Rapidly Deployable Radio Network (RDRN) Link Budget

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1 Introduction

This technical report develops the link budgets for the Rapidly Deployable Radio Network (RDRN) initial prototype test. For the test, a single point-to-point radio link will be established over several paths ranging in distance of up to 10 km. Although all of the basic link parameters have been specified, the key unknown at this stage is the propagation characteristics of the channel. As this report will show, achieving the specified fidelity depends critically upon the propagation characteristics. This report presents analyses of the RDRN link assuming several radio channel models ranging from the best case of an additive white Gaussian noise (AWGN) only model to the worst case of a slow Rayleigh fading model. In-between cases of Rician fading and the two-ray or single multipath reflection channel are also presented. The relationship between the bit error rate and the distance has been plotted for the Rayleigh fading channel, Rician fading channel, and AWGN channel with two-ray approximation. This report also analyzes the packet error rate for an ATM cell and the link budget has been done assuming transmission of up to 10 ATM cells as a block of data. Finally, the relationship between the antenna beamwidth and the available bandwidth is described.

A key conclusion of this report is that techniques to combat fading are not necessary for the RDRN test link that we are considering. However such techniques need to be considered if the range of operation is increased or the bit error rate is lowered and/or the data rate is increased. Forward error correction coding (FEC) is one possible technique to combat fading. If the FEC system currently being built into the RDRN system is to be effective, then interleaving will be necessary to counter the slow fading, including interleaving between ATM cells. If this is not technically possible or desirable, then diversity combining or spread-spectrum will be necessary.

Section 2 gives the project parameter requirements. Sections 3 and 4 describes the link budget assuming AWGN channels, the latter section with the two-ray model. Sections 5 and 6 illustrate the link budget assuming slow Rayleigh fading and slow Rician fading channels. The packet error rate analysis and the link budget for packet transmission has been done in section 7. A discussion about the frequency non-selective nature of fading and the dependence of coherence bandwidth on antenna beamwidth is included in section 8. Section 9 details the scope for future research. Conclusions are drawn in section 10.

2 Project requirements

The Rapidly Deployable Radio Network (RDRN) has the following communication parameter requirements :

- Data rate (r_d) of 1.0 Mbps for uncoded BPSK and coded QPSK and 2.0 Mbps for uncoded QPSK.
- Operating frequency range from 1.24 to 1.30 GHz, with a center transmit frequency of 1.27 GHz
- Communication range (d) of 10 km
- Bit Error Rate (BER) range of 10^{-5} to 10^{-7}

For the initial prototype of the system, the following assumptions were made :

- BPSK modulation scheme with data rate of 1.0 Mbps
- Bit error rate of 10^{-5}

- Stanford Telecomm STEL-9236 modem with an implementation loss L_I of approximately 1.0 dB
- 8 element adaptive antenna array for the transmit antenna with a gain of approximately $G_t = 15.5$ dB for one steered beam [1]
- Isotropic receive antenna has been assumed with $G_r = 0$ dB
- Transmitter power (p_t) is 680 mW per element yielding 5.44 W
- The system is assumed to operate in suburban man made noise environment ("Average" ground [3]).

In this report, the upper case notations indicate values in dB scale and the lower scale notations indicate numerical values in the corresponding units.

3 Analysis assuming an ideal AWGN channel

In this section, the link budget has been calculated assuming an ideal AWGN channel. This analysis is done to compare the performance of an ideal channel with other fading models. The values for the total noise density and space loss for the ideal channel have been determined in the following subsections.

3.1 Noise Environment

The total noise density consists of both receiver thermal noise and man made noise. The thermal noise density at a temperature of $T_s = 290$ K is calculated as

$$kT_s = (1.38X10^{-23})(290) = -203.98 \text{ dBW/Hz}$$

where k is the Boltzmann's constant.

From available noise tables [2], the level of man made noise for a suburban environment at a center frequency of $f = 1.27$ GHz is approximately $F_A = 1.0$ dB above the thermal noise density. The composite noise density N_o is then

$$N_o = kT_s + F_A = -203.98 + 1.0 = -202.98 \text{ dBW/Hz} \quad (1)$$

3.1.1 Receiver noise figure

The composite noise density, N_o, in (1) does not include the receiver noise figure. Since we do not have a exact value for the receiver noise figure, we have calculated the link budget for two values of the noise figure. The assumed values for the receiver noise figure were 5 dB for the optimistic case and 10 dB for the pessimistic case. Therefore, the composite noise density would be -197.98 dBW/Hz for the 5 dB assumption and -192.98 dBW/Hz for the 10 dB assumption.

3.2 Space loss

For a clear and ideal AWGN channel, only the direct (LOS) path exists. Therefore, the space loss term based on the LOS path is given as

$$l_s = \left(\frac{4\pi r}{\lambda}\right)^2 \quad (2)$$

where r is the slant height between the transmit and receive antennas. However, when the heights of the antennas are negligible when compared to the distance between the two, then $r \approx d$, where d is the distance between the two antennas. Therefore, the space loss term is then given by (2), with r replaced by d. If the distance between the transmit and receive antennas is 10 km, then the space loss is

$$L_s = \left(\frac{4(\pi)(10000)(1.27X10^9)}{3X10^8}\right)^2 = 114.52 \text{ dB} \quad (3)$$

3.3 Required E_b/N_o for BPSK modulation scheme

The theoretical expression for the bit error rate,ϵ, for BPSK, in a AWGN channel, is given by

$$\epsilon = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{e_b}{n_o}}\right) \tag{4}$$

Therefore, for a bit error rate requirement of 10^{-5}, the required bit energy to noise density ratio, E_b/N_o in dB, is

$$\left(\frac{E_b}{N_o}\right)_{req} = 10\ \log_{10}[\text{erf}^{-1}(1 - 2X10^{-5})]^2 = 9.6\ \text{dB} \tag{5}$$

3.4 Closing the Link

The link can be closed by equating the available and required carrier to noise density ratios. For a bit error rate of 10^{-5}, the required transmit power can be determined by closing the link as follows,

$$\begin{aligned} R_d + \left(\frac{E_b}{N_o}\right)_{req} + L_I &= P_t + G_t - L_s + G_r - N_o \\ P_t &= R_d + \left(\frac{E_b}{N_o}\right)_{req} + L_I - G_t + L_s - G_r + N_o \end{aligned} \tag{6}$$

