Minimum Duration Outages in Rayleigh Fading Channels

Jie Lai and Narayan B. Mandayam

WINLAB, Rutgers University

73 Brett Rd., Piscataway, NJ 08854-8060

Email: jlai@winlab.rutgers.edu, narayan@winlab.rutgers.edu

Abstract

Minimum duration outages have been introduced in [1, 2] for lognormal shadow fading where the durations of signal fades were considered in evaluating outages. In this paper we develop and analyze such minimum duration outages for channels susceptible to Rayleigh fading. The results show that under typical Doppler frequencies the outages due to Rayleigh fading are more likely to cause frame or packet errors rather than call dropping due to the short time scales in effect.

Keywords: Minimum Duration Outages, Fading Channels, Level Crossings, Performance Analysis

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1 Introduction

Traditionally, studying outage for cellular systems has been based on the signal-to-interference ratio (SIR) dropping below a required threshold. In real cellular environments, it is not the instantaneous drop of SIR below the threshold that determines outage. It is, in fact, the duration of time that the SIR stays below a threshold that determines outage for cellular systems. Moreover, the static analysis of outage precludes the time correlation in the signals which is important in real systems owing to mobility, fading and power control. The notion of "minimum duration outage" was introduced in [1, 2] as the SIR staying below a threshold longer than a certain "minimum duration" τ_m. The above notion is motivated by the fact that a very short interval of signal dropping below a threshold results in little or no impairment, while a longer duration may cause quality degradation, reduced intelligibility, or even call dropping[1]. Similarly, in data communications, burst error correcting codes may determine these minimum durations which may result in packet errors. In [1, 2], the focus of time-dependent performance was for lognormal shadow fading situations. Performance measures such as the average duration of outage, the frequency of outage, and the probability of outage and the effect of τ_m on these quantities was analyzed. In [4], the same methodology was used for analysis of slow shadow fading with reception diversity.

In this paper, we extend the minimum duration outage concept to fast Rayleigh fading. Rayleigh fading generally characterizes the rapid signal level fluctuations in a cellular system. Usually, the study of outage due to Rayleigh fading is based on the threshold crossing rate, the average duration of fade, and the probability of fade. Instead of directly assuming constant interference as in [1, 2, 4] we first evaluate the approximation of using a nonfading noise type signal to represent the joint interference composed of multiple mutually independent Rayleigh signals under the condition of large number of interferers and high fade margins. Using the concept of minimum duration outage, we extend asymptotic results on level crossings from the work by S.O. Rice [5] and analyze the average duration of outage, the frequency of outage, and the probability of outage as functions of the minimum duration τ_m, the fade margin F and

[1]A similar characterization for signal fluctuation has also been presented in [3], where these minimum duration outages were referred to as "dropouts"

Doppler frequency f_m.

The paper is organized as follows. In section 2, we present the general formulation of time-dependent performance measures for Rayleigh fading channels and justify the simplification of using a nonfading signal to represent the joint interference of multiple mutually independent Rayleigh signals with large interferer number and high fade margins. The analysis based on asymptotic level crossings is presented in 3. The numerical results are presented in section 4, with discussions and conclusions in section 5.

2 Problem Formulation

The minimum duration outage and its performance measures are defined in general as follows [1,2].

Definition 1 . *An outage event is defined as $SIR(t)$ going below a required threshold z and staying below at least τ_m seconds. In mathematical form,*

$$SIR(t) < z, \ \forall \ t \ \in [\tau_a, \tau_b] \text{ and } (\tau_b - \tau_a) \ \geq \ \tau_m. \tag{1}$$

Definition 2 . *Frequency of outage is defined as the average rate of outage events*

$$f_{out} = \lim_{t\to\infty} \frac{Total\ number\ of\ outages\ in\ [0,t]}{t}. \tag{2}$$

Definition 3 . *Probability of outage is the fraction of time that the system is in outage*

$$P_{out} = \lim_{t\to\infty} \frac{Total\ outage\ time\ in\ [0,t]}{t}. \tag{3}$$

Now we examine the signal and interference in Rayleigh fading channels. In a typical cellular system, the received signal shows rapid fluctuations around relatively slow variation of the mean level. This received signal can be well characterized by the fast Rayleigh signal around the log-normally distributed mean level [3,6]. Moreover, each interfering signal also comprises a Rayleigh and lognormal superimposed fading signal. In this paper, we assume that the slowly varying shadow fading and distance loss are perfectly compensated through power control whereas the fast fluctuations of signal and interference due to multipath fading remain uncompensated. Thus we assume that at the receiver, the desired signal for the user of interest is a Rayleigh signal with constant mean power and the interference signal is the sum of multiple mutually independent Rayleigh signals each with constant mean power.

