Adaptive Coding and Modulation Techniques for Mobile Satellite Communications: a State Estimation Approach

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Abstract—In the last years we are witnessing the increasing presence of multimedia application, in a wide variety of terminals, from the PC to the notebook, from the smartphone to the tablet. In order to exploit such advanced services the requirement is to have an ubiquitous and broadband connection. While urban or suburban areas can be covered by using terrestrial wireless broadband networks, there are several rural or low populated areas with narrowband access. To this aim, satellite technologies allow to cover very large areas. However, they still have some issues in covering mobile users with broadband connections. One of the most important approaches is to develop adaptive waveforms techniques able to exploit the variable channel behavior. Adaptive coding and modulation (ACM) belongs to this family of algorithms, by adapting the modulation and coding scheme based on the channel behavior. In this paper a comparison among three different techniques is proposed by focusing on a state approach for increasing the user throughput, and considering different mobile speeds.

I. INTRODUCTION

The most recent trend in terms of communications environment is the ability of connecting to the Internet everywhere in the world with a reliable and broadband connection. While this requirement is respected in urban areas, it still remains an open issue in rural or scarcely inhabited areas where satellite communications seem to be the only viable option even if suffering broadband access, especially for mobile users. Adapting the waveform is an option for allowing a broadband access for satellite communications.

The basic idea behind waveform adaptation techniques is to select the transmission parameters to take advantage of the different channel conditions. While the fundamental parameters subject to variations are modulation and coding levels, other quantities can in principle be adjusted: power level (as in power control), spreading factor, signaling bandwidth, packet and symbol timing, subcarrier allocation.

Often in the literature this class of techniques is referred as link adaptation since the transmission parameters are adapted to the link status. Link adaptation is widely recognized as a key solution to increase the spectral efficiency of communication systems [1].

Our focus is on satellite communication systems. In this scenario the principle of link adaptation is to exploit the variations of the wireless channel (over time, frequency, and/or space) by dynamically adjusting certain key transmission parameters to the changing environmental and interference conditions observed between the transmitter and the receiver. An important indicator of the popularity of such techniques is their use in several terrestrial wireless communication standards, such as UMTS/HSPA, IEEE 802.16-2009 and IEEE 802.11n, which include link adaptation as a means to provide a higher data rate [2].

Adaptive Coding and Modulation (ACM) techniques are an option for performing the link adaptation in wireless networks [3]. ACM works by defining a set of schemes, characterized by different modulation and coding types (MODCOD); in a system that performs link adaptation by using ACM, the best MODCOD in terms of throughput maximization is selected, considering that in an environment with low SNR (i.e., poor channel conditions) it is better to use low order modulation and coding, while in high SNR environments it is better to use higher order modulation and coding.

With ACM, the power of the transmitted signal is held constant, while the modulation and coding formats are changed to match the current received signal quality. The choice of the best scheme is based on the monitoring of certain parameters related to the channel state information in order to adapt the modulation and coding schemes. The information to be monitored can include a great variety of parameters; each communication system is more vulnerable to some parameters, and has to take into account them in a specific way.

In the literature several papers have been proposed regarding the ACM, by focusing their attention on cellular systems [4], on OFDM communication systems [5], on WiMAX based systems [6], or by considering Markov chain based approaches [7]. Also the more general link adaptation topic has been considered in the literature by focusing on cellular system [1], or on the TETRA/TEDS system [8]. As for the satellite communication, it is worth to notice that [9] studies in depth the ACM problem; here we propose a novel scheme where multiple parameters are taken into account for...
improving the system efficiency in terms of throughput.

II. SYSTEM MODEL

Our focus is on a two-way mobile satellite system, where both forward and reverse links will be taken into account with the aim of adapting their transmission waveforms to the changing channel behavior in order to optimize the system performance. The system parameters that we will consider are:

- Satellite Orbit: GEO
- Band: S
- Duplexing: FDD
- Forward Link Frequency: 2 GHz
- Reverse Link Frequency: 2.2 GHz
- Channel: Intermediate Tree Shadowed Area [10], [11]
- Elevation: 40°
- DVB-S2 Codeword Length: 16200 [12]
- Modulation: QPSK, 8PSK, 16APSK, 32APSK
- Coding Rate: (1/4), (1/3), (2/5), (1/2), (3/4), (2/3), (3/4), (4/5), (5/6), (8/9), (9/10)

It is worth to notice that, even if we will work on the S-band, we will consider the DVB-S2/DVB-RCS as the reference systems for the framing structure. With reference to this the combinations of modulation and coding is limited to those schemes used in this standards, and reported in Tab. I; we consider in the following only the forward link leaving to a companion paper the reverse link adaptation. The thresholds defined in the table refer to the Quasi Error Free MODCOD selection, i.e., having a BER = 10^{-5}, and they will be used in the following in the ACM algorithms evaluation: in bold there are those MODCOD used in the Section IV as a comparison with the adaptive techniques.

