Robust Adaptive Coding and Modulation Scheme for the Mobile Satellite Forward Link

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***Abstract*—We consider the application of adaptive backoff margins to mobile satellite links. The mapping of channel state information to modulation and coding schemes is complemented by a margin which is obtained as the result of a stochastic gradient descent scheme which uses the decoding history reported by the receiver. The proposed solution does not rely on the knowledge of the channel model and its parameters, which helps to improve its robustness with respect to previous schemes. Analysis and simulations are provided to certify the potential of the exposed ideas.**

I. Introduction

Time-varying channels are more the rule than the exception in modern wireless communications, so that adjustment of transmission parameters to the conditions of the communication channel is standard practice in many cases. This adaptation is critical to get the most of channels which evolve with time due to, for example, mobility, atmospheric changing conditions or interference. Link adaptation has been successfully included not only in several terrestrial standards but also in satellite communications; let us consider, for example, cellular technologies (3GPP LTE [1], IEEE 802.16 [2]), wireless local area networks (IEEE 802.11 [3]) and satellite standards (DVB-S2 [4], DVB-RCS [5]). Even mobile satellite links, for which the tracking of the channel conditions is difficult due to the high round trip time (RTT), conceive the use of adaptive communications [6]. Feedback, in diverse forms, is key to track the channel response and adapt conveniently. Link adaptation requires some sort of coordination between the transmitter and the receiver to be able to track the channel changes. In particular, channel state information (CSI) at the transmitter (CSIT) is necessary (or at least desirable) to apply link adaptation methods. This CSIT can be obtained by means of a feedback channel from the receiver, that reports back information on the channel quality, the decoding performance or both. Most current wireless standards include some sort of feedback mechanism that allows the application of link adaptation. This channel quality indicator (CQI) can be in diverse forms such as estimated SNR or supported rate. However, a complete characterization of optimal solutions for feedback channels has proved elusive over the years, although several schemes which address a variety of practical situations exist [7]. For the case of flat-fading channels, as those found in different types of satellite connections, the objective is the adjustment of the modulation and coding scheme (MCS) and power to maximize the spectral efficiency, subject to an error rate constraint [8]–[11]. If we focus on the rate adaptation problem, the proposed methods consist basically of a look-up table (LUT) that matches the received SNR feedback to an MCS. This table is obtained by means of theoretical calculations or link level simulators in controlled conditions, which lead to the selection of appropriate thresholds to switch the different MCS. If the link level simulations are representative of the scenario where the link adaptation protocol is going to operate, then the LUT-based approach will offer a near-optimal performance. However, the inaccuracy of the CSIT is a common source of performance degradation. In the case of mobile satellite links, the large RTT causes CSIT to be outdated even for moderate terminal speeds. Different techniques have been developed, such as the combination of automatic repeat request (ARQ) and multi-layer coding [12], or HARQ-IR protocols based on layering coding [13].

In this paper we study the application of adaptive backoff margins to mobile satellite links, in an attempt to improve on the use of unnecessarily large link margins to account for fading. ARQ will not be explicitely considered, although the related ACK/NAK will be exploited. In a previous work we applied these ideas to the return link [14], by using a judicious combination of open and closed loop quality metrics in addition to an adaptive margin. Here we focus on the forward link, by deriving as in [14] the backoff margin as a stochastic programming solution to an optimization problem.

In the next section we present the model of the system under study. In Section III we derive the adaptation scheme of the back-off margin, with its convergence analytically studied in the Appendix. The scheme is numerically illustrated by simulations in Section IV.

II. System Model

We consider a narrowband mobile satellite link operating at the S-band and which complies with the requirements of the standard S-UMTS (Satellite component of UMTS), in particular, the broadband global area network (BGAN) system [6]. Next we describe the signal model and the assumptions for performance prediction.

Transmission is organized in time slots of 80 ms for the forward link, each carrying a frame. Although within a given frame one or more FEC blocks can be accommodated, we will choose an operating mode for which one FEC block spans the whole frame, so FER (Frame Error Rate) will be used

TABLE I: Coding rate options for the F80T1Q1B bearer [6], QPSK constellation.