The transmit power for a receiver noise figure of 5 dB is

$$\begin{aligned} P_t &= 9.6 + 60.0 + 1.0 - 15.5 + 114.52 + 0.0 - 197.98 \\ &= -28.36\ \text{dBW} = 1.459\ \text{mW} \end{aligned} \tag{7}$$

The transmit power for a receiver noise figure of 10 dB is

$$\begin{aligned} P_t &= 9.6 + 60.0 + 1.0 - 15.5 + 114.52 + 0.0 - 192.98 \\ &= -23.36\ \text{dBW} = 4.613\ \text{mW} \end{aligned} \tag{8}$$

Thus, a transmit power of 1.459 mW is required to close the link for an AWGN channel for a receiver noise figure of 5 dB and 4.613 mW is required to close the link for a receiver noise figure of 10 dB. Comparing to the required transmit power requirement of 5.44 W, we obtain a link margin of 35.72 dB for a receiver noise figure of 5 dB and 30.72 dB for a receiver noise figure of 10 dB. It implies that the link closes for the AWGN only assumption.

4 Analysis assuming a AWGN channel with two-ray approximation

Let us now consider another AWGN channel in which a second path, in addition to the LOS path, exists. The difference between this case and the previous case is that in this channel, the path loss will take into account the gain/loss due to multipath. The following subsection deals with the calculation of the path loss for the two-ray model.

4.1 Path loss

Multipath interference occurs when a signal interferes with itself because of the reflection from surfaces near the transmitting or receiving antenna [3]. A two-ray model, as shown in fig.(1), is one in which there is only one reflected signal that interferes with the direct-path signal. When the distance between the transmit and receive antennas is much larger when compared to the heights of either antennas, then the two-ray approximation method can be used.

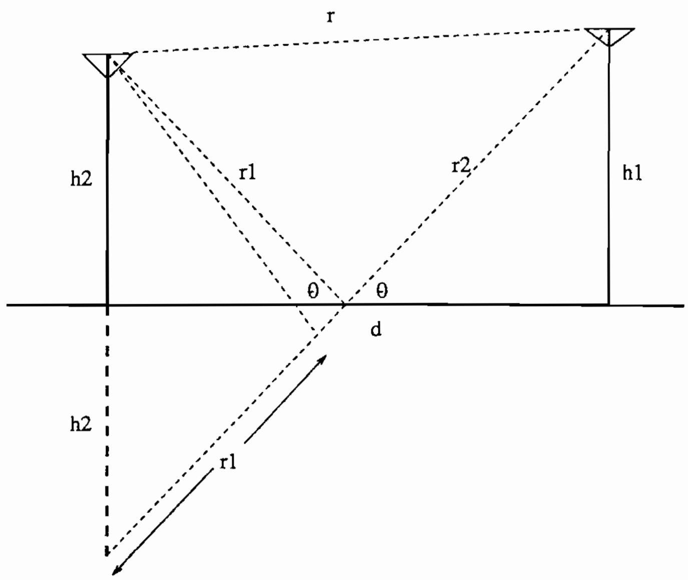

Figure 1: Two ray model geometry

For the two-ray model the composite received signal is given by

$$s_r = s_d + s_d \rho e^{-j\theta_t} = s_d(1 + \rho e^{-j\theta_t}) \tag{9}$$

with

$$\theta_t = \frac{2\pi\Delta r}{\lambda} + \phi$$

where the complex reflection coefficient of the reflecting medium is given by

$$\Gamma = \rho e^{-j\phi}$$

and λ is the wavelength. Using the the concept of similar triangles in fig.(1), we get Δr ($\Delta r = r_1 + r_2 - r$) as $2h_2 \sin(\theta)$. Therefore the gain due to multipath is written as

$$g_m = \left|\frac{s_r}{s_d}\right| = 1 + 2\rho\cos(\theta_t) + \rho^2 \tag{10}$$

When the two antennas are close enough so that the direct ray and the multipath ray are not parallel , then the angle of incidence is given by

$$\theta = \tan^{-1}\left(\frac{h_1 + h_2}{d}\right)$$

and Δr can be approximated as

$$\Delta r \cong \frac{2h_1 h_2}{d} \tag{11}$$

Therefore the space loss term modified to include the multipath effect is given as

$$l_s = \frac{1}{g_m}\left(\frac{4\pi d}{\lambda}\right)^2 \tag{12}$$

where g_m is the gain due to the multipath. For small incidence angles all the values of Γ approach -1 for all surfaces. Also $r \cong d$ in this case. These approximations when substituted in (10) yield

$$\begin{aligned} g_m &\cong 1 - 2\cos\left(\frac{2\pi}{\lambda}\frac{2h_1 h_2}{d}\right) + 1 \\ &\cong \left(\frac{4\pi h_1 h_2}{\lambda d}\right)^2, \ d \gg h_1 + h_2 \end{aligned} \tag{13}$$

Then the path loss term is obtained by substituting (13) in (12) as in [3],

$$l_s \cong \left(\frac{d^2}{h_1 h_2}\right)^2 \tag{14}$$

Therefore, the path loss L_s in dB, assuming the two-ray approximation, a path length of $d = 10$ km and transmit and receive antenna heights of 2m each, is calculated as

$$L_s \cong \left(\frac{10000^2}{(2)(2)}\right)^2 = 147.95 \text{ dB} \tag{15}$$

It can be observed that the value for the path loss in two-ray model is more than the space loss in a AWGN channel. This is because of the destructive addition of the multipath to the line-of-sight ray which results in the path loss being proportional to d^4 rather than d^2.

