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14. Abstract/Notes

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LINK AVAILABILITY IN SATELLITE TELECOMMUNICATION SUBJECT TO CORRELATED RAIN ATTENUATION AT THE GROUND TERMINALS

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ABSTRACT

A link model for satellite telecommunication is presented, and the problem of link outage due to signal strength attenuation caused by rain in the two propagation paths (earth-to-space and space-to-earth) is considered. A joint probability density for up-path and down-path losses is used for computation of link availability by numerical integration of the density over the region of the plane that corresponds to satisfactory telecommunication. It is shown that correlation between the marginal probability densities for the two path losses can have a significant effect on link availability for SCPC networks. The importance of this result lies in the fact that, in satellite networks with a large number of thin-route users, ground terminals are sometimes so close to each other that rain events and rates of rainfall at their sites cannot be assumed independent.

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1. INTRODUCTION

A basic specification in satellite telecommunication system design is link availability, the fraction of time in which it is required that received signal quality be satisfactory. Because of random radio wave propagation losses besides those of free space, it is usually necessary to provide a power margin in link calculations. This power margin should be estimated with great care: for economic reasons, it should be as small as possible, but it must be sufficient to assure the specified link availability.

In the microwave frequencies commonly used or planned for use in space telecommunications, the most important propagation effect is signal strength attenuation caused by rain. In a satellite link, this attenuation depends on the radio frequencies used in the up-path and down-path, the rainfall rates in the neighborhoods of the transmitting and receiving earth stations, and the antenna elevation angles of these stations. In frequencies above 10 GHz, the amount of attenuation due to rain can be considerable (such as 10 dB or more), even for elevation angles above 30^{o} and rain rates as low as 50 mm/h.

In this paper, the combined effect of rain-induced attenuation in the up-path and down-path of a satellite link is obtained by means of a parameterized expression that approximates the joint probability density function of the two losses due to rain. It is shown that correlation between these losses (which is closely related to correlation between rain events near the two earth stations) can affect link availability to a significant degree. Previous analyses, such as that of Bantin and Lyons [1], have assumed statistical independence between rain events near the transmitting and receiving earth stations. This assumption is justified only when there is a sufficient separation between earth stations, as indeed was always the case in satellite telecommunications until recently. Two related developments have changed the situation: a sharp reduction in the "critical distance" below which a terrestrial link is more economical than a satellite link for a point-to-point connection and, more important, the emergence of satellite networks interconnecting a very large number of low-capacity earth stations, some of which may be as close as a few blocks from each other in the same city.

Although only signal strength attenuation is considered in this paper, it is clear that other losses caused by rain (such as depolarization losses) can be dealt with in a similar way.

The link model and the probability density functions for rain rates and for path losses are given in the next two sections. Section 4 gives the result of numerical calculation of link availability for a single-channel-per-carrier (SCPC) network and for a TDMA network. In both examples, the radio frequencies are in the 14 and 12 GHz bands, and a large number of small earth stations are involved.

2. SATELLITE LINK MODEL

A simple satellite link model, applicable to transmission through satellites equipped with conventional nonregenerative, nonlinear transponders, is shown in Figure 1. For simplicity, the frequency translation is not represented in this power-flow diagram, where the symbols are to be interpreted as follows:

P_t - Carrier signal power at the transmitting earth station antenna input.

G_{tu} - Transmitting earth station antenna gain.

A_u' - Net loss in the up-path.

G_{su} - Satellite receiving antenna gain.

N_u - Up-path thermal noise power.

N_i - Satellite intermodulation noise power (in the SCPC application), a function of transponder operation point.

H - Satellite transponder gain, a function of its operating point.

G_{sd} - Satellite transmitting antena gain.

A'_d - Net loss in the down-path.

G_{td} - Receiving earth station antenna gain.

N_d - Down-path thermal noise power.

In the case of an SCPC system with hundreds of carriers per transponder, random rain-induced power losses in the up-paths of individual SCPC links have an insignificant effect on the transponder operating point. Since H and N_i are not directly affected by those losses, the SCPC link model is approximately linear[1]. In a pure TDMA system, N_i is zero and H depends on the up-path loss of the individual link under consideration, since it takes up the whole transponder during its time frames.

