ABSTRACT

A very important problem in fade countermeasure systems is the need to detect signal quality quickly and accurately. In fact, the countermeasure has to be initiated before the signal degradation effect on the bit error rate is detected by the user. This paper presents an overview of different methods to evaluate signal quality, which are based on the availability of soft quantized levels of PSK demodulated signals at the receiver. It is shown that this class of methods has a good theoretical performance. Also, an innovative procedure is presented which adapts one of the methods to some existing hardware, and tunes-up a set of parameters in order to compensate to the fact that the hardware is to some extent impaired.

QUALITY ESTIMATION OF PSK MODULATED SIGNALS

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*T*he use of the Ka band (30/20 GHz) for satellite communication systems raises the problem of dealing with rain attenuation. As opposed to the traditionally used Ku band (14/12 GHz), the Ka band is much more affected by atmospheric events that lead to bad signal conditions, ranging from a slowly changing attenuation of the signal to a sudden deep fade that blocks all communication. Many methods for countermeasuring rain attenuation have been proposed [1-9]. Some of these methods, such as space or frequency diversity [7, 9], allow a very high level of link availability to be achieved, but they are very complex and expensive. Other methods, which are based on the dynamic adjustment of the energy per information bit [1-3], can be employed when a moderate level of link availability is required. They are not very complex and are cost effective. These methods require a modem that is able to change the transmitting power and the data bit rates, and a convolutional encoder/Viterbi decoder with puncturing, in order to realize a real variable coding rate.

All fade countermeasure systems require an attenuation meter that can make accurate estimates of signal degradation in real time, in order to trigger the countermeasure in a timely fashion. When the transmission power control is used to compensate for up-link attenuation, the latter must be estimated separately from the down-link attenuation. A traditional method of measuring the signal attenuation is to use beacon receivers at the earth stations. This requires beacon transmitters at frequencies that are very close to the signal frequency bands. Two beacon transmitters at the satellite and two receivers at each earth station are necessary if one needs to distinguish between the attenuations on the up- and down-links. The big drawback of this method is the high cost of the hardware required. The other disadvantage is that the measurement of the attenuation is made out of signal band, and this leads to inaccuracies. In fact, even if the beacon and the signal frequencies are very close together, there is always some uncorrelation between the relative attenuation values.

Another method to estimate attenuation is by measuring the power level of the received signal which, given a clear-sky reference level, depends on the up- and down-link attenuations. For a digital modem, this usually requires little additional hardware, because the modem already needs an instantaneous measure of the power level received, which is made with a fast AGC (automatic gain control) in order to demodulate the data. This method is very cheap and does not lead to inaccuracies due to the measurement frequency offset, but it does not allow a separate evaluation of the up- and down-link attenuations.

An alternative way to estimate signal quality is to evaluate the signal to noise ratio (SNR), from which an evaluation of the bit error rate (BER) is straightforward. This method is much more accurate than the signal attenuation measurement, since it takes into account the noise level variation due to the attenuation, i.e. the changes in sky temperature. Furthermore, SNR evaluation methods consider the effect of the total noise, including interference. Not even by using this method the contributes of the up- and down-link attenuations can be distinguished.

The SNR evaluation methods referred to in this paper deal with considering the power distribution of the received signal around its mean value. In the following we show how this measure can be made with very little additional hardware, provided that the receiver is equipped with a soft decision level convolutional decoder. With respect to measuring the received power level, this method has the additional advantage of being independent of any reference level, thus requiring no tuning by an operator. It can thus be useful for end-user equipment, such as mobile, nomadic, or hand-held terminals, where ease of use is an essential requirement.

In the following, a set of methods to estimate the E_b / N_0 ratio, in an additive white Gaussian noise environment, are presented in order of increasing performance and complexity.

CHANNEL QUALITY ESTIMATION USING BER

Methods of measuring the signal quality that do not rely on dedicated (beacon) receivers have to rely on the characteristics of the received signal itself. In optimal coherent detection of B/QPSK (binary/quadrature phase-shift-keyed) signals, the BER is a function of the channel E_b / N_0 [22]

$$BER = \frac{1}{2} erfc\,(\sqrt{\rho}), \text{ where } erfc(x) \stackrel{\Delta}{=} \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \text{ and } \rho \stackrel{\Delta}{=} E_b / N_0. \quad (1)$$

The instantaneous E_b / N_0 can thus be computed by directly measuring the BER of the signal before the convolutional decoder at the receiver. This is done by re-encoding the decoded data and comparing the resulting bit stream with the input bit stream, as shown in Fig. 1.

