Cross-Layer Designed Adaptive Modulation Algorithm with Packet Combining and Truncated ARQ over MIMO Nakagami Fading Channels

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***Abstract*—This paper presents an optimal adaptive modulation (AM) algorithm designed using a cross-layer approach which combines truncated automatic repeat request (ARQ) protocol and packet combining. Transmissions are performed over multiple-input multiple-output (MIMO) Nakagami fading channels, and retransmitted packets are not necessarily modulated using the same modulation format as in the initial transmission. Compared to traditional approach, cross-layer design based on the coupling across the physical and link layers, has proven to yield better performance in wireless communications. However, there is a lack for the performance analysis and evaluation of such design when the ARQ protocol is used in conjunction with packet combining. Indeed, previous works addressed the link layer performance of AM with truncated ARQ but without packet combining. In addition, previously proposed AM algorithms are not optimal and can provide poor performance when packet combining is implemented. Herein, we first show that the packet loss rate (PLR) resulting from the combining of packets modulated with different constellations can be well approximated by an exponential function. This model is then used in the design of an optimal AM algorithm for systems employing packet combining, truncated ARQ and MIMO antenna configurations, considering transmission over Nakagami fading channels. Numerical results are provided for operation with or without packet combining, and show the enhanced performance and efficiency of the proposed algorithm in comparison with existing ones.**

***Index Terms*—Cross-layer design, adaptive modulation, packet combining, truncated ARQ, packet loss rate, MIMO.**

I. Introduction

In recent years, cross-layer design approach has been receiving increasing attention in the wireless research community [1]–[5]. Such design consists in an optimization based on the interdependency between different techniques at the different layers of the protocol stack, and is generally implemented by means of adaptive modulation algorithms such as in [1]–[3]. In the latter works, the focus was on the implementation of other physical and link layer techniques in addition to adaptive modulation, such as truncated automatic repeat request (ARQ) [6], where the number of retransmissions per packet is limited as opposed to being unbounded as in standard ARQ protocols, and multiple-input multiple-output (MIMO), however, optimization of the considered adaptive modulation algorithm was neglected.

Furthermore, works in this context consider very simple schemes for the mapping of the signal-to-noise ratio (SNR) into a modulation level [1], [3], or focus on the optimization of the combining of packets at the receiver [7], [8]. The SNR-to-modulation mapping consists in selecting SNR delimiters on which the modulation level changes in order to satisfy the required quality of service (QoS). Actually, this mapping plays a major role and can significantly degrade the overall transmission performance if not selected carefully. Indeed, in [1] and [2], the mapping is based on packet loss rate (PLR) models that suppose additive white Gaussian noise (AWGN) and do not take into consideration the fading. The work in [3], on the other hand, takes into account the fading distribution and tries to achieve the maximum allowed PLR, which is not necessarily the optimal choice to maximize the average spectral efficiency (ASE) of the system.

In this paper, in stark contrast to existing works, we propose an adaptive modulation (AM) algorithm which considers a general scenario where the SNR-to-modulation mapping can be different from a transmission to another. Indeed, with the use of truncated ARQ protocols, selecting the same mapping for all transmissions of a packet is not necessarily the optimal solution for maximizing the ASE under PLR constraint. In fact, the mapping depends on the frame structure and whether packet combining is implemented in the communication system or not. Herein, we consider that retransmissions of a packet do not necessarily use the same modulation format as in the initial transmission and that packet combining is implemented at the receiver. Copies resulting from several transmission attempts of a packet are combined together at the bit level rather than at the symbol level using log-likelihood ratios (LLRs) to describe bits' correctness. The PLR for such type of packet combining is complex to formulate [9]. Hence, by means of a novel PLR modeling proposed herein, we present a new flexible and easy way to analyze the cross-layer designed algorithm, for operation with and without packet combining. Specifically, through exponential modeling of the the PLR, key performance metrics, namely, average PLR and ASE, are used in the optimization problem under study and in the performance analysis. Furthermore, performance evaluation of the proposed scheme is provided along with comparisons to two popular AM algorithms, considering 10^{-2} as the maximum value for the allowable PLR, which is suitable for multimedia traffics. In particular, it is shown that using a simple SNR-to-modulation mapping has a very negative effect on performance, whereas the scheme proposed in this paper yields enhanced performance when operating whether with or without packet combining.

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In detailing the aforementioned contributions, the remaining of this paper is structured as follows: Section II describes the system model and main modules. In Section III, we detail the proposed PLR model. Development of the performance metrics and the proposed optimal AM algorithm are provided in Section IV. Performance evaluation and comparisons are then presented in Section V, followed by the paper's conclusion in Section VI.