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(1) *It is assumed that the network comprises a large number of low-capacity earth stations scattered over the service area. The linear approximation is not justified if a very large fraction of the SCPC carriers originate from the same location, because of correlation among up-path losses due to rain for those carriers.*

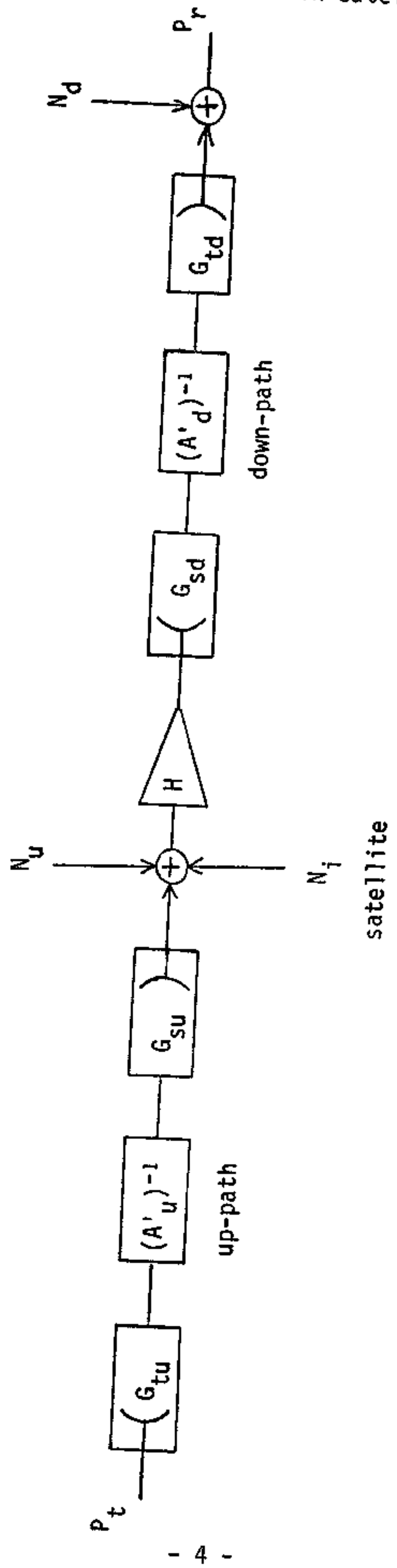

Fig. 1 - Satellite link model.

For the purposes of this paper, the link carrier-to-noise ratio (CNR) is synonymous with signal quality and serves to define link availability. The following expression for CNR is used to compute the results of Section 4:

$$CNR = \frac{P_t G_{tu} G_{su}}{A_u A_u''(4\pi D_u/\lambda_u)^2 \; kB\left[T_u + T_i + T_d A_d A_d''(4\pi D_d/\lambda_d)^2/HG_{sd}G_{td} \right]} \quad (1)$$

In (1), k is Boltzmann's constant and B is the channel bandwidth; the symbols A, A', D, λ, and T stand for loss due to rain, loss (in excess of free space loss) due to other causes, range, wavelength, and noise temperature, respectively; the subscripts u, d, s, t, and i refer to up-path, down-path, satellite, earth station, and intermodulation, respectively. The following relationships were used to obtain (1) from inspection of Figure 1:

$$N_u = kT_u B \qquad N_i = kT_i B \qquad N_d = kT_d B$$

$$A_u' = A_u A_u''(4\pi D_u/\lambda_u)^2 \qquad A_d' = A_d A_d''(4\pi D_d/\lambda_d)^2.$$

Whereas A_u and A_d are random variables, A_u'' and A_d'' (which include losses caused by atmospheric obstacles other than rain, antenna pointing errors, etc.) are assumed constant in this paper. Thermal noise temperatures, T_u and T_d, include the variable noise temperature contributions associated with radio wave propagation in the (possibly rainy) atmosphere.

3. JOINT PROBABILITY DENSITY OF PATH LOSSES DUE TO RAIN

For a given radio frequency, statistics for signal strength attenuation caused by rain in earth-to-space or space-to--earth transmission can be estimated from statistics for the rate of rainfall in the neighborhood of the earth station [2]-[4] . An empirical relationship between rain rate, R (measured with the usual 5-minute integration time), and path loss, a, expressed in decibels (dB), is

$$a = \alpha R^{\beta} L(\varepsilon, R), \tag{2}$$

where α and β are constant for a given radio frequency, and L is the effective length of the path segment subject to rain attenuation, a decreasing function of the earth station antenna elevation angle, ε, and of the rain rate itself. The following empirical formula for $L(\varepsilon,R)$, proposed by Lin [3], is used in this paper:

$$L = \left(\frac{\sin \varepsilon}{H - h} + \frac{R - 6.2 \text{ mm/h}}{2636 \text{ km.mm/h}}\right)^{-1}. \tag{3}$$

In (3), H is the average height of the 0^{o} isothermal surface in the atmosphere (approximately 5 km in the tropical zone, lower in the temperature zone), and h is the altitude of the earth station site. It is noted that the dependence of L on R is less pronounced for higher elevation angles.

