Analysis of Mobile Packet Radio Networks in Rayleigh Fading Environments

Rudolf Mathar, Jürgen Mattfeldt, and Rolf Hager

Abstract—**In this paper, we consider a Rayleigh fading channel for mobile radio networks. The distribution of cumulated instantaneous interference power is determined when interfering stations are located at random. The corresponding distances from a reference station are represented by a (deterministically delayed) renewal process with finite horizon. This distribution serves as a basis for determining the probability of successful transmission. We start with a short survey on existing models in the literature.**

I. Introduction

COMMUNICATION within mobile radio environments has drawn increasing attention during the last years. An economical use of the scarce resource "radio channel" is essential, due to growing networks with large numbers of stations. The results are narrowband radio frequency channels shared among varying numbers of radio stations.

Research in the field of mobile communication has produced a lot of investigations on different components of communication systems. In this paper, we focus on modeling the most important communication resource, the channel itself. There exist a large number of characteristics leading to different mathematical models which allow for analytical investigations of communication systems.

In its simplest form, the transmitted signal power is assumed to be constant within the transmission range, leading to the so-called ideal channel model. A more realistic model must take account of the variation of signal strength (depending on time and space), called fading. Multipath propagation causes short-term variations of signal power, which usually is very closely approximated by a Rayleigh distribution. In the case of a direct line of sight, this probability law is replaced by a Rice distribution. The movement of vehicles is accompanied by shadowing effects due to obstacles like buildings in urban environments, large vehicles (trucks), etc. Therefore, the area mean signal power varies slowly compared to short-term variation. Lognormal distributions are well suited to describe the variability of the mean.

Due to the competition for channel capacity by different stations, cochannel interference occurs. This can be modeled either as binary (complete destruction in the case of a collision), or depending on the strongest received signal power. If a specific capture ratio is exceeded, the strongest signal succeeds, and this signal is captured by the receiver. The capture effect has strong impacts on the performance of mobile communication networks [10]. Typical bit or packet error rates directly result from certain fading and capture conditions.

Obviously, the performance of a communication system under a certain network and node model is heavily influenced by the channel model. In the literature, various publications with specific configurations of models and evaluation techniques can be found. Subsequently, we give a brief survey.

The simple ideal channel model has served as a basis for a number of investigations on network performance with radio channels using the slotted ALOHA protocol, see [5], [7], [8], [12]. In this paper, we generalize the spatial distributional model used in these references.

A more realistic channel model is used in [3], taking into account the propagation power law. The authors analyze packet radio networks (PRN's) with slotted ALOHA and capture. Different improvements of throughput due to capture ratios, and additional techniques for analyzing performance are considered.

In the following publications, analyses of fading effects can be found. Hansen and Meno [4] investigate bit error rates (BER) under the condition of superimposed lognormal distribution of area mean signal level and a Rayleigh fading threshold model. A strong interdependence between BER and relative signal level is shown. French [2] studies the effect of Rayleigh fading on channels. Quantitative interrelationships between cochannel interference and reuse distance factors are found. Zainal and Garcia [13] consider ALOHA channels with Rayleigh fading and different capture threshold models. Various results on throughput and load under specific noise considerations are investigated. Prasad [10] analyzes PRN's with Rayleigh fading channels with capture and lognormal distributed area mean signal power. Network nodes are assumed to access the channel by the ISMA protocol. Interesting curves of throughput are obtained. Prasad and Liu [11] compare ALOHA and ISMA type protocols in Rice and Rayleigh fading environments with capture. No specific mobility model is used in [10], [11]. The number of interferers is assumed as Poissonian, all interferers with i.i.d. distances from the reference station. This, of course, is strongly simplifying.