II. System and Channel Models

In the communication system under consideration, frame-by-frame transmission is adopted, with each frame composed of a number of packets. The packet and frame structures used are the same as in [1]. Packet and frame sizes are fixed and equal to $N_{\rm b}$ bits and $N_{\rm f}$ symbols, respectively. After each frame transmission, channel quality signaling is sent by the receiver to the transmitter in the form of an SNR value which is then mapped by the transmitter into a modulation level n of the quadrature amplitude modulation (2^n-QAM) suitable for the next frame transmission and with the aim to satisfy the required QoS in terms of PLR. Further, we consider slow fading channels and assume perfect estimation of the SNR at the receiver with ideal feedback to the transmitter.

Packets in the same frame can be received either correctly or with error. In the latter case, the receiver sends the indexes of the erroneously received packets to the ARQ controller at the transmitter. The latter then determines the number of packets[1] that can be carried out by the next frame to be transmitted: $N_{\rm pkt} = nN_{\rm f}/N_{\rm b}$. In addition to the indexes of the packets to be retransmitted, the ARQ controller sends to the packet controller the number of new packets that can be added and carried on the next frame. We consider that the number of packets to be retransmitted is small enough so that all of them can be included in the next frame transmission even if the modulation level changes. To prove the validity of this assumption, let's suppose the extreme case when the difference between the modulation levels used for two consecutive frame transmissions is equal to two, for instance, the initial frame transmission uses 16-QAM while the following one uses 4-QAM. In such case, we are able to retransmit all the erroneously received packets, pertaining to the initial frame transmission, on the same next frame transmission even if the PLR is high, e.g., 0.25. In practice, the PLR is required to be much less than this value, e.g., around 0.01. Therefore, the assumption is valid in realistic scenarios. A packet is retransmitted until it is correctly received or that the maximum number of transmissions $N_{\rm arq}$ is reached, in which case the packet is considered lost and get purged at the receiver and the transmitter.

A frame is composed of retransmitted and new packets. Hence, if we consider different SNR-to-modulation mappings for the first transmission and subsequent retransmissions of a packet, i.e., different SNR delimiters on which the modulation level changes, we can have an SNR value for which a modulation level n must be used for new packets and a different modulation level n' must be utilized for packets to be retransmitted. This cannot be implemented because all packets are carried on the same frame with a single modulation level. Thus, from this simple analysis we can conclude that, due to the considered frame structure, all packet transmissions must use the same SNR-to-modulation mapping.

Each frame is then forwarded to the space-time block coding (STBC) module. SBTC is the most attractive MIMO technique for current and future wireless networks, such as sensor networks, because of its processing simplicity which induces very low power consumption at the transmitter and the receiver, in addition to its good performance in terms of spectral efficiency [10], [11]. In this paper, STBC with code rate $R_{\rm c}$ is used over MIMO configuration with $N_{\rm T}$ transmit antennas and $N_{\rm R}$ receive antennas, which can be modeled by an equivalent single-input single-output (SISO) model. We consider that each link between an antenna at the transmitter and another at the receiver is affected by slow Nakagami-m fading. However, the same analysis presented herein can be applied for other fading scenarios such as those presented in [12].

The SNR $\gamma^{\rm STBC}$ of the equivalent SISO model follows a Gamma distribution given by [2]

$$p_{\gamma^{\rm STBC}}(\gamma) = \frac{\gamma^{m\mathcal{K}-1}}{\Gamma(m\mathcal{K})}\left(\frac{mN_{\rm T}R_{\rm c}}{\overline{\gamma}}\right)^{m\mathcal{K}} \exp(-\frac{mN_{\rm T}R_{\rm c}\gamma}{\overline{\gamma}}), \tag{1}$$

where $\mathcal{K} \triangleq N_{\rm T}N_{\rm R}$ and $\overline{\gamma}$ is the average SNR per receive antenna.

At the receiver side, frames are space-time decoded and then demodulated. Individual packets are forwarded to the packet combining module. Here, the PLR expressions are complex because of the many considered transmission techniques and cannot be used as a tool in the design of the AM algorithm [9]. Next, we propose a new and simple PLR model where all the physical and link layer techniques under consideration are taken into account.