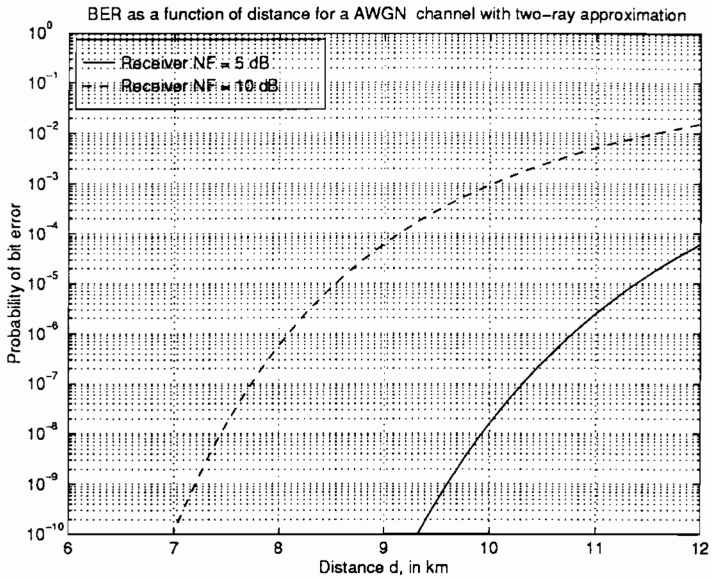

Figure 2: BER as a function of distance for an AWGN channel with two-ray approximation

4.2 Closing the link

For the AWGN channel with the two-ray model, the link can be closed using (6) by substituting for the path loss term using (15). Therefore, for a receiver noise figure of 5 dB and a range of operation of 10 km, the transmit power requirement can be estimated as

$$\begin{aligned} P_t &= 9.6 + 60.0 + 1.0 - 15.5 + 147.95 + 0.0 - 197.98 \\ &= 5.07 \text{ dBW} = 3.21 \text{ W} \end{aligned} \quad (16)$$

The transmit power required for a receiver noise figure of 10 dB is,

$$\begin{aligned} P_t &= 9.6 + 60.0 + 1.0 - 15.5 + 147.95 + 0.0 - 192.98 \\ &= 10.07 \text{ dBW} = 10.16 \text{ W} \end{aligned} \quad (17)$$

The link margins are 2.29 dB and −2.71 dB for the 5 dB and 10 dB receiver noise figure assumptions respectively. It is evident that the transmit power requirement for this case as compared to the previous case has increased significantly due to the effect of multipath. It can be seen that the link closes only for the 5 dB assumption for this channel model. Fig. (2) shows the BER as a function of distance for this channel. It has been plotted assuming a transmit power requirement of 5.44 W.

5 Analysis assuming a Rayleigh fading channel

Multipath exists in a mobile communication link. In this section, the mobile channel has been modeled as a slow Rayleigh fading channel, which has been shown to be the case experimentally in many practical situations [2]. Also, the Rayleigh fading channel gives the worst performance of all channels. For mobile communication links, the Doppler spread is of the order of a few hundred Hertz [5]. Since the signal bandwidth is much larger than the Doppler spread, the fading channel can be characterized as a slow fading channel. And as data rates are increased, the slow fading assumption becomes more valid. The transmit power requirement for this channel model has been determined by closing the link as it was done in the previous section.

The bit error rate (BER) expression for coherent BPSK in a slow Rayleigh fading channel as a function of $\frac{e_b}{n_o}$ is given by,

$$\epsilon = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{e_b}{n_o}}{1+\frac{e_b}{n_o}}}\right) \tag{18}$$

When $\frac{e_b}{n_o} \gg 1$, then the above equation can be approximated as

$$\epsilon \cong \frac{1}{4\frac{e_b}{n_o}} \tag{19}$$

Fig.(3) shows the bit error rate curves for the AWGN channel and the Rayleigh fading channel. It can be observed that there is a considerable degradation in performance

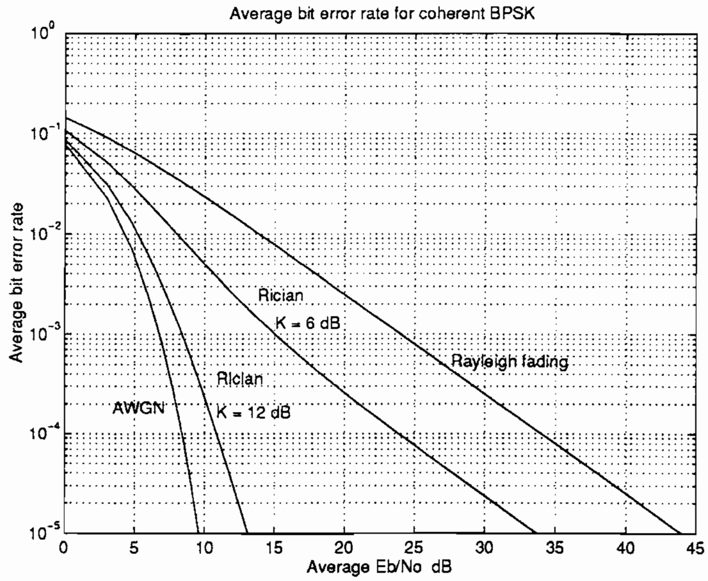

Figure 3: BER performance of Coherent BPSK for AWGN, Rayleigh fading and Rician fading channels

for the Rayleigh fading condition. From fig.(3), the fade margin, M_{fading} in dB, for a bit error rate of 10^{-5}, can be found as

$$M_{fading} = \left(\frac{E_b}{N_o}\right)_{Rayleigh fading} - \left(\frac{E_b}{N_o}\right)_{AWGN} = 43.98 - 9.6 = 34.38 \text{ dB} \quad (20)$$

5.1 Link calculations for a Rayleigh fading channel

In the link calculations for the Rayleigh fading channel, the multipath effects have been taken into consideration while deriving the pdf of the channel. Therefore, in the link calculations only the space loss term as in (2) is used to represent the path loss in the link. The transmit power required in a Rayleigh fading channel at a range of 10 km, when no error control coding techniques are implemented, can then be found by closing the link as follows,

$$P_t = \left(\frac{E_b}{N_o}\right)_{req} + L_I - G_t + L_s + M_{fading} + N_o + R_d \quad (21)$$

The transmit power required for a receiver noise figure of 5 dB is

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 34.48 - 197.98 + 60.0 \\ &= 6.02 \text{ dB } = 3.99 \text{ W} \end{aligned} \tag{22}$$

The transmit power required for a receiver noise figure of 10 dB is

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 34.48 - 192.98 + 60.0 \\ &= 11.02 \text{ dB } = 12.65 \text{ W} \end{aligned} \tag{23}$$