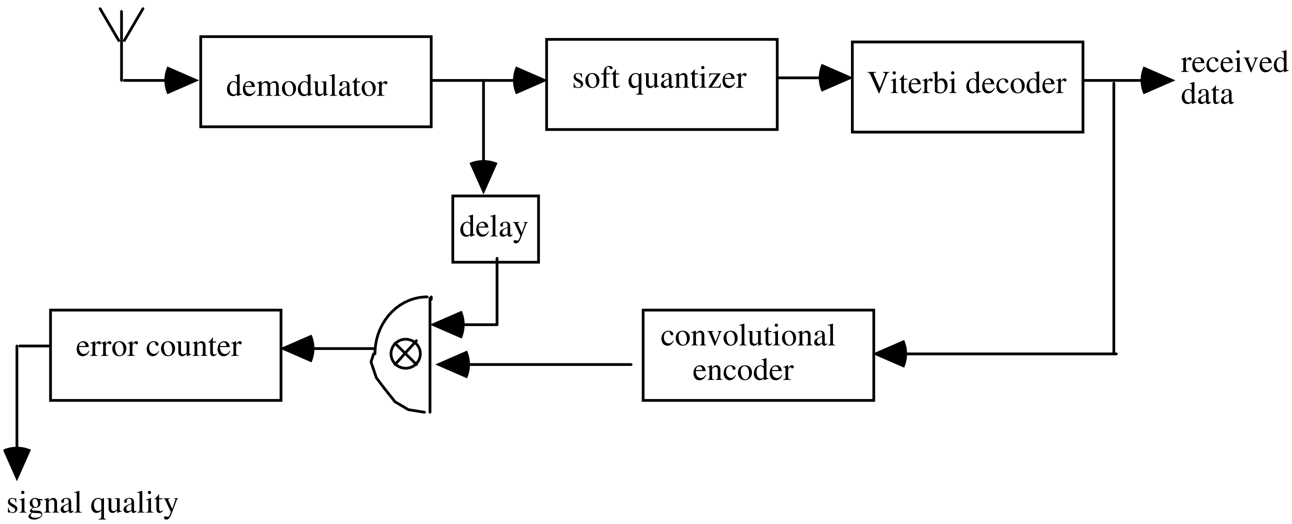

Figure 1. *Block diagram of BER counter.*

Only the errors recovered by the convolutional decoder are counted, but the approximation is generally very good. For example, from Fig. 2 we can deduce that for E_b / N_0 values greater than 0 dB, less than 1% of the bit errors are undetected, and less than 0.1% for E_b / N_0 greater than 1 dB. This method is simple, but it has very low precision (or alternatively it is very slow) at high E_b / N_0 values. The probability of detecting n errors by inspecting N bits is