III. Packet Loss Rate Modeling

The maximum on the PLR value at the link layer is equivalent to the maximum packet error rate (PER) value at the physical layer. The relationship between the PLR and the PER depends on the techniques used. Hence, by modeling the PER for different modulation levels, we can deduce the equivalent PLR model. Instead of using exact PER formulas corresponding to transmission over AWGN channels [9], the analysis can be simplified using a well-fitted approximation of the PER similar to what was done in previous works [1]–[3]. However, contrary to previous approaches where the PER model is defined by an exponential function with two modulation-dependent coefficients, we use an exponential function with: (i) a coefficient that is modulation-dependent; (ii) another coefficient determined by the packet size only. This is well suited to our analysis which considers the combining of packets which were not necessarily transmitted using the same modulations as will be presented hereafter.

The PER model in AWGN channel[2] is defined by

$$PER_n(\gamma) = \min\left(1, P_n^{\rm DoI}(\gamma)\right) \tag{2}$$

[1]The number of control symbols is neglected in the analysis.

[2]Similar equations can be provided in the case with channel coding such as in the case without packet combining [1].

TABLE I
COEFFICIENTS a_n FOR DIFFERENT M-QAM MODULATIONS ($M_n = 2^n$)

M_n	2	4	8	16	32	64	128	256
a_n	0.9930	0.4953	0.1685	0.1021	0.052	0.025	0.0128	0.0063

with, $$P_n^{\mathrm{DoI}}(\gamma) = L \exp(-a_n \gamma), \tag{3}$$

where L is a coefficient which depends on the considered packet size only, and a_n is a coefficient related to the constellation (2^n-QAM) where n is the modulation level. We refer to $P_n^{\mathrm{DoI}}(\cdot)$ as the *degree of interest* (DoI) in using modulation level n. Indeed, the higher the value of the maximum allowed DoI is, the higher is the probability and interest to select a higher modulation level, thus increasing the spectral efficiency of the corresponding transmission.

Different modulation levels n are considered: for $n = 1,2,3,4,6,8$, constellations are rectangular, while for $n = 5,7$ cross-modulation is used because it provides better performance than rectangular. In order to avoid the use of padding bits, the packet size must be a multiple of the modulation level n. In our simulations, we consider the smallest possible packet size $N_{\mathrm{b}} = 1680$ bits, for which the PER model can be evaluated and straightforwardly extended to a general packet size which is a multiple of its smallest value, i.e., concatenation of packets with the smallest packet size $N_{\mathrm{b}} = 1680$ bits.

Using the exact PER formulae in a AWGN channel for these modulations and least square error (LSE) minimization, we obtain $L^0 = 132$ in the case $N_{\mathrm{b}}^0 = 1680$, which can be generalized to $L = 0.0785 N_{\mathrm{b}}$ for other packet size values, using the direct relationship between the PER and the bit error rate (BER), given by $PER = 1 - (1 - BER)^{N_{\mathrm{b}}} \simeq N_{\mathrm{b}} BER$ when no channel coding is employed. Indeed, the BER is independent of the packet size N_{b} because the bits are uncorrelated, hence, the PER is a linear function[3] of the packet size N_{b}. The PER in a scenario with a general packet size N_{b} can then be deduced from any PER value PER^0, equivalent to the packet size N_{b}^0, by means of the following equation $PER = N_{\mathrm{b}}(PER^0/N_{\mathrm{b}}^0)$. Considering a scenario with $N_{\mathrm{b}}^0 = 1680$bits, the PER can be rewritten as $PER = N_{\mathrm{b}}(L/N_{\mathrm{b}}^0).\exp(-a_n.\gamma) = 0.0785 N_{\mathrm{b}} \exp(-a_n.\gamma)$, and we deduce directly that the values of a_n are independents of the packet size. The values for the modulation-dependent coefficients a_n are provided in Table I. Fig. 1 shows that the proposed PER model provides perfect match with the exact PER even with one modulation-dependent parameter, instead of two as in [1], [3].

If we consider the use of truncated ARQ with a maximum number of transmissions N_{arq} and no packet combining, the PLR can be formulated as [1]:

$$PLR_{N_{\mathrm{arq}}} = \prod_{l=1}^{N_{\mathrm{arq}}} PER_{n(l),l}, \tag{4}$$

where $n(l)$ and $PER_{n(l),l}$ are the modulation level and the PER at transmission index l ($l = 1, \ldots, N_{\mathrm{arq}}$).