If the interference is composed of n mutually independent Rayleigh signals with identical mean power $\bar{p}$, the probability density function (pdf) of the interference power p_t can be expressed as a gamma function [3]

$$f_{p_t}(p_t|n) = \frac{p_t^{n-1}}{(n-1)!\bar{p}^n} \exp(-\frac{p_t}{\bar{p}}). \tag{4}$$

The pdf of the desired signal power in Rayleigh fading is exponential

$$f_{p_s}(p_s) = \frac{1}{\bar{p_s}} \exp(-\frac{p_s}{\bar{p_s}}). \tag{5}$$

The cumulative distribution function (CDF) of SIR can be calculated as

$$\begin{aligned} P(SIR \equiv \frac{p_s}{p_t} \leq z) &= \int_0^\infty (\int_0^{zp_t} \frac{1}{\bar{p_s}} \exp(-\frac{p_s}{\bar{p_s}}) dp_s) \frac{p_t^{n-1}}{(n-1)!\bar{p}^n} \exp(-\frac{p_t}{\bar{p}}) dp_t \\ &= 1 - (1 + \frac{z\bar{p}}{\bar{p_s}})^{-n}. \end{aligned} \tag{6}$$

As the mean SIR being constant, $\frac{\bar{p_s}}{\bar{p_t}} = \frac{\bar{p_s}}{n\bar{p}} = const = \gamma$, then

$$\lim_{n\to\infty} P(SIR \leq z) = 1 - \exp(-\frac{z}{\gamma}). \tag{7}$$

This result is the same as we consider the interference as a nonfading noise type signal with mean power $\bar{p_t} = n\bar{p}$

$$\begin{aligned} P(SIR_m \equiv \frac{p_s}{\bar{p_t}} \leq z) &= P(p_s < z\bar{p_t}) \\ &= 1 - \exp(-\frac{z}{\gamma}). \end{aligned} \tag{8}$$

This implies that we could use a nonfading noise type signal to approximate the joint interference of multiple independent Rayleigh signals when the number of interferers is large ($n >> 1$). As known from the central limit theorem, the interference tends toward band-limited Gaussian noise when the number of interferers increases.

For the general case of interference composed of n Rayleigh signals with arbitrary different mean powers $\bar{p_k}, k = 1, 2, ..., n$, the pdf of the interference power can be approximated by the gamma distribution [3]

$$f_{p_t}(p_t|m) = \frac{p_t^{m-1}}{\Gamma(m)\bar{p}^m} \exp(-\frac{p_t}{\bar{p}}) \tag{9}$$

with

$$\bar{p} = \frac{\sum_{k=1}^{n} \bar{p_k}^2}{\sum_{k=1}^{n} \bar{p_k}} \tag{10}$$

and

$$m = \frac{[\sum_{k=1}^{n} \bar{p_k}]^2}{\sum_{k=1}^{n} \bar{p_k}^2}. \tag{11}$$

Thus the interference power p_t approximated by the gamma pdf has the same mean and standard deviation as the exact interference power p_t. Note that m now is a real number with $1 \leq m \leq n$. As in the case of equal mean power for each interferer, when the number of interferers gets larger ($n, m >> 1$), the pdf of the total interference power becomes narrower, i.e., the variance is reduced.

Furthermore, when we look at a real cellular system, it should be designed to operate at a low outage probability. This implies that the fade margin is high. The interference power is much lower than the desired signal power ($\bar{p_t} << \bar{p_s}$). The instantaneous SIR will drop below the required threshold only when the desired signal experiences a deep fade. Fluctuations of the interference has a less effect on the SIR than fluctuations in the desired signal. Hence, in the case of relatively high fade margin and large number of interferers (as for a heavily loaded system), the joint interference power can be well approximated by a nonfading noise type signal with mean power $\bar{p_t} \approx n\bar{p}$. Similar conclusions can also be found in [3, 7]. Thus we can simplify the time dependent SIR outage problem as the level crossing problem of a single desired Rayleigh signal. The threshold level for the desired Rayleigh signal about which the crossings are considered is the value which is F dB (F is the fade margin) down from the desired Rayleigh signal mean power. Here the fade margin (in dB) is defined as the difference between the mean SIR and the SIR threshold [3]. In the simulation results, we will show the influence of n (the number of interferers) on the accuracy of the analysis.

