Cross Layer Link Adaptation in Time Varying Mobile Satellite Channels with Statistical and Outdated CSIT

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***Abstract*—The inherently large propagation delay present in satellite communications makes link adaptation procedures difficult to apply. Particularly, channel state information at the transmitter (CSIT) can be completely outdated after a round-trip time for high-speed receivers. For moderate speeds, some correlation is expected between the current channel and the CSIT. In this paper we present a link adaptation procedure that uses both CSIT and statistical information about the channel variation. We exploit the use of retransmissions to alleviate the rate backoff induced by the outage constraint. The link adaptation procedure is stated as the maximization of the throughput subject to a packet error probability constraint, and the channel variation is captured by a time-homogeneous Markov chain.**

I. Introduction

Link adaptation –the process of changing the transmit parameters according to changes in the channel– involves choosing an adequate modulation and coding scheme (MCS) to maximize the throughput subject to a reliability constraint. This selection is considered of paramount importance for mobile satellite channels, as it allows a much more cost-effective transmission. However, two characteristics of the channel hinder its application: the variations of the signal envelope within the time span of a codeword, and the huge communication delays involved, which cause channel state information (CSI) to quickly run outdated.

The first problem can be conveniently addressed by the use of appropriate look-up tables, or effective signal-to-noise ratio (ESNR) metrics [1], [2]. The second problem turns out to be more involved, but previous works prove it is still possible to exploit the information available at the transmitter, be it outdated CSI, statistics of the channel, or both. As an example, [3] was able to exploit outdated CSI at the transmitter (CSIT) by simply introducing a backoff function.

One way of taking advantage of the available information in mobile satellite channels is by using retransmission protocols, which exploit the existing time diversity. In [4], the authors obtained the optimum MCS sequence to be used in the retransmissions of a packet which undergo independent realizations of the channel. It was proven that a sequence of unequal MCS achieved the optimum tradeoff between reliability and throughput [5], and greatly improved performance even with very simple forms of CSI like a plain exchange of ACK/NAK.

However, solutions for independent channels are too optimistic when different transmissions experience correlated channels. Such channels have been extensively studied in the literature [6]–[8], and are often modeled with Markov chains. In this paper, we extend the work in [4] to account for correlated fading. By resorting to a one-step Markovian model for the quantized ESNR values of the channel, we derive the optimum MCS sequence for different levels of CSIT. Results show that an ACK/NAK exchange alone can provide enough information to maximize the throughput while meeting a predefined outage constraint.

The remainder of this paper is structured as follows: Section II describes the system model and the underlying assumptions, Section III formalizes the statement of the problem, Section IV describes the different adaptation algorithms, Section V reports simulation results illustrating their performance, and Section VI summarizes the most relevant findings.

II. System Model

Consider a point to point mobile satellite communication system where a transmitter conveys packets of b bits to a receiver. Time is divided into slots $\{T_t\}_{t=0}^{+\infty}$ of duration τ symbol periods. Each slot T_t represents a *transmission opportunity* that does not need to be contiguous in time to T_{t+1}[1]. In the i-th slot, the transmitter performs modulation and coding in two steps. First, a block of ℓ_t bits is formed by attaching $\ell_t - b$ bits to the packet under study. We assume that the bits for padding come from data intended for other users, so no spectral efficiency is lost. This is a common procedure to include multiuser information in satellite systems with constant codeword length [9]. The block of ℓ_t bits is mapped to τ symbols $\mathbf{x}_t = [x_{t,1}, x_{t,2}, \ldots, x_{t,\tau}]^T$ by performing modulation and coding of rate $R_t \triangleq \frac{\ell_t}{\tau}$. The MCS is selected

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[1] If stop-and-wait is used for retransmissions, for example, there is a delay of one round trip time between the end of T_t and the start of T_{t+1}.

from a discrete finite set $\mathscr{R} = \{r_1, \ldots, r_{\mathcal{R}}\}$. We define the *used transmit resources* in slot T_t as $L_t \triangleq \frac{b}{R_t}$.