[3]In a case with channel coding, the linear relationship between the BER and the PLR will not be valid anymore, because in such a case the bits become correlated

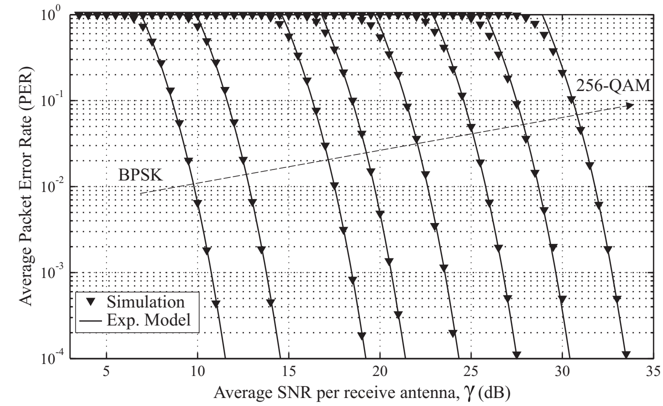

Fig. 1. Simulated PER with its fitting exponential model for modulation levels $n = 1, \ldots, 8$.

The PLR considering packet combining in addition to truncated ARQ and AM is in general more complicated to formulate, especially when packets are modulated differently from a transmission to another. Herein, considering the combining of packets generated with different modulations, we propose a new PLR approximation defined by an exponential function deduced from the DoI functions, $P_{n(l),l}^{\mathrm{DoI}}$, of each transmission. Using extensive simulations, we show that the PLR can be well approximated by the proposed function even if packets are transmitted over channels with different average SNRs. Specifically, in the packet combining case, the proposed PLR model can be expressed as

$$\begin{aligned} PLR_{N_{\mathrm{arq}}} &= \min\left(1, L\, e^{-\sum_{l=1}^{N_{\mathrm{arq}}} a_{n(l)} \cdot \gamma^{(l)}}\right) \\ &= \min\left(1, L^{-(N_{\mathrm{arq}}-1)} \prod_{l=1}^{N_{\mathrm{arq}}} P_{n(l),l}^{\mathrm{DoI}}\right), \end{aligned} \tag{5}$$

where $\gamma^{(l)}$ is the average SNR at transmission index l of the same packet.

Fig. 2 shows that the proposed exponential model (5) gives a good matching with the Monte-Carlo simulated PLR for the case when $N_{\mathrm{arq}} = 2$ and a tight upper bound when $N_{\mathrm{arq}} = 4$. In the provided results, combined packets are generated assuming that the transmissions are performed over channels with the same average SNR. In other scenarios such as cooperative MIMO networks, packets to be combined can be carried over channels with different average SNRs. Fig. 2 also shows the PLR of combined packets carried over channels with 2dB difference in their respective average SNRs. For instance, $M = 32, 4$ (2dB) denotes combination of two packets modulated using 32-QAM and 4-QAM, respectively, when the average SNR of the second transmission is 2dB higher than that of the first one.

IV. Optimal Adaptive Modulation Algorithm

The maximization of the ASE under the PLR constraint can be formulated as

$$\begin{aligned} \max_{\{\gamma_n | n=1,\ldots,M\}} &\quad \overline{SE} \\ \text{s.t.} &\quad \overline{PLR} \leq \overline{PLR}_{\max}, \end{aligned} \tag{6}$$

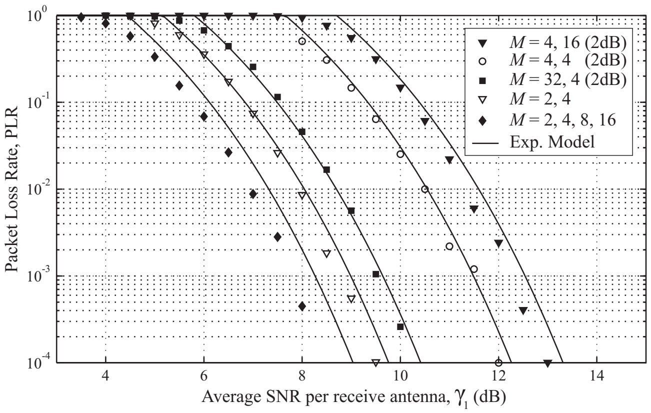

Fig. 2. Simulated PLR and its fitted exponential model considering packets with different modulation formats and different average SNRs, where (2dB) denotes a difference of 2dB between the average SNRs of the first and second combined transmissions, γ_1 and γ_2, with $N_{\rm arq} = 2, 4$.

where γ_n, $n = 1, \ldots, M$, represent the SNR delimiters associated with the M modulation levels, $\overline{PLR}_{\max}$ is the maximum allowed PLR and $\overline{SE}$ is the ASE defined as the ratio of the average number of correctly received packets over the average number of transmitted packets.