3 Analysis Based on Asymptotic Level Crossings

As mentioned in last section, we are interested in the situations where the SIR drops below the required threshold only when the desired signal has a deep fade, that is, the high fade margin case. S.O. Rice [5] gave an asymptotic result for the fade duration distribution function of deep fades by a Rayleigh signal $r(t)$. It is shown that when $r(t)$ crosses downward through the level R ($R \to 0$), the probability that it will remain below R for a duration $\tau_f \geq \tau$ is given as:

$$P_{\tau_f}(\tau_f \geq \tau) = \frac{2}{u} I_1(\frac{2}{\pi u^2}) exp(-\frac{2}{\pi u^2}) \tag{12}$$

where u is the normalized fade duration with respect to mean fade duration $\bar{\tau}_f$, defined as $u = \frac{\tau}{\bar{\tau}_f}$, and $I_1(\cdot)$ is the modified Bessel function of the first kind.

Starting from Rice's asymptotic result, we derive the following analytical expressions for the time-dependent performance measures defined in section 2. The details of the derivations are given in the Appendix.

Firstly, the average duration of a minimum duration outage is given as

$$\begin{aligned} \bar{\tau}_{out} &= \tau_m + \frac{\tau_m}{2I_1(\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2)\exp(-\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2)} \sum_{k=0}^{\infty} \frac{1}{k!(k+1)!2^{2k+1}} \\ &\cdot \{(2k)! - [(\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2)^{2k} + (2k)(\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2)^{2k-1} + ... + (2k)!] \exp(-\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2)\}. \end{aligned} \tag{13}$$

Further, the frequency of a minimum duration outage can be shown to be

$$f_{out} = 2\sqrt{2\pi} f_m \rho \exp(-\rho^2)(\frac{\bar{\tau}}{\tau_m}) I_1(\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2) \exp(-\frac{2}{\pi}(\frac{\bar{\tau}}{\tau_m})^2) \tag{14}$$

where f_m is the maximum Doppler frequency and $\rho = \frac{R}{R_{rms}}$. Finally, the probability of outage is expressed as[2]

$$P_{out} = f_{out} \bar{\tau}_{out}. \tag{15}$$

4 Numerical Results

We use Clarke's model [8] to simulate the Rayleigh fading signal. In the simulation two independent Gaussian random signals are filtered by Doppler spectrum shaped filters to generate a complex Gaussian signal. The envelop of this complex Gaussian signal forms the Rayleigh

[2]Note that we are approximating the probability of outage by multiplying the frequency and duration of outage. Such an approximation may not necessarily hold for random processes, however, our analysis will be validated by simulations

fading signal at baseband. The filter is implemented in the frequency domain using the spectrum shaping method described in [9]. A reduced complexity implementation of the algorithm is presented in [10] to improve the simulation efficiency.

