An inexpensive rain fade countermeasure technique for DA-TDMA satellite systems

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Abstract. *Rain attenuation countermeasure systems for geostationary satellite transmissions have been proposed that use a variety of methods. This paper presents a technique which only requires a burst modem that is able to vary its bit and coding rate on a sub-burst basis coupled with a convolutional encoder/Viterbi decoder. A complete method for predicting the attenuation at the receive time is described for two different DA-TDMA systems, using centralised and distributed control, respectively. The method is used for choosing the up power, bit and coding rate of the data to be transmitted. Its performance is evaluated on the basis of experimental results.*

Introduction

The Ku band (14/12 GHz) is currently being used for geostationary satellite communication systems. Migration towards the Ka band (30/20 GHz) is not problem free, because of the much more serious rain attenuation experienced at those frequencies. It is therefore necessary to use some kind of rain attenuation countermeasure to ensure an acceptable availability of the link [7-12].

The fade countermeasure system we propose is not very complex and is cost effective compared to some methods such as space or frequency diversity. Only a modem that is able to change the transmit power and the bit and coding rates on a sub-burst basis is required. Such a modem has been used for the development of the FODA/IBEA system [2-4]. Our scheme is based on the adaptation of the energy per information bit to the channel fading conditions, in order to maintain the quality of data within the requirements specified by the user. The total attenuation of each link (up-link plus down-link) is compensated for by varying the transmission power, coding and bit rates. A multicarrier access to the satellite transponder is envisaged to exploit the entire transponder bandwidth with limited data rates of each carrier. The modest performance required by the earth stations allows the antennas to be installed on the user's premises. The transmission power variation must ensure a constant back-off at the transponder input to avoid excessive intermodulation noise. The power control can thus be used to compensate for up-link attenuations only, while the total compensation is completed by varying the coding and bit rates as well.

A very important problem in fade countermeasure systems is the need to detect the signal quality quickly and accurately. In fact, the countermeasure has to be made before the signal degradation effect on the bit error rate (BER) is detected by the user.

A performance evaluation is presented of both the signal quality and the attenuation estimators used in the fade countermeasure system adopted by two similar channel access schemes. The signal quality estimator is based on the statistics of quantised levels of the PSK demodulated signal, while a narrow band signal level estimator is employed to evaluate the up-link attenuation. We assume that we are operating in the presence of additive white Gaussian noise (AWGN) alone: this means that the satellite channel corruption is only due to thermal noise. No attempt is made to consider interference noise as well.

The channel access schemes considered are user-oriented demand-assignment systems operating in TDMA, used for LAN interconnection. They support both real-time (telephony and video) and non real-time (computer data exchange) application traffic.

One of the two systems, named FODA/IBEA (Fifo Ordered Demand Assignment/Information Bit Energy Adaptive) [2, 3], was developed and tested on the Italsat satellite. It is based on a centralised control of the channel capacity assignment algorithm, according to user demand. The other system, named FEEDERS (Faded Environments Effective Distributed Engineering Redundant Signaling) [5], is an evolution of FODA/IBEA, based on an almost entirely distributed algorithm for the channel capacity assignment. A comparative study of the performance of the two systems is reported in [6] from the point of view of the delay experienced by the non real-time traffic. Here a comparison is made from the point of view of the fade countermeasure system performance.

Both schemes need a master station responsible for system synchronisation and, in the centralised case, for the capacity allocation on request of the traffic stations. To accomplish its task the master sends a reference burst, which contains the transmission times of the single stations (allocations), computed according to specific algorithms for real-time and non real-time capacities, respectively. In the first case the allocations are computed by the master alone, and the traffic stations receive the allocations two round trips after sending their requests. In the second case, the traffic stations monitor all the requests and compute the allocations simultaneously, so they can transmit only one round trip after sending their requests. In both systems each active station transmits one burst per frame, containing control information plus any number of data packets with individual parameters, such as address, length, application type, data coding and bit rates. The power of the received reference burst is assumed as the reference level, and all the stations do their best to track it with their own bursts by varying their transmission power. The master estimates its down-link attenuation using a beacon receiver, and its up- plus down-link attenuation using a narrow-band carrier envelope estimator; the up-link attenuation is then obtained from the difference. Any up-link residual attenuation, after up-power control, contributes to the total degradation of the signal, in addition to the down-link E_b/N_0 degradation of the receiving station. To compensate for link degradation, data is made redundant by reducing the coding rate first, and then reducing the bit rate as well, if necessary. This countermeasure was developed in the FODA/IBEA system by using a modem prototype, which can dynamically change the data bit rates on a sub-burst basis. The sub-burst is the sequence of data addressed to a certain station within a data burst.