Further performance investigations first of all need a more refined channel model. A key point is to investigate the

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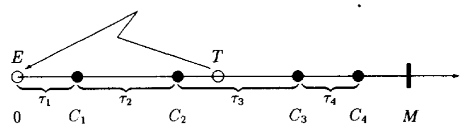

Fig. 1. Location of stations.

distribution of cumulated instantaneous interference power in a Rayleigh fading channel. Mathar and Mattfeldt [9] determine this distribution via Laplace transforms using a deterministic lattice and a Poisson point process as a model for positions of interferers in one and two dimensions, respectively. Though valuable approximations turn out, certain degeneracies occur due to the infinite location model with arbitrarily close stations.

In this paper, we consider a renewal process controlling the distances of interfering stations, and truncate this process at a finite horizon M. This seems to be a model closely adapted to certain realistic scenarios. Taking the capture effect into consideration, we will obtain numerical solutions of interference power distribution and probability of a successful transmission via an interesting integral equation.

II. Model Assumptions

We consider a station E being prepared to receive a signal from some transmitter T. The distance between E and T is denoted by d. Furthermore, we assume an infinite number of interfering stations $T_1, T_2, \ldots$ whose distances from E follow a (nondelayed) renewal process

$$N_t = \sup\{n \in \mathbb{N}_0 \mid \textstyle\sum_{i=1}^n \tau_i \le t\}, t \ge 0, \tag{1}$$

with i.i.d. interarrival times (spacings between neighboring stations) τ_n, $n \in \mathbb{N}$. τ_n is assumed to have density $f_\tau(y)$ with distribution function

$$F_\tau(y) < 1 \quad \text{for all} \quad y \in \mathbb{R}, \quad \text{and} \quad F(0) = 0. \tag{2}$$

The whole scenario may be visualized by locating E at the origin of the nonnegative real axis, and interfering stations at positions $0 < C_1 < C_2 < \ldots \in \mathbb{R}$. We take account of the process only up to a finite horizon, given by a fixed number M. Fig. 1 gives a comprehensive view of the locations.

Transmission of T to E is jammed by transmission of stations in the interval $[0, M]$ whose number N_M is random and finite with probability one. The cumulated instantaneous interference power at E may be described by the random variable

$$S = \textstyle\sum_{i=1}^{N_M} S_i, \tag{3}$$

S_i denoting the individual transmission power of station T_i at E. We assume a Rayleigh fading channel with no direct line of sight between transmitting stations and E, such that the distribution of S_i, conditional on $C_i = d_i$, has density

$$f_{S_i|C_i=d_i}(s) = \frac{d_i^\alpha}{k} \exp\Big(-\frac{d_i^\alpha s}{k}\Big), \quad s \ge 0, \tag{4}$$

where $k\, d_i^{-\alpha}$ is the average signal power determined by the constant k (electromagnetic environment) and $\alpha \in [2, 5]$ (radio environment), see [6]. Accordingly, the distribution of the signal power X of T at E is characterized by the density

$$f_X(x) = \frac{d^\alpha}{k} \exp\Big(-\frac{d^\alpha x}{k}\Big), \quad x \ge 0.$$

Furthermore, X and $\{S_i, \ \tau_i\}$, $i \in \mathbb{N}$ are assumed to be independent.

We take account of the capture effect, i.e., the ability of E to capture the reference signal from T, if its power X sufficiently exceeds the joint power S of all interfering stations. Thus, the probability of a successful transmission from T to E is given by

$$\begin{aligned} p_{\text{suc}} &= P(X \ge \kappa, X/S \ge \gamma) \\ &= \int_\kappa^\infty P(S \le X/\gamma \mid X = x) f_X(x)\, dx \\ &= \int_\kappa^\infty P(S \le x/\gamma) f_X(x)\, dx, \end{aligned} \tag{5}$$

where κ is a certain minimum threshold for a signal to be decodable, and γ denotes the relevant capture (signal-to-noise) ratio.