Firstly, we evaluate the validation of using a nonfading noise type signal to approximate the joint interference composed of multiple mutually independent Rayleigh signals. We are especially interested in the influence of such an approximation on the fade duration statistics. Figure 1(a) shows the complementary CDF of fade durations in the cases of 3, 6, and 9 interferers with identical mean power. The result using constant nonfading interference power and the asymptotic theoretical result (equation (12)) are also shown for comparison. In the examples shown in Figure 1, the required SIR threshold z is chosen to be 5 dB. According to the joint interference power, the desired signal power is adjusted to make the mean SIR γ to be 15 dB. Hence the fade margin F is 10 dB. The Doppler frequency of the desired signal is 38 Hz (for mobile speed $v = 30$mph and carrier frequency $f_c = 850$MHz). The Doppler frequencies of interferers are uniformly distributed from 1.27Hz ($v = 1$mph) to 75.98Hz ($v = 60$mph), which implies that the interferers can have different speeds from that of the desired user. Notice that when the interferer number is large (e.g. $n = 6, 9$) the result of the complementary CDF of τ_f has a very good match with the result using constant nonfading interference power and the asymptotic theoretical result. The match is better for the larger interferer number. For a more realistic situation, Figure 1(b) shows the complementary CDF of fade durations in the cases of 3, 6, and 9 interferers with different mean powers. The interferer mean powers are assumed to be lognormally distributed. The standard deviation of the interferer mean power is assumed to be 6 dB. All the other conditions are the same as in Figure 1(a). The results are found similar to the cases of identical interferer mean power. For the case of different interferer mean powers, it is the parameter m in the gamma distribution (equation (9)) which determines the approximation. Since m is always smaller than the interferer number n (and m is always larger than 1), the results indicate that the analysis is more accurate in the case of identical interference mean power for the same interferer number. However as n increases m will also increase. Thus the match will be better, as shown in Figure 1(b). From these simulation results, we can see that the joint interference power of multiple mutually independent Rayleigh signals can be well approximated by a nonfading noise type signal when the number of interferers is large and the fade margin is high. Thus our minimum duration outage problem can be simplified as the level crossing problem of the desired Rayleigh signal with the threshold level being the value which is F dB (F is the fade margin) down from the desired Rayleigh signal mean power.

The simulation results are compared with analytical results derived in equations (13 - 15). Figure 2(a) shows the probability of outage as a function of the minimum duration τ_m for different fade margins. The comparison of the frequency of outage under the same conditions is shown in Figure 2(b). The results show that there is a good match between the analysis and simulations.

The effects of different Doppler frequencies on the probability and frequency of the outage are shown in Figure 3(a) and 3(b), respectively, with a fixed fade margin of F = 10 dB. In Figure 3(a), the probabilities of outage for different Doppler frequencies originate from the same static probability (when $\tau_m = 0$) since the probability of a fade is independent of Doppler frequency in the static case. As τ_m increases, the probability of outage for higher Doppler frequency decreases faster. In Figure 3(b), the frequency of outage decreases with the increasing of the minimum duration, and the family of curves have intersections with each other. The frequency of outage for a higher Doppler frequency starts from a higher value and eventually drops below that for a lower Doppler frequency. As a result, when the minimum duration τ_m is small, the frequency of outages is higher for higher Doppler frequencies. In contrast, when the minimum durations τ_m are longer, the frequency of outages is higher for lower Doppler frequencies. Also notice that the durations of outages due to Rayleigh fading are on the order of milliseconds. Thus these outages will have more impact on packet data communication in terms of packet error rate rather than the capacity for voice communication.

Figure 4 shows the different outage performance measures as functions of fade margin (F) with different values of minimum duration τ_m. When τ_m equals zero (the traditional static definition of outage) the probability of outage is inversely proportional to the fade margin (F). However when τ_m is not equal to zero (the minimum duration definition of outage), the average duration of outage ($\bar{\tau}_{out}$) converges to $1.5\tau_m$ as the fade margin (F) increases and τ_m becomes much larger than the average fade duration $\bar{\tau}_f$. Asymptotically, both the frequency of outage and the probability of outage are inversely proportional to the square of the fade margin (F).

Regarding the sensitivity of performance measures to minimum durations, note that the above results can also directly be used to compare the traditional static analysis with the minimum duration analysis. Specifically, when τ_m equals zero, the expressions for $\bar{\tau}_{out}$, f_{out} and P_{out} will become the mean duration of fade $\bar{\tau}$, the mean level crossing rate N_R, and the probability of fade $P(r \leq R_{req})$, respectively. Our results indicate that even a relatively small value of τ_m, such as 5 ms, may cause the performance measures f_{out} and P_{out} to change dramatically from static values.

5 Discussion and Conclusion

In mobile radio communications, not only the probability of a signal fade but also the duration of a fade determines the quality of communication. In this paper, we extended the "minimum duration" outage concept to cellular systems with Rayleigh fading. We justified using a nonfading noise type signal to approximate joint interference composed of multiple mutually independent Rayleigh signals under the situation of large number interferers and high fade margins. The statistics of outages were derived based on Rice's asymptotic results on the probability distribution function of the fade durations of Rayleigh fading signals. These analytical results were validated via simulations using Clarke's model which is commonly used for land mobile radio channels. It was shown that the asymptotic results were accurate and could be used to make more realistic evaluations of system performance than existing static methods.