	L8	L7	L6	L5	L4	L3	L2	L1	R
Coding rate	0.34	0.40	0.48	0.55	0.63	0.70	0.77	0.83	0.87
Rate (spectral efficiency)	0.68	0.80	0.96	1.10	1.26	1.40	1.54	1.66	1.74
γ_{th} (dB)	-2.1534	-1.2166	-0.0879	0.8317	1.8474	2.7278	3.6674	4.5384	5.1930

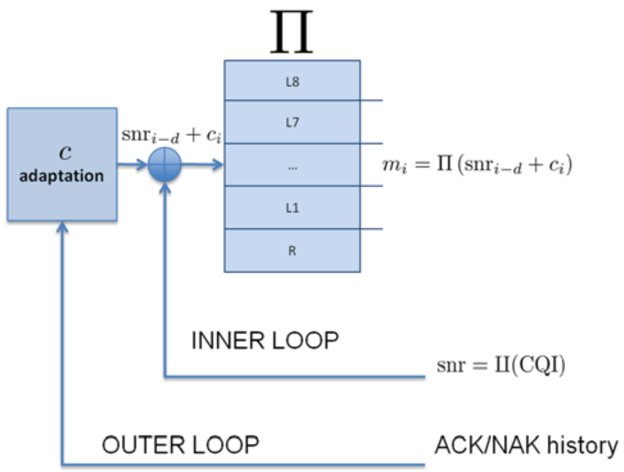

Fig. 1: Outer/inner adaptation loop.

as equivalent to WER (Word Error Rate) and BLER (Block Error Rate)[1]. The transmitter will use an appropriate MCS chosen from Table I. The corresponding symbol rate will be constant and equal to 33.6 Ksymbol/s. During the reception of a frame, the channel amplitude can experience significant changes, especially for high speeds. Since the average SNR is not a reliable performance metric for this case, we will resort to effective SNR metrics to predict decoding errors; in particular, we will use the mutual information metric as in [14] for the simulations. Using this metric, we assume that the transmission of the i-th frame fails when its effective received SNR is below the corresponding threshold SNR of the MCS used in Table I, and that it succeeds otherwise. In principle, there are multiple options for signalling from the mobile terminal to the gateway. Some sort of signal to noise (and interference) ratio metric can be used (this is the case in BGAN), although an index with the supported rate or MCS can save precious bandwidth in the return link. As CQI we consider the index of the highest MCS supported by a channel with an effective SNR equal to that obtained from a given number of received frames. The selection of the MCS is illustrated in Figure 1. The function Π maps an MCS index to its corresponding SNR threshold in Table I. Then, a look-up table (LUT) maps the SNR to an MCS after applying a conveniently chosen back-off margin c_i:

$$m_i = \Pi(\mathrm{snr}_{i-d} + c_i). \tag{1}$$

The reported CQI by the receiver will get to the transmitter after a delay d at least equal to the RTT, which for the case of geostationary satellites is half a second. If we define ϵ_i as the error event of the i-th codeword, then ϵ_i will be equal to 1 if a decoding error occurs and 0 otherwise. This error event will be reported back to the receiver; in case the return signalling does not include this decoding flag in the form of ACK/NAK, the back-off margin can be computed at the receiver and the selected MCS m_i in Figure 1 sent back to the transmitter as CQI.

[1]Fragments of packets addressed to different receivers are expected to coexist within the same frame. The process of aggregration of these packets is out of the scope of this paper.

For the simulations, we will assume that the channel follows a Loo distribution [15]: slow variations in the line-of-sight component (shadowing) are described by a log-normal distribution, whereas fast fluctuations of the signal amplitude (fading) are given by a Rician distribution. No knowledge about the specific parameters of the channel model will be assumed for the operation sketched in Figure 1.