Signal degradation prediction

The compensation for both up- and down-link attenuations must be made by considering the total degradation of the signal, i.e. the resulting E_b/N_0 available at the receiving station input. Since all the stations keep a constant power level at the satellite transponder input, the up- and down-link attenuation contributions can be estimated separately. When a station T is going to transmit to another station R, T asks for an allocation. The size of the allocation needed by T depends on the up-link attenuation of T and on the down-link attenuation of R. A prediction of the attenuation levels is necessary because the allocation will be granted to T only some time after the request. At the time it makes a request, T then needs to know what the attenuation levels will be at the time it receives the allocation. In order to allow the prediction, each station predicts its own down-link degradation for the receiving time, and broadcasts this information to all the other stations. Station T thus adds the down-link degradation of R to its own up-link degradation predicted for the transmitting time. The total degradation level is used to compute the code and bit rates of the transmitting signal, needed to ensure the BER performance required by the user [2]. The up-link degradation is actually any attenuation portion which the up-link power control has not compensated for, due to the insufficient power reserve of the transmitting station. A suitable margin due to the prediction errors must be considered, in addition to the degradation level computed. The evaluation of this margin and the strategies to minimise it are the subject of the rest of the paper.

Let us denote by A a generic attenuation and by R the E_b/N_0 ratio. The subscripts u and d refer to up-link and down-link parameters, respectively. The above quantities are expressed in dB when a capital letter is used. For example, for the down-link attenuation we have: $A_d = 10 \ Log_{10} a_d$.

We divide the attenuation range into belts each with an amplitude of 1 dB for the down- and 2 dB for the up-link attenuations, centred at attenuation values A_n. We consider the process $W(t, A_n)$, which gives the attenuation difference between two instants whose distance is t . For each pair of values t and A_n the process W is assumed to be Gaussian with distribution $N(0, \ \sigma_W^2)$. In [1] data obtained by the CSTS (Centro Studi sulle Telecomunicazioni Spaziali) Institute, on behalf of the ASI (Italian Space Agency) are analysed and the attenuation evolution is modelled as a fractional Brownian motion process whose variance and Hurst parameter depend on the attenuation itself. The scintillation effect is also kept into account with a constant parameter added to the process variance.

Let us firstly deal with the E_b/N_0 predicted by the receiving station. We define R_r as the value of E_b/N_0 at the receiving station input when the reference power level is received at the satellite transponder. We then consider the process $\Delta R_r(A_d, t)$ defined, similarly to W, as the difference between two values of R_r at two time instants whose difference is t . To evaluate the variance $\sigma_{R_r}^2(R_r, \ t)$ of the process ΔR_r, we consider the approximate relation which gives the resulting E_b/N_0:

$$r = r_u \, r_d \, / \, (r_u + r_d). \qquad (1)$$

If we neglect the variation of the equivalent noise temperature with a_d, we have $r_d = r_{d_c} \, / \, a_d$, where r_{d_c} is the reference value in clear sky conditions. The condition of a constant reference power level received at the satellite input implies that r_u is equal to the clear sky value r_{u_c}, so the reference E_b/N_0 at the station input is:

$$r_r = r_{u_c} \, r_{d_c} \, / \, (a_d \, r_{u_c} + r_{d_c}). \qquad (2)$$

We limit our analysis to the linear case, i.e. we suppose that the amplitude of the down-link attenuation difference process W_d, is small enough to justify the relation

$$\Delta R_r = W_d \, \frac{dR_r}{dA_d} \, . \qquad (3)$$

Assuming that dR_r/dA_d, is constant within each sufficiently small interval of A_d, the distribution of ΔR_r within the same interval, can be assumed to be Gaussian, like the distribution of W_d Thus, considering (3), we can assume that the variance of ΔR_r is