With typical Doppler frequencies, Rayleigh fading causes fast fluctuations of the signal to interference ratio and the fade durations are in the order of milliseconds. Thus it is more likely that the outages due to Rayleigh fading will cause frame or packet errors rather than call dropping. In digital transmission systems, with protection against burst errors (such as error-correction and interleaving), the minimum duration τ_m for a frame or packet is determined based on the burst error-correcting capacity of the frame or packet. The asymptotic level crossings of a Rayleigh process can also be used to study the effect of fade and interfade durations on the performance of forward error correcting codes in packet data channels [11].

Appendix

We will derive the analytical expressions for $\bar{\tau}_{out}$, f_{out}, and P_{out} as presented in section 3. The well-known results for the level crossing rate N_R and the mean fade duration $\bar{\tau}_f$ for Rayleigh signal, which are needed in the derivation, are given as follows [6]

$$N_R = \sqrt{2\pi} f_m \rho e^{-\rho^2}, \tag{16}$$

and

$$\bar{\tau}_f = \frac{e^{\rho^2} - 1}{\sqrt{2\pi} f_m \rho}. \tag{17}$$

The pdf of the fade duration is derived from equation (12)

$$\begin{aligned} f_{\tau_f}(\tau) &= -\frac{dP_{\tau_f}(\tau_f \geq \tau)}{du}\frac{du}{d\tau} \\ &= -\frac{1}{\bar{\tau}_f}\frac{d}{du}[\frac{2}{u}I_1(\frac{2}{\pi u^2})\exp(-\frac{2}{\pi u^2})]. \end{aligned} \tag{18}$$

Using the above equation and Definition 1, the pdf of the outage duration τ_{out} can be obtained as

$$f_{\tau_{out}}(\tau_{out}) = \begin{cases} \frac{f_{\tau_f}(\tau_{out})}{P_{\tau_f}(\tau_f \geq \tau_m)} & \text{if } \tau_{out} \geq \tau_m \\ 0 & \text{otherwise.} \end{cases} \tag{19}$$

The average duration of outage is now given as

$$\begin{aligned} \bar{\tau}_{out} &= \int_{\tau_m}^{\infty} \tau_{out} f_{\tau_{out}}(\tau_{out}) d\tau_{out} \\ &= \frac{\bar{\tau}_f}{P_{\tau_f}(\tau_f \geq \tau_m)} \int_{\tau_m/\bar{\tau}_f}^{\infty} (-u) d[\frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}}] \\ &= \frac{\bar{\tau}_f}{P_{\tau_f}(\tau_f \geq \tau_m)}\{(-u)\frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}}|_{\tau_m/\bar{\tau}_f}^{\infty} + \int_{\tau_m/\bar{\tau}_f}^{\infty} \frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}} du\} \\ &= \tau_m + \frac{\bar{\tau}_f}{P_{\tau_f}(\tau_f \geq \tau_m)} \int_{\tau_m/\bar{\tau}_f}^{\infty} \frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}} du. \end{aligned} \tag{20}$$

Consider the integral on the RHS of the above equation. It can be simplified as follows:

$$\int_{\tau_m/\bar{\tau}_f}^{\infty} \frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}} du = \int_{\tau_m/\bar{\tau}_f}^{\infty} \frac{2}{u}\sum_{k=0}^{\infty}\frac{1}{k!(k+1)!}(\frac{1}{\pi u^2})^{2k+1}e^{-\frac{2}{\pi u^2}} du. \tag{21}$$

Now, substituting $2/(\pi u) = x$ in the above equation, we obtain

$$\int_{\tau_m/\bar{\tau}_f}^{\infty} \frac{2}{u}I_1(\frac{2}{\pi u^2})e^{-\frac{2}{\pi u^2}} du$$

$$
\begin{aligned}
&= \int_0^{\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2} \frac{1}{2}\sum_{k=0}^{\infty} \frac{1}{k!(k+1)!}(\frac{x}{2})^{2k} e^{-x} dx \\
&= \frac{1}{2}\sum_{k=0}^{\infty} \int_0^{\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2} \frac{1}{k!(k+1)!2^{2k}} x^{2k} e^{-x} dx \\
&= \sum_{k=0}^{\infty} \frac{1}{k!(k+1)!2^{2k+1}} \{(2k)! - [(\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2)^{2k} \\
&\quad +(2k)(\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2)^{2k-1} + ... + (2k)!]e^{-\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2}\}, \qquad (22)
\end{aligned}
$$

which results in an infinite series expression for easy calculation. Combining equation (20) and (22), the average duration of outage can be obtained as in equation (13) in section 3.