Analysis of pluviometric data from many different locations has shown that the long-term distribution of the rate of rainfall (during rain events) is approximately log-normal for any given location [5]. Hence the following probability distribution model for R:

$$\Pr\{R = 0\} = 1 - P \tag{4a}$$

$$\Pr\{R \geq r\} = \frac{P}{2} \operatorname{erfc}\left(\frac{\ell n(r/\mu)}{\sqrt{2}\,\sigma}\right), \tag{4b}$$

where P is the probability of rain at the site, erfc is the complementary error function, and μ and σ are respectively the median and the standard deviation of R during rain events.

Given that R has the log-normal distribution (4), it turns out that the distribution of the path loss caused by rain, computed by (2), is closely approximated[1], in the range of interest, by another log-normal distribution - a fact also known from experiment [5]. The probability density function of the log-normal distribution for path loss is written

$$f(a) = (1 - P)\,\delta(a) + \frac{P}{\sqrt{2\pi}\,S}\exp\left\{-\frac{1}{2}\left[\frac{\ln(a/M)}{S}\right]^2\right\}, \qquad (5)$$

where M and S are respectively the median and the standard deviation of a during rain events.

If rain events and rain rates occur independently at the sites of the transmitting and receiving earth stations, the joint probability density of the path attenuations is the product of two marginal densities of the type (5). If, on the other hand, occurrences of rain and rates of rainfall are not independent at the two sites, as is certainly the case if the sites are close to each other, the joint density takes a different form. Measured data are lacking for the determination of correlation distances, but the main thrust of this paper is to ascertain the effects of specified amounts of correlation between path losses on link availability.

In the following, the subscripts 1 and 2 refer to the transmitting and receiving sites, respectively. Define the following joint rain event probabilities, which add to one:

p_{00} - no rain at either site;

p_{10} - rain at site 1 only;

---

(1) *The distribution of a is exactly log-normal if L is considered independent of R.*

p_{02} - rain at site 2 only;

p_{12} - simultaneous rain at both sites.

The marginal rain event probabilities at the two sites are $P_1 = p_{10} + p_{12}$ and $P_2 = p_{02} + p_{12}$. It is easy to show that the correlation coefficient between the indicator functions, χ_1 and χ_2, of the marginal rain events ($\chi_i = 1$ if it rains at site i; $\chi_i = 0$ otherwise) is

$$r = \frac{p_{12} - P_1 P_2}{\sqrt{P_1 \overline{P}_1 P_2 \overline{P}_2}}, \tag{6}$$

where $\overline{P}_1 = 1 - P_1$ and $\overline{P}_2 = 1 - P_2$. The correlation coefficient has the property.

$$\max\left\{ -\sqrt{\frac{P_1 P_2}{\overline{P}_1 \overline{P}_2}},\ -\sqrt{\frac{\overline{P}_1 \overline{P}_2}{P_1 P_2}} \right\} \leq r \leq \min\left\{ \sqrt{\frac{P_1 \overline{P}_2}{\overline{P}_1 P_2}},\ \sqrt{\frac{\overline{P}_1 P_2}{P_1 \overline{P}_2}} \right\}. \tag{7}$$

In practice, cases of negative correlation should not be common.

The following plausible form of joint probability density function is postulated and used in this paper for the up-path and down-path rain losses of a satellite link:

$$f(a_1,a_2) = p_{00}\ \delta(a_1)\ \delta(a_2) + p_{10}\ \phi_1(a_1)\ \delta(a_2) + p_{02}\ \delta(a_1)\ \phi_2(a_2) + p_{12}\ \phi(a_1,a_2,\rho), \tag{8}$$

where

$$\phi_i(a_i) = (1/\sqrt{2\pi}\, S_i\, a_i) \exp(-z_i^2/2), \quad i = 1,2, \tag{9}$$

$$\phi(a_1,a_2,\rho) = \frac{1}{2\pi\, S_1\, a_1\, S_2\, a_2 \sqrt{1-\rho^2}} \cdot \exp\left[-\frac{1}{2(1-\rho^2)} \cdot (z_1^2 - 2\rho z_1 z_2 + z_2^2)\right], \qquad (10)$$

$$z_i = \frac{\ell n(a_i/M_i)}{S_i}, \quad i = 1,2.$$

The coefficient ρ expresses the degree of correlation between the rates of rainfall at the two sites, given that it is raining at both sites.