$$P_n = \binom{N}{n} p_e^n (1 - p_e)^{N-n}. \quad (2)$$

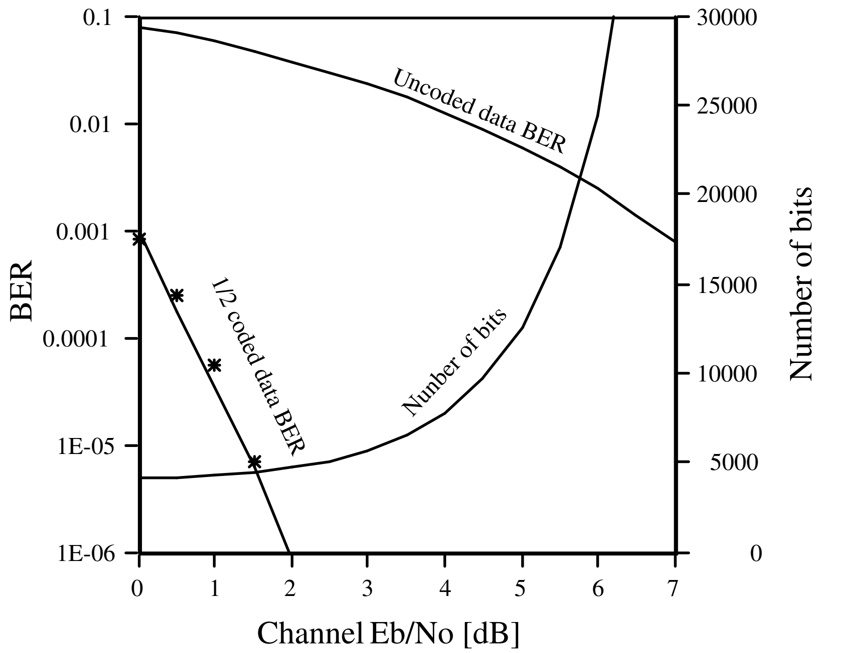

Figure 2. *Number of bits needed to evaluate Eb/No using BER. 1/2 coded data BER as a function of the channel Eb/No, and uncoded data BER are also reported.*

The above binomial distribution has $\mu = n/N$, and variance $\sigma^2 = p_e(1-p_e)/N$ [21]. When the product Np_e is large, which is always the case for any significant measure of this kind, we can approximate the binomial distribution with a Gaussian distribution that has the same mean and variance. Denoting by R the E_b/N_0 expressed in dB, that is $R = 10 \log_{10}(E_b/N_0)$, the estimated value of R can be obtained by inverting the monotonic function (1). When the variance of the estimator p_e is small, the distribution of the estimate of R can be considered Gaussian as well, with mean and variance

$$\mu_R = R(p_e) \quad \sigma_R^2 = \frac{p_e\,(1-p_e)}{\left(dp_e(R)/dR\right)^2 N}. \tag{3}$$

A measure of the precision of the method is thus given by the number N of symbols that must be examined to get a measure with a 99% confidence interval of ±0.5 dB, which is

$$N = \frac{2.58^2\,\sigma_R^2}{0.5^2}, \text{ since } erfc\left(\frac{2.58}{\sqrt{2}}\right) = 1\%. \tag{4}$$

However, the variance of the estimator p_e is not always small, so the distribution of the estimate of R is not Gaussian, and using (4) may lead to an optimistic evaluation of N. However we can use (4) if, instead of (3), we adopt an overestimation of the variance given by

$$\sigma_R^2 = \frac{p_e(1-p_e)}{\left(\Delta p_e(R)/\Delta R\right)^2 N}, \tag{5}$$

where $\Delta p_e/\Delta R = min\left\{\left[\Delta p_e/\Delta R\right]^+, \left[\Delta p_e/\Delta R\right]^-\right\}$ $[\cdot]^+$ and $[\cdot]^-$ are the right and left incremental ratios, respectively, and $\Delta R = 2.58\ \sigma_R$. The resulting N obtained with this method is plotted in Fig. 2.

CHANNEL QUALITY ESTIMATION USING PSEUDO ERRORS

In [10] a variety of methods for measuring the signal attenuation are summarized. In particular, a technique is described which implies measuring the PSK signal amplitude vector and estimating its variance. A simple variation on this theme, described in [11, 16], is valid for B/QPSK. This variation can be inexpensively applied to all coherent demodulators that produce a soft-level quantization of demodulated data for a convolutional (typically Viterbi) decoder.

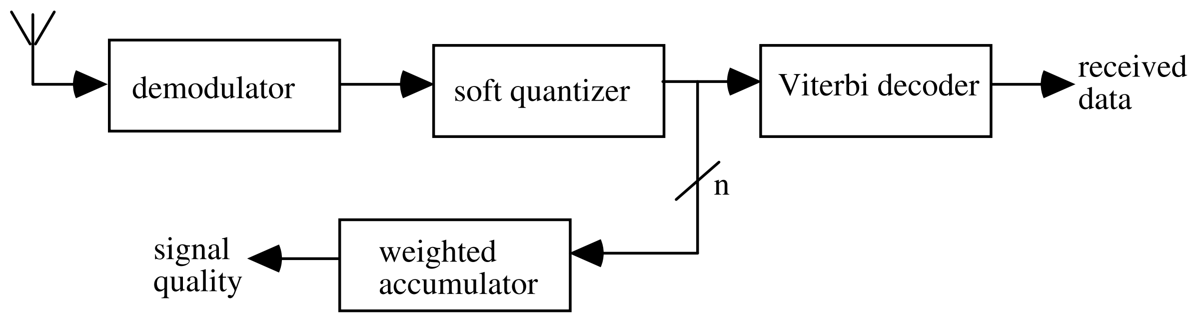

Figure 3. *Block diagram of the quality meter.*

Figure 3 shows a block diagram of the arrangement, which only requires a small finite state machine connected to the output of the soft quantizer. The method we are going to describe, as well as all the following ones, applies to both BPSK and QPSK modulated signals, since QPSK can be considered as two independent (in-phase and quadrature) channels.