We assume a narrowband fading signal, such that the received signal $y_{t,i}$ is the result of scaling the transmitted sequence by a random complex gain $h_{t,i}$ and adding white noise $w_{t,i} \sim \mathcal{CN}\left(0, \sigma^2\right)$

$$y_{t,i} = h_{t,i} x_{t,i} + w_{t,i}. \tag{1}$$

The message transmitted in the t-th slot is correctly decoded if the mutual information between the transmitted symbols $\mathbf{x}_t$ and the received symbols $\mathbf{y}_t \triangleq [y_{t,1}, \ldots, y_{t,\tau}]^T$ is greater than the number of uncoded bits. We define the random variable $U_t \in \{0, 1\}$ as the unsuccessful or successful decoding of the t-th message:

$$U_t = \begin{cases} 0 & \text{if } \mathcal{I}(\mathbf{x}_t; \mathbf{y}_t) < \ell_t \\ 1 & \text{otherwise} \end{cases}. \tag{2}$$

In general, it is complicated to characterize the joint probability density function of the random variables $U_t, U_{t+1}, \ldots U_M$. First, the mutual information function for inputs in a discrete alphabet does not have a closed form expression:

$$\begin{aligned}\mathcal{I}(x_i, y_i) = & 1 - \frac{1}{M \log_2 M} \\ & \times \sum_{m=1}^{M} \mathbb{E}_w \left[\log_2 \left(\sum_{k=1}^{M} e^{-\frac{|X_m - X_k + w| - |w|^2}{1/\gamma_i}} \right) \right]\end{aligned} \tag{3}$$

with $\gamma_i \triangleq \frac{|h_i|^2}{\sigma^2}$, $w \sim \mathcal{CN}(0, 1/\gamma_i)$ and $\{X_m\}_{m=1}^{M}$ the set of complex points in the constellation. Second, the mutual information itself is a random variable, since it depends on the possibly correlated channel values h_i, and a closed form expression for its probability density function (PDF) does not even exist for the simple case of uncorrelated Rayleigh fading [5]. Last, in land mobile satellite (LMS) communication the statistical description of the channel follows intricate expressions [10], thus discouraging the derivation or even approximation of the mutual information PDF. In this paper, we propose a simple alternative characterization of the LMS channel by the use of a Markov chain.

A. Markovian Description of the Channel

For each slot T_t we define a channel state S_t. The random process $\{S_t\}_{t=0}^{\infty}$ is assumed to be a Markov chain of order one, i.e., $\mathbb{P}(S_t = i_t | S_{t-1} = i_{t-1}, S_{t-2} = i_{t-2}, \ldots) = \mathbb{P}(S_t = i_t | S_{t-1} = i_{t-1})$. The set of possible states is discrete and finite, with cardinality $1 + \mathcal{R}$, and is denoted by $\mathscr{S} = \{s_0, \ldots, s_{\mathcal{R}}\}$. We also assume that the Markov chain is aperiodic and irreducible [11], so that S_t has a unique stationary distribution $\boldsymbol{\pi} = [\pi_0, \ldots, \pi_{\mathcal{R}}]^T$, i.e.

$$\lim_{t \to +\infty} \mathbb{P}(S_t = s_i) = \pi_i \;\; \forall \mathbf{p}^{(0}, i = 0, \ldots, \mathcal{R} \tag{4}$$

where $\mathbf{p}^{(i} = [\mathbb{P}(S_i = s_0), \mathbb{P}(S_i = s_1), \ldots, \mathbb{P}(S_i = s_{\mathcal{R}})]$ denotes the probability density function of the i-th slot. We define $p_{i,j} \triangleq \mathbb{P}(S_t = s_i | S_{t-1} = s_j)$, and $\mathbf{P}$ as a $(\mathcal{R}+1) \times (\mathcal{R}+1)$ matrix with entries $[\mathbf{P}]_{i,j} = p_{i,j}$. With the previous definitions, we have that $\mathbf{p}^{(i+\Delta} = \mathbf{P}^{\Delta} \mathbf{p}^{(i}$. Also, the existence of a unique stationary distribution guarantees that $\boldsymbol{\pi}$ is an eigenvector of $\mathbf{P}$, and that $\boldsymbol{\pi} = \lim_{\Delta \to \infty} \mathbf{P}^{\Delta} \mathbf{p}$ for every probability vector $\mathbf{p}$.