4. COMPUTATION OF LINK AVAILABILITY: SCPC AND TDMA EXAMPLES

4.1 - Numerical Integration Procedure

The satellite link is available (signal quality is satisfactory) if the output carrier-to-noise ratio, given by (1), exceeds a specified threshold CNR_0. The method of computation consists in determining the region S of the first quadrant of the $a_1 \times a_2$ plane where $CNR > CNR_0$ (recall that a_1 and a_2 are the decibel versions of A_u and A_d, respectively) and then integrating $f(a_1,a_2)$ over S. The integration is performed numerically and includes probability point and line masses at the origin and on the coordinate axes. If S exists, it is a simply connected region adjacent to the origin (Figure 2). Link availability may be computed as a sum of four terms (assuming that S contains at least the origin):

$$P_A = p_{00} + p_{10} \int_0^{a_1^*} \phi_1(a_1)da_1 + p_{02} \int_0^{a_2^*} \phi_2(a_2)da_2 + p_{12} \iint_S \phi(a_1,a_2,\rho)da_1\, da_2. \qquad (11)$$

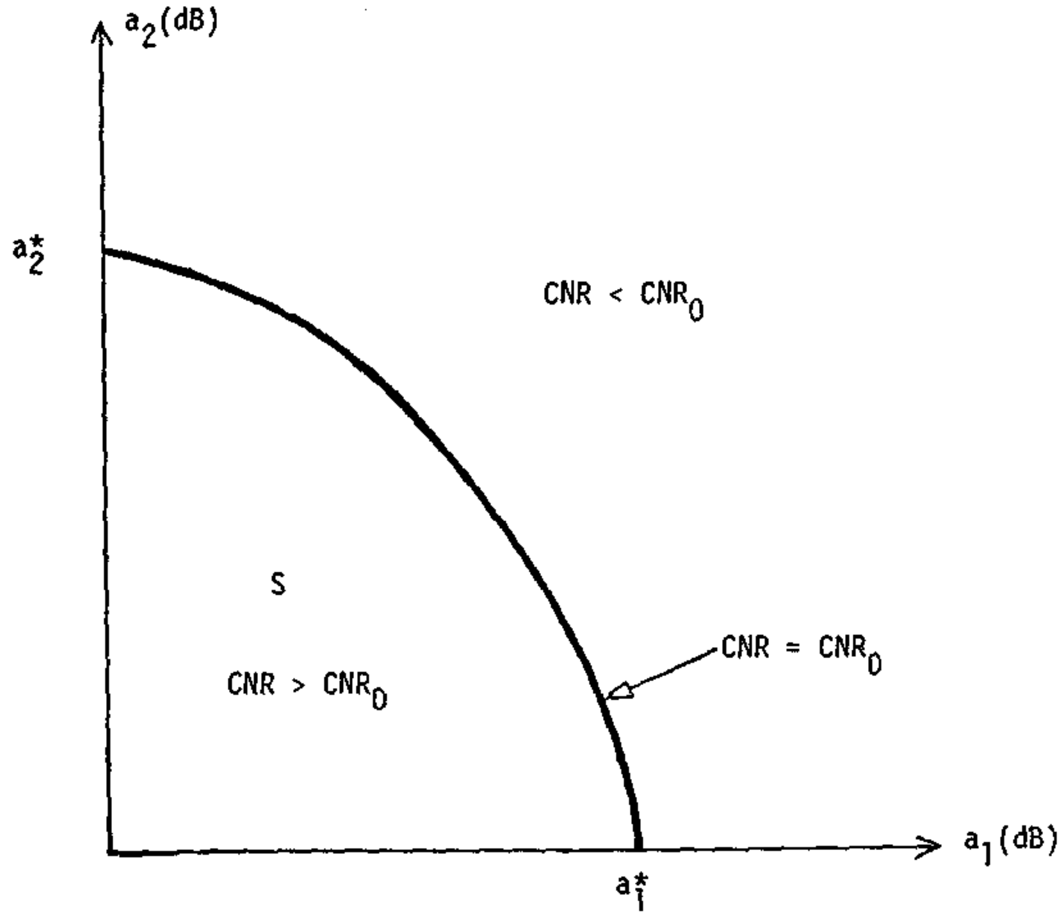

Fig. 2 - The region S.

4.2 - Basic Assumptions and Data for the Examples

In the following examples, the satellite link is between two hypothetical locations in the tropical zone, both having rainfall statistics described by (4), with

$$P = 0.044 \qquad \mu = 3.3 \qquad \sigma = 1.23.$$

Both sites view the satellite at an elevation angle of 60^o. The carrier frequencies are 14.3 GHz for the up-path and 12.0 GHz for the down--path. The values of α and β for these frequencies [4] were combined in (2) and (3) with the rainfall statistics, to obtain the best-fit log-normal distributions for the path losses with $\varepsilon = 60^o$. The following table summarizes the data:

frequency	α	β	M	S
14.3 GHz	0.0324	1.122	0.79	1.28
12.0 GHz	0.0215	1.136	0.53	1.30

The geostationary satellite under consideration is assumed to have typical TWTA transponders. Other characteristics of interest are:

Antenna gains toward transmitting and receiving sites:
G_{su} = 30 dB, G_{sd} = 29 dB.

Transponder bandwidth: 36 MHz (this is the value of B for the TDMA example).

Amplification at TWTA saturation (assumed clear-sky operating point for TDMA): H = 108 dB.