It is easy to count the number of times the demodulated quantized signal S falls below a designated threshold $T\mu_s$, where μ_s is the expected value of S and $0<T<1$, and then to obtain the frequency of such an event (*pseudo error*). Figure 4 depicts this concept.

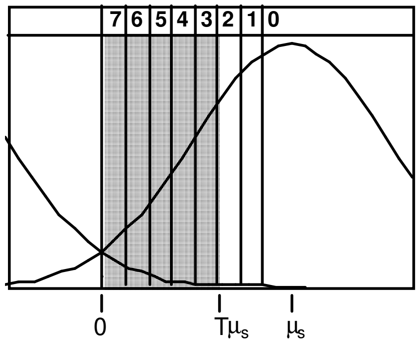

Figure 4. *The quantized signal when T=5/8*

The probability of the signal S being smaller than $T\mu_s$, i.e. the probability of a pseudo error, is given by

$$P\{S < T\mu_s\} = \frac{1}{2} erf2\left((1-T)\sqrt{\rho},\ (1+T)\sqrt{\rho}\right), \text{ where } erf2(a,b) \stackrel{\Delta}{=} \frac{2}{\sqrt{\pi}} \int_a^b e^{-t^2} dt. \quad (6)$$

Only the magnitude of the signal is considered, without any knowledge of whether the bit has been correctly decoded. Function (6) can be inverted, so the E_b / N_0 and the BER of the signal can be obtained from the frequency of the event $\{S < T\mu_s\}$. This method can be analyzed analogously to the measure of the BER presented in the previous section using (6) instead of (1). The results are plotted in Fig. 5 for different values of the threshold T. We can see that a good performance can be obtained by choosing the value of T that gives the maximum sensitivity in the range of interest of the application. The drawbacks of this method are the limited size of the application field for each value of the threshold, and the bad performance at very low E_b / N_0 values. In this last case the BER method performs much better, as shown in Fig. 5.

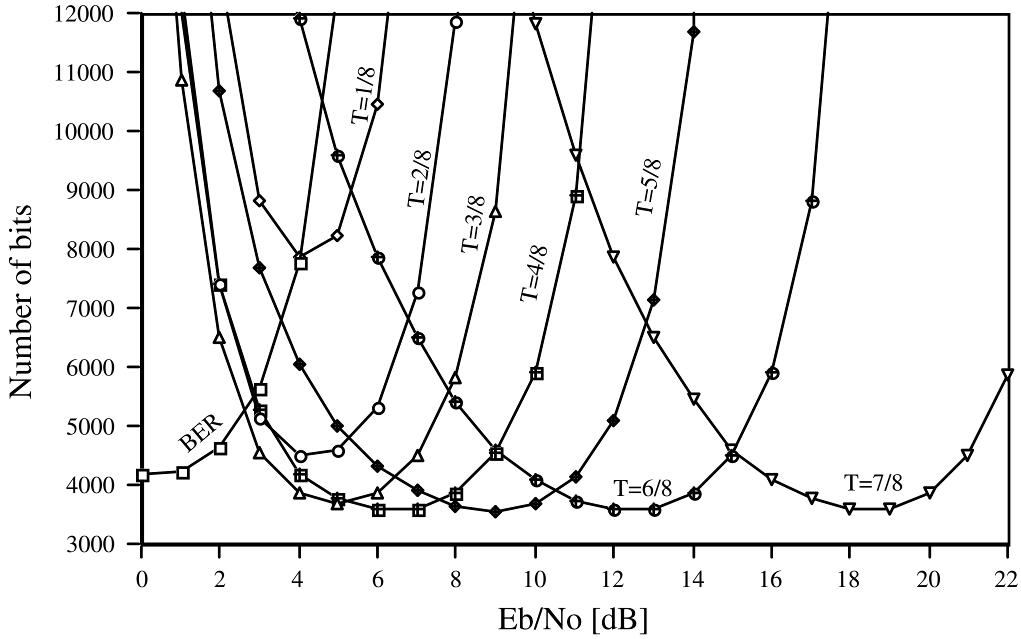

Figure 5. *Number of bits needed to evaluate Eb/No using the pseudo error method.*

IMPROVED CHANNEL QUALITY ESTIMATION SYSTEMS

An improvement to the pseudo error method has been proposed in [12]. Figure 4 highlights that a lot of information is thrown away when the pseudo error method is used. Indeed, for each symbol, the measure of the amplitude, which is an n bit quantity, is used to find out whether or not the symbol amplitude is below the threshold, which is a one bit information. On the other hand, if we use the average discrete amplitude of the signal, we manage to use much more information. We call this the *method of the mean*.