As in the previous channel model assumption, the link closes only for the 5 dB receiver noise figure assumption. The corresponding link margins are 1.34 dB and -3.66 dB for the 5 dB and 10 dB receiver noise figure assumptions. For the Rayleigh fading channel, assuming a transmit power of 5.44 W, the bit error rate can be plotted as a function of the distance. The required E_b/N_o under Rayleigh fading conditions can be obtained from (19) as a function of the bit error rate. The path loss as a function of distance d is given in (2). Using these in (21), the bit error rate, ϵ, as a function of d, for a receiver noise figure of 5 dB, is obtained as

$$\epsilon = \frac{1}{4\left[10^{(15.98-\log_{10}(\frac{4\pi d}{\lambda})^2)}\right]} \tag{24}$$

and for a receiver noise figure of 10 dB, the bit error rate as a function of d is,

$$\epsilon = \frac{1}{4\left[10^{(15.48-\log_{10}(\frac{4\pi d}{\lambda})^2)}\right]} \tag{25}$$

The above equations are plotted in fig.(4), assuming the antenna heights to be 2 m each. From the plot we can observe that for a bit error rate requirement of 10^{-5} and a Rayleigh fading channel, the maximum range of operation is 12.0 km for a receiver noise figure of 5 dB and 6.5 km for a receiver noise figure of 10 dB.

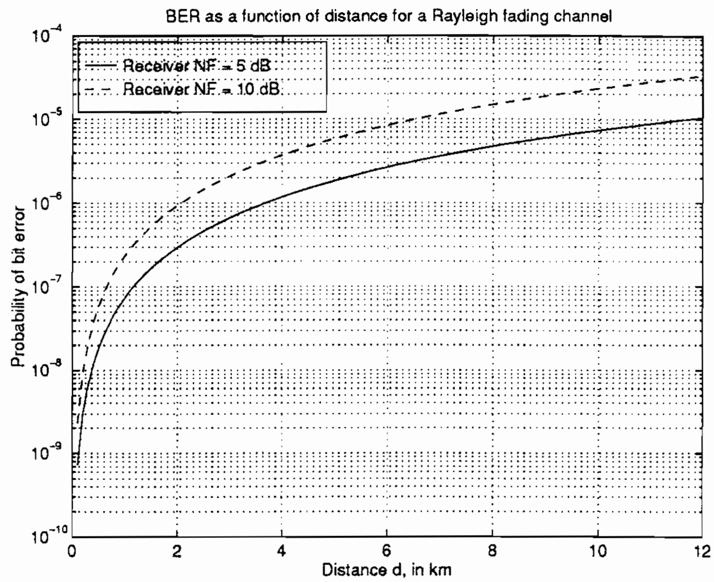

Figure 4: BER as a function of distance for a Rayleigh fading channel

However, we want the range of operation to be 10 km. But at a distance of operation of 10 km the bit error rate performance is far below the required value for the bit error rate for a receive noise figure of 10 dB. In order to achieve better range of operation for the required bit error rate of 10^{-5}, coding can be used as explained in the next subsection.

5.1.1 Rayleigh fading with coding

It is clear from the above section that a Rayleigh fading channel could severely restrict the performance of the communication link. But there are techniques to combat fading. These techniques include diversity combining, error-correction coding, spread-spectrum and smart antennas.

Block codes or convolutional codes are used to decrease the required bit energy to noise density ratio significantly in a fading channel. However, in some cases like Golay coding for a Rayleigh fading channel, the coded performance is worse than

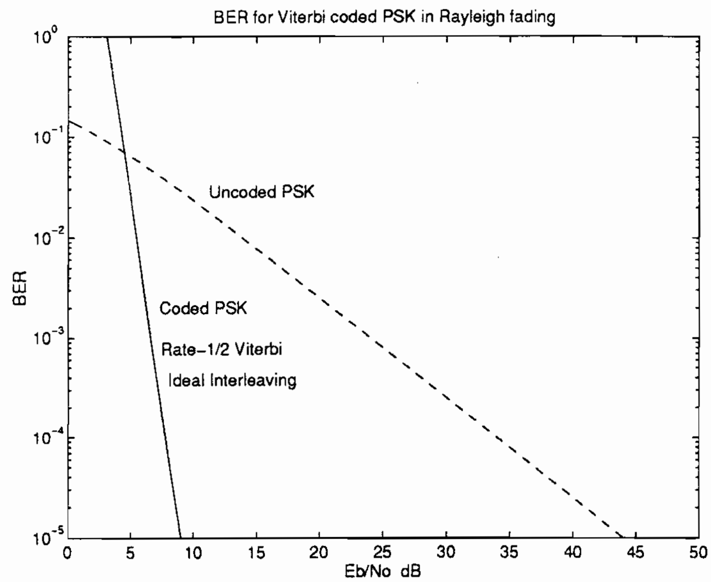

Figure 5: BER for Viterbi coded PSK in Rayleigh fading

the uncoded performance [3]. The problem is due to introduction of burst errors by the fading channel. Therefore, along with coding, interleaving is done to randomize the burst errors. When a rate-$1/2$, $K = 7$, Viterbi code with an ideal interleaver is used, approximately the same transmit power as in the AWGN channel case can be achieved [3]. Figure (5) shows the performance of the rate-$1/2$ Viterbi code with ideal interleaving.

6 Analysis assuming a Rician fading channel

This section calculates the transmit power requirement assuming a Rician fading channel. A Rician fading channel model gives a performance that falls between the worst case - Rayleigh fading channel model and the ideal case - clear AWGN channel model. Since we do not know the exact channel characteristics for RDRN, we can safely assume the Rician channel model, with a reasonable value for the specular-to-random ratio, for analysis purposes. For a Rician fading channel, the bit error rate expression for coherent BPSK as a function of $\frac{e_b}{n_o}$ is given in [3] as,

$$\begin{aligned}\epsilon &= Q\left(\sqrt{\frac{K}{2}}[1-\mu(K)], \sqrt{\frac{K}{2}}[1+\mu(K)]\right) \\ &- \frac{1}{2}[1+\mu(K)]e^{-(\frac{K}{2})[1+\mu^2(K)]}I_o\left((\frac{K}{2})[1-\mu^2(K)]\right) \end{aligned} \tag{26}$$

where the parameter K is the specular-to-random ratio, that is, the ratio of the specular or constant energy to the random energy. The parameter μ is given by

$$\mu(K) = \sqrt{\frac{e_b/n_o}{1+K+e_b/n_o}}, \tag{27}$$

$Q(.,.)$ is the Marcum Q-function and $I_o()$ is the zero-order modified Bessel function of the first kind.