The frequency of outage is now given as

$$
\begin{aligned}
f_{out} &= \{\text{crossing rate}\} \times \text{Prob}\{\text{the crossing is an outage}\} \\
&= N_R P_{\tau_f}(\tau_f \geq \tau_m) \\
&= 2\sqrt{2\pi} f_m \rho \exp(-\rho^2) \frac{\bar{\tau}_f}{\tau_m} I_1(\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2) \exp(-\frac{2}{\pi}(\frac{\bar{\tau}_f}{\tau_m})^2). \qquad (23)
\end{aligned}
$$

Finally, using the above expressions, the probability of outage is given as

$$
P_{out} = f_{out}\bar{\tau}_{out}. \qquad (24)
$$

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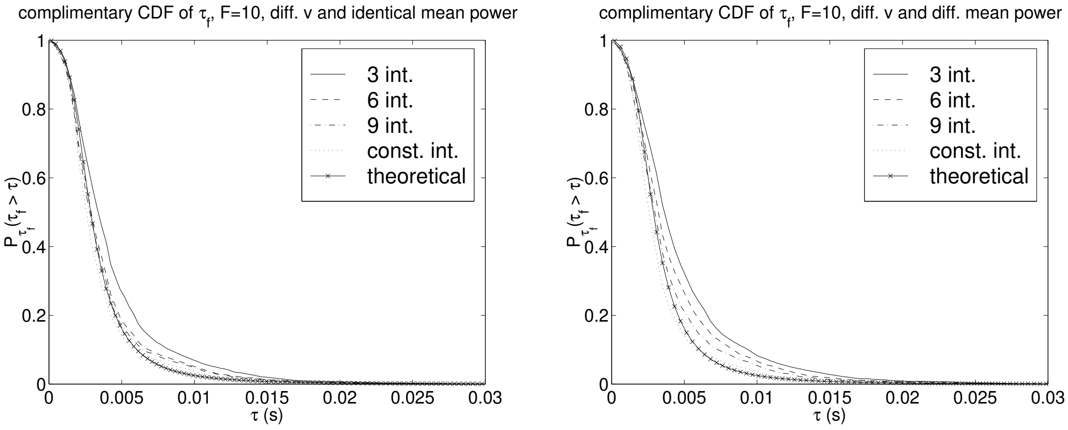
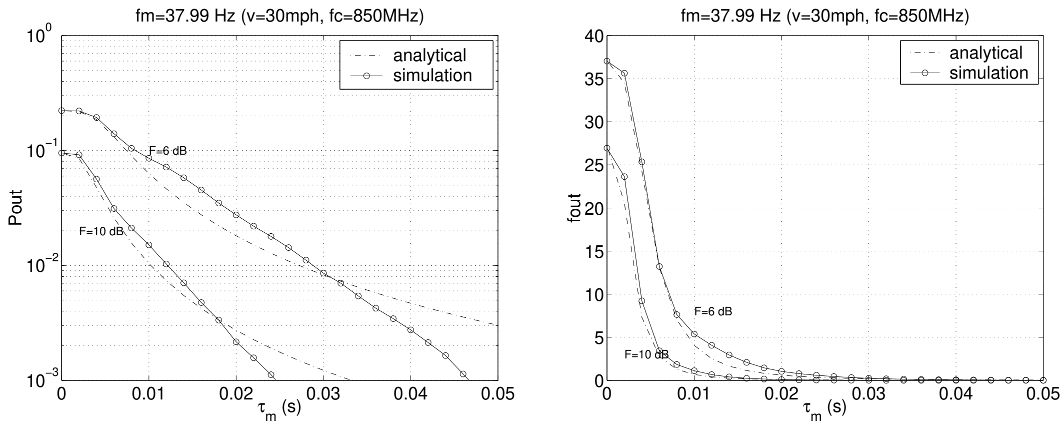