Amplification with 7 dB input backoff from saturation (assumed clear-sky operating point for SCPC): H = 113.5 dB.

Noise temperatures: T_i = 6900 K (for SCPC, at 7-dB backoff), T_u = 1600 K.

Each of the two networks considered (SCPC and TDMA) has a total capacity of 1200 voice channels (600 circuits) for one satellite transponder. The ground segment in each case comprises hundreds of low-capacity earth stations, with the following characteristics:

EIRP per voice channel: P_tG_{tu} = 50.0 dBW for SCPC (during voice-activation times), P_tG_{tu} = 54.0 dBW for TDMA (average power).

Receiving antenna gain: G_{td} = 49.3 dB.

Receiver noise temperature: T_r = 200 K.

Total clear-sky down-path noise temperature: T_d = 284 K.

4.3 - Link Availability in the SCPC Network

Figure 3 shows constant CNR lines on the $a_1 \times a_2$ plane for an SCPC link under the conditions specified above. The constant CNR lines are very nearly straight, with slope somewhat more negative than -1, indicating that attenuation is more harmful in the up-path than in the down-path. Each line bounds a region S that corresponds to a different CNR threshold (CNR_0).

Two plots of availability versus CNR_0 for SCPC links are given in Figure 4. The first curve is for a link between two widely separated earth stations, such that both the rain event and the rain rate correlation coefficients are zero. The second curve is for earth stations so close to each other that $r = 0.9$ and $\rho = 0.6$. Comparison of the two curves reveals that, in this example, availability is lower for the link between nearby locations for all CNR_0 values below 12.5 dB (which corresponds to 98% availability for both SCPC links). For very low values of CNR_0, which may be chosen in designing certain power-limited coded systems, there is a difference of the order of 40% between outage times for the two links.