Fig.(3) shows the bit error rate curve for Rician fading (for K = 6 dB and 12 dB) as a function of E_b/N_o. It can be shown that for a very small K, the Rician fading performance is identical to that of a Rayleigh fading channel and that for a large K, the performance is identical to a AWGN channel. The fade margin, M_{fading} in dB for K = 6 dB, for a bit error rate of 10^{-5} can be found from fig.(3) as

$$M_{fading} = \left(\frac{E_b}{N_o}\right)_{Ricianfading} - \left(\frac{E_b}{N_o}\right)_{AWGN} = 34.0 - 9.6 = 24.4 \text{ dB} \tag{28}$$

and for K = 12 dB it is

$$M_{fading} = \left(\frac{E_b}{N_o}\right)_{Ricianfading} - \left(\frac{E_b}{N_o}\right)_{AWGN} = 13.5 - 9.6 = 3.9 \text{ dB} \tag{29}$$

6.1 Link calculations for a Rician fading channel

For a range of 10 km and antenna heights of 2 m each, the power requirement in a Rician fading channel can be estimated by using (21). For K = 6 dB and a receiver

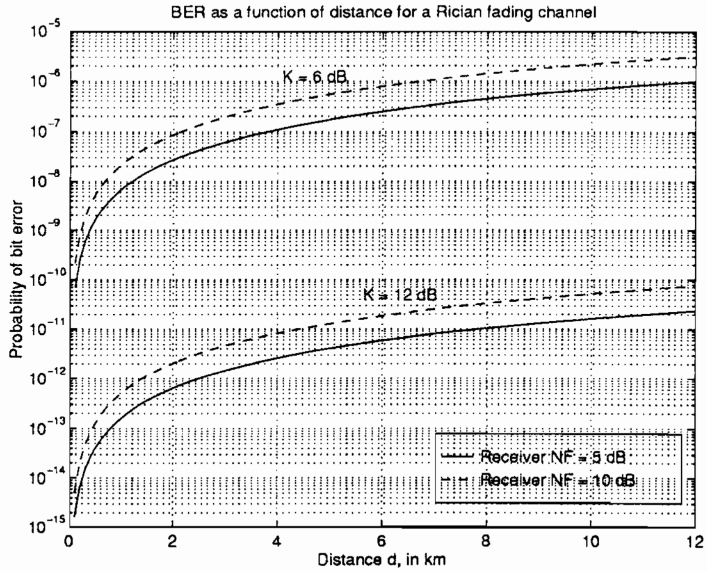

Figure 6: BER as a function of distance for Rician fading channel

noise figure value of 5 dB, the transmit power requirement is,

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 24.4 - 197.98 + 60.0 \\ &= -3.96 \text{ dB } = 0.4018 \text{ W} \end{aligned} \quad (30)$$

Similarly, for K = 12 dB and a receiver noise figure value of 5 dB, the transmit power requirement is,

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 3.9 - 197.98 + 60.0 \\ &= -24.46 \text{ dB } = 3.581 \text{ mW} \end{aligned} \quad (31)$$

For a receiver noise figure value of 10 dB, the corresponding transmit power requirements are 1.27 W for K = 6 dB and 11.32 mW for K = 12 dB. Unlike in the Rayleigh fading channel, the link for the Rician fading model (K = 6 dB and 12 dB) closes for both the assumptions of the receiver noise figure. For a receiver noise figure of 5 dB, the link margins are 11.32 dB and 31.82 dB for K = 6 dB and K = 12 dB respectively. The corresponding values for the receiver noise figure of 10 dB

Table 1: Summary of transmit power requirements for a range of operation of 10 km

Channel model	Receiver NF	Transmit Power required	Link margin
AWGN	5 dB 10 dB	1.459 mW 4.613 mW	35.72 dB 30.72 dB
AWGN two-ray model	5 dB 10 dB	3.21 W 10.16 W	2.29 dB -2.71 dB
Rayleigh fading	5 dB 10 dB	3.99 W 12.65 W	1.34 dB -3.66 dB
Rician fading K = 6 dB	5 dB 10 dB	0.4018 W 1.27 W	11.32 dB 6.32 dB
Rician fading K = 12 dB	5 dB 10 dB	3.581 mW 11.32 mW	31.82 dB 26.82 dB

are 6.32 dB and 26.82 dB respectively. Fig.(6) shows the variation of bit error rate with distance. It can be seen from fig.(6) that for a distance of 10 km, the bit error rate for a $K = 6$ dB Rician fading channel is 4.0 x 10^{-7} for a receiver NF of 5 dB and 2.0 x 10^{-6} for a receiver NF of 10 dB. The corresponding values for $K = 12$ dB Rician fading channel are 2.0 x 10^{-11} and 5.0 x 10^{-11} respectively.

The transmit power requirements for the analysis in the above cases is summarized in table (1). From the table, it is clear that the transmit power required is highest for the Rayleigh fading channel, followed by the Rician fading channel and it is the lowest for a clear AWGN channel. However, the transmit power requirement for the fading channels can be brought down significantly by resorting to coding techniques. Figs. (7) and (8) show the comparison of the BER versus distance for different channels for receiver noise figures of 5 dB and 10 dB. As is evident, the Rayleigh fading channel gives the worst performance of all the channels shown in these figures.

