New error prediction techniques for turbo-coded OFDM systems and impact on adaptive modulation and coding

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Abstract

This paper deals with Packet Error Rate (PER) prediction and its impact on Adaptive Modulation and Coding (AMC) for an OFDM turbo coded transmission on a multipath channel. We compare four Link Quality Metrics (LQM), including the Signal to Noise Ratio (SNR), the capacity, and two LQM which we designed to exploit the soft outputs of the turbo-decoder. Since error prediction is used to perform AMC, we assess the throughput performance of a realistic system employing each of the four LQM. The comparison shows that while SNR performs poorly and capacity remains suboptimum, the two metrics exploiting soft outputs approach the throughput which would be achieved by perfect PER prediction.

I. Introduction

Many modern wireless communication systems improve the average spectral efficiency by adapting the Modulation and Coding Scheme (MCS) to the varying wireless channel conditions. This is the function that the Adaptive Modulation and Coding (AMC) mechanism accomplishes. Other terms for this technique are link adaptation and rate adaptation. A generic AMC mechanism selects among a predefined set of MCS the one that maximizes the momentary system throughput for the channel state predicted at the next packet transmission time. In this paper, we focus on turbo-coded OFDM systems, for which an MCS is the combination of a constellation and a puncturing pattern. For a given MCS, neglecting the signaling overhead introduced by the Medium Access Control (MAC) protocol, the link throughput ρ with Automatic Repeat Request (ARQ) and unlimited number of retransmissions equals:

$$\rho = r_{MCS} \cdot (1 - PER) \quad (1)$$

Therefore, the PER determines the link throughput, given the raw bit rate r_{MCS} of the selected MCS. The PER also determines the statistics of the number of retransmissions required for successful packet delivery to the upper layers. Quality of Service (QoS) constraints can be imposed to the AMC, in terms of tolerated delay and residual PER when the packet is delivered to the upper layers. Of course, the delivery delay in a network with multiple users depends on many parameters such as the access scheme (e.g. CSMA/CA, TDMA,...) the resource allocation algorithm and the traffic load. However, by targeting a given PER value PER_{target} at the PHY layer for every selected MCS, the AMC algorithm can provide a guarantee on the residual PER after a given number of transmission attempts. This enables the computation of a delivery delay, for a given access scheme and traffic load. In Wireless Local Area Networks (WLAN) such as IEEE 802.11a/g, a typical value for the target PER is a few percent. For instance, imposing $PER_{target} \leq 10{-}^{1}$ results in a residual PER below 10^{-5} after 4 retransmissions.

In summary, the performance of the AMC algorithm depends on the quality of PER prediction. In this paper, we make assumptions which are valid for an OFDM WLAN, operating in a noise limited environment. In this case, the channel is assumed to remain constant at least for the duration of a packet, and typical channel coherence time of 10ms represents tens to hundreds of packet durations. The PER is assumed to be a function of the MCS, noise variance, current channel coefficients and packet length. In OFDM WLANs, the large number of channel coefficients makes it impossible to store a table associating every combination of these parameters to a PER value. Instead, error prediction techniques in the literature aim to compute a real-valued function of these parameters, called Link Quality Metric (LQM), which can then be directly mapped onto PER prediction by means of a look-up table. For each MCS, it is possible to define a range of LQM values over which the MCS maximizes (1). The boundaries of this range are called MCS switching thresholds (ST).

The predicted PER can be very different from the actual

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value for two reasons. First, the channel may change at the next transmission. Second, the defined LQM might not represent accurately enough the effect of all parameters on the PER. The second case is illustrated in [4], in which the authors show that the SNR is not a good LQM for OFDM WLAN systems in frequency-selective channels. Assume that the PER vs LQM table and the ST are constructed from the PER vs SNR performance averaged over a large number of independent channel trials. It can be observed that in the LQM range where a given MCS maximizes the average throughput and its average PER is below PER_{target}, most channels perform better than average but a few ones exhibit a very high PER, and a throughput close to zero. Therefore, selecting this MCS can lead to catastrophic link adaptation, in which the link is practically broken for a duration determined by the channel coherence time. Since in a WLAN the latter can be very long, the QoS may not be respected. This problem can be solved by shifting the ST by a fixed safety margin to impose a more robust MCS selection. This results in a sub-optimum average throughput but the QoS constraints are assured.