III. Robust Adaptive Margin

The application of adaptive margins with CQI information is a common strategy, [16]–[18], also used in satellite communications for slowly variant fixed communications [19], although mostly based on ad-hoc justifications. The margin c_i in (1) accounts for the modeling errors and the obsolescence of SNR, which is received by the transmitter at least an RTT after the corresponding block was sent. An adequate choice of c_i seems to require the knowledge of the channel statistics. Nevertheless, in an effort to obtain a flexible solution not requiring a specific knowledge about the channel, the margin can be obtained as the solution of an optimization problem for a given FER p_0:

$$\min_c J(c) = \min_c \left|\mathbb{E}[\epsilon] - p_0\right|^2. \tag{2}$$

The choice of a good p_0 is not trivial, since it will have an impact on the final throughput, which will also depend on the existence of retransmission mechanisms. In practical cases $p_0 = 0.1$ is acknowledged to be a good reference [20], although this is not necessarily the case in the setting under study. If we apply a gradient descent operation to solve (2), then

$$c_{i+1} = c_i - \mu_i \frac{\partial J}{\partial c}\left(c_i\right) \tag{3}$$

with μ_k a sequence of positive numbers. The value of the derivative is

$$\frac{\partial J}{\partial c} = \frac{\partial \mathbb{E}[\epsilon]}{\partial c}\left(\mathbb{E}[\epsilon] - p_0\right) \tag{4}$$

so the gradient descent is

$$c_{i+1} = c_i - \mu_i \frac{\partial \mathbb{E}\left[\epsilon\right]}{\partial c}\left(\mathbb{E}\left[\epsilon\right] - p_0\right). \tag{5}$$

Note that (5) depends on the function $\mathbb{E}\left[\epsilon\right]$ and, therefore, cannot be obtained without statistical knowledge of the channel. We propose two modifications to (5). First, we substitute $\mathbb{E}\left[\epsilon\right]$ by the error ϵ_{i-d}, available at the transmitter at time instant i, so we transform the gradient descent in a stochastic gradient descent. Second, we interpret the term $\frac{\partial \mathbb{E}[\epsilon]}{\partial c}$ as a positive[2] time varying adaptation weight, so we include its effect in μ_i. Therefore, the stochastic adaptation rule is

$$c_{i+1} = c_i - \mu_i \left(\epsilon_{i-d} - p_0\right). \tag{6}$$

Let us denote by $p\left(c\right)$ the error probability when the margin is c. Assume that p is a continuously differentiable function, with derivative bounded by $\delta_0 < \frac{\partial}{\partial c} p\left(c\right) < \delta_1 \, \forall c$, with $\delta_0 > 0$. Let us denote by $c_\star$ the value[3] such that $p\left(c_\star\right) = p_0$. Additionally, the stepsize in (6) will remain constant and equal to μ. If $d = 0$ in (6), then the following convergence results hold.

Theorem 1: If $\mu < 2/\delta_1$, then $\left|\mathbb{E}\left[c_i\right] - c_\star\right| < \eta^i \left|\mathbb{E}\left[c_0\right] - c_\star\right|$, with $0 < \eta < 1$, which grants an exponential convergence of (6). In addition, the expectation of the mean squared error $\mathbb{E}\left[\left(c_i - c_\star\right)^2\right]$ converges as

$$\lim_{i\to\infty} \mathbb{E}\left[\left(c_i - c_\star\right)^2\right] < \frac{\mu}{2\delta_0 - \mu\delta_0^2}. \tag{7}$$

If $d > 0$, convergence is still expected for sufficiently low stepsize μ, although formal proof is only provided for $d = 0$ in the Appendix.

In order to speed up the convergence of the adaptive (outer loop) scheme, a Normalized Least Mean Squares (NLMS) variant can also be used [14]:

$$c_{i+1} = c_i - \frac{\mu}{\theta^2 + \mathrm{snr}_{i-2d}^2}(\epsilon_{i-d} - \tilde{p}_{0,i}) \cdot \theta \tag{8}$$