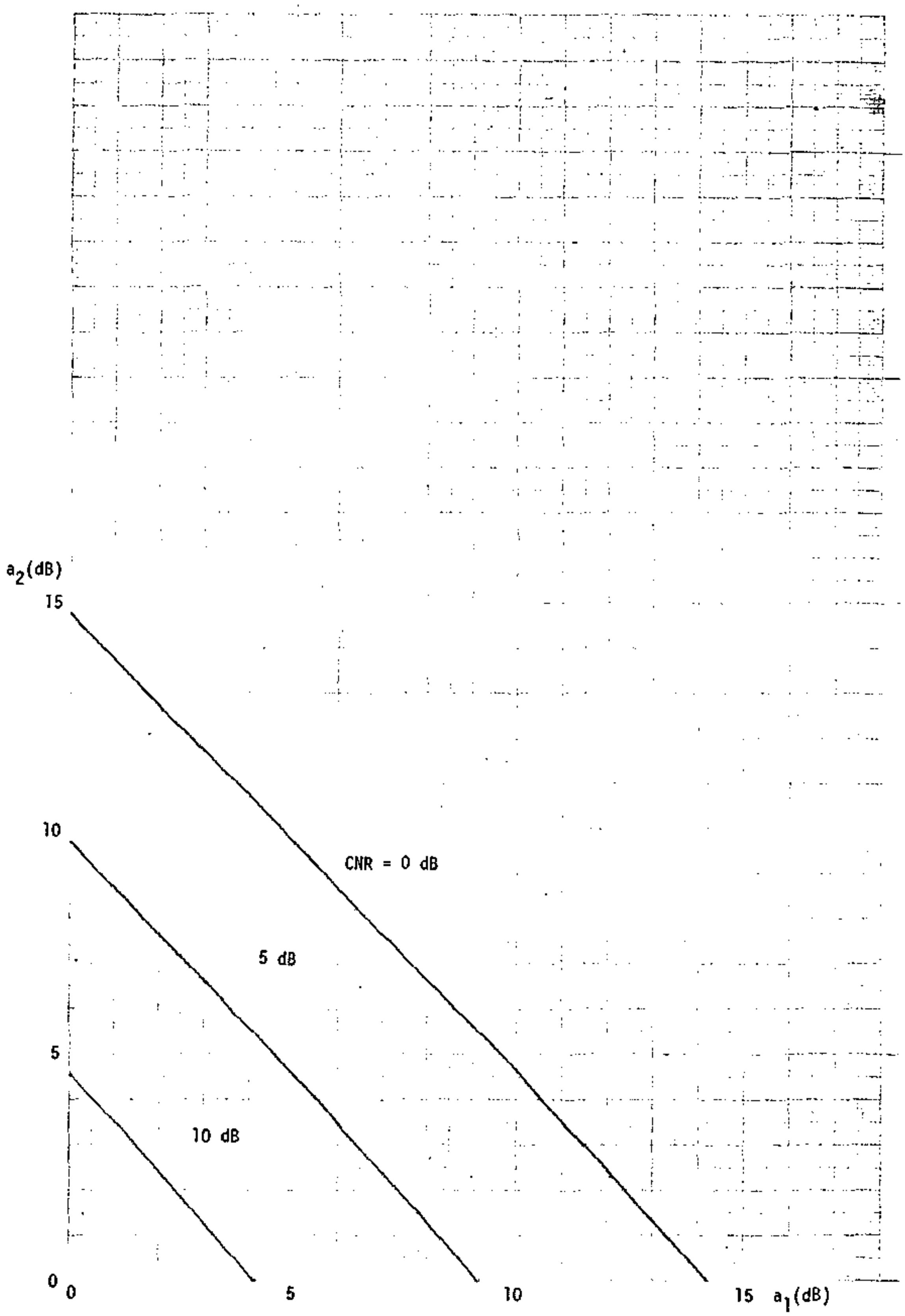

Fig. 3 - Constant CNR lines for an SCPC link.

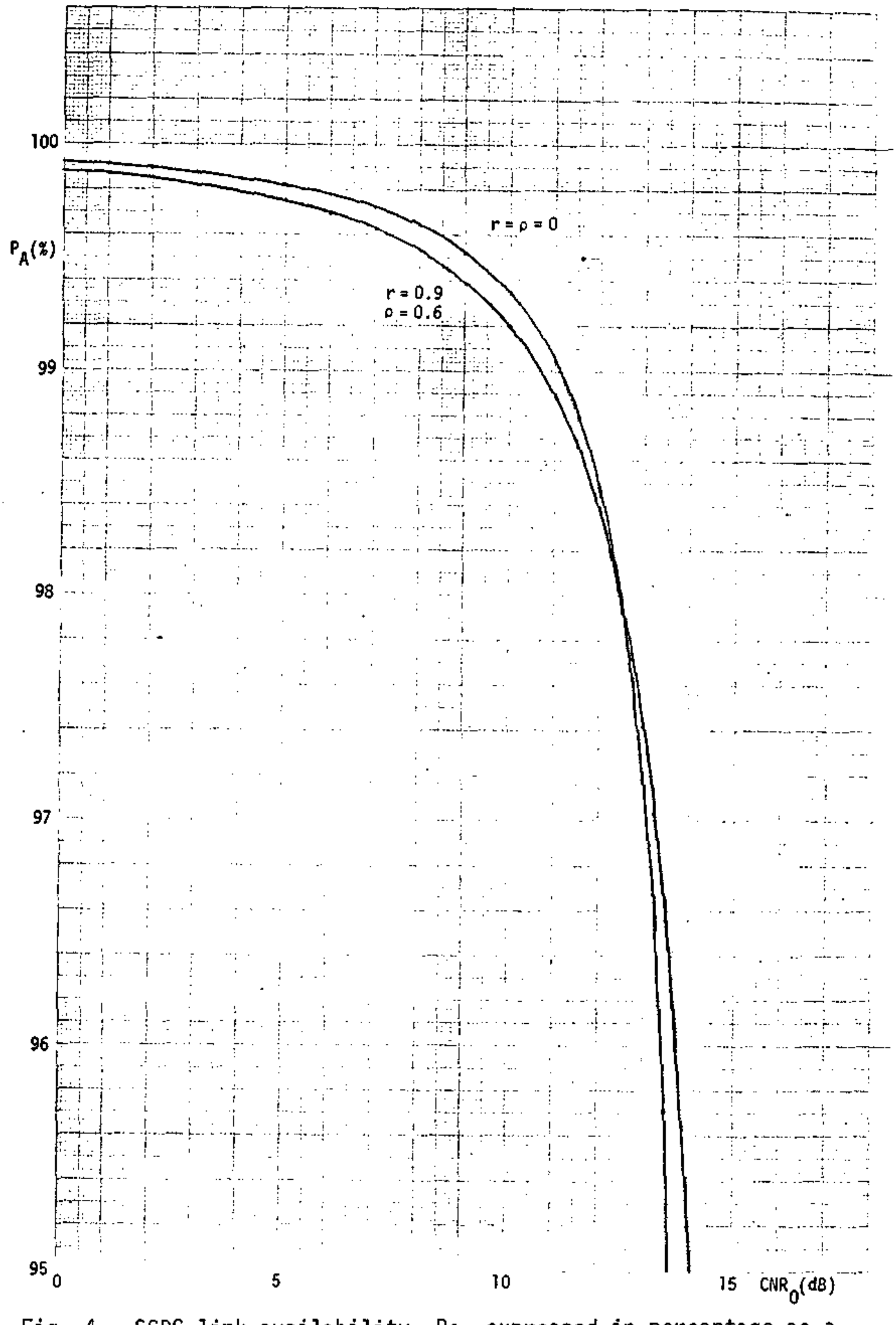

Fig. 4 - SCPC link availability, P_A, expressed in percentage as a function of CNR_0, for $r = \rho = 0$ and for $r = 0.9$ and $\rho = 0.6$.