The key problem in (5) is to determine F_S, the distribution function of cumulated instantaneous interference power S. For this purpose, we introduce the delayed renewal process $N_t^{(a)}$, $a \ge 0$, which will play an important role in the following:

$$N_t^{(a)} = \sup\{n \in \mathbb{N}_0 \mid a + \textstyle\sum_{i=1}^n \tau_i \le t\}, t \ge 0, \tag{6}$$

where $\sup \emptyset$ is defined as zero. In our context, $N_t^{(a)}$ counts the number of interfering stations within distance t, when each T_i is located at $a + \sum_{\ell=1}^i \tau_\ell$. Obviously, it holds that $N_t^{(0)} = N_t$ from (1). Analogously to the above we define

$$S^{(a)} = \textstyle\sum_{i=1}^{N_M^{(a)}} S_i^{(a)}, 0 \le a \le M,$$

as the sum of interference power $S_i^{(a)}$ over all stations T_i within distance M, when stations are distributed according to the process $N_t^{(a)}$. Let

$$g(a, s) = P\big(S^{(a)} \le s\big), s \ge 0, \tag{7}$$

denote the distribution function of $S^{(a)}$. By successively conditioning on the position of the first interfering station T_1 and its signal power $S_1^{(a)}$ at E, we get the following:

$$\begin{aligned} P\big(S^{(a)} \le s\big) &= P\big(N_M^{(a)} = 0\big) \\ &\quad + \int_0^{M-a} P\big(S^{(a)} \le s \mid C_1 = y + a\big) \cdot f_\tau(y)\, dy \\ &= 1 - F_\tau(M - a) \\ &\quad + \int_0^{M-a} f_\tau(y) \int_0^s P\big(S^{(a)} \le s \mid C_1 = y + a, S_1^{(a)} = r\big) \\ &\quad \cdot \frac{(y+a)^\alpha}{k} \exp\Big(-\frac{r(y+a)^\alpha}{k}\Big)\, dr\, dy \\ &= 1 - F_\tau(M - a) \\ &\quad + \int_0^{M-a} f_\tau(y) \int_0^s P\big(S^{(y+a)} \le s - r\big) \\ &\quad \cdot \frac{(y+a)^\alpha}{k} \exp\Big(-\frac{r(y+a)^\alpha}{k}\Big)\, dr\, dy. \end{aligned}$$

This yields the following integral equation for $g(a,s)$, $(a,s) \in [0,M] \times [0,\infty) = \mathcal{D}_M$.

$$\begin{aligned} g(a,s) &= 1 - F_\tau(M-a) \\ &\quad + \int_0^{M-a} f_\tau(y) \int_0^s \frac{(y+a)^\alpha}{k} \exp\Big(-\frac{r(y+a)^\alpha}{k}\Big) \\ &\quad \cdot g(a+y, s-r)\, dr\, dy \\ &= 1 - F_\tau(M-a) \\ &\quad + \int_a^M \int_0^s f_\tau(y-a)\, h(y, s-r)\, g(y,r)\, dr\, dy \end{aligned} \tag{8}$$

where $h(y,r) = \frac{y^\alpha}{k}\exp\big(-\frac{ry^\alpha}{k}\big)$, $r, y \geq 0$. The distribution function of S in (3) is obtained from a solution as $g(0,s)$, $s \geq 0$.

III. Solving the Integral Equation

The aim of this chapter is to show that $g(a,s)$ is completely characterized by the integral equation (8). Moreover, a numerical method to calculate $g(a,s)$ is given. Both aspects are pursued by the following theorem and its proof.

Theorem: Let $F(y)$ be a distribution function with $F(0) = 0$, $F(y) < 1$ for all $y \in \mathbb{R}$, and continuous density $f(y)$, $y \in \mathbb{R}$. Suppose that the function $h(u,v) \geq 0$, $u, v \geq 0$, is continuous and fulfills $\int_0^\infty h(u,v)\, dv = 1$ for all $u > 0$. Then, for each fixed $M > 0$, the integral equation

$$g(a,s) = 1 - F(M-a) + \int_a^M \int_0^s f(y-a)\, h(y, s-r)\, g(y,r)\, dr\, dy \qquad (a,s) \in \mathcal{D}_M \tag{9}$$

has a unique continuous solution on $\mathcal{D}_M$.