We assume that the region between 0 and μ_s is divided (quantized) into q equal-sized regions, numbered from 0 to q-1, and that when the signal exceeds μ_s it is considered as belonging to the region labelled with "0". This is the way the signal in input to a Viterbi decoder is usually quantized, although in [18] it is argued that some improvements can be obtained by slightly changing the quantization step. The mathematical analysis of this method follows the same guidelines as the previous methods, but instead of (1) used in the BER method or (6) used in the pseudo error method, we use (7), which is invertible as well.

$$M(\rho)=\frac{1}{2}\sum_{i=1}^{q-1} i\left[erf2\left(\frac{i}{q}\sqrt{\rho},\frac{i+1}{q}\sqrt{\rho}\right)+erf2\left(\left(2-\frac{i+1}{q}\right)\sqrt{\rho},\left(2-\frac{i}{q}\right)\sqrt{\rho}\right)\right]. \qquad (7)$$

Relation (7) assumes that the magnitude of a bit is measured, regardless of whether the bit has been correctly received or not. By using a logic similar to the one shown in Fig. 1, it is possible to know, for each bit, whether or not it has been correctly received. This additional information can be used to improve the performance of the quality meter. In this case, instead of (7), we have:

$$M_e(\rho)=\frac{1}{2}\sum_{i=1}^{2q-2} i\, erf2\left(\frac{i}{q}\sqrt{\rho},\frac{i+1}{q}\sqrt{\rho}\right)+\frac{1}{2}(2q-1)\, erfc\left(\left(2-\frac{1}{q}\right)\sqrt{\rho}\right).$$

In [12,13] it is shown that the choice of q=8 is a good compromise between performance and complexity, so this value is assumed throughout the rest of the paper. The performance of this method is shown in Fig. 6, with and without the use of the error bit logic.

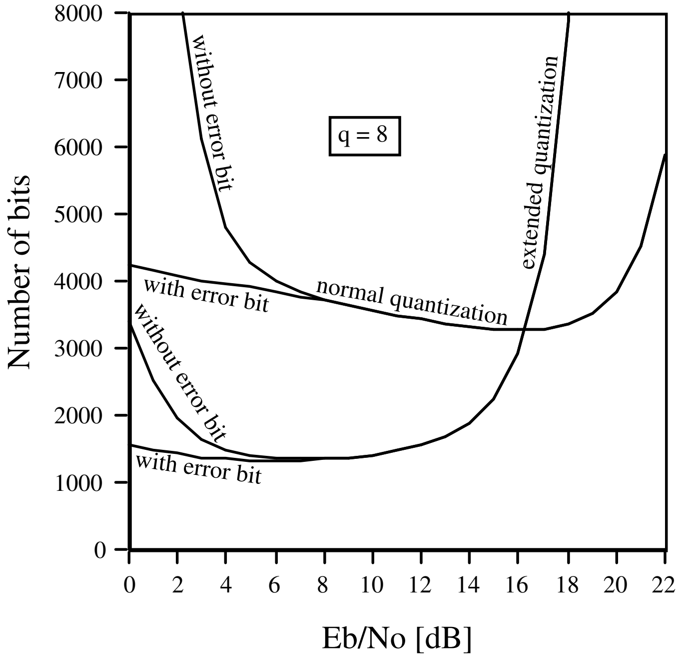

Figure 6. *Number of bits needed to evaluate E_b / N_0 using the method of the mean.*

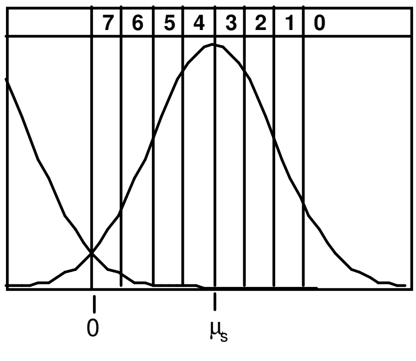

Figure 7. *Extended quantization, assuming n = 3.*

In [13] another improvement is proposed to the method of the mean, which the authors call *extended quantization*. This method requires a modification to the quantization logic, as shown in Fig. 7, and the block diagram shown in Fig. 3 does not hold any more, because some little logic must be added to the quantizer, in order to obtain both the outputs for the Viterbi decoder and the extended quantization meter.