Based on the PLR model of combined packets without AM in AWGN channels, expressed in (5), and adopting a similar methodology as in [1], [3], we compute the metrics used in the design and performance evaluation of the proposed AM algorithm, namely, the average PLR, the ASE and the outage probability.

As mentioned previously, we consider the use of packet combining over MIMO slow Nakagami-m fading channels. In the case of AM with block fading consideration, the mapping between the SNR and the modulation level is the same for all frame transmissions. Hence, we consider that if SNR $\gamma^{(t)}$ at transmission t falls in the interval $[\gamma_n, \gamma_{n+1})$, then modulation level n should be used. For $\gamma_0 < \gamma^{(t)} < \gamma_1$ with $\gamma_0 = 0$, transmission is suspended. Accordingly, the probability to use modulation level n is given by

$$p_n = \int_{\gamma_n}^{\gamma_{n+1}} p_{\gamma^{\rm STBC}}(\gamma) d\gamma = Q\left(m\mathcal{K}, mN_{\rm T}R_{\rm c}\frac{\gamma_n}{\overline{\gamma}}\right) - Q\left(m\mathcal{K}, mN_{\rm T}R_{\rm c}\frac{\gamma_{n+1}}{\overline{\gamma}}\right), \quad (7)$$

where $Q(a,x) = \frac{1}{\Gamma(a)}\int_x^{+\infty} t^{a-1}e^{-t}dt$ is the regularized Gamma function, and $\Gamma(\cdot)$ is the complete Gamma function.

In addition, the average DoI, $\overline{P}_n^{\rm DoI}$, considering modulation level n, is given by

$$\overline{P}_n^{\rm DoI} = \frac{1}{p_n}\int_{\gamma_n}^{\gamma_{n+1}} P_n^{\rm DoI}(\gamma)\; p_{\gamma^{\rm STBC}}(\gamma)d\gamma = \frac{L}{p_n}\left(\frac{mN_{\rm T}R_{\rm c}}{b_n\overline{\gamma}}\right)^{m\mathcal{K}}\left[Q(m\mathcal{K}, b_n\gamma_n) - Q(m\mathcal{K}, b_n\gamma_{n+1})\right], \quad (8)$$

where $b_n = a_n + mN_{\rm T}R_{\rm c}/\overline{\gamma}$.

The overall average $\overline{P}^{\rm DoI}$ considering AM is given by

$$\overline{P}^{\rm DoI} = \frac{\sum_{n=1}^{M} np_n\overline{P}_n^{\rm DoI}}{\sum_{n=1}^{M} np_n}. \quad (9)$$

Then using (5), the average PLR can be formulated as

$$\overline{PLR} = \min\left(1, L^{-(N_{\rm arq}-1)}\prod_{l=1}^{N_{\rm arq}}\overline{P}^{\rm DoI}\right) = \min\left(1, L^{-(N_{\rm arq}-1)}\left(\overline{P}^{\rm DoI}\right)^{N_{\rm arq}}\right). \quad (10)$$

Hence, a maximum on the average PLR, $\overline{PLR}_{\max}$, is equivalent to a maximum on the DoI, $\overline{P}_{\max}^{\rm DoI}$. Considering that $\overline{PLR}_{\max} < 1$ and using (10), we can easily define this relationship by

$$\overline{P}_{\max}^{\rm DoI} = L^{\left(1-N_{\rm arq}^{-1}\right)}\left(\overline{PLR}_{\max}\right)^{N_{\rm arq}^{-1}}. \quad (11)$$

Equation (11) shows that the achieved gain from using packet combining and truncated ARQ can be defined by $G = L^{(1-N_{\rm arq}^{-1})}$, and in the case without packet combining by $G = 1$. The value of $\overline{P}_{\max}^{\rm DoI}$ is not necessarily smaller than one. Indeed, without packet combining $\overline{P}_{\max}^{\rm DoI} < 1$, but with packet combining this is not the case.