Proof: According to the method of successive approximation [1], we consider the sequence $\{g_n\}_{n\in\mathbb{N}_0}$ with

$$\begin{aligned} g_0(a,s) &= 1 - F(M-a), (a,s) \in \mathcal{D}_M \\ g_{n+1}(a,s) &= 1 - F(M-a) \\ &\quad + \int_a^M \int_0^s f(y-a)\, h(y, s-r)\, g_n(y,r)\, dr\, dy \\ &\qquad (a,s) \in \mathcal{D}_M. \end{aligned} \tag{10}$$

By assumption, for $q_M = \sup_{x\in[0,M]} F(x)$, we have $q_M < 1$ and

$$\begin{aligned} &|g_0(a,s) - g_1(a,s)| \\ &= \int_a^M \int_0^s f(y-a)\, h(y,s-r)\,(1 - F(M-y))\, dr\, dy \\ &\leq \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, drdy \\ &\leq \int_a^M f(y-a)\, dy \leq q_M. \end{aligned}$$

It follows that for all $n \in \mathbb{N}_0$

$$\begin{aligned} &|g_n(a,s) - g_{n+1}(a,s)| \\ &\leq \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, |g_n(y,r) - g_{n-1}(y,r)|\, dr\, ds \\ &\leq q_M^n \int_a^M f(y-a)\, dy \;\leq\; q_M^{n+1} \end{aligned}$$

since by induction $|g_{n-1}(a,s) - g_n(a,s)| \leq q_M^n, n \in \mathbb{N}$. The sequence $\{g_n\}_{n\in\mathbb{N}_0}$ converges uniformly on $[0,M] \times [0,\infty)$, because $|g_n(x) - g_m(x)| \leq \sum_{i=m}^n |g_{i+1}(a,s) - g_i(a,s)| \leq \sum_{i=m}^\infty q_M^{i+1} \longrightarrow 0 (m \to \infty)$, $m \leq n, (a,s) \in \mathcal{D}_M$. The limit function g of the sequence $\{g_n\}_{n\in\mathbb{N}_0}$ satisfies integral equation (9), since

$$\begin{aligned} g(a,s) &= \lim_{n\to\infty} g_n(a,s) \\ &= \lim_{n\to\infty}\Big(1 - F(M-a) \\ &\quad + \int_a^M \int_0^s f(y-a)\, h(y, r-s)\, g_{n-1}(y,r)\, dr\, dy\Big) \\ &= 1 - F(M-a) \\ &\quad + \int_a^M \int_0^s f(y-a)\, h(y,r-s) \lim_{n\to\infty} g_{n-1}(y,r)\, dr\, dy \\ &= 1 - F(M-a) \\ &\quad + \int_a^M \int_0^s f(y-a)\, h(y,r-s)\, g(y,r)\, dr\, dy. \end{aligned}$$

Limit and integrals may be interchanged because $\{g_n\}_{n\in\mathbb{N}_0}$ is a uniformly convergent sequence of continuous functions.

Now, suppose that $\tilde{g}(a,s)$, $(a,s) \in \mathcal{D}_M$, is a different continuous solution of (9). Let $\mathcal{D}_{M,S} = \{(a,s) \in \mathcal{D}_M \mid 0 \leq s \leq S\}$, $S > 0$, and $\|\tilde{g}\|_{\mathcal{D}_{M,S}} = \sup_{(a,s)\in\mathcal{D}_{M,S}} |\tilde{g}(a,s)|$. Then,

$$\begin{aligned} &|\tilde{g}(a,s) - g_0(a,s)| \\ &\leq \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, |\tilde{g}(y,r)|\, dr\, dy \\ &\leq \|\tilde{g}\|_{\mathcal{D}_{M,S}} \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, dr\, dy \\ &\leq q_M \|\tilde{g}\|_{\mathcal{D}_{M,S}}, \end{aligned}$$

