplicity and extra degree of freedom.

Finally, an evaluation of a pico-cellular IWC system is done for the 19th floor. When the fixed transmitter is placed in a room, the smallest cluster size will be three with a one room cell area. The small reuse distance justifies the use of a cellular system in an indoor environment.

Appendix A

Rician distribution is given by [9, p. 253]:

$$f(A) = \frac{A}{\sigma^2} \exp\left(\frac{-A^2 + s^2}{2\sigma^2}\right) I_0\left(\frac{As}{\sigma^2}\right) \; 0 \leq A < \infty. \quad \text{(A.1)}$$

The Rician distributed signal is the sum of a Rayleigh distributed amplitude, x, and a sinusoid, s.

$$A = s + x = \sqrt{(s_i + x_i)^2 + (s_q + x_q)^2} \quad \text{(A.2)}$$

where s_i is the in phase component of s, s_q is the quadrature component of s, x_i is the in phase component of x and x_q is the quadrature component of x. This means that the average squared amplitude, $E[A^2]$, equals:

$$E[A^2] = E[(s_i + x_i)^2 + (s_q + x_q)^2]. \quad \text{(A.3)}$$

For a Rayleigh process $E[x_i] = E[x_q] = 0$ and $E[x_i^2] = E[x_q^2] = 2\sigma^2$ [9, p. 173].
Rewriting (A.3) results in:

$$E[A^2] = E[s_i^2 + s_q^2 + x_i^2 + x_q^2] + E[2s_i x_i + 2s_q x_q] = s^2 + 2\sigma^2. \quad \text{(A.4)}$$

An expression will be derived for the average amplitude $E[A]$ [16, p. 4]:

$$E[A] = \int_0^\infty A f(A) dA. \quad \text{(A.5)}$$

First, $E[x]$ will be calculated, which is given by:

$$x = A\frac{s}{\sigma^2} \Rightarrow \frac{dA}{dx} = \frac{\sigma^2}{s} \wedge E[A] = \frac{\sigma^2}{s} E[x]. \quad \text{(A.6)}$$

Substituting (A.6) in (A.1), $f(x)$ is obtained as:

$$f(x) = \frac{\sigma^2}{s^2} x \exp\left(-\frac{\sigma^2}{2s^2}x^2 - \frac{s^2}{2\sigma^2}\right) I_0(x). \quad \text{(A.7)}$$

With the help of $f(x)$, $E[x]$can be calculated:

$$E[x] = \int_0^\infty xf(x)dx = \frac{\sigma^2}{s^2}\exp\left(-\frac{s^2}{2\sigma^2}\right) \times \int_0^\infty x^2 \exp\left(-\frac{\sigma^2}{2s^2}x^2\right) I_0(x)dx. \quad \text{(A.8)}$$

The following expression is obtained by partially integrating:

$$E[x] = \frac{\sigma^2}{s^2}\exp\left(-\frac{s^2}{2\sigma^2}\right)\left[\left(\frac{1}{2b}+\frac{1}{8b^2}\right)C_1 + \frac{1}{8b^2}C_2\right] \quad \text{(A.9)}$$

with $b = \frac{\sigma^2}{2s^2}$
and C_1 and C_2 as [17, p. 487]:

$$C_1 = \int_0^\infty \exp(-bx^2)I_0(x)dx = \sqrt{\frac{\pi}{4b}}\exp\left(\frac{1}{8b}\right)I_0\left(\frac{1}{8b}\right) \quad \text{(A.10)}$$

$$C_2 = \int_0^\infty \exp(-bx^2)I_2(x)dx = \sqrt{\frac{\pi}{4b}}\exp\left(\frac{1}{8b}\right)I_1\left(\frac{1}{8b}\right). \quad \text{(A.11)}$$