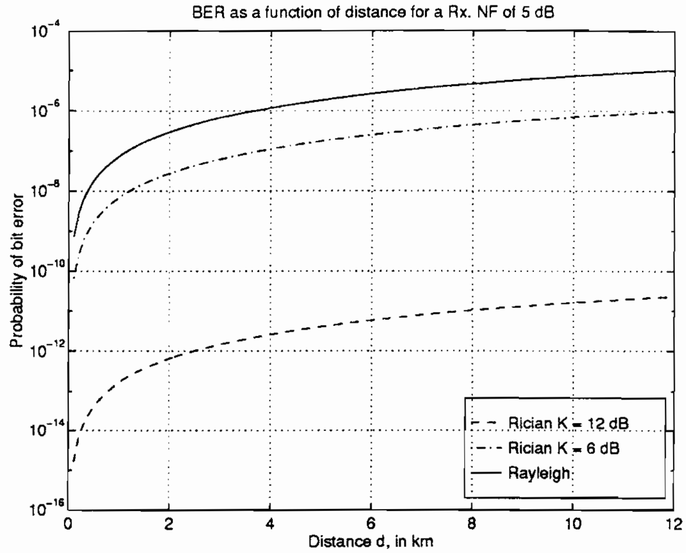

Figure 7: BER as a function of distance for a receiver noise figure of 5 dB

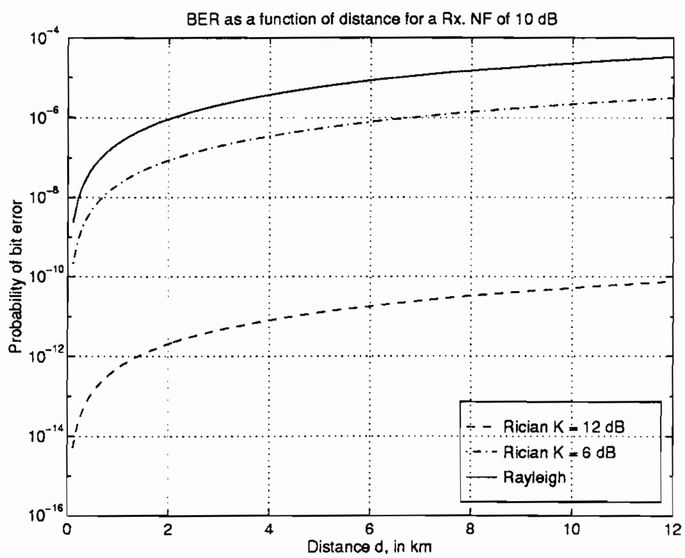

Figure 8: BER as a function of distance for a receiver noise figure of 10 dB

7 Analysis of Packet Error Rate for an ATM cell

In the previous sections, the link analysis was performed assuming a bit by bit transmission. This section deals with the link analysis using packetized data. To start with let us consider a single ATM cell, i.e., with a packet length of $N = 424$ bits (53 bytes). The probability of correct packet reception in AWGN, is given by

$$P_r = [1 - \epsilon(\gamma)]^N \tag{32}$$

where $\epsilon(\gamma)$ is the bit error rate in AWGN and γ is the bit energy to noise density ratio. Therefore, the probability of at least one bit in the packet being in error is

$$PER = 1 - [1 - \epsilon(\gamma)]^N \tag{33}$$

When $N\epsilon(\gamma) \ll 1$, as it is in this case, the probability of packet error in (33) can be approximated as

$$PER \approx N\epsilon(\gamma) \tag{34}$$

Then the packet error probability for BPSK in a AWGN channel is given by (33), where $\epsilon(\gamma)$ is the bit error rate for BPSK in a AWGN channel as given in (4). The bit error rate as a function of γ for a Rayleigh fading channel with BPSK as the modulation scheme is given in (19). However, for large N and bit energy to noise density ratio, the step function approximation can be used [4]. Therefore, the packet error probability for slow Rayleigh fading and BPSK is given by

$$PER_{slow\_fade} \cong 1 - e^{(-\gamma_{o\_no\_code}/\gamma)} \tag{35}$$

where $\gamma_{o\_no\_code}$ is computed using (36) as in [4].

$$\gamma_{o\_no\_code} = \int_0^\infty \left[1 - (1 - \frac{1}{2}\text{erfc}(\sqrt{x}))^N\right] \mathrm{d}x = 4.5292, \text{ for } N = 424 \tag{36}$$

The values for $\gamma_{o\_no\_code}$ are listed in a table in [4] for various values of the packet size N. More on the step function approximation can be found in [4], where the authors have derived the packet error probability in slow Rayleigh fading for non-coherent and coherent signaling schemes using the step function approximation method.

7.1 Link Analysis for ATM cells transmission

In this section, the transmit power requirement will be determined for transmitting ATM cells. The packet error rate is given by (33), where N is the packet length in bits, $\epsilon(\gamma)$ is the bit error rate and γ is the bit energy to noise density ratio. Therefore, for a packet length of 53 bytes, the packet error rate can be computed using (33) as,

$$PER = 1 - [1 - 10^{-5}]^{424} = 4.231 \text{ x } 10^{-3} \tag{37}$$

Using (35), the required bit energy to noise density ratio to maintain the same packet error rate in Rayleigh fading can be obtained as

$$4.231 \text{ x } 10^{-3} \cong 1 - e^{(-4.5292/\gamma)}$$

or

$$\gamma = \left(\frac{E_b}{N_o}\right)_{req} = 30.28 \text{ dB} \tag{38}$$

For a packet error rate determined in (37), the required E_b/N_o in a AWGN channel can be computed from (4) and (33) as

$$\left(\frac{E_b}{N_o}\right)_{AWGN} = 9.6 \text{ dB} \tag{39}$$

Thus the fade margin required for slow Rayleigh fading with respect to bit energy to noise density ratio requirement in AWGN is

$$M_{fading} = \left(\frac{E_b}{N_o}\right)_{req} - \left(\frac{E_b}{N_o}\right)_{AWGN} = 30.28 - 9.6 = 20.68 \text{ dB} \tag{40}$$

With all other parameters remaining the same, the required transmit power for a packet error rate of 4.231 x 10^{-3} is calculated using (21). For a receiver noise figure of 5 dB, the transmit power requirement is

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 20.68 - 197.98 + 60.0 \\ &= -7.68 \text{ dBW} = 0.171 \text{ W} \end{aligned} \quad (41)$$

For a receiver noise figure of 10 dB, the transmit power requirement is

$$\begin{aligned} P_t &= 9.6 + 1.0 - 15.5 + 114.52 + 20.68 - 192.98 + 60.0 \\ &= -2.68 \text{ dBW} = 0.539 \text{ W} \end{aligned} \quad (42)$$

We find that the link closes in the above cases. the respective link margins are 15.04 dB and 10.04 dB. The link analysis was also performed with the assumption that more than one ATM cell is transmitted as a block of data. The analysis has been done for data blocks containing 1 to 10 ATM cells. Table (2) shows these results for a fixed bit error rate of 10^{-5}.