and for arbitrary $n \in \mathbb{N}$

$$\begin{aligned} &|\tilde{g}(a,s) - g_n(a,s)| \\ &\leq \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, |\tilde{g}(y,r) - g_{n-1}(y,r)|\, dr\, dy \\ &\leq q_M^n \|\tilde{g}\|_{\mathcal{D}_{M,S}} \int_a^M \int_0^s f(y-a)\, h(y,s-r)\, dr\, dy \\ &\leq q_M^{n+1} \|\tilde{g}\|_{\mathcal{D}_{M,S}}. \end{aligned}$$

Therefore, $\|\tilde{g} - g_n\|_{\mathcal{D}_{M,S}} \longrightarrow 0$ as $n \to \infty$. This yields $\tilde{g} = g$ on $\bigcup_{S>0} \mathcal{D}_{M,S} = \mathcal{D}_M$.

Remark. Resembling the arguments of Section II, in the case $M = \infty$, the function $g(a,s)$ satisfies the integral equation

$$g(a,s) = \int_a^\infty \int_0^s f(y-a)\, h(y,s-r)\, g(y,r)\, dr\, dy \qquad (a,s) \in \mathbb{R}_{\geq 0} \times \mathbb{R}_{\geq 0}. \tag{11}$$

Unfortunately, in this case, the method of successive approximation cannot be applied because the integral operator $\mathcal{I}$,

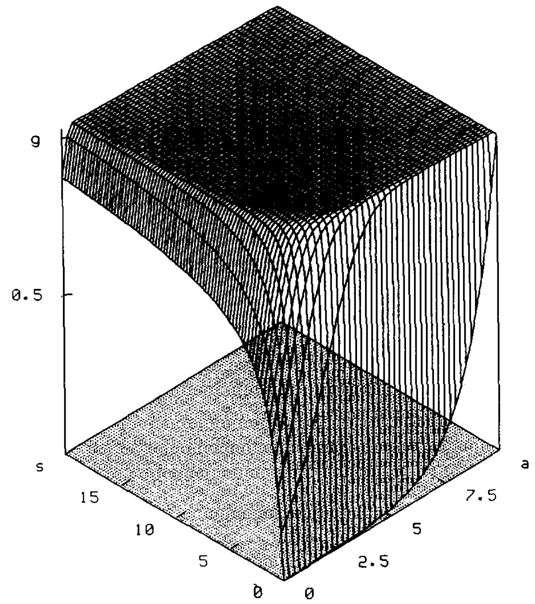

Fig. 2. $g(a,s)$. $0 \le a \le 10$, $0 \le s \le 20$, $\lambda = 0.75$, $M = 10$.

defined by

$$\mathcal{I}(g)(a,s) = \int_a^{\infty} \int_0^s f(y-a)\, h(y, s-r)\, g(y,r)\, dr\, dy$$
$$(a,s) \in \mathbb{R}_{\ge 0} \times \mathbb{R}_{\ge 0}$$

fails to be a contraction.

IV. Numerical Results

It seems to be rarely hard to derive a closed form expression $g(a,s)$ from integral equation (9). Nevertheless, the proof of existence and uniqueness of a solution is numerically constructive. Carrying out iteration (11) on a discrete grid for (a,s) over $\mathcal{D}_M$ allows us to calculate a solution at arbitrary precision.