with $\tilde{p_0}$ adjusted as

$$\tilde{p}_{0,i+1} = \tilde{p}_{0,i} - \lambda(\epsilon_{i-d} - p_0). \tag{9}$$

IV. Numerical Evaluation

We report the results of the adaptive margin approach for the forward link of the Land Mobile Satellite channel. Only one state will be considered [21], corresponding to a line-of-sight (LOS) situation. As mentioned in Section II, the reported CQI by the receiver will be the result of mapping the average effective SNR to the highest supported MCS. Each frame has a duration of 80 ms. A geostationary satellite is considered, so the RTT will be approximately equal to 6 frames. Adaptation was performed with the NLMS algorithm, with $\theta = 10$ and $\mu = 1$ in (8) and $\lambda = 0.001$ in (9). Figures 2 and 3 show the evolution of the margin c_i for different speeds and simulation conditions. The cumulative FER is also shown. Due to the long duration of the frames, the variance of the effective SNR decreases for higher speeds, so the required back-off margin is lower (in absolute value). In both cases the CQI is computed after mapping the effective SNR averaged during 8 frames. The margin which guarantees the target FER is a function of the speed (among other parameters), which illustrates the flexibility of the proposed adaptive solution against a fixed margin allocation. This becomes more clear in Figure 4, where fixed margin allocation performance contrasts with that for adaptive margin. Average spectral efficiency and cumulative FER are plotted for a LOS SNR ranging from 0 to 10 dB. Spectral efficiency based on perfect knowledge of the SNR is also shown as reference. Average spectral efficiency is defined as $\frac{1}{N}\sum_{i=1}^{N}(1-\epsilon_i)r_{m_i}$, with r_j the rate of the j-th MCS, and m_i the selected MCS for the transmission of i-th frame. In the same figure we have also tested the simultaneous adaptation of the margin c and a weight ξ of the SNR, which can be of interest for those cases with a more frequent feedback of the SNR. The choice of the MCS by the LUT would follow now

$$m_i = \Pi(\xi_i \cdot \mathrm{snr}_{i-d} + c_i) \tag{10}$$

with the corresponding NLMS scheme

$$\begin{pmatrix} c_{i+1} \\ \xi_{i+1} \end{pmatrix} = \begin{pmatrix} c_i \\ \xi_i \end{pmatrix} - \frac{\mu}{\theta^2 + \mathrm{snr}_{i-2d}^2}(\epsilon_{i-d} - \tilde{p}_{0,i}) \begin{pmatrix} \theta \\ \mathrm{snr}_{i-2d} \end{pmatrix}. \tag{11}$$

A similar adaptation scheme, including also the SNR measured by the receiver, was applied in [14] for the return link. We have compared different configurations in terms of number of adaptive parameters: a fixed margin of -1 dB, adaptive margin and adaptive margin and weight. The use of adaptation (either one or two parameters) outperforms the fixed back-off margin approach, which would require the knowledge of the operation point and the channel statistics to achieve the target FER (in this example this occurs for a LOS SNR close to 8 dB).

V. Conclusions

In this paper we have shown the application of adaptive back-off margins to the forward link of a mobile satellite link. The mapping of the reported channel quality to the corresponding transmission rate is modulated by a margin which accounts for the reliability degree of this channel information to predict the channel transmission capacity in subsequent frames. A stochastic gradient descent algorithm was derived, and its convergence proved analytically and tested by simulations for narrowband links. Application to broadband links, with shorter frame durations, looks quite promising now that the recently published extension DVB-S2X [22] to DVB-S2 enhances the applicability of the latter to mobile receivers by incorporating special frames able to work in very low SNR conditions.

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Appendix

We have performed a convergence analysis of the adaptive outer loop to certify the mean and MSE convergence of the margin c_i in (6) for $d = 0$. The proof is based on the results in [23]. We can write the expected value of c_{i+1} conditioned on c_i as

$$\mathbb{E}\left[c_{i+1} | c_i\right] = c_i - \mu\left(p\left(c_i\right) - p_0\right). \tag{12}$$

[2]Note that rigorously speaking $\mathbb{E}\left[\epsilon\right]$ is a non-continuous function.

[3]As p_0 is a monotonic increasing function, this value is unique.