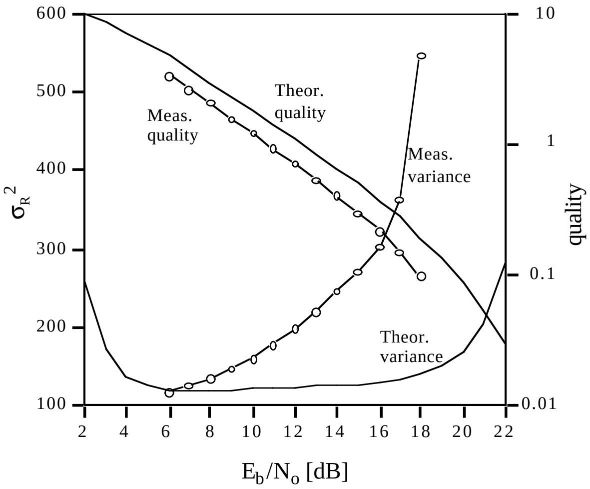

Figure 1. Mean and variance of the signal quality estimator. Theoretical and real cases.

$$\sigma^2_{R_r}(R_r,\ t) = \sigma^2_{W_d}(R_r,\ t)\left[\frac{dR_r}{dA_d}\right]^2, \qquad (4)$$

where $\sigma_{W_d}{}^2$ is obtained from the attenuation process model described in [1].

Let us now see the effect of the up-link attenuation on r. Due to the multicarrier access to the transponder, the satellite HPA (high power amplifier) must operate in the linear zone, without automatic gain control. We can thus consider the satellite transponder as a linear device, so $r_u = r_{u_c} / a_{u_r}$, $r_d = r_{d_c} / (a_{u_r}\, a_d)$, where a_{u_r} is the residual up-link attenuation after up-power control, i.e. $A_{u_r} = \max[0,\ (A_u - A_{p_r})]$, where $[0,\ A_{p_r}]$ is the up-power control range.

From (1) and (2) we have

$$R = R_r - A_{u_r}, \qquad (5)$$

i.e. the dB contribution of the residual up-link attenuation can be simply subtracted from the reference E_b/N_0, to get the resulting E_b/N_0 available at the receiving station input.

As data is sent at a certain time after the last estimation of the signal quality, the signal degradation needs to be predicted, in order to choose the most suitable data transmission parameters. We observed that a linear prediction actually worsens the results with respect to the assumption of stationariness. This is due to the particular behaviour of the attenuation process. In fact, whenever an inversion of the process tendency occurs (which actually happens very often), the error on the prediction is bigger than the one made considering the process as being invariant since the last estimation.

We then propose the following simple procedure, where only the last estimation of the process is considered and its variance is predicted for a suitable time. In summary, first the process estimation $\hat{x}$ is produced, together with its variance $\sigma_{\hat{x}}^2$ at the instant t, then the variance is propagated for the instant $t+\tau$ in which data is sent. Assuming a complete uncorrelation between the estimation error and the process evolution, the resulting variance is:

$$\sigma_x^2 = \sigma_{\hat{x}}^2 + \sigma_\tau^2, \qquad (6)$$

where σ_τ^2 is $\sigma_W{}^2(\tau)$ when the process A_u is considered, and is obtained from (4) when the process R_r is considered. Both the variances on the right hand side of (6) depend on the allocation scheme and on the measurement interval time [1].

The R_r process is evaluated with the soft level quality estimator described in [1], whose performance is shown in Figure 1, while each station estimates its A_u by measuring the difference of power levels between its own burst and the reference burst. A narrow-band carrier envelope estimator is used for this purpose. This device mostly uses the hardware already employed for the demodulation, in particular the fast AGC, which builds the data reference level. The module of the demodulated data is low-pass filtered, squared and converted into dB. The dB variance of each signal level sample, is [1]

$$\sigma_s^2 = \left[(10\,Log_{10}e)\sqrt{\frac{2N_0}{E_b\alpha_b}}\right]^2,$$

where α_b is the ratio between the signal and the low-pass filter bandwidths. In our prototype modem the α_b value was fixed at 64 as a compromise between the noise excision and the ability of the AGC to reach the steady state level even when the output sampling instant occurs at the end of the shortest burst in play.