We have applied this idea to $g(a,s)$ with a Poisson process describing positions of interfering stations, i.e., i.i.d. exponentially distributed interarrival times τ_i in (2) with density

$$f_\tau^{(\lambda)}(y) = \lambda\, e^{-\lambda y}, \quad y \ge 0.$$

The following calculations are based on the settings $\alpha = 2$ (free space propagation) and $k = 1$. Varying k simply means to rescale units of signal power. Fig. 2 shows the points $g(a,s)$ plotted against (a,s) as a 3-D surface in the rectangle $0 \le a \le 10$, $0 \le s \le 20$, for $\lambda = 0.75$ and $M = 10$. As is expected from representation (7), $g(a,s)$ increases for fixed s with increasing delay constant a, i.e., stochastically decreasing interference power $S^{(a)}$. On the other hand, for any fixed a, we have a distribution function in s with an atom at $s = 0$ corresponding to the event $\{S^{(a)} = 0\}$.

The cut at $a = 0$, i.e., $g(0,s)$, $s \ge 0$, yields the distribution function of cumulated interference power S in (3), which is represented in Fig. 3 for $\lambda = 0.1, 0.25, 0.5, 0.75$, and

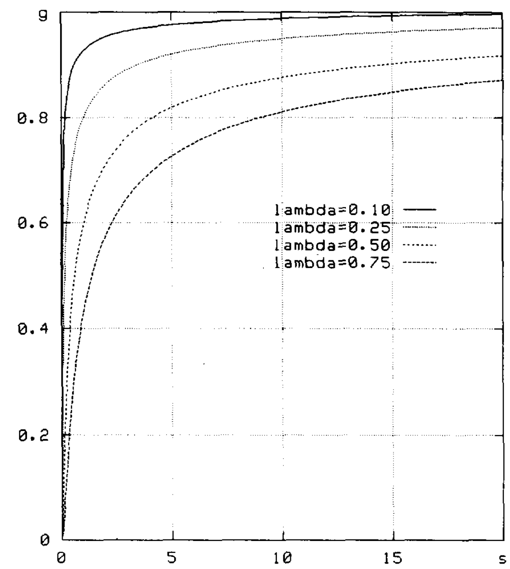

Fig. 3. $g(0,s)$. $0 \le s \le 20$, $\lambda = 0.1, 0.25, 0.5, 0.75$, $M = 10$.

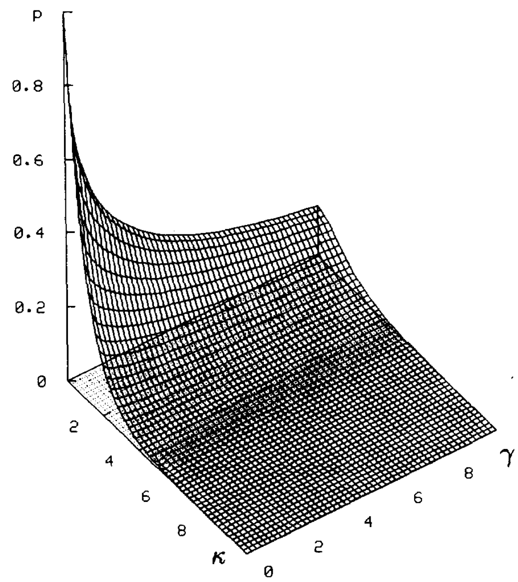

Fig. 4. $p_{\text{suc}}(\kappa, \gamma)$. $d = 1$, $\lambda = 0.5$, $M = 10$.

$M = 10$. With the help of this distribution function, the probability of a successful transmission p_{suc} may be derived by (5).

Fixing λ and the distance d between receiving and reference station, p_{suc} is a function of threshold κ and signal-to-noise ratio γ. Figs. 4 and 5 show p_{suc} as a 3-D surface plot in the domain $0 \le \kappa, \gamma \le 10$ for $d = 1$, $M = 10$, and $\lambda = 0.5$ and 0.2, respectively. The expected number of interfering stations in the interval $[0, M]$ is 5 (0.5 stations between E and T on average) in the first case, and 2 (0.2) in the latter one. Obviously, p_{suc} increases as λ decreases. It also becomes evident that even for moderate λ-values the probability of a successful transmission is fairly low at reasonable values of

