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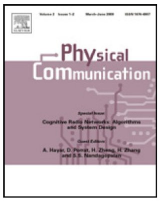

Full length article

Performance analysis of SNR threshold-setting strategies for adaptive modulation and coding under fading channels

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ABSTRACT

Adaptive Modulation and Coding (AMC) is a popular technique that dynamically adapts the employed Modulation and Coding Scheme (MCS) to the instantaneous channel quality, typically expressed in terms of the instantaneous Signal-to-Noise Ratio (SNR). The optimum MCS is selected based on a set of SNR thresholds, which define the range of SNR values on which each MCS is employed. The calculation of the SNR thresholds is a key aspect in the design and performance of AMC. This work performs a detailed and rigorous analysis of SNR threshold setting strategies for AMC, not only considering conventional methods commonly used in the literature but also proposing new methods to attain specific performance targets in terms of error rate, delay and spectral/energy efficiency. Closed-form expressions for these performance metrics are analytically derived under Rayleigh fading and employed to comparatively assess the performance of the considered solutions. The obtained results demonstrate that the proposed SNR threshold setting methods provide significant improvements in terms of error rate, delay and spectral/energy efficiency with respect to traditional methods.

1. Introduction

Wireless communication systems typically feature several Modulation and Coding Schemes (MCS) in order to provide varying levels of resilience to transmission errors under different radio propagation conditions and consequently adapt the transmission data rate. Each MCS is characterised by a different trade-off between data rate and error protection, which is determined by the modulation type and order, and the amount of redundant information introduced by the channel coding scheme. The employed MCS is dynamically adapted to the instantaneous channel quality in order to optimise the system performance: MCS with little or no error protection are used when the channel quality is favourable, while MCS with extra error protection are selected under poor channel quality conditions. This technique, referred to as Adaptive Modulation and Coding (AMC), has been adopted by several wireless communication technologies, including cellular mobile communication systems such as EDGE [1], HSDPA [2] and LTE [3,4], wireless local [5–7], personal [8–10] and broadband [11,12] area networks (IEEE 802.11/15/16) as well as satellite communication networks [13,14], to mention some examples.

The method employed to select the optimum MCS is a key aspect in the design and performance of AMC. Existing methods can broadly be classified into two categories. The first category includes methods that adapt the employed MCS to the real-time variations of a certain performance metric (e.g., short-term error rate or throughput) with the aim to achieve a predefined performance target (e.g., long-term error rate or throughput) [6,15,8,9,2]. The second category, where the focus of this work lies, embraces methods that adapt the employed MCS to the instantaneous value of a certain link quality metric, typically the instantaneous Signal to Noise Ratio (SNR). The optimum MCS is selected by comparing the instantaneous SNR to a set of SNR thresholds that determine the range of SNR values where each MCS is employed. In this type of methods the criterion employed to compute the SNR thresholds has an important impact on the resulting AMC performance. A criterion commonly used in the literature is to select the SNR thresholds so as to maximise the throughput [16,11,12,15,2]. This criterion, however, may sometimes result in high error rates and therefore in a high number of retransmissions, thus leading to a degraded performance for delay-sensitive services. To avoid frequent retransmissions, a common alternative criterion is to maximise the throughput subject to a maximum target error rate [1,11,15,17]. Other delay-oriented methods recompute the SNR thresholds for each transmitted packet based on the packet size and reception deadline in order to optimise the delay performance [18,19,15]. The maximisation of the user quality of experience (e.g., the image quality of video services [20]) has also been proposed. More recently, some investigations have included energy efficiency aspects into SNR threshold selection criteria [21,22,10].

While AMC has received a great deal of attention, the performance of SNR threshold-setting methods for AMC has not received

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to date a unified, formal and rigorous treatment where fundamental methods are analysed and compared under a common unified framework. Many theoretical results lack of sufficient practical applicability in the design and performance evaluation of real wireless communication systems. For instance, a commonly used approach for the analysis of AMC under fading channels is to employ the Shannon capacity [23], or a modified version thereof [24,25], as a model for the transmission data rates. The expressions thus obtained are of theoretical value and can provide interesting insights but can hardly be employed to predict the actual performance of real systems since the particular features of individual MCS cannot be captured by such models. By contrast, some other studies have provided more detailed and realistic models. For example, throughput performance models are obtained analytically in [26] for AMC under log-normal shadow fading, in [27] for maximum ratio combining receivers with AMC under Rice fading correlated channels, and in [28] for a broader set of fading models including Rayleigh, Nakagami-m, Nakagami-q (Hoyt), Nakagami-n (Rice), η-μ and κ-μ. However, the developed models have not been employed to comparatively evaluate the performance of existing SNR threshold-setting methods along with their merits and shortcomings. Moreover, as it will be shown, traditional methods commonly used to compute the SNR thresholds are in general unable to meet certain performance requirements, or are able to do so to a limited extent.