When the ATM cell is coded and decoded using a Viterbi decoder, the packet error probability can be derived as

$$PER_{slow\_fade\_code} \cong 1 - e^{(-\gamma_{o\_code}/\gamma)} \quad (43)$$

The value of γ_{o_code}, assuming no interleaving, for a packet size of 424 bits is 2.0172. The bit error rate for the Viterbi codec is given by

$$\epsilon_b <\approx \frac{1}{2}\Sigma_{i=10}^{20} b_i \text{erfc}(\sqrt{ie_s/n_o}) \quad (44)$$

where b_i is the weight distribution values for the Viterbi codec [3].

Figure (9) shows the packet error rate in a slow Rayleigh fading environment. It can be observed from the figure that coding without interleaving produces negligible

Table 2: Link analysis for transmission of ATM cells for a fixed bit error rate

No. of ATM cells	$\gamma_{o\_no\_code}$	Packet Error Rate	$\left(\frac{E_b}{N_o}\right)_{req}$ dB	Rx NF dB	Tx power req in mW	Link margin dB
1	4.5292	0.00423	30.28	5	171	15.04
				10	539	10.04
2	5.1634	0.00844	27.85	5	97	17.49
				10	315	12.49
3	5.5373	0.01264	26.39	5	69	18.97
				10	220	13.97
4	5.8038	0.01682	25.34	5	55	19.96
				10	173	14.96
5	6.0110	0.02098	24.53	5	45	20.83
				10	144	15.83
6	6.1806	0.02512	23.86	5	39	21.45
				10	123	16.45
7	6.3244	0.02924	23.29	5	34	22.05
				10	108	17.05
8	6.4491	0.03335	22.79	5	30	22.59
				10	96	17.59
9	6.5592	0.03744	22.35	5	27	23.05
				10	89	18.05
10	6.6578	0.04151	21.96	5	25	23.38
				10	79	18.38

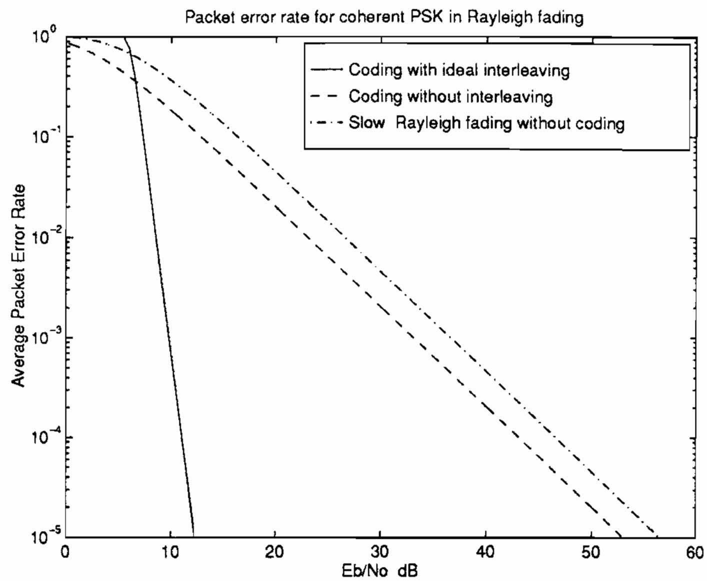

Figure 9: Packet Error Probability in Rayleigh fading

gain when compared to uncoded packet error rate. This is due to the occurance of burst errors in fading channels. However, when ideal interleaving is employed, the packet error rate performance increases dramatically. When rate-1/2 coding and ideal interleaving is employed along with Viterbi decoder, the coded bit error rate performance in a Rayleigh fading environment is similar to the bit error rate performance in a AWGN channel. Taking this into account the packet error rate with coding and interleaving can be determined by substituting for $\epsilon(\gamma)$ in (33), where $\epsilon(\gamma)$ is the coded and interleaved bit error rate in Rayleigh fading.

The fading will be slow over the length of a single ATM cell. Therefore, interleaving within a single ATM cell might not produce much gain. Interleaving coded symbols among several ATM cells would become necessary since the fading is slow. However, in the case of voice traffic, interleaving between large number of ATM cells cannot be done due to the delay in the receiving side that has to wait for all the interleaved ATM cells to arrive before deinterleaving can start. This will

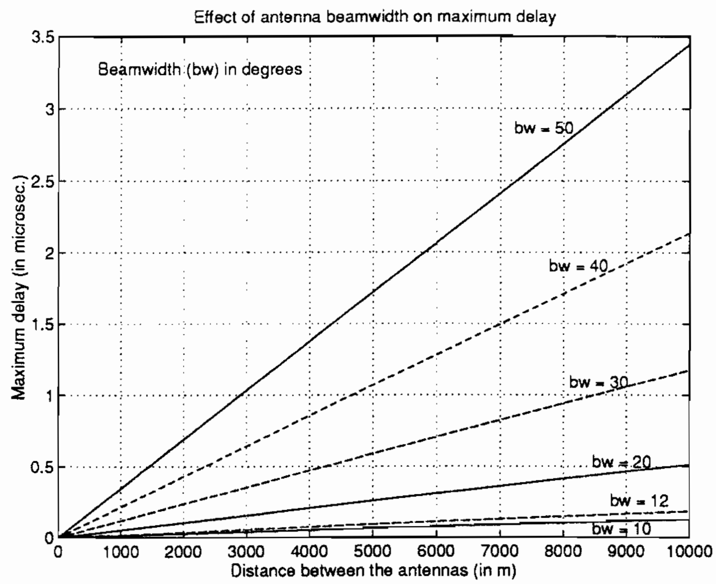

Figure 10: Maximum delay as a function of the distance between the antennas

form the basis for research in future for RDRN. If coding and interleaving does not produce the desirable gain or technically not feasible, then we should resort to other techniques like diversity combining or spread-spectrum techniques to combat the effects of fading.