We design the states so that the decoding event can be written as

$$\mathbb{P}(U_t = 1 | R_t = r_j, S_t = s_i) = \begin{cases} 1 & \text{if } j \leq i \\ 0 & \text{if } j > i \end{cases}, \tag{5}$$

for $j = 1, \ldots, \mathcal{R}$, $i = 0, \ldots, \mathcal{R}$. The probability density function of S_t is obtained from the empirical distribution of the mutual information, so that

$$\pi_i = \mathbb{P}(S_t = s_i) = \mathbb{P}\left(r_i < \frac{1}{\tau} \mathcal{I}(\mathbf{x}, \mathbf{y}) \leq r_{i+1} \right) \tag{6}$$

with $r_0 = -\infty$ and $r_{\mathcal{R}+1} = +\infty$. The conditional probabilities $p_{i,j}$ are defined in a similar way. In the case of having two MCS r_1, r_2, for example, we would have states s_0, s_1, s_2. In state s_0 both MCS will always fail, in state s_1 MCS r_1 will be successful, and in state s_2 both MCS would be successful.

B. The ARQ Process

The transmitter combines adaptive modulation and coding with adaptive repeat request (ARQ). After each frame T_t, and before the next slot T_{t+1} starts, the receiver feeds back a NAK or ACK to the transmitter by an error free channel, so U_{t-1} is known at the transmitter before slot T_t. If a NAK is received, then the same message is retransmitted up to $T-1$ times, i.e., T transmissions for the same message. After the T-th transmission, the transmitter drops the packet and transmits a new one. This allows limiting the end-to-end delay. Under the proposed channel model, and with some additional assumptions[2], the ARQ process can be also modeled as a Markov chain. Define by $\{A_t\}_{t=0}^{+\infty}$ the random process taking values on $\mathscr{A} = \{a_1, \ldots, a_T\}$. a_1 is the state where the ARQ protocol is transmitting a new packet, a_2 is the first retransmission, and so on. Not all the transitions between states are possible, due to the restrictions induced by the ARQ protocol. We denote by m_i the error probability at the i-th ARQ state. The m_i values can differ among different states due to the variation of the channel and the use of different MCS in different retransmissions. Thus, m_i is a function of the selected MCS r_j, and we will explicitly denote this dependency as $m_i(r_j)$ when needed. The transition probability matrix $\mathbf{M}$ of the ARQ protocol is

$$\mathbf{M} = \begin{bmatrix} 1 - m_1 & 1 - m_2 & \cdots & 1 - m_{T-1} & 1 \\ m_1 & 0 & \cdots & 0 & 0 \\ 0 & m_2 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & m_{T-1} & 0 \end{bmatrix}. \tag{7}$$

[2] The one-step memory assumption holds for memoryless channels, for the case where the state is known before the first transmission, and for the case where the initial state is randomly drawn with respect to $\boldsymbol{\pi}$ for every new packet.

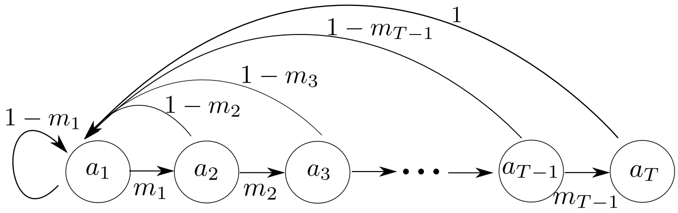


Figure 1: Markov chain of ARQ operation.