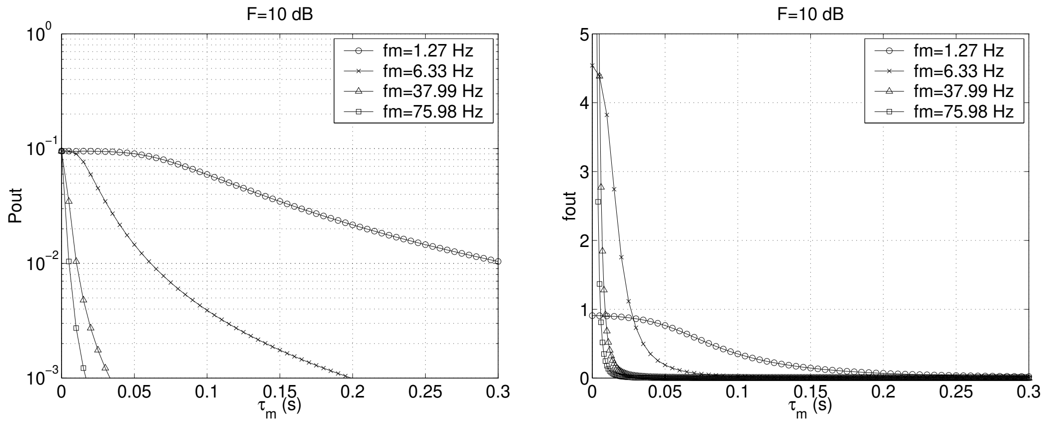
(a) (b)

Figure 1: Analytical and simulation results of complimentary CDF of fade durations: (a) interferers with identical mean power; (b) interferers with different mean powers.



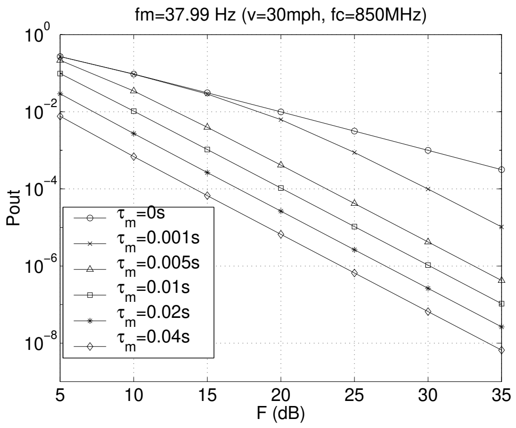
(a) (b)

Figure 2: Analytical and simulation results with different fade margins (F): (a) probability of outage; (b) frequency of outage.

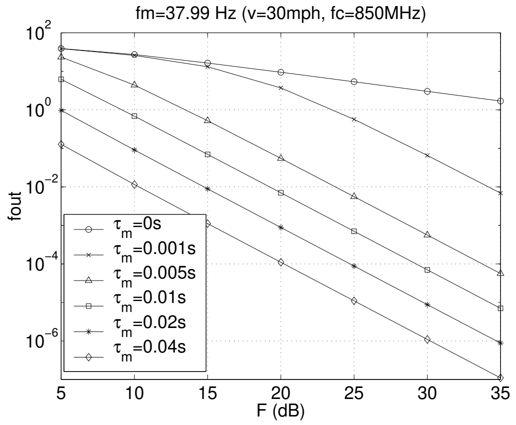


(a) (b)

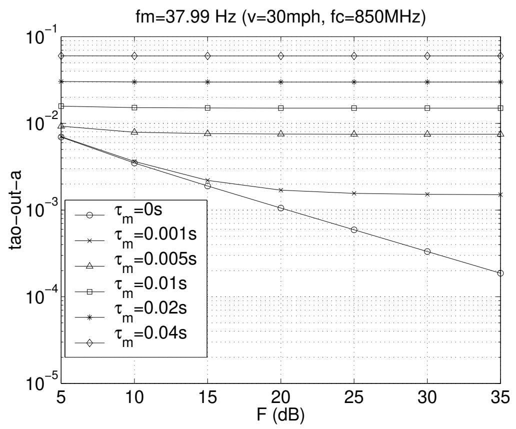
Figure 3: Analytical results with different Doppler frequencies (f_m): (a) probability of outage; (b) frequency of outage.



(a)



(b)



(c)

Figure 4: Analytical results with different fade margins (F): (a) probability of outage; (b) frequency of outage; (c) average duration of outage.