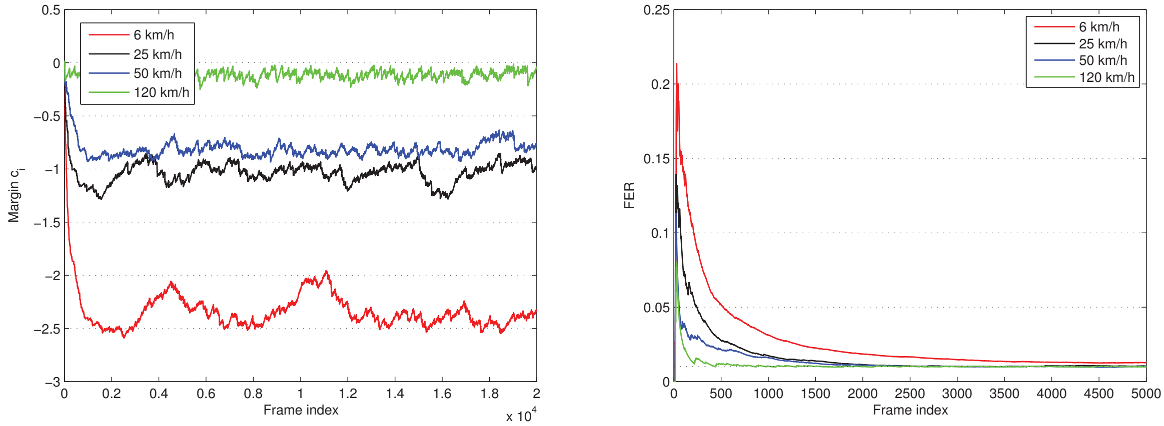

Fig. 2: Margin (left) and cumulative FER (right) evolution. Suburban environment, target FER of 0.01 and 6 dB of LOS SNR.

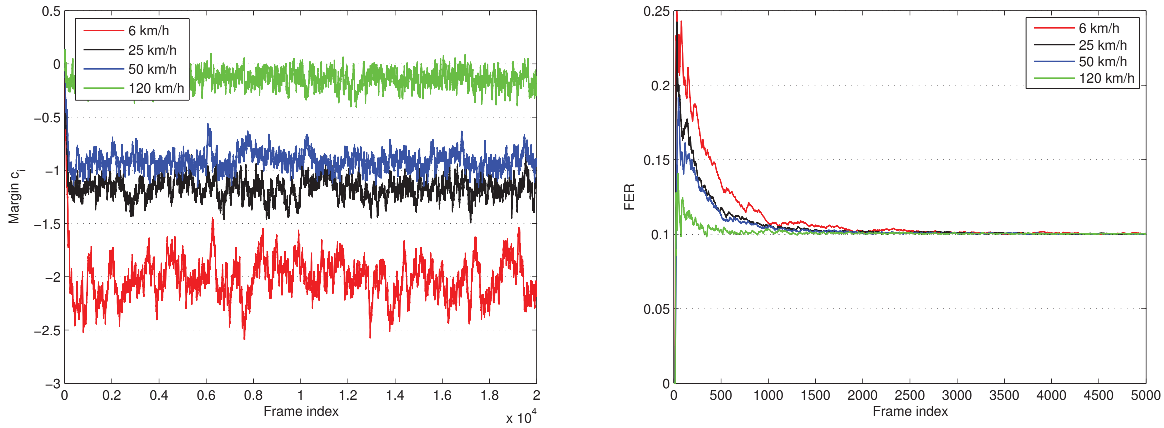

Fig. 3: Margin (left) and cumulative FER (right) evolution. Intermediate tree shadowing environment, target FER 0.1 and 2 dB of LOS SNR.