The state diagram of the ARQ process is depicted in Figure 1. The stationary state distribution $\boldsymbol{\mu} \triangleq [\mu_1, \ldots, \mu_T]^T$ with $\mu_i = \lim_{t\to\infty} \mathbb{P}(A_t = a_i)$ can be obtained from the fact that $\mu_i = m_{i-1}\mu_{i-1}$ for $i > 1$ and $\sum_{i=1}^{T} \mu_i = 1$, so [4]

$$\mu_i = \frac{\prod_{j=1}^{i-1} m_i}{\sum_{j=1}^{T} \prod_{k=1}^{j-1} m_i}. \tag{8}$$

III. Problem Statement

The objective of the link adaptation algorithm is to maximize the long term throughput subject to a constraint on the packet error rate. A delay constraint is implicitly introduced in the problem by limiting the number of retransmissions to $T - 1$. The long term throughput η is defined as the number of successfully decoded bits divided by the total used transmit resources L_t

$$\eta \triangleq \lim_{N\to+\infty} \frac{\frac{1}{N}\sum_{t=0}^{N} U_t b}{\frac{1}{N}\sum_{i=0}^{N} L_t} = \frac{b\mathbb{E}[U]}{\mathbb{E}[L]} \tag{9}$$

with U and L random variables representing a randomly picked U_t and L_t. Both the numerator and denominator can be calculated by marginalizing over the ARQ state

$$\mathbb{E}[U] = \sum_{i=1}^{T} \mu_i \mathbb{E}[U|a_i] = \sum_{i=1}^{T} \mu_i (1 - m_i) \tag{10}$$

$$\mathbb{E}[L] = \sum_{i=1}^{T} \mu_i \frac{1}{\tilde{R}_i} \tag{11}$$

where we denote by $\tilde{R}_i$ the MCS to be used in the i-th transmission. A simplified expression for the long term throughput η is obtained by applying (10) and (11) in (9), and substituting μ_i by its value (8)

$$\eta = \frac{1 - \prod_{i=1}^{T} m_i}{\sum_{i=1}^{T} \left(\prod_{j=1}^{i-1} m_j\right) \frac{1}{\tilde{R}_i}}. \tag{12}$$

The problem consists in selecting the MCS sequence that maximizes the throughput subject to a constraint p_0 on the packet error rate

$$\begin{aligned} &\text{maximize} && \frac{1 - \prod_{i=1}^{T} m_i}{\sum_{i=1}^{T} \left(\prod_{j=1}^{i-1} m_j\right) \frac{1}{\tilde{R}_i}} \\ &\text{subject to} && \prod_{i=1}^{T} m_i \le p_0 \end{aligned} \tag{13}$$

The selection of the MCS depends on the amount of available statistical CSI at the transmitter together with the feedback from the receive side. For example, if the transmitter knows the channel state *a priori*, i.e., knows $S_t = s_i$ before the transmission of the t-th packet, an MCS can be selected to guarantee zero outage (except for i=0). In general, availability of perfect CSI is not possible. In the following section, we derive adaptation strategies for different degrees of outdated and statistical CSI at the transmitter.

IV. Adaptation Algorithms

The MCS selection problem depends on the availability of different degrees of CSI at the transmitter. We take into account the following degrees of CSI:

- **Outdated CSI**: The transmitter knows the channel state in a previous slot. When designing the MCS for slot T_t, the transmitter knows the state S_{t-1}. In this paper, we assume that the outdated CSI is available only before the transmission of a new packet, i.e., no CSI feedback is received if we are triggering a retransmission.
- **Partial statistical CSI:** The transmitter knows the probability to be in a certain state π_i but does not know the transition probabilities between states $p_{i,j}$. If this is the only statistical CSI available, the transmitter can perform link adaptation under an assumption of uncorrelation between states.
- **Complete statistical CSI:** The transmitter knows the transition probabilities $p_{i,j}$ of the Markov chain.