Results

As already mentioned, both the variances on the right hand side of (6) depend on the measurement time. We thus need to find the time that minimises the resulting variance, on both down and up sides separately. Our results also include a computation of the best measurement times for the estimate of the up-link and of the down-link attenuations.

Table I reports the values of the parameters used for both the centralised (FODA/IBEA) and the distributed (FEEDERS) systems.

An E_b/N_0 ratio at the receiver input equal to 12 dB is chosen as the reference value in clear sky conditions; it gives a BER of 10^{-8} with uncoded data. Using coding this BER can be maintained for E_b/N_0 that drops to 6 dB. By reducing the data rate from 8 to 1 Mbit/s a further gain of 9 dB can be obtained, so the gain in the code plus bit rate variations is 15 dB, which added to 10 dB of up power control range gives a 25 dB span for the fade countermeasures considered. Figures 2 and 3 report these variances together with the optimum measure interval times as functions of R_r and A_u for the two systems considered, and for both down- and up-link cases, respectively.

The variance of R_r is obtained by minimising (6), using the measurement time as a parameter and taking the measured values for the bit quality variance shown in Figure 1. The

PARAMETER	FOD
RB bit rate	
TB header bit rate	
data bit rate	
data coding rate	
RB length	10
frame length	
RB repetition period	2
average RB bit rate	50
t_{rt} (round trip time)	
t_m (measure interval time)	
E_b/N_0 prediction interval time	1,250 m
A_u prediction interval time ($A_u \le A_{p_r}$)	
A_u prediction interval time ($A_u > A_{p_r}$)	750 ms
$R_{u_c} = R_{d_c}$	
RB E_b/N_0 in clear sky	
TB E_b/N_0	m

Table I. Values of the parameters. used RB: Reference

values of the measurement time, which appear in Figures 2 and 3, are rounded up to the closest multiple of the reference burst repetition period.

Each traffic station estimates its A_u as the excess power (with respect to the clear sky condition) it must transmit to receive its own burst at the same power level as the reference burst. The master uses a beacon receiver to measure its down-link fade, and the power level available at its receiver to estimate its up- plus down-link fade. In order to express the variance of the master reference level as a function of a single variable we assume

$$A_d = 0.5 \ A_u, \tag{7}$$

using the long-term frequency scaling formula given in [10].

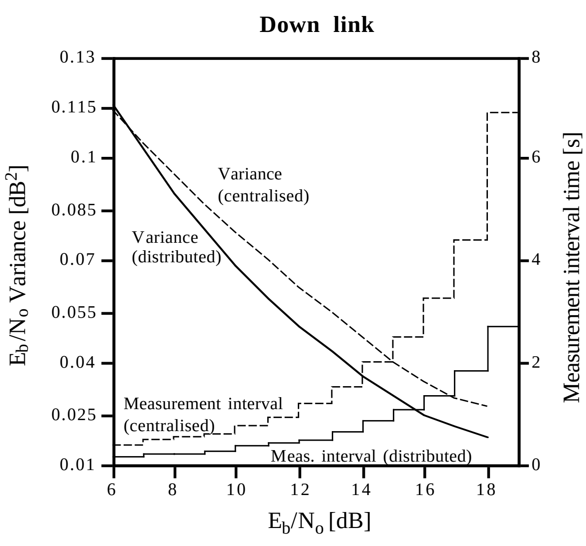

Figure 2. Variance of the E_b/N_0 at the station input when the reference power level is received at the satellite and corresponding optimum measure time.

Figure 3 shows that the variance of the master does not vary significantly for attenuations below 10 dB, i.e. below the full up-link compensation limit, within which we suppose that the master operates. We can thus assume that this value is constant and equal to its value at 10 dB. The variance of the A_u prediction computed by each traffic station is then minimised taking the measurement time as a parameter and assuming (7).

Let us now see how the variances of the predictions are used in practice. Each traffic station broadcasts its R_r estimate to all the others. The sending station estimates its A_u and computes R using relation (5). Then it decreases R by a margin value M, which depends on the chosen probability p_s that the BER falls below the specified value. Denoting the variance of the R estimation with σ_R^2, we have $M = K\sigma_R$, where K is such that $erfc(K) = p_s$.