<table>
<thead>
<tr>
<th>Threshold (dB)</th>
<th>Modulation and Coding Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.5</td>
<td>QPSK 1/4</td>
</tr>
<tr>
<td>-1.4</td>
<td>QPSK 1/3</td>
</tr>
<tr>
<td>-0.5</td>
<td>QPSK 2/5</td>
</tr>
<tr>
<td>0.9</td>
<td>QPSK 1/2</td>
</tr>
<tr>
<td>2.1</td>
<td>QPSK 3/5</td>
</tr>
<tr>
<td>3.0</td>
<td>QPSK 2/3</td>
</tr>
<tr>
<td>3.9</td>
<td>QPSK 3/4</td>
</tr>
<tr>
<td>4.6</td>
<td>QPSK 1/4</td>
</tr>
<tr>
<td>5.1</td>
<td>QPSK 5/6</td>
</tr>
<tr>
<td>5.7</td>
<td>8PSK 3/5</td>
</tr>
<tr>
<td>6.1</td>
<td>QPSK 8/9</td>
</tr>
<tr>
<td>6.6</td>
<td>8PSK 2/3</td>
</tr>
<tr>
<td>7.9</td>
<td>8PSK 3/4</td>
</tr>
<tr>
<td>8.9</td>
<td>16APSK 2/3</td>
</tr>
<tr>
<td>9.3</td>
<td>8PSK 5/6</td>
</tr>
<tr>
<td>10.1</td>
<td>8PSK 8/9</td>
</tr>
<tr>
<td>10.9</td>
<td>16APSK 3/4</td>
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<tr>
<td>11.0</td>
<td>16APSK 4/5</td>
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<tr>
<td>11.5</td>
<td>16APSK 5/6</td>
</tr>
<tr>
<td>12.6</td>
<td>32APSK 3/4</td>
</tr>
<tr>
<td>12.8</td>
<td>16APSK 8/9</td>
</tr>
<tr>
<td>13.6</td>
<td>32APSK 4/5</td>
</tr>
<tr>
<td>14.1</td>
<td>32APSK 5/6</td>
</tr>
<tr>
<td>15.5</td>
<td>32APSK 8/9</td>
</tr>
</tbody>
</table>

The properly modeled signal at the receiver can be expressed as:

\[
r(t) = \Re \left\{ \sum_{n} \alpha_n(t) e^{-j2\pi(f_c-f_d)\tau_n(t)} s(t - \tau_n(t)) \right\} e^{j2\pi f_c t} + n(t) \tag{1} \]

where \(\gamma\) is the transmission power introduced by the transmitting end, \(\alpha_n(t)\) is the attenuation factor of the \(n\)-th path, \(f_d\) is the Doppler frequency (or fading bandwidth), \(\tau_n(t)\) is the delay of the \(n\)-th path, \(n(t)\) is the AWGN.

The aim is to consider the behavior of the received signal in order to adapt \(s(t)\) by changing its parameters in terms of MODCOD in order to maximize the throughput at the receiver end. Even if the problem has been extensively explored in terrestrial wireless communications, it still remain an open issue in mobile satellite communications, mainly due to the very high round trip time (RTT) that does not allow to implement any effective feedback technique for sending back the channel state information (CSI) to the transmitting end.

III. ACM TECHNIQUES

The waveform adaptation aims to optimize some specific parameters of the transmitted signal in order to respect some QoS constraints by following the channel behavior. In particular, among other waveform adapting parameters, we focus our attention on the modulation and coding order, by aiming to select at each transmission instant the best combination for the given QoS requirements. We consider those parameters to be estimated and considered for the MODCOD selection. Such parameters can be exploited in open or closed loop algorithms.