$E[A]$ is found with the help of (A.6), (A.9)–(A.11), as:

$$E[A] = \frac{s^2}{\sqrt{2\sigma^2}}\sqrt{\pi}\left[\left(\frac{\sigma^2}{s^2}+\frac{1}{2}\right)I_0\left(\frac{s^2}{4\sigma^2}\right) + \frac{1}{2}I_1\left(\frac{s^2}{4\sigma^2}\right)\right] \times \exp\left(-\frac{s^2}{4\sigma^2}\right). \quad \text{(A.12)}$$

This expression is verified by taking some limiting values for s and σ. When $\sigma = 0$, the Rayleigh component is canceled leaving the dominant component with amplitude s. So $E[A]$ should become s.

$$\lim_{\sigma\to 0} E[A] = s, \text{ with } \lim_{x\to\infty} I_0(x) = \lim_{x\to\infty} I_1(x) \sim \frac{e^x}{\sqrt{2\pi x}} \quad \text{[17, p. 377].} \quad \text{(A.13)}$$

When $s = 0$ the Rayleigh distribution results with its well known $E[A]$:

$$\lim_{s\to 0} E[A] = \sqrt{\frac{\pi}{2\sigma}}, \text{ with } I_0(0) = 1 \wedge I_0(0) = 0. \quad \text{(A.14)}$$

With (A.4) and (A.12) the relationship between $E[A]$, $E[A^2]$ and K follows as:

$$\frac{E[A]}{\sqrt{E[A^2]}} = \sqrt{\frac{\pi}{4(1+K)}}e^{\frac{-K}{2}} \times \left[(1+K)I_0\left(\frac{K}{2}\right) + KI_1\left(\frac{K}{2}\right)\right]. \quad \text{(A.15)}$$

Appendix B

Assuming equal Rice factor, K_i, and local mean power, p_{0i}, for each interferer, the pdf of the instantaneous power, p_i, of an interferer is in the form of (2) with the simple substitutions: $p \to p_i$, $p_0 \to p_{0i}$ and $K \to K_i$ and can be written as

$$f(p_i) = C_i e^{-A_i p_i} I_0(B_i\sqrt{p_i})$$

where

$$C_i = \frac{K_i+1}{p_{0i}}e^{-K_i}$$
$$A_i = \frac{K_i+1}{p_{0i}}$$
$$B_i = \sqrt{\frac{4K_i(K_i+1)}{p_{0i}}}. \quad \text{(B.1)}$$

The pdf of n interferers is found by convolving (B.1) n times, assuming they are independent. In the Laplace domain convolution becomes a multiplication. The Laplace transform of a zero order modified Bessel function is given by [18, p. 747]

$$I_0(2\sqrt{p}) \overset{\mathcal{L}}{\longleftrightarrow} \frac{e^{\frac{1}{s}}}{s}. \quad \text{(B.2)}$$

With the help of standard Laplace transforms, the Laplace transform for the pdf of one interferer is found as:

$$C_i e^{-A_i p_i} I_0(B_i\sqrt{p_i}) \overset{\mathcal{L}}{\longleftrightarrow} C_i \frac{ue^{\frac{1}{u(s+A_i)}}}{u(s+A_i)} \quad \text{with } u = \frac{4}{B_i^2}. \quad \text{(B.3)}$$

n times multiplication of (B.3) is given by

$$C_i^n \frac{1}{(s+A_i)^n} e^{\frac{1}{d(s+A_i)}} \quad \text{with} \quad d = \frac{u}{n} \quad \text{(B.4)}$$

which transforms back into

$$C_i^n e^{-A_i p_n} \int_0^{p_n}\int_0^{y_{n-1}}\int_0^{y_{n-2}} \cdots \int_0^{y_1} \times I_0(B_i\sqrt{nx_1})dx_1 dx_2 \cdots dx_n. \quad \text{(B.5)}$$

The integral of (B.4) is of the form [17,p. 484]:

$$\int_0^y x^{\frac{v-1}{2}} I_{v-1}(B_i\sqrt{nx})dx = \frac{2}{B_i\sqrt{n}} y^{\frac{v}{2}} I_v(B_i\sqrt{ny}). \quad \text{(B.6)}$$