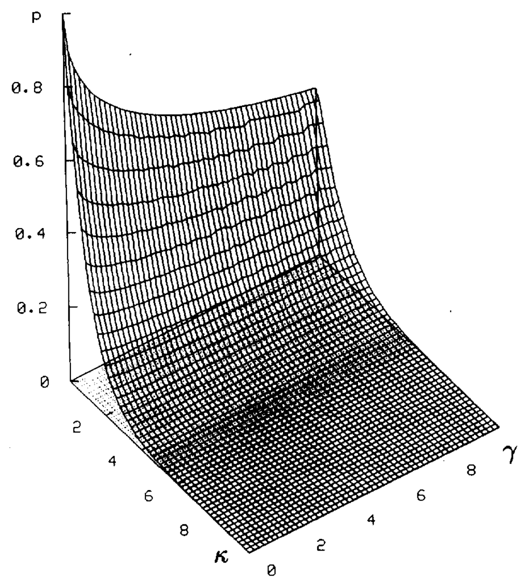

Fig. 5. $p_{\text{suc}}(\kappa, \gamma)$. $d = 1$, $\lambda = 0.2$, $M = 10$.

TABLE I
$p_{\text{suc}}(\kappa, \gamma)$. $d = 1$, $\lambda = 0.5$, $M = 10$

κ \ γ	1.6	2.2	2.8	3.4	4.0	4.6
1	0.2266	0.2055	0.1894	0.1750	0.1618	0.1516
2	0.0938	0.0871	0.0816	0.0766	0.0722	0.0689
3	0.0367	0.0345	0.0326	0.0312	0.0299	0.0285
4	0.0140	0.0133	0.0128	0.0122	0.0116	0.0113
5	0.0053	0.0051	0.0049	0.0047	0.0045	0.0044

κ and γ. $\lambda = 0.2$ and $\kappa = 2$, $\gamma = 2.8$ for instance give $p_{\text{suc}} = 0.1150$.

Tables I and II contain selected values from Figs. 4 and 5, respectively.

V. Conclusions

Unfortunately, even in the simplest case when stations are distributed according to a homogeneous Poisson process, the distribution of cumulated instantaneous interference power is rather complicated. Subsequent analysis of communication protocols along the lines of [10], [11] seems to be very tedious under the realistic interference power distribution derived in this paper. What we need is an easy-to-manage, but accurate, analytical approximation of $g(0, s)$, $s \geq 0$. This will be aimed at in future work.

As has been pointed out, the method of successive approximation fails if $M = \infty$. On the basis of the results in [9], we claim that the Laplace transform of $g(0, s)$ is given by

$$\lim_{n \to \infty} \frac{\lambda^{n+1}}{n!} \int_0^\infty e^{-\lambda x} \left(x - \sqrt{s} \operatorname{atan}\left(x/\sqrt{s}\right) \right)^n dx, \quad s \geq 0,$$

for the nontrivial, up to a multiplicative constant unique solution $g(a, s)$ of (11), if positions of stations are distributed according to a Poisson point process.

TABLE II
$p_{\text{suc}}(\kappa, \gamma)$. $d = 1$, $\lambda = 0.2$, $M = 10$

κ \ γ	1.6	2.2	2.8	3.4	4.0	4.6
1	0.3134	0.3042	0.2981	0.2861	0.2780	0.2752
2	0.1195	0.1169	0.1150	0.1134	0.1123	0.1114
3	0.0452	0.0446	0.0431	0.0429	0.0428	0.0424
4	0.0168	0.0166	0.0165	0.0162	0.0158	0.0157
5	0.0063	0.0061	0.0060	0.0060	0.0059	0.0058

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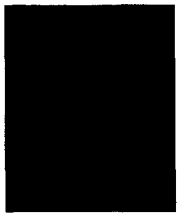

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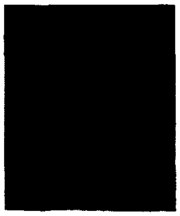

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