In real scenarios outdated CSI is usually available at the transmitter, as a result of a receiver performing channel estimation and feeding back the quality of the channel. Statisitcal CSI acquisition is not usually described by any communication standard, but can be acquired by estimating the state or transition probabilities from the reception of ACK/NAK values [4]. In the following, we present four different adaptation techniques arising from the application of different degrees of CSIT. We analyze how the error probabilities $m_k(r_i)$ can be estimated from the available statistical information

A. Only Outdated CSI

If only outdated CSIT is available, the transmitter can perform link adaptation by assuming that the channel remains constant through the first transmission and subsequent retransmissions of the next packet. Basically, it assumes that the channel remains constant for a relatively large amount of time, which is a low speed or small delay approximation. Formally, if the received feedback is $S_{t-1} = s_j$, then the transmitter assumes that $S_t = S_{t+1} \ldots = S_{t+T-1} = s_j$. Under this assumption, the error probabilities m_j can be estimated as

$$\hat{m}_k(r_i|S_{t-1} = s_j) = \begin{cases} 1 & \text{if } i < j \\ 0 & \text{otherwise} \end{cases}. \tag{14}$$

The optimization problem (13) is solved by selecting MCS r_j if state s_j is fed back, $j > 0$. For $j = 0$ the outage constraint is never met, as (14) estimates an error probability of 1 regardless of the selected MCS. In this case, we chose to select the lowest rate MCS r_1.

B. Uncorrelated - Partial Statistical CSI

In this case, the transmitter knows the state probabilities π_i but is not aware of the transition probabilities $p_{i,j}$. Adaptation can be performed by assuming uncorrelation between states, i.e. $\mathbb{P}(S_t = s_j | S_{t-1} = s_i) = \mathbb{P}(S_t = s_j)$. The error probabilities of one MCS do not depend on the retransmission index, and are obtained as the sum of the probabilities of the states where they fail:

$$\hat{m}_k(r_i) = 1 - \sum_{j=i}^{T} \pi_i \tag{15}$$

C. Complete Statistical CSI

The case of having complete knowledge of the transitions of the Markov chain is more complicated to analyze. For the first transmission, we assume no state information, and that t is large enough to assume a stationary distribution; its error probability is

$$\hat{m}_1(r_i) = 1 - \sum_{j=i}^{T} \pi_i. \tag{16}$$

To calculate the error probabilities of the subsequent retransmissions we use the transition probabilities of the channel, and the fact that the previous transmissions were not correct. For example, if MCS 1 was selected for transmission in slot T_t and it triggered a NAK, then we know that $S_t = s_0$. With the transition probabilities we can calculate the state probabilities for slot T_{t+1} and obtain the error probabilities. To formalize this, let us define the operator $g_i(\mathbf{p})$ that transforms a probability vector $\mathbf{p}$ into a probability vector $\hat{\mathbf{p}}$

$$\hat{\mathbf{p}} = g_i(\mathbf{p}), [\hat{\mathbf{p}}]_j = \begin{cases} 0 & \text{if } j \geq i \\ \dfrac{[\mathbf{p}]_j}{\sum_{k=0}^{i-1} [\mathbf{p}]_k} & \text{otherwise} \end{cases}. \tag{17}$$

Essentially, the operator g_i transforms the probability vector $\mathbf{p} = [\mathbb{P}(S_t = s_0), \ldots, \mathbb{P}(S_t = s_{\mathcal{R}})]$ into $\hat{\mathbf{p}} = \left[\mathbb{P}\left(S_t = s_0 | S_t \in \{s_k\}_{k=0}^{i-1}\right), \ldots, \mathbb{P}\left(S_t = s_{\mathcal{R}} | S_t \in \{s_k\}_{k=0}^{i-1}\right)\right]$. The subset of possible states $\{s_k\}_{k=0}^{i-1}$ is the result of receiving a NAK when transmitting with an MCS with rate R_i. Let us denote as $\mathbf{p}_i$ the state probability distribution in the i-th transmission ($i-1$ retransmission). If the MCS to be used in the i-th transmission is r_j, then

$$\mathbf{p}_{i+1} = \mathbf{P} g_j(\mathbf{p}_i) \tag{18}$$

with $\mathbf{p}_1 = \boldsymbol{\pi}$. The error probabilities can be estimated as