The focus of this paper is on the design of LQMs which enable a PER prediction accurate enough that the impact of the safety margin on the average throughput be minimized. In [9], dynamic ST selection is proposed by adjusting the thresholds for a particular MT according to the ratio of the received ACK/NACKs in Hybrid ARQ or the measured channel conditions. In [6] it is proposed to dynamically adapt the ST to the current channel state by means of an indicator that depends on the current channel transfer function. In [3], the Shannon capacity is used as LQM. However in this paper, we verify that the latter still leads to suboptimum performance. There are LQMs for which the reliability of PER prediction can be improved by taking into account the effect of the forward error coding (FEC) scheme. In advanced FEC schemes such as turbo codes and LDPC, the received symbols are decoded with turbo principle (e.g. the MAP [1] or MAX-LOG-MAP). For such FEC schemes, the soft information on decoded bits available for each received packet can be exploited to compute an LQM [3], [13], [2]. We show that these LQMs adequately capture the effects of multipath realization and FEC, and significantly improve the PER prediction reliability. Moreover, they are robust to SNR estimation errors. This can be especially interesting in environments where interference is not negligible. Whereas an error δ on the knowledge of Noise plus Interference power σ^2_{n+I} has little or null impact on soft output decoding ([11], [10], [2]), the statistical moments of LLR strongly depends on δ. As shown in [13] for the AWGN channel and in [2] for frequency selective block fading channels, if the LQM is derived as a ratio of statistical moments of the LLR distribution, PER prediction becomes insensitive to δ.

The remainder of this article is organized as follows. In the next section advantages and limitations of four LQMs for PER prediction are discussed. In section III their PER prediction reliability and AMC system throughput performance are benchmarked for a turbo coded OFDM transmission by simulation means. Section IV summarizes the main aspects with some conclusive remarks.

II. Description of the investigated Link Quality Metrics

In this section, four LQMs for PER prediction are compared: instantaneous SNIR, Capacity, and two LQMs based on soft output decoding proposed in [11], [2]. In the following, we assume an M-QAM OFDM transmission similar to IEEE 802.11a [7]. The complex channel frequency coefficients H_i are known to the receiver for every useful sub-carrier of index $i = 0 \ldots N_u - 1$. We denote with G_i the squared modulus of the coefficients ($G_i = \mid H_i \mid^2$). In addition, the noise plus interference variance σ^2_{n+I} is assumed constant throughout the packet and its estimate might have an estimation error δ. The transmitter signal power is σ^2_s.

A. SNIR

The SNIR is defined as:

$$SNIR = \frac{1}{N_u} \cdot \sum_{i=0}^{N_u-1} \frac{G_i \cdot \sigma^2_s}{\sigma^2_n} \tag{2}$$

The instantaneous SNIR is often adopted for link adaptation [8]. The SNIR is mapped to the average PER for a given set of parameters (packet size, MCS, link environment, etc.). SNIR is a good LQM for PER prediction over AWGN or flat fading channels. On the contrary, in a multipath scenario, where the channel experiences frequency selectivity, the PER depends as well on the exact channel state at the reception instant. Two different channel states with same average SNIR can experience drastic different PER performance. It is therefore difficult to accurately predict the instantaneous PER considering only the SNIR. Moreover, if a co-channel interference is present, the instantaneous SNIR can be estimated with severals dBs of uncertainty. This uncertainty directly spoils the PER prediction quality.

B. Capacity

The Capacity is defined as:

$$C = \frac{1}{N_u} \cdot \sum_{i=0}^{N_u-1} log_2 \left(1 + \frac{G_i \cdot \sigma^2_s}{\sigma^2_n}\right) \tag{3}$$

This metric indicates the maximum spectrum efficiency that could ideally be reached assuming ideal channel coding, and perfect noise plus interference estimate. This metric has the drawback that ideal FEC is implicitly assumed. Moreover, it is directly affected by an SNIR estimation error.