Among others, we consider the following parameters:

- **SNR/SNIR** - The Signal-to-Noise Ratio or the Signal-to-Noise plus Interference Ratio take into account the ratio between the received signal power and the noise (and the interference). It is quite simple to be estimated; however, in mobile channels, affected by fast and slow fading, could incur in very vast variations;
- **RSSI** - The Received Signal Strength Indication allows to have information on the received power. It does not consider the noise as separate (as for the SNR/SNIR indicator). It is very simple to be implemented, however it suffers of the same problem of the SNR/SNIR estimator in terms of high variability;
- **Rice factor** - The Rice factor is a channel behavior measure that consider the variation of the Rice modeled channel. The three states channel model [10], [11] considered in this work is based on the widely known Rice model. The Rice factor is less variable respect to the other parameters, however it is difficult to be directly connected with specific MODCODs;
- **Doppler frequency** - The Doppler frequency (or fading bandwidth) is directly related to the relative speed between the transmitter and the receiver.
• BER/PER/FER - The error probability can be expressed in terms of Bit Error Rate, or Packet Error Rate, or Frame Error Rate and can be evaluated by exploiting some known fields at the receiver such as the preamble/midamble/postamble or pilot symbols. Even if very simple, the error rate tracking is not reliable in fast varying channels due to its inherit latency.

In our case the transmitted signal \( s(t) \) is function of:

- Modulation scheme
- Coding rate
- Power

In order to have a reliable ACM algorithm we search for those parameters that are almost constant in a RTT window, i.e., remaining within a certain usage interval for the selected MODCOD. It is evident that the constant attribute is also influenced by the number of MODCODs and their applicability intervals. Hence, we have to map the value of the considered parameter to a specific MODCOD. The coupling has to be done properly by considering also the target QoS value. On one hand the reduction of the amount of MODCODs allows to remain in the same scheme for a longer period of time thus reducing the outage probability. On the other hand such an approach could reduce the achievable maximum efficiency, with the trivial case when only one scheme is selected, thus reducing to a fixed modulation and coding environment.

In the following we have considered three approaches. In the first, named Instantaneous Channel State Information we consider to exploit a CSI value instantaneously estimated at the transmitter or the receiver, depending on the open or closed loop algorithm. As a second option we aim to estimate the state in which a communication is, where the state is that defined in the Three States channel model [10], [11]: we consider to assign one MODCOD to each state and use it when the estimated channel is within that state. Finally we consider to refine the state selection scheme by implementing a two step adaptation algorithm, as a nested states scheme: in the first step we estimate the channel state, while at the second step we aim to refine the MODCOD selection based on a second parameter estimation among those above defined.

A. Instantaneous Channel State Information algorithm

In the instantaneous CSI we consider to have an instantaneous information about the channel state. We have considered both closed and open loop approaches. The difference is in terms of delay and considered channel information. If on one hand the closed loop allows to have a more precise information about the channel state, it suffers a very high delay. On the other hand the open loop allows to reduce the delay to about one half (excluding other delays non directly depending to the transmission time), with the disadvantage of estimating the channel on the opposite link. In this case the last estimated CSI value is used for selecting the MODCOD to be sent at a certain time instant; we suppose to track continuously the channel.

B. State estimation algorithm

As a second option, we have considered to estimate the state in which the channel is. As said previously, the channel model we are considering can be represented by three states [10], [11]. Each state represents a specific environmental situation in terms of shadowing conditions. The idea is that we can associate one single MODCOD scheme to each state; the difference respect to the instantaneous estimation is that using a state estimation the probability of remaining within the same usability interval for a specific MODCOD is higher, thus decreasing the outage probability. Moreover, by using a state estimation we can also consider to use an open loop estimation that, even if not estimating perfectly the CSI, allows to reduce the delay to about one half. Indeed, the forward and reverse channels can be considered identical from the shadowing caused by obstacles, while they differs in terms of scattering and the multipath fading. To this aim estimating the state on one link corresponds to an optimal estimation of the state for the opposite link.

When estimating the states we average the CSI by considering an averaging interval equal to \( L_{corr}/s \), where \( s \) is the mobile speed for that scenario and \( L_{corr} = 4.5 \text{ m} \), is the correlation length of very slow variations causing the state transitions.

Our problem is then modeled in two main steps: we have to define a method for a reliable estimation of the state and we have to assign to each state a specific MODCOD.

Concerning the state estimation, we consider an hysteresis interval, with an amplitude equal to the variance of the shadowing process characterizing each state, so that we select the upper state only if the lower threshold of that state is exceeded, while the lower state is selected if the upper threshold of that state is overcome.