$$\hat{m}_k(r_i) = 1 - \sum_{j=i}^{T} [\mathbf{p}_k]_j. \tag{19}$$

D. Statistical and Outdated CSI

If both outdated and statistical CSI are available, then the probability distribution of the state in the first transmission, given the outdated CSI $S_{t-1} = s_j$, is

$$\mathbf{p}_1 = \mathbf{P}\mathbf{e}_{j+1} \tag{20}$$

Table I: MCS evolution, 10 m/s

LOS SNR (dB)	MCS 1	MCS 2	MCS 3
Uncorrelated			
0 dB	QPSK 1/4	QPSK 1/4	QPSK 1/4
10 dB	QPSK 5/6	QPSK 2/5	QPSK 1/3
20 dB	QPSK 5/6	QPSK 5/6	QPSK 5/6
30 dB	QPSK 8/9	QPSK 8/9	QPSK 8/9
Complete statistical CSI			
LOS SNR (dB)	MCS 1	MCS 2	MCS 3
0 dB	QPSK 1/4	QPSK 1/4	QPSK 1/4
10 dB	QPSK 5/6	QPSK 1/3	QPSK 1/4
20 dB	QPSK 5/6	QPSK 3/4	QPSK 3/4
30 dB	QPSK 8/9	QPSK 8/9	QPSK 8/9

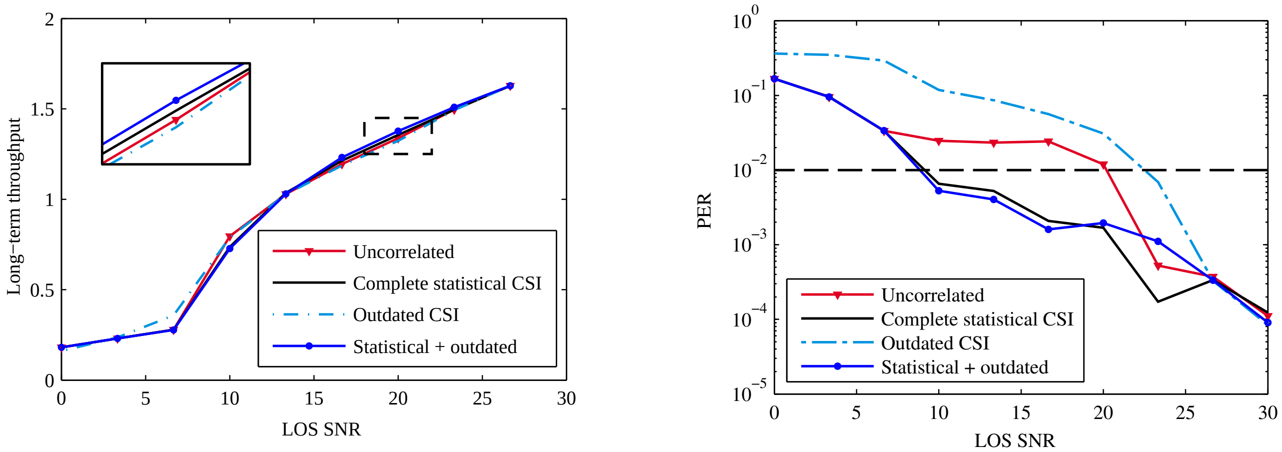
with e_i the vector of the canonical base of $\mathbb{R}^{\mathcal{R}+1}$ with a 1 in the i-th position. The probabilities for the i-th transmission, $i > 1$ can be obtained as in (18), and the error probabilities as in (19). When performing link adaptation with outdated and statistical CSI, we fixed the error probability constraint p_0 to be met for every outdated CSI value. In a more general setting, we could design $\mathcal{R}+1$ PER constraints $\bar{p}_0, \ldots, \bar{p}_{\mathcal{R}}$ such that $\sum_{i=0}^{\mathcal{R}} \pi_i \bar{p}_i = p_0$, and the MCS sequence when s_i is received as feedback is designed to meet the PER constraint $\bar{p}_i$.