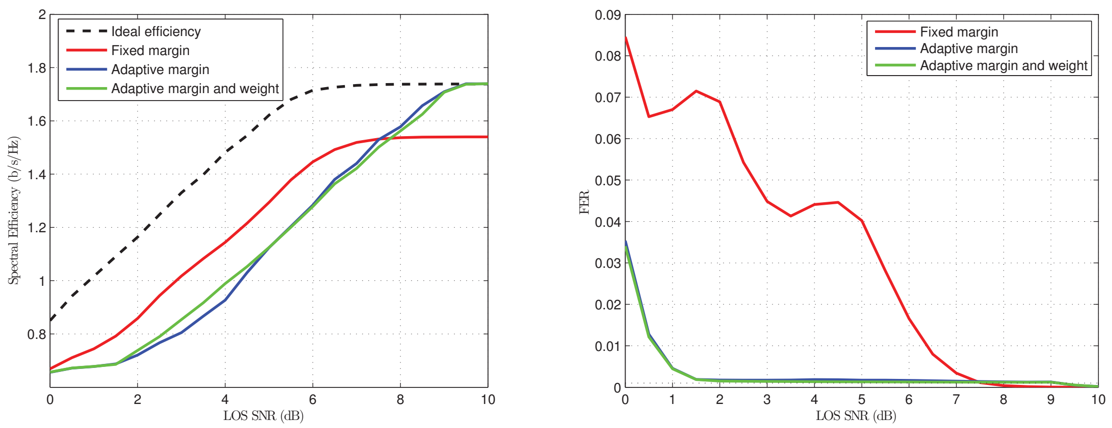

Fig. 4: Spectral efficiency (left) and cumulative FER (right) after averaging four realizations of $6 \cdot 10^4$ transmitted frames. Urban environment, target FER 0.001 and speed 5 Km/h.

Note that, by definition, $p_0 = p(c_\star)$. By using the mean value theorem, we can find $\tilde{c}$ between c_i and $c_\star$ such that $p(c_i) - p_0 = p'(\tilde{c})(c_i - c_\star)$. Therefore,

$$\mathbb{E}[c_{i+1}|c_i] - c_\star = (c_i - c_\star)(1 - \mu p'(\tilde{c})). \quad (13)$$

If we take the expectation over c_i on both sides of the equation, we have that

$$|\mathbb{E}[c_{i+1}] - c_\star| = |\mathbb{E}[c_i] - c_\star| \, |1 - \mu p'(\tilde{c})|. \quad (14)$$

Note that the new $\tilde{c}$ is not necessarily the same as before, after applying the first mean value theorem for integration. Convergence is guaranteed if $|1 - \mu p'(\tilde{c})| < 1$ or, equivalently, if $\mu < 2/p'(\tilde{c})$. Since the value of the derivative is upper bounded by δ_1, it suffices to choose $\mu < 2/\delta_1$. In such a case,

$$|\mathbb{E}[c_i] - c_\star| < \eta^i |\mathbb{E}[c_0] - c_\star| \quad (15)$$

with $\eta = |1 - \mu\delta_1|$. Thus, exponential convergence of the expectation $\mathbb{E}[c_i]$ has been proved.

Next we perform a second order analysis. From (6) we have

$$\mathbb{E}\left[(c_{i+1} - c_\star)^2\right] = \mathbb{E}\left[(c_i - c_\star)^2\right] - 2\mu\mathbb{E}\left[(c_i - c_\star)(\hat{p}(c_i) - p_0)\right] + \mu^2\mathbb{E}\left[(\hat{p}(c_i) - p_0)^2\right] \quad (16)$$

where we are referring to ϵ_{i-d} as $\hat{p}(c_i)$. If we write $\hat{p}(c_i) = p(c_i) + w_i$, with w_i a zero-mean random variable, then we have that $\mathbb{E}\left[w_i^2\right] < 1$. Note that we can accommodate more precise estimates of the probability of error in (6) by, for example, averaging a sequence of consecutive ACK/NAK; the bound for $\mathbb{E}\left[w_i^2\right]$ could be tightened accordingly. Next we will use also that $\mathbb{E}\left[(c_i - c_\star)(p(c_i) - p_0)\right] = p'(\tilde{c})\mathbb{E}\left[(c_i - c_\star)^2\right]$ after applying the mean value theorem and the first mean value theorem for integration. Analogously, $\mathbb{E}\left[(p(c_i) - p_0)^2\right] = (p'(\tilde{c}))^2\mathbb{E}\left[(c_i - c_\star)^2\right]$. With this, and given that $\delta_0 \leq p'(c) \leq \delta_1$, we have that

$$\mathbb{E}\left[(c_{i+1} - c_\star)^2\right] \leq (1 - \mu\delta_0)^2\mathbb{E}\left[(c_i - c_\star)^2\right] + \mu^2 \quad (17)$$

which, in the limit leads to

$$\lim_{i\to\infty} \mathbb{E}\left[(c_i - c_\star)^2\right] < \frac{\mu}{2\delta_0 - \mu\delta_0^2}. \quad (18)$$

Finally, convergence of average BLER $\lim_{n\to\infty} \frac{1}{n}\sum_{i=1}^{n} \epsilon_i$ to the target BLER p_0 can also be proved following a similar reasoning as in [23].

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