8 Antenna beamwidth considerations

A fading channel can be characterized as either frequency non-selective or frequency selective. A fading channel is termed as a frequency non-selective or flat if the signal bandwidth is always less than coherence bandwidth B_c. The Coherence bandwidth is the reciprocal of the multipath spread. If B_c is always greater than the signal bandwidth, then the fading is frequency selective. Most often, fading is flat. However, for large data rates, the possibility of frequency selective fading increases. To counter frequency selective fading, either data rates can be decreased or channel

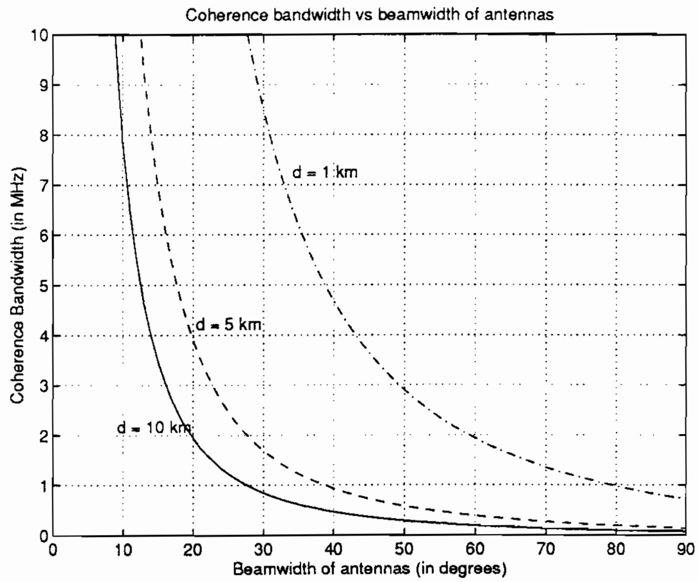

Figure 11: Antenna beamwidth versus coherence bandwidth

equalization can be done.

In this section, the relationship between the antenna beamwidth and the coherence bandwidth is explained. It has been assumed that both the transmit and receive antennas have the same beamwidth and are directed towards each other. The delay caused due to the path length difference between the direct (LOS) path and the deflected path results in intersymbol interference. The path length difference is maximum at the point of intersection of the two antenna beams. Using simple geometrical concepts, the maximum path length difference is

$$\Delta d = d \left[\frac{\sin(\theta) - 2\sin(\theta/2)}{\sin(\theta)} \right] \tag{45}$$

where d is the distance between the two antennas and θ is the antenna beamwidth. The maximum delay can then be obtained by taking the ratio of the maximum path length and the velocity of light. The coherence bandwidth is then the reciprocal of the maximum delay. Fig.(10) shows the maximum delay versus the distance between the antennas. Fig.(11) illustrates the relationship between the antenna beamwidth and the coherence bandwidth of the channel. From fig.(11) it can be inferred that for a range of operation of 10 km and for a bandwidth availability of 2 MHz, the antenna beamwidth needs to be 20^o.

When two 8 element phased arrays are used, one each at the transmit and receive side, the beamwidth for this antenna can be calculated, assuming an inter-element distance as $l = 0.125$ m [1], as

$$\theta_B = \frac{50.9}{N\frac{l}{\lambda}} = 12.02^o \quad (46)$$

From fig.(10) it can be observed that the maximum delay for a beamwidth of 12.02^o is less than $0.2\mu sec$. For a communication range of 10 km and a antenna beamwidth of 12.02^o, the coherence bandwidth required is approximately 5 MHz. Since the signal bandwidth is less than 5 MHz, the fading can be characterized as frequency non-selective or flat.

9 Future Investigations

The major aspect of investigation in the near future would be to study the effect of interleaving between several ATM cells. The prospects of using diversity combining or spread-spectrum techniques should also be evaluated. On a parallel note, the concept of multicarrier modulation as applied to RDRN will be studied. Here instead of sending data over a frequency selective channel, data will be sent over many sub-channels each with a different carrier frequency. In such a system, the possibility of sending coded and interleaved symbols over different sub-channels and regrouping them at the receiver will be studied.

10 Conclusions

The link budget has been done assuming four channel models - clear AWGN channel, AWGN channel with two-ray approximation, Rayleigh fading channel and Rician fading channel. It has been observed that the link does not close for the Rayleigh fading channel, and the AWGN channel with two-ray model, for a receiver noise figure of 10 dB in both the cases. However, the link closes when rate-1/2 Viterbi coded with ideal interleaver is used for a Rayleigh fading channel, which gives us the worst case results. It can also be said that the link margin can be significantly increased in all other cases when coding and interleaving are used.

A link budget has also been done for transmission of multiple ATM cells as a block of data. The relationship between the antenna beamwidth and coherence bandwidth has been established, assuming that the antennas have the same beamwidth and are directed toward each other. A beamwidth of 12.02^o was obtained for the 8 element phased array antenna with a inter-element spacing of 0.125 m . For this beamwidth, the resulting coherence bandwidth was determined to be approximately 5 MHz for a range of operation of 10 km.

The results from this technical report can be summarized as follows

- For a range of operation of 10 km and assuming bit by bit transmission, the links close for all the assumed channel models, except for the AWGN channel with two-ray model with a receiver noise figure of 10 dB and the Rayleigh fading channel with a receiver noise figure of 10 dB. The link budget has been summarized in table 1.
- The fading channels can be characterized as slow and flat fading channels.
- The link also closes for packet transmission in a Rayleigh fading environment.

The link margins for packet transmission have been tabulated in table 2.

- It can hence be concluded that for the link we have considered in this report coding is not necessary since for packet transmission in Rayleigh fading the link closes with considerable link margin.

- However, coding and interleaving and other techniques to combat fading should be considered for the following reasons :

  - For lower bit error rates since the required bit error rate for RDRN ranges from 10^{-5} to 10^{-7}.

  - For increased range of operation.

  - For increased data rates.

- Coding with interleaving is one possible solution to combat fading. Diversity combining and spread-spectrum are the alternative solutions should coding and interleaving be not desirable.

- For packet transmission, a significant gain over the coding only case was obtained when ideal interleaving was also employed with coding. It can hence be concluded that interleaving is essential when coding is used.

- Since the fading is slow, interleaving among several ATM cells is necessitated.

11 References

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