When we take $v = 1$, we get the inner integral of (B.5),

$$\int_0^{y_1} I_0(B_i\sqrt{nx_1})dx_1 = \frac{2}{B_i\sqrt{B_i n}}\left[y_1^{\frac{1}{2}} I_1(B_i\sqrt{ny_1})\right]. \quad \text{(B.7)}$$

The part between brackets on the right of (B.7) is again of the form (B.6). Putting this back into (B.6) the result will be one order higher between the brackets with a multiplication by a constant. This results in a closed form for the multiple integral of (B.5)

$$\left(\frac{2\sqrt{p_n}}{B_i\sqrt{n}}\right)^{n-1} I_{n-1}(B_1\sqrt{np_n}) \quad \text{(B.8)}$$

where P_n = the total interference power. The pdf of n interferers is then given by:

$$f_{p_n}(p_n) = C_i^n e^{-A_i p^n}\left(\frac{2\sqrt{p_n}}{B_1\sqrt{n}}\right)^{n-1} I_{n-1}(B_i\sqrt{np_n}). \quad \text{(B.9)}$$

Substituting the A_i, B_i and C_i back into (B.9) results in (7).

APPENDIX C

The conditional cochannel interference probability is defined as:

$$F(\mathrm{CI} \mid n) = \Pr\left[\frac{p_d}{p_n} < \alpha\right] = \int_0^\infty \int_0^{\alpha p_n} f(p_d, p_n) dp_d dp_n \quad \text{(C.1)}$$

where p_d is the desired instantaneous signal power, p_n is the interfering instantaneous signal power, α is the protection ratio and $f(p_d, p_n)$ is the combined probability density function of p_d and p_n. The desired and interfering signals are assumed to be independent which means that the outage probability can be written as follows:

$$\Pr\left[\frac{p_d}{p_n} < \alpha\right] = \int_0^\infty \int_0^{\alpha p_n} f(p_d) dp_d f(p_n) dp_n. \quad \text{(C.2)}$$

First, the pdf of the interfering signal, $f(p_n)$, will be calculated. This is an n times convolution of the individual exponential distributions (n equals the number of interferers).

The exponential distribution is given by:

$$f(p_i) = \frac{1}{p_{0i}} e^{-\frac{p_i}{p_{oi}}} \quad \text{(C.3)}$$

where p_i is the received instantaneous signal power of the ith interferer and p_{0i} is the local mean power of the ith interferer.

In the Laplace domain the convolution becomes a multiplication of the individual Laplace transforms. The following transform pair is obtained:

$$f(p_1) * f(p_2) * \cdots * f(p_n) \overset{\mathcal{L}}{\longleftrightarrow} \prod_{i=1}^n \frac{a_i}{(s + a_i)} \quad \text{(C.4)}$$

where $a_i = p_{0i}^{-1}$.

The Laplace transform of (C.4) can be written as:

$$\prod_{i=1}^n \frac{a_i}{(s+a_i)} = \prod_{i=1}^n a_i \sum_{j=1}^n \frac{\mu_j}{(s+a_j)} \quad \text{(C.5)}$$

where

$$\mu_j = \prod_{\ell=1 \wedge \ell \neq j}^n \frac{1}{(-a_j + a_\ell)}.$$

The inverse Laplace transformation of (C.5) results in the following expression:

$$\begin{aligned} f(p_1) * f(p_2) * \cdots * f(p_n) &= \prod_{i=1}^n a_1 \sum_{j=1}^n \mu_j e^{-a_j p_j} \\ &= \prod_{i=1}^n a_i \left[\frac{\mu}{a_1} a_1 e^{-a_1 p_1} + \frac{\mu_2}{a_2} \right. \\ &\quad \left. \times a_2 e^{-a_2 p_2} + \cdots + \frac{\mu_n}{a_n} a_n e^{-a_n p_n}\right]. \quad \text{(C.6)} \end{aligned}$$