Conversely, some special-purpose satellite telecommunication systems have been considered with a link availability requirement lower than 98%. Figure 4 shows that if $CNR_0 > 12.5$ dB is required by the modulation system, it is the link between distant earth stations that will have more outage time in this example.

The crossing of the two lines in Figure 4 is intuitively explained as follows. For high CNR_0, the link margin is so small that moderate rainfall at *either* site is sufficient to break the communication. Since simultaneous rain at both sites is very common in the high correlation link and quite rare in the zero correlation link, there is nearly twice as much rain time in the latter than in the former. On the other hand, low CNR_0 provides high reliability by means of a large link margin. In the high correlation link, this margin is typically taken up by simultaneous fairly heavy rain at both sites, whereas in the zero correlation link it is typically taken up by extremely heavy rain (which is rare) at one or the other site.

4.4 - Link Availability in the TDMA Network

For telecommunication links of a pure TDMA network through a nonlinear transponder near saturation, constant CNR lines on the $a_1 \times a_2$ plane are convex curves, as shown in Figure 5. In this example, more attenuation can be tolerated in the up-path than in the down-path. Figure 6 shows that the difference in availability between the zero correlation link and the high correlation link is smaller in the TDMA network than in the SCPC network. The availability of the high correlation link becomes superior above $CNR_0 = 13$ dB in this example.

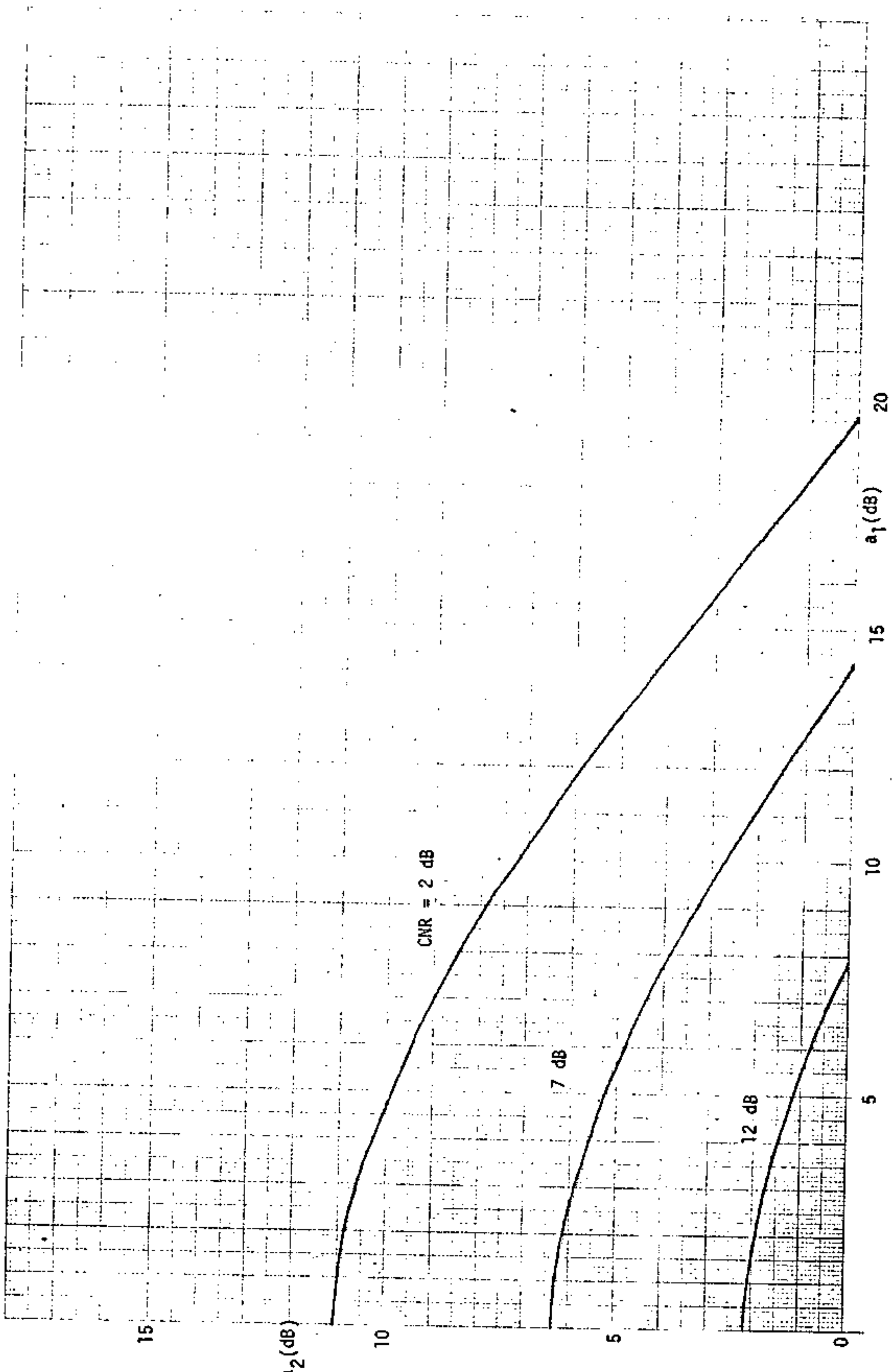

Fig. 5 - Constant CNR lines for a TDMA link.