Concerning the MODCOD to be used within a certain state we have to introduce a parameter that relates the CSI at the receiver and the transmitter; we have considered the impact of the difference between the estimated and the received CSI, by introducing the variable \( \Delta(t) \). We can define:

\[
\Delta(t) = \bar{\text{CSI}}(t - d) - \text{CSI}(t)
\]

(2)

where \( \bar{\text{CSI}} \) and CSI are, respectively, the estimation and the effective selected CSI parameter. In case of open loop, CSI corresponds to the CSI at the transmitter, while CSI is the CSI at the receiver. Finally, \( d \) is the delay between the estimation and the effective CSI, corresponding to RTT in case of closed loop and RTT/2 in case of open loop technique.

The behavior of (2) can be exploited by considering a margin \( \Delta \) related to \( \Delta(t) \) during the selection of a MODCOD. By noticing that there is a biunique correspondence between a MODCOD and a threshold, we select the MODCOD that allows to have a difference between the estimated CSI and the threshold higher than \( \Delta \), i.e., we select the higher order MODCOD respecting:

\[
\bar{\text{CSI}}(t - d) - \text{th}(\text{MODCOD}_i) > \Delta
\]

(3)
where \( \text{th}(\text{MODCOD}_i) \) is the threshold for the \( i \)-th MODCOD as defined in Tab. I. This allow to have a safety margin in relation with the channel behavior, thus minimizing the probability of selecting a MODCOD with a threshold over the CSI.

The algorithm is represented in Fig. 1, where it is possible to see the selection of the state based on the channel information. The algorithm is repeated at each received frame.

**C. Nested States algorithm**

As a further step we consider to integrate the adaptive approach of state selection with a finer selection of MODCOD by using the estimation of additional parameters. The overall idea is that we can have a first rough estimation of the MODCOD based on state estimation. The additional parameter can be used to vary the selection of the MODCOD by limiting to the nearer MODCOD schemes. Whenever the status estimation inform that the status is changed, this would be done accordingly, and again the refinement on the selected MODCOD is done within the new state.

When estimating the nested states we average the CSI by considering an averaging interval equal to \( L_{\text{corr}}^2/s \), where \( s \) is the mobile speed and \( L_{\text{corr}}^2 = 1.5 \) m is the correlation length of the shadowing variations due to the scattering effects. This value is lower respect to the state estimation value above defined, allowing to track more precisely the faster variations within the states.

In Fig. 2, there is a representation of such approach, where we consider to switch from one state estimation to one other. We associate one main MODCOD to each state. Further approximations are done within that state based on secondary parameters (in this figure we limit this to the previous and successive MODCOD only for visual clarity). The previously introduced State estimation algorithm considers only the transition among states.

The algorithm is represented in Fig. 3, where it is possible to see the selection that is done in multiple step by considering the three correlation lengths. The algorithm is repeated at each received frame.

**IV. Numerical results**

In this section we will show the numerical results obtained by computer simulations. The system parameters have been already introduced in Section I; the computer simulations have been performed by varying the mobile speed at ground, by selecting a pedestrian (1 m/s), a slow vehicular (15 m/s) and a fast vehicular (40 m/s) scenario. For space constraints, we do not consider here the closed loop technique. This is also justified by the fact that closed loop introduces a very long delay between estimation and usability of a certain parameters, thus it can be considered as unfeasible.

In this paper we focus our attention on forward link, leaving the return link to a companion paper. As for the tracked parameter, we focus in this paper on the RSSI and the Rice factor for estimating the channel behavior; however, the proposed techniques is more general and it is now under study the exploitation of different parameters at the same time for increasing the adaptation techniques. While the RSSI is used for the state estimation, the Rice factor, and again the RSSI, are used for the state refinement on the Nested States algorithm.

We have also considered a variable transmission power, respect to the average channel attenuation, from 0 dB to 20 dB with steps of 5 dB.

The performance has been evaluated in terms of throughput, mismatching and outage. The throughput has been evaluated by comparing the performance of the three above described algorithm with some Fixed Coding and Modulation and with a *Genie Aided* case. The Genie Aided is defined as that ideal algorithm that allows to know ideally and perfectly the best MODCOD to be used, due to perfect knowledge of the CSI at the receiver at the same timing instant the signal is received. This is an ideal hypothesis, but we can use it as an upper bound for performance evaluation. Concerning the comparison with fixed MODCOD, due to clarity in the figures, we have limited the comparison to those schemes in bold in Tab. I.

The mismatching is defined as the probability of selecting a MODCOD different from that selected by the Genie Aided algorithm; moreover, a loose mismatching has been also defined by considering the probability to select a MODCOD with a higher index respect to the Genie Aided. In this case we consider that a MODCOD with a lower index allows to have a reliable transmission even if not optimizing the throughput, so that even if the mismatching is high, a low loose mismatching value allow to have a reliable transmission.