In this context, this work performs a detailed and rigorous performance analysis of SNR threshold-setting strategies for AMC. Based on a technology- and service-agnostic approach (i.e., without considering particular features of specific radio technologies or services, and abstracting them wherever required), this work reviews the fundamental methods for the calculation of SNR thresholds and proposes new strategies to effectively and more accurately achieve specific performance targets in terms of error rate, delay and spectral/energy efficiency. Moreover, closed-form expressions for these performance metrics are analytically derived and employed to comparatively assess the performance of existing and proposed SNR threshold-setting methods. The following contributions are provided by this work:

1. A generic model for the error performance of MCS under AWGN is proposed. As opposed to existing models, which have been envisaged for either analytical tractability or practical accuracy, the proposed model not only is analytically tractable but also reproduces with remarkable accuracy the actual error rate of MCS from real wireless communication systems.
2. Fundamental SNR threshold-setting methods commonly used in the existing literature are formulated analytically under a common technology- and service-agnostic unified framework.
3. Novel SNR threshold-setting methods envisaged to accurately meet specific performance targets in terms of error rate, delay and spectral/energy efficiency are proposed as well.
4. Closed-form expressions for the average error rate, delay and spectral/energy efficiency of SNR threshold-setting methods under fading channels are derived analytically.
5. The performance of the considered SNR threshold-setting strategies is assessed and comparatively evaluated under fading channels, highlighting their benefits, costs, advantages and drawbacks.

The rest of this work is organised as follows. First, Section 2 presents the considered system model. A generic model for the error performance of MCS under AWGN is proposed in Section 3. Based on this model, closed-form expressions for the error rate, delay and spectral/energy efficiency are analytically derived in Section 4. Existing and new SNR threshold-setting methods are formulated in Sections 5 and 6. The performance of the considered methods is comparatively assessed in Section 7, where numerical results obtained with the developed analytical models are presented and analysed. A discussion on the extension to specific radio technologies is provided in Section 8. Finally, Section 9 summarises and concludes this work.

2. System model

Let N denote the number of MCS available in the considered wireless communication system. Each MCS can be characterised by two properties: $\varepsilon_n(\gamma)$, which represents the error rate at the bit (BER), symbol (SER), block (BLER), packet (PER) or frame (FER) level of the nth MCS as a function of the instantaneous SNR γ; and R_n, which represents the gross data rate of the nth MCS (i.e., the total amount of information bits transmitted per time unit). MCS are indexed such that $R_n < R_{n+1}, n = 1, \dots, N-1$.

The employed MCS is dynamically adapted to the instantaneous SNR based on a set of SNR thresholds $\{\gamma_n^{th}\}_{n=1}^N$, which define the range of values of γ on which each MCS is used. The nth MCS is selected whenever $\gamma \in [\gamma_n^{th}, \gamma_{n+1}^{th})$, except for the Nth MCS which is used in the interval $\gamma \in [\gamma_N^{th}, \infty)$.

An SNR threshold-setting method is defined as a method to compute the values $\{\gamma_n^{th}\}_{n=1}^N$ based on $\varepsilon_n(\gamma)$, R_n, and possibly other parameters, according to a predefined criterion. Two types of methods are distinguished in this work: *unconstrained* methods ($\gamma_1^{th} = 0$) which always select an MCS for the current SNR value no matter how low it is, and *constrained* methods ($\gamma_1^{th} > 0$) which allow transmission only when the instantaneous SNR is above a *cut-off* threshold γ_1^{th}. The latter approach prevents the transmission of users under extremely poor channel quality conditions (who might not benefit from transmitting) so that other users in better conditions can exploit the available radio resources more efficiently.

3. Model for the error performance of MCS

The bit and symbol error probabilities of modulation schemes under AWGN are well known from the theory of digital communication systems. The error probabilities for groups of bits such as blocks, packets or frames, which quantify more accurately the actual performance experienced by the user at higher layers, can be approximated by the probability of receiving at least one bit in error [29]. However, the introduction of channel coding techniques to increase the robustness against transmission errors complicates the analytical derivation of closed-form expressions for the error probabilities of MCS. As a result, a common approach is to fit a mathematical model to the exact curves $\varepsilon_n(\gamma)$, which are typically obtained by means of simulations.

Some proposed approximations can be easily manipulated in analytical studies but fail to provide a practical level of accuracy over the whole range of SNR values [30, eq. (3)], [31, eq. (5)]. Other approximations are accurate but difficult to manipulate in analytical studies [32, eq. (5)]. To overcome this drawback, the following model is here proposed:

$$\varepsilon_n(\gamma) = \mathcal{Q}(\alpha_n \gamma - \beta_n) \tag{1}$$

where $\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-z^2/2) dz$ is the Gaussian Q-function and $\alpha_n > 0$ and $\beta_n > 0$ are MCS-specific fitting coefficients. As a part of this work, the model in (1) was fitted to the BLER-versus-SNR curves[1] of the LTE system provided in [33, Fig. 5] and a maximum absolute error of less than 1% was observed. Thus, the proposed model not only provides the desired analytical tractability but also sufficient accuracy.

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[1] The expression in (1) may also be fitted to similar curves available in the literature for other error metrics such as BER, SER, PER, FER, etc.