As shown in Fig. 6, the precision achieved by this method is considerably better than the *normal quantization* method, because about twice the information is gathered.

REFINEMENTS TO THE METHOD OF THE MEAN

The demand assignment FODA/IBEA TDMA[1] access scheme [2, 3], developed in the framework of experimental projects on the Olympus satellite, requires a signal quality measurement in order to counter the signal fade by using data redundancy.
Indeed, during a signal fade event, data is made redundant (by reducing coding and bit rates) by a factor that is sufficient to meet some given specifications, typically in the form of a BER threshold. If the uncertainty on the measure of the fade is large, a proportionally large security margin must be added to the measured value, in order to guarantee the quality of service desired. This, in turn, entails increasing the data redundancy, and thus the bandwidth occupied, with a consequent reduction in the overall utilization efficiency of the channel. The speed of the meter is important as well. In fact, since the signal fade may have a very fast variation in time, a further uncertainty is introduced, which increases with the measurement time span. Moreover, since data is received after the fade is measured, both these margins must be suitably increased because a prediction on the fading has to be made by the receiver when it informs the transmitter about its own fade situation.

FODA/IBEA was implemented and tested using a prototype modem [4] with an 8 level soft quantizer of the signal amplitude, followed by a Viterbi decoder. Due the structure of the hardware, it was impossible to use either the extended quantization or the error bit method, so we used the normal quantization method without error bit. Given the high bit rate used (8 Mbit/s), we nonetheless expected a good quickness, but our measures showed a performance much worse than the theoretical one. This was due to the fact that the reference level, computed by the logic of the modem, was not stable. In fact, it oscillates with a frequency lower than the symbol rate, thus invalidating the hypothesis on which the analyses made in the previous section are based. In order to examine the new situation, we tried to model the behaviour of the modem by superimposing a sinusoidal wave to the symbol amplitude, thus obtaining a distribution of the amplitude that deviates from the Gaussian. We obtained a model that matches our measures well, as shown in Fig. 8. In order to deal with such an impaired situation we further refined the method presented in [12]. We thus obtained a procedure which can be “customized” to match the particular oddities of a given modem, and which is guaranteed to get the best possible performance from the hardware for a given number of quantization levels. This procedure also gives a marginally better performance in the theoretical case, with respect to the methods presented in the previous section.

In order to maximize the information obtained from the quantized levels, each level is given a different weight, obtained by numerically minimizing the number of bits needed to get a reliable measure at the desired values of E_b / N_0. The methods presented in [11], [12] and [13] are particular cases of this technique. For example, given a 3 bit (8 level) quantization, the pseudo error method with T=3 is equivalent to have weights set to $\begin{bmatrix}0 & 0 & 0 & 1 & 1 & 1 & 1 & 1\end{bmatrix}$, the method of the

[1]Fifo Ordered Demand Assignment/Information Bit Energy Adaptive - Time Division Multiple Access

mean with normal quantization is equivalent to have a weight vector set to $[0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7]$, and the method of the mean with extended quantization is equivalent to have a weight vector set to $[3 \quad 2 \quad 1 \quad 0 \quad 0 \quad 1 \quad 2 \quad 3]$. The variance of the measure is invariant to scaling and translation of the weight vector, which means that using a vector **w** is equivalent to using a vector $a + b\mathbf{w}$. This implies that the first element of the weight vector can be arbitrarily set to 0 and the next non-zero element can be set to 1. The optimization thus only needs to be carried on the remaining elements. When using an arrangement like the one depicted in Fig. 3, the elements are constrained to be integer (usually small ones). Assuming $\mathbf{w}[0] = 0$, the function we use is now

$$W(\rho) = \frac{1}{2}\sum_{i=1}^{q-1} \mathbf{w}[i]\left[erf2\left(\frac{i}{q}\sqrt{\rho}, \frac{i+1}{q}\sqrt{\rho}\right) + erf2\left(\left(2 - \frac{i+1}{q}\right)\sqrt{\rho}, \left(2 - \frac{i}{q}\right)\sqrt{\rho}\right)\right]. \qquad (8)$$

Whether or not (8) is invertible depends on the weight vector **w**. However, the minimization of the variance, which is used to obtain the best value of **w**, guarantees that (8) is monotonic and thus invertible. In fact, in the points where (8) has a null derivative an infinite number of bits would be required to get an estimate. Figure 8 shows the performance of the *weighted quantization*.
The weight vector used for the real case is $[0 \quad 1 \quad 3 \quad 6 \quad 10 \quad 15 \quad 20 \quad 27]$.