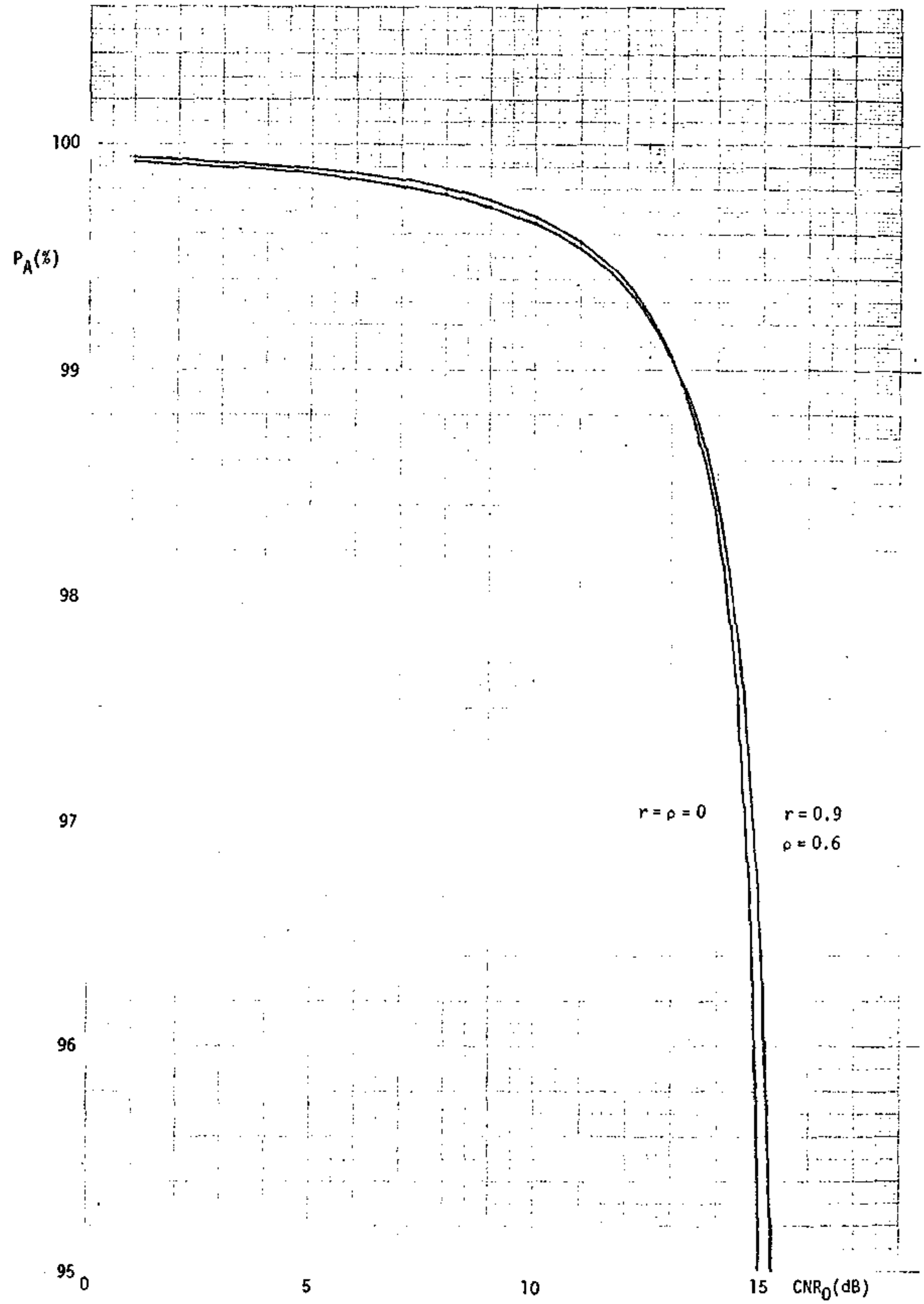

Fig. 6 - TDMA link availability, P_A, expressed in percentage, as a function of CNR_0, for $r = \rho = 0$ and for $r = 0.9$ and $\rho = 0.6$.

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