We assume that there is a complete uncorrelation between processes W_u and ΔR_r Thus we have

$$\sigma_R^2 = \tilde{\sigma}_{R_r}^2 + \tilde{\sigma}_{A_u}^2 .$$

Finally, the resulting R is used to choose the appropriate coding and bit rates of the data to send, according to the required BER. From an implementation point of view, since all the above calculations must be made in real-time for each individual transmission, a set of look up tables is employed to get a fast result.

In order to provide a quick means of evaluation, Figure 4 shows the value of the margin M for two levels of the probability p_s that the BER is greater than the one specified by the user. In Figure 4a we assume that the receiving station has no attenuation at all (R_r=18 dB), and M is reported here as a function of the sending station up-link attenuation. In Figure 4b we assume that the sending station experiences an up-link attenuation lower than 10 dB (full compensation), and M is reported as a function of the receiving station reference

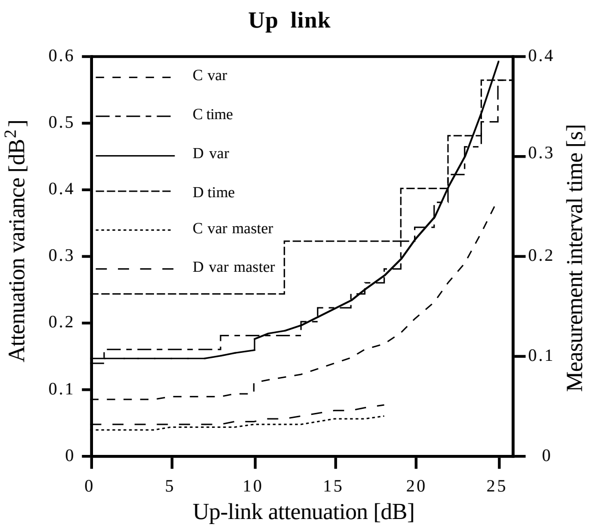

Figure 3. Variance of the up-link attenuation and corresponding optimum measure time. The master up-link attenuation variance is shown as well. In the legend, C stands for centralised, D for distributed.

E_b/N_o.

Conclusions

We have shown the performance of a complete fade countermeasure system, applied in a centralised and in a distributed control TDMA access scheme. The most relevant characteristic of our system is the use of a margin, which is varied with the attenuation, in the estimation of the overall signal to noise ratio. This margin varies from values close to 1 dB to values of almost 2.5 dB. Using a margin which is made variable with the attenuation allows us to save more than 1 dB on average. In fact, the system spends most of the time in almost unfaded conditions and the value of the margin averaged over a long time is very close to the minimum value. In the distributed case, the lower average bit rate of data used to estimate signal degradation is compensated for by the shorter propagation time of the attenuation process variances. This explains why the results for the centralised and the distributed case are so similar.

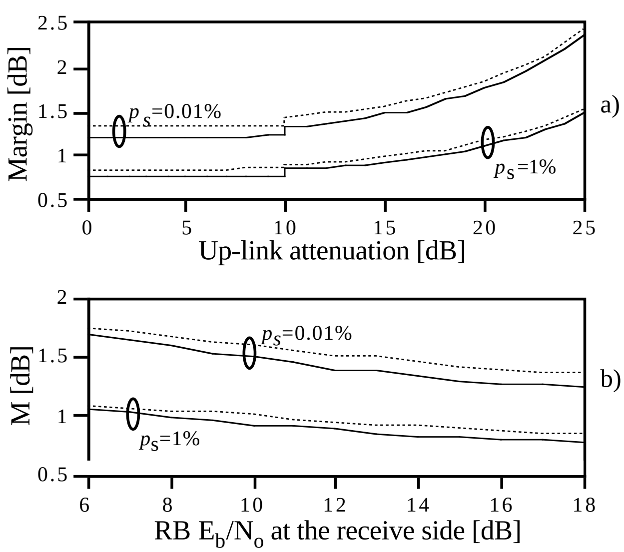

Figure 4. Estimation error margin M: no down-link attenuation (a) and up-link attenuation Ap_r (b). Centralised (continuous lines) and distributed (dotted lines) cases for up- and down-links are shown for two different values of P_s.

Acknowledgements

The authors wish to thank Dr. Mario Mauri from the CSTS (Centro Studi sulle Telecomunicazioni Spaziali) Institute for his collaboration.

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