If the hardware allows to set the span of the quantization levels, other interesting results can be obtained. Using normal quantization, the signal levels are set to $i\mu_s / q$ where i = 0,1,2,...q-1, while using extended quantization the levels are set to $2i\mu_s / q$. If the hardware allows the levels to be set to $ki\mu_s$, where k is a tuneable quantity, a further improvement can be obtained by appropriately choosing k and **w.** In practice, our results showed that the optimum k is very close to the situation where one of the quantization zones is centred on the Gaussian, that is, when $k = 2/(q\text{-}1)$ (Fig. 9).

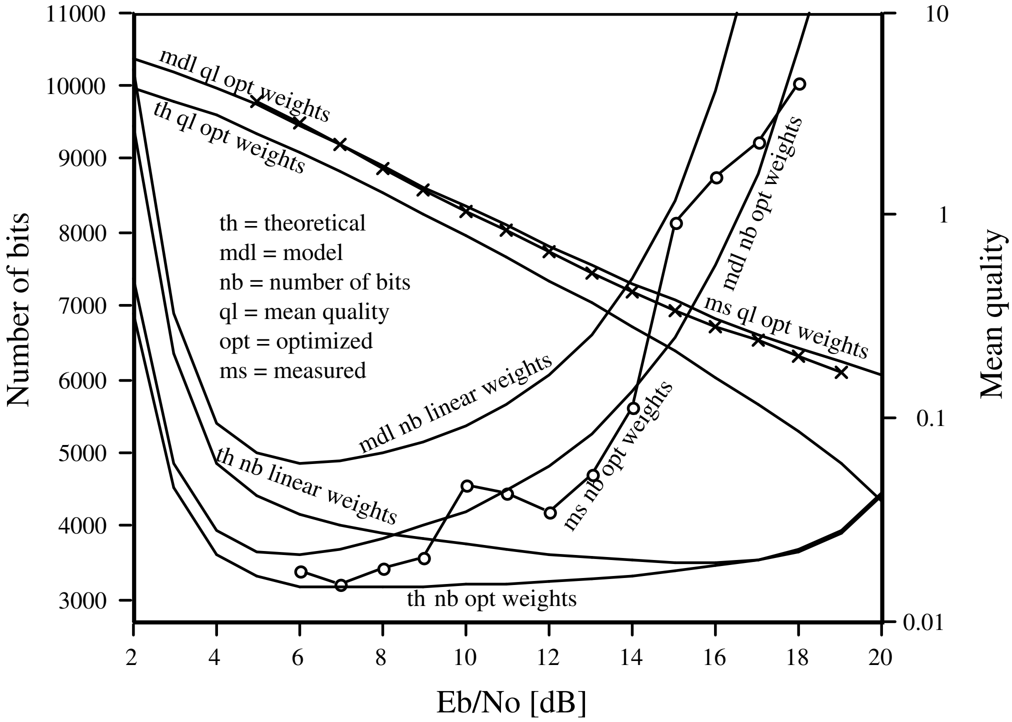

Figure 8. *Mean quality and sample size using normal quantization, as functions of E_b / N_0. Theoretical, modelled and real cases.*

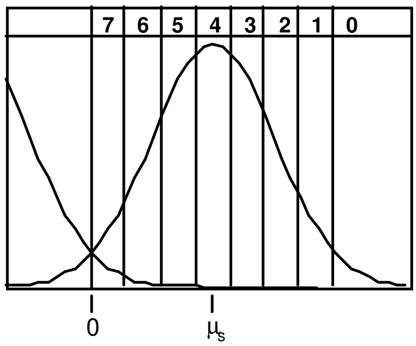

Figure 9. *Optimized extended quantization.*

In Fig. 10 the performances of extended quantization are shown, both with linear weights (method of the mean) and with optimized levels and weights. The improvement due to the adoption of the error bit is shown as well.