In addition to the average PLR metric, and considering truncated ARQ and packet combining, the average number of transmissions per packet can be formulated as

$$\overline{N}\left(N_{\rm arq}, \overline{P}^{\rm DoI}\right) = 1 + \min\left(\overline{P}^{\rm DoI}, 1\right) + \min\left(L^{-1}\left(\overline{P}^{\rm DoI}\right)^2, 1\right) + \cdots + \min\left(L^{-(N_{\rm arq}-1)}\left(\overline{P}^{\rm DoI}\right)^{N_{\rm arq}}, 1\right). \quad (12)$$

Accordingly, the ASE [1], [13] can be formulated as

$$\overline{SE} = \frac{\sum_{n=1}^{M} np_n}{\overline{N}\left(N_{\rm arq}, \overline{P}^{\rm DoI}\right)}. \quad (13)$$

Finally, in the case with packet combining, the outage probability, denoted $P_{{\rm out},N_{\rm arq}}$, is equal to the product of the average number of transmissions per packet, i.e., $\overline{N}(N_{\rm arq}, \overline{P}^{\rm DoI})$ given in (12), and the outage probability during one transmission, $P_{\rm out}$. Hence, it is expressed by $P_{{\rm out},N_{\rm arq}} = P_{\rm out} \cdot \overline{N}(N_{\rm arq}, \overline{P}^{\rm DoI})$, where

$$P_{\rm out}(\gamma_1) = \int_0^{\gamma_1} p_{\gamma^{\rm STBC}}(\gamma)d\gamma = 1 - Q\left(m\mathcal{K}, mN_{\rm T}R_{\rm c}\frac{\gamma_1}{\overline{\gamma}}\right). \quad (14)$$

Now, using the above performance metrics, we present the AM algorithm and solve the optimization problem given in (6). Using (11), the latter problem can be reformulated as

$$\max_{\{\gamma_n|n=1,\ldots,M\}} \overline{SE} \quad \text{s.t.} \quad \overline{P}^{\rm DoI} \leq \overline{P}_{\max}^{\rm DoI}. \quad (15)$$

This is a constrained multivariable optimization problem, where the M SNR delimiters γ_n need to be determined. In order to solve this problem, we separate it into two sub-problems formulated by:

(P1) Determine the optimal SNR delimiters, γ_n, $n = 1, \ldots, M$, which maximize the ASE under the condition that the average DoI equals a target value $\overline{P}_{\mathrm{T}}^{\mathrm{DoI}}$; and

(P2) Determine the average DoI, $\overline{P}_{\mathrm{T}}^{\mathrm{DoI}}$, which maximizes the ASE, using the SNR-to-modulation mapping deduced from the above.

Taking into consideration that the average number of transmissions per packet $\overline{N}\left(N_{\mathrm{arq}}, \overline{P}^{\mathrm{DoI}}\right)$ depends only on the value of $\overline{P}^{\mathrm{DoI}}$, then using (13) and (15), the first sub-problem can be formulated as

$$\max_{\{\gamma_n | n=1,\ldots,M\}} \quad \sum_{n=1}^{M} n p_n \qquad \text{s.t.} \quad \frac{\sum_{n=1}^{M} n p_n \overline{P}_n^{\mathrm{DoI}}}{\sum_{n=1}^{M} n p_n} = \overline{P}_{\mathrm{T}}^{\mathrm{DoI}}. \tag{16}$$

The solution of this first sub-problem is given by,

$$\begin{cases} P_n^{\mathrm{DoI}}(\gamma_n) = P^{\mathrm{op}} & \text{for } n = 1, \\ n P_n^{\mathrm{DoI}}(\gamma_n) - (n-1) P_{n-1}^{\mathrm{DoI}}(\gamma_n) = P^{\mathrm{op}} & \text{for } n = 2, \ldots, M, \end{cases} \tag{17}$$

where P^{op} is the new variable of the maximization problem, with $\overline{P}_{\mathrm{T}}^{\mathrm{DoI}} < P^{\mathrm{op}}$. Indeed, instead of a multivariable problem, we now have a problem with only one unknown, P^{op}. This variable is the key solution for the second sub-problem.

Because of the discrete modulation level set, and involvement of regularized Gamma functions, there is no analytical solution for the second sub-problem. However, given that there is only one parameter to find, a direct search for the solution has a very low complexity. Accordingly, we propose the following algorithm:

1) Search for $P_{\max}^{\mathrm{op}} > \overline{P}_{\mathrm{T}}^{\mathrm{DoI}}$ that gives $\overline{P}^{\mathrm{DoI}} = \overline{P}_{\max}^{\mathrm{DoI}}$ using (9) and (16);
2) Search for $0 < P^{\mathrm{op}} \leq P_{\max}^{\mathrm{op}}$ which maximizes the ASE, $\overline{SE}$ given in (13).