V. Simulation Results

This section reports the performance obtained after simulating the different adaptation techniques. The channel's Markov chain was obtained assuming a transmission frequency $\mathbf{f}_c = 1550\,\text{MHz}$ (L band), symbol period $T_{\text{symb}} = 1/33600\,\text{s}$ and codeword length 2688 symbols. The channel corresponds to Fontan's intermediate tree-shadowed (ITS) area [10]. The MCS table is the same as in [1]. The optimization problem was solved by exhaustive search, i.e., trying all the possible MCS combinations, and choosing the one leading to a higher throughput while meeting the outage constraint.

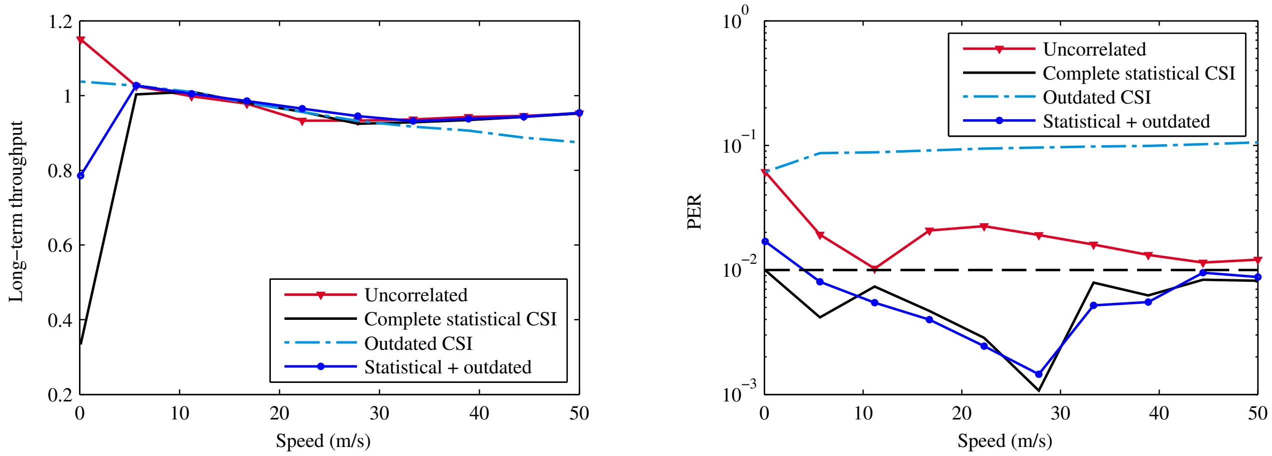
Figure 2 depicts performance, in terms of throughput and outage, as a function of line-of-sight (LOS) SNR (terminal speed is 10 m/s); Figure 3 shows the same results, but as a function of speed (with an average SNR of 13 dB). In both cases, differences are minimal in terms of throughput, but remarkable in terms of outage; in particular, only techniques with statistical CSI are able to meet the PER constraint (even though, as expected, no technique meets the constraint at low SNR). Indeed, assuming uncorrelated channel states leads to a poor outage performance except for very high speed values. Also, Table I shows some examples of optimum MCS sequences with statistical CSI, and it can be seen that different MCS per transmission are selected specially for medium values of SNR; also, it is confirmed that more optimistic MCS are selected in the uncorrelated case.

As a final remark, it is worth noticing that the exchange of ACK/NAK alone provides enough information to meet the constraint.



(a) Long term throughput (b) Outage probability

Figure 2: Simulation results for different degrees of CSIT as a function of the LOS SNR. Speed 10 m/s



(a) Long term throughput (b) Outage probability

Figure 3: Simulation results for different degrees of CSIT as a function of speed. LOS SNR = 13 dB

VI. Conclusions

In this work we have designed the optimum MCS sequence to be used in the retransmissions of an ARQ protocol operating over a time-correlated mobile satellite channel. By resorting to a one-step Markovian model of the channel, solutions for different levels of CSIT have been found. Results show that even an ACK/NAK exchange alone can provide enough information to boost the throughput while meeting an outage constraint.

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