We have shown that the methods outlined in this paper for measuring the E_b / N_0 ratio of a BPSK/QPSK signal by using soft level quantization improve on each other. There is a limit to this improvement, which is plotted in Fig. 10 as a horizontal line that indicates the minimum possible number of bits needed to get the required precision, assuming that the signal amplitude can be measured with an arbitrary precision. In order to obtain this result, let us consider that measuring the amplitude of N demodulated bits is equivalent to taking N samples from a normal distribution. We are interested in the variance of this distribution, that is, the N_o value, given that E_b is normalized to 1. The error we make in measuring the variance can be evaluated by considering the distribution of the measure of the variance, and using it to obtain a confidence interval for the measured variance. Thus we can say that we are taking N samples z_i with a normal distribution $N\ (\mu,\sigma^2)$, and we estimate the sample variance as $\boxed{\hat{\sigma}^2 = \frac{1}{N}\sum_{1}^{N}(z_i-\mu)^2}$. The random variable $N\hat{\sigma}^2/\sigma^2$ follows a $\chi^2(N)$ distribution [19] which, for $N>100$, is well approximated by $\mathrm{N}\ (N,\ 2N)$ [20]. In order to match the 99% confidence interval of ±0.5 dB that we have used throughout this article, we consider a 99% confidence interval of $[10^{-0.5/10}, 10^{+0.5/10}]$ computed on the $\chi^2(N)/N$ distribution. Such an interval is asymmetric. Instead of this, for simplicity we use the symmetric conservative interval $\pm(1-10^{-0.5/10})$. The optimum number of bits N_{opt} can thus be computed by using the relation $2.58\sqrt{2/N_{\mathrm{opt}}} = 1-10^{-0.5/10}$.

In [13] the same limit is obtained by assuming an infinite number of quantization levels.

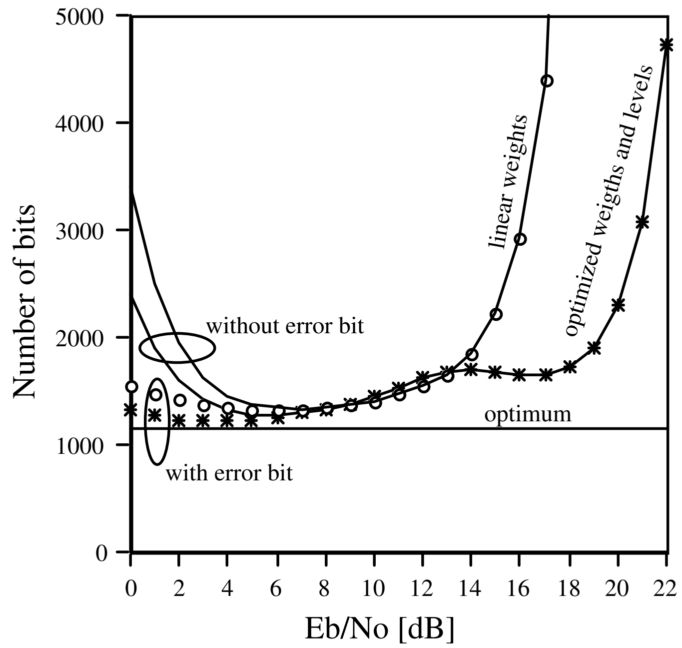

Figure 10. *Performance of extended quantization. Linear weights and optimized levels and weights, with and without the error bit logic.*

CONCLUSIONS

As the exploitation of the K_a band for satellite communication increases, the need for a quick and accurate estimate of the E_b/N_0 ratio available at the receiver is gaining importance. Since redundancy-based counterfade systems can be employed even in low-cost implementations, hand-held appliances can benefit from simple and efficient E_b/N_0 measurement systems. We have presented (in increasing sophistication and chronological order) a class of methods for evaluating in real time the E_b/N_0 ratio of a received BPSK/QPSK signal. Apart from the BER method, which is applicable for very low E_b / N_0 ratios only, we have shown that the theoretical performance of all the other methods is satisfactory. In particular, the performance of the most sophisticated system is very close to the best possible attainable performance. All the systems presented are however very cheap, because they mostly use the logic needed by a Viterbi decoder used in soft quantization mode, which is the most common technique employed in digital satellite communications. We have also presented a real case, which uses a novel procedure that optimizes the results, thus limiting the effects due to the impairments of the realization.

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