The outage is defined as the probability that the system cannot transmit with any MODCOD because it is under the lowest threshold.
In Fig. 4 we report the state estimation effectiveness for the slow vehicular environment. Similar behavior can be seen for the other two environments. We compare the behavior of the estimated states respect to the channel behavior at the receiver. It has to be noted a general agreement between state estimation and channel behavior, except for a timing shift representing the transmission delay. According to [10], [11], state 1 represents the LOS state, state 2 the moderate shadowing, and state 3 the deep shadowing.

In Fig. 5 the performance in terms of throughput is reported by comparing the Genie Aided, with the Instantaneous CSI and the State Estimation for variable values of the transmission power. It is possible to see that the state algorithm outperforms the simple Instantaneous CSI algorithm.

We have then considered the behavior of $\Delta(t)$ as defined in (2). Due to the open loop scenario and the transmission delay the two channels do not corresponds. The evaluation of the behavior of $\Delta(t)$ is depicted in Fig. 6, limited for space constraints to the slow vehicular environment; similar behavior can be seen also in the other two environments. The histogram of the occurrences of $\Delta(t)$ is reported; it is possible to see that the difference is for the most of the time within 5 dB.

In Fig. 7, we have varied the value of $\bar{\Delta}$, defined as the margin to be considered when selecting a certain MODCOD in order to have a safety margin. The performance is evaluated by fixing the value of the transmission power to 10 dB. It is possible to see that the chosen value has a great impact in terms of performance. In particular, we can see that there is an optimal value of $\bar{\Delta}$ around 2 dB, where the performance is maximized; increasing the value incurs in lower performance, due the fact that higher values of $\Delta$ implies the selection of a lower order, thus less efficient, MODCOD while lower values increases the error probability. We have reported here for space constraints only the case performance for the slow vehicular environment; similar behavior is obtained for the other two environments.

We have then fixed $\bar{\Delta}$ to 2 dB for maximizing the throughput and introduced the the Nested States algorithm, by considering as a further step the behavior of the RSSI and the Rice factor. To this aim we consider to switch to the higher or lower MODCOD if the RSSI/Rice factor differs by 2 dB respect to the value at the previous fast fading correlation length, that is $L_{\text{corr}} = \frac{3}{8} \lambda$, where $\lambda = \frac{c}{f}$ is the wave-length for the forward link. It is possible to see that by considering an optimized value of $\Delta$ the performance for the States algorithm is increased, and that by considering a further adaptation with the nested states

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**Fig. 2.** System model for the nested state algorithm with secondary parameter refinement.

**Fig. 3.** Nested states algorithm for MODCOD selection.

**Fig. 4.** State estimation versus forward channel behavior for the slow vehicular environment.
algorithm the performance are even more increased, even if the difference between the nested with RSSI and Rice factor is very small. Moreover we can see that the algorithm allows to obtain better performance respect to the fixed MODCOD for slow speed environments; this is as expected because, when the speed at the ground terminal increases also the states variability increases resulting.

Finally we have considered the outage and mismatching probabilities, as defined in the previous, in Figs. 9 and 10. By comparing the three proposed algorithms in terms of outage it is possible to see that the States and Nested states algorithms have similar performance between the Genie aided and the Instantaneous CSI and, as expected, higher values of transmission power allow to decrease the outage. Concerning the mismatch we can see that, even if the mismatch itself is high, the loose mismatch it is much lower. We can highlight that the state estimation algorithm is more conservative respect to the other, but, as seen in Fig. 7, at the cost of a lower throughput.
Fig. 8. Performance in terms of throughput with $\Delta=2$ dB and variable transmission power.

Fig. 9. Outage probabilities with variable transmission power.
V. Conclusion

The demand for higher broadband access is a necessity for most modern services. However, even if in expansion, terrestrial wireless technologies cannot cover all the areas, especially rural or less populated areas. Satellite Communications can cover very large areas, allowing also to cover all the world surface with a limited number of satellites; the counter effect is its actual performance when considering broadband access. In this paper, we have considered the problem of designing adaptive waveform techniques for mobile users, by focusing the attention on ACM techniques. We have proposed three algorithms, performing an instantaneous, state based and nested state based approaches for improving the throughput. Numerical results shows that the proposed approaches allow to increase the performance respect to the fixed case even if the SatCom environment still represents a challenging scenario.

References