Equations (C.3) and (C.6) show that the conditional cochannel interference probability can be calculated by summing the conditional cochannel interference probability caused by each individual interferer multiplied with a weight factor. Hence, the conditional cochannel interference probability is given by:

$$F(\mathrm{CI} \mid n) = \sum_{i=1}^n \beta_1 F(\mathrm{CI} \mid i)$$

with

$$\begin{aligned} \beta_1 &= \prod_{j=1 \wedge j \neq i}^n \frac{1}{(1 - \frac{\mathrm{SI}_i}{\mathrm{SI}_j})} \\ \mathrm{SI}_i &= \frac{P_{0d}}{P_{0i}}. \end{aligned} \quad \text{(C.7)}$$

Now the conditional cochannel interference probability for the ith interfering signal, $F(\mathrm{CI} \mid i)$, will be calculated. When $f(p_i)$ substitutes $f(p_n)$ in (C.2) it can be seen that the inner integral can be calculated first, which is given by:

$$\begin{aligned} \int_0^{\alpha p_n} f(p_d) dp_d = \int_0^{\alpha p_n} \frac{K_d+1}{P_{0d}} \exp\left(-\frac{K_d+1}{P_{0d}} p_d - K_d\right) \\ \times I_0\left(\sqrt{\frac{4(K_d^2 + K_d)p_d}{P_{0d}}}\right) dp_d. \end{aligned} \quad \text{(C.8)}$$

This integral can be written in a closed form with the help of Marqum's Q-function which is given by [12, p. 394]:

$$Q(\lambda, \mu) = \int_\mu^\infty x e^{-\frac{\lambda^2 + x^2}{2}} I_0(\lambda x) dx. \quad \text{(C.9)}$$

Substituting the following in (C.8),

$$\begin{aligned} \lambda &= \sqrt{2K_d} \\ \mu &= \sqrt{2\alpha p_n \frac{K_d+1}{P_{0d}}} \end{aligned} \quad \text{(C.10)}$$

integral (C.8) simplifies to:

$$\int^{\alpha_{p_n}} f(p_d) dp_d = 1 - Q\left(\sqrt{2K_d}, \sqrt{2\alpha p_n \frac{K_d+1}{P_{0d}}}\right). \quad \text{(C.11)}$$

The last integral that has to be solved is the infinite integral over p_i. This integral simplifies, with the help of [12, p.395], to:

$$F(\mathrm{CI} \mid i) = \frac{1}{1 + \frac{\mathrm{SI}_i}{(K_d+1)\alpha}} \exp\left[-\frac{K_d}{\frac{(K_d+1)\alpha}{\mathrm{SI}_i} + 1}\right]. \quad \text{(C.12)}$$

The final expression for the total conditional interference probability is obtained with (C.7) and (C.12) as:

$$\begin{aligned} F(\mathrm{CI} \mid n) \\ = \sum_{i=1}^n \frac{1}{1 + \frac{\mathrm{SI}_i}{(K_d+1)\alpha}} \exp\left[-\frac{K_d}{\frac{(K_d+1)\alpha}{\mathrm{SI}_i} + 1}\right] \prod_{j=1 \wedge j \neq i}^n \frac{1}{1 - \frac{P_{0j}}{P_{0i}}}. \end{aligned} \quad \text{(C.13)}$$

ACKNOWLEDGMENT

The authors are grateful to Ir. Rob J. P. M. Mulder of the PTT Research Leidschendam, The Netherlands, for fruitful discussions. They would like to thank the anonymous reviewers for valuable suggestions.

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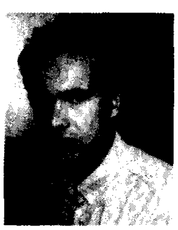

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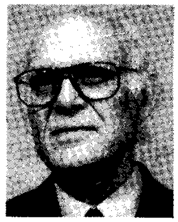

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