V. Performance Evaluation and Discussions

The maximum allowed $\overline{P}_{\max}^{\mathrm{DoI}}$ is not necessarily the optimal choice which maximizes the ASE. This is exactly the weakness of the two popular AM algorithms presented in [1], [3], and for which we provide herein an overview of their ASE performance. In these algorithms, packet combining is not considered and hence our so-called combining gain is equal to $G = 1$. As such, the average DoI in this case is equivalent to the average PER.[4] The AM intervals $[\gamma_n, \gamma_{n+1})$, $n = 1, \ldots, M$, are defined by $P_n^{\mathrm{DoI}}(\gamma_n) = (\overline{PLR}_{\max})^{N_{\mathrm{arq}}^{-1}}$ in [1], and by $\overline{P}_n^{\mathrm{DoI}} = (\overline{PLR}_{\max})^{N_{\mathrm{arq}}^{-1}}$ in [3], starting by γ_1 and then deducing successively the γ_n's for $n = 2, \ldots, M$. The corresponding AM algorithms guarantee that the maximum allowed PLR, $\overline{PLR}_{\max}$, is not exceeded, but remain sub-optimal and also yield poor performance when used in conjunction with packet combining. To illustrate this, we proceed with numerical simulations and discuss the performance of the proposed AM algorithm in comparison to those in [1] and [3]. In our simulations, we consider the Alamouti MIMO scheme ($N_{\mathrm{T}} \times N_{\mathrm{R}} = 2 \times 1$) with STBC rate $R_c = 1$, and Nakagami fading parameter $m = 1$, i.e., Rayleigh fading.

[4]For clarity, expressions in [1] and [3] are shown using our notations.

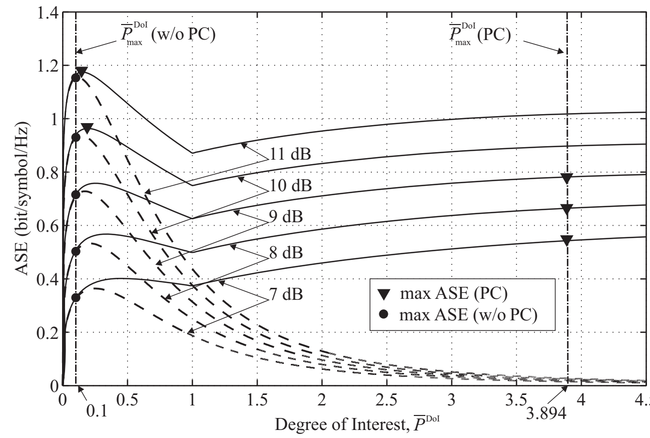

Fig. 3. ASE versus $\overline{P}^{\mathrm{DoI}}$ of the proposed AM algorithm with (solid line) and without (dashed line) packet combining (PC) ($N_{\mathrm{arq}} = 3$ and $\overline{PLR}_{\max} = 10^{-4}$).

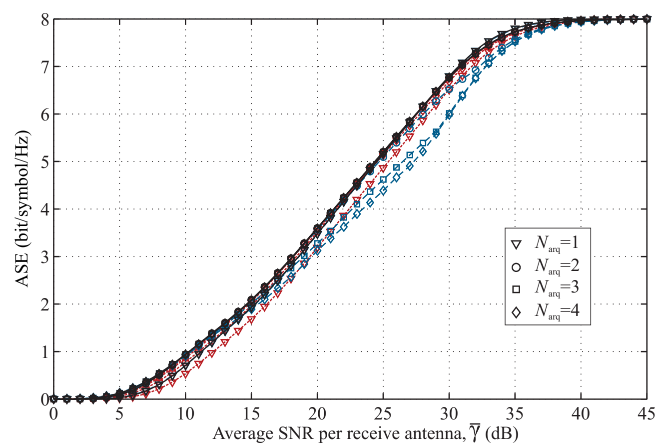

Fig. 4. Achieved ASE for different AM algorithms: optimal algorithm (black solid line), algorithm in [1] (red dotted line), and algorithm in [3] (blue dashed line), when used without packet combining ($\overline{PLR}_{\max} = 10^{-2}$ and $N_{\mathrm{arq}} = 1, 2, 3, 4$).

Fig. 3 shows for different average SNRs, $\overline{\gamma} = 7\mathrm{dB}, \ldots, 11\mathrm{dB}$, the achieved ASE versus $\overline{P}^{\mathrm{DoI}}$ for $N_{\mathrm{arq}} = 3$, and the optimal DoI values corresponding to $\overline{PLR}_{\max} = 10^{-4}$ when using the proposed AM algorithm with and without packet combining (PC). For instance, in the packet combining scenario, for $\overline{\gamma} = 7, 8, 9\mathrm{dB}$ the maximum ASE is achieved for $\overline{P}^{\mathrm{DoI}} = 3.894$, while for an average SNR $\overline{\gamma} = 10\mathrm{dB}$ the maximum is achieved for $\overline{P}^{\mathrm{DoI}} = 0.19$. Hence, the maximum ASE is not always achieved using the maximum allowed $\overline{P}^{\mathrm{DoI}}$, which is equal to 3.894 in this case. This difference between the optimal $\overline{P}^{\mathrm{DoI}}$ values for SNR=9dB and SNR=10dB shows a gap between the corresponding $\overline{PLR}$ values (10).

In terms of ASE, Fig. 4 shows that for $\overline{PLR}_{\max} = 10^{-2}$ and $N_{\mathrm{arq}} = 1, 2, 3, 4$, the proposed algorithm (black solid line) outperforms the algorithms proposed in [1], [3] when packet combining is not used. For low average SNR values,

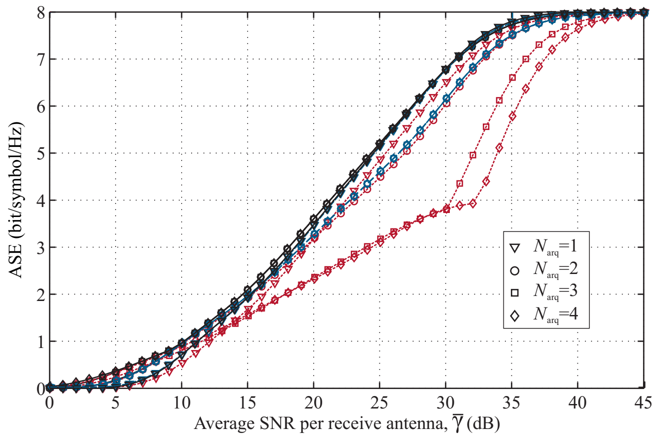

Fig. 5. Achieved ASE for different AM algorithms: optimal algorithm (black solid line), algorithm in [1] (red dotted line), and algorithm in [3] (blue dashed line), when used with packet combining ($\overline{PLR}_{\max} = 10^{-2}$ and $N_{\rm arq} = 1, 2, 3, 4$).

the algorithm in [3] (blue dashed line) outperforms the one proposed in [1] (red dotted line), while the latter is better for large SNR values. In addition, for medium and large average SNR values, our proposed algorithm achieves the maximum ASE with only one transmission ($N_{\rm arq} = 1$).

On the other hand, as observed in Fig. 5, using the proposed AM algorithm with packet combining improves the ASE performance for low average SNRs only, between 0dB and 9dB, while for higher SNRs, it yields the same ASE performance. Indeed, the maximization problem in (15) is defined by a constraint on the DoI which is less strict when $N_{\rm arq}$ increases (11). However, for large $\overline{PLR}_{\max}$ values and high SNRs, even with $N_{\rm arq} = 1$ the constraint is totally relaxed and we achieve the maximum possible ASE. Hence, the selection of higher $N_{\rm arq}$ has a negligible effect on the maximum ASE that can be reached when $N_{\rm arq} = 1$. This is not the case with the algorithms in [1], [3]. Indeed, performance results in the case with combined packets (e.g., $N_{\rm arq} = 4$) are worse than those with a single transmission ($N_{\rm arq} = 1$) for average and high SNR values. In conclusion, for a PLR requirement of $\overline{PLR}_{\max} = 10^{-2}$, the optimal AM algorithm, proposed in this work, provides better performance, at least 10% in the low average-SNR range, for the case without packet combining, and is the only algorithm adapted for operation with packet combining, whereas the others fail to provide an acceptable ASE performance.

VI. Conclusion

This paper presented a performance analysis of a new cross-layer designed adaptive modulation algorithm which accounts for the use of truncated ARQ and packet combining in MIMO Nakagami-m fading channels. A novel packet loss rate (PLR) model was proposed for scenarios with and without packet combining. This model was then used in the design of an optimal adaptive modulation (AM) algorithm which maximizes the average spectral efficiency (ASE) and satisfies the required quality of service. Performance evaluation and comparisons between the proposed AM algorithm and two popular ones were conducted and showed the enhanced performance of the proposed technique in terms of the ASE for the scenario without packet combining. In addition, the proposed AM algorithm is the only one yielding a gain from the use of packet combining, while other popular algorithms fail to provide an acceptable ASE performance and generate no gain from packet combining.

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