C. Soft Output decoding based LQMs

When the receiver implements soft output decoding, the soft information on decoded bits available at each received packet can be exploited to compute an LQM. In [2], [13], two LQM are proposed based on an estimate of the log-likelihood ratio (LLR) distribution. These metrics are presented hereafter:

H LQM

This metric is derived by computing the expectation of a function of LLR. It was used in [12] to accelerate Monte-Carlo simulation of physical layers. The metric is defined as follows:

$$H = log\left(\frac{1}{N}\cdot\sum_{i=1}^{N}\frac{1}{1+e^{|LLR_i|}}\right) \quad (4)$$

As discussed in [2], this metric accounts for both FEC and frequency selectivity of the fading channel. The weakness of this metric is discussed in [2], [13]: the statistical moments of LLR distribution for a convolutionally/turbo coded transmission depend on both σ_n^2 and δ. Consequently this metric provides a PER prediction that depends on δ. As said before, this problem is also present for both SNIR and Capacity LQMs. We solved this issue with our new proposal , the LQM Λ.

Λ LQM

Λ is defined as:

$$\Lambda = \frac{E[\,|LLR|\,]}{\sqrt{E[(\,|LLR|\, - E[\,|LLR|\,])^2]}} \quad (5)$$

This LQM provides approximately the same PER prediction accuracy than (4) in terms of channel frequency selectivity. The main difference between (4) and (5) is that Λ is derived as a ratio of statistical moments of the LLR distribution. Consequently, as discussed in [2], PER predicted with this LQM does not depend on δ.

III. Performance comparison

In this section we outline the effect of PER prediction reliability on the AMC algorithm. The LQMs presented in section II are here compared in terms of average system throughput on top of the MAC layer. Simulation results are given here for a turbo coded OFDM transmission. Performance is reported here for 25 representative realizations of the typical 5GHz indoor Wireless LAN channel [5]. Note that we observed that estimators H and Λ require only 10000 bits to converge to accurate enough value. Therefore, we assume that they converge faster than the channel variations in our simulations. In the system both AMC and ARQ are implemented. The simulated AMC algorithm selects the MCS with maximum throughput while meeting the PER_{target} constraints. We propose in table I the set of MCS adopted here for the AMC algorithm. We fix the $PER_{target} = 5\%$, and determine the ST based on the worst channel realization, in order to avoid the catastrophic link adaptation problem. The 1/3 rate turbo code with 4-state RSC(7,5) constituents is adopted. Puncturing can be applied to obtain a rate 1/2 and 2/3. The information block length is 1024 bits, the soft output decoder is the Max-Log-MAP and the number of decoding iteration is limited to 12. On Fig. 1 we show the performance of the same AMC algorithm based on the above LQMs for PER prediction, considering perfect σ_{n+I}^2 estimation ($\delta = 0dB$). The performance upper bound corresponds to an AMC based on perfect PER prediction for every channel realization (Genie AMC, curve 1). Performance is compared in terms of average link throughput versus E_s/N_0. As shown on Fig. 1, worst performance is reached when using SNIR (curve 2) for PER prediction having up to 3 dBs of gap from the Genie performance. PER prediction based on Capacity (curve 3) is poor as well having performance up to 1.5 dBs from the Genie. On the contrary, both H (curve 4) and Λ (curve 5) based PER prediction have slightly the same average system throughput than the Genie.

PHY mode	**Modulation**	**Code Rate**	**Net rate on top of PHY**	**Byte per Symbol**
1	*BPSK*	1/3	4 Mbit/s	2
2	*BPSK*	1/2	6 Mbit/s	3
3	*QPSK*	1/3	8 Mbit/s	4
4	*QPSK*	1/2	12 Mbit/s	6
5	*QPSK*	2/3	16 Mbit/s	8
6	*16-QAM*	1/2	24 Mbit/s2	12
7	*16-QAM*	2/3	32 Mbit/s	16
8	*64-QAM*	1/2	36 Mbit/s	18

TABLE I

PROPOSED PHY MODES FOR IEEE 802.11A ADOPTING TURBO CODING

On Fig. 2 we introduced an σ_{n+I}^2 estimation error ($\delta \in [-3,3]$ dB). Worst performance is still obtained when using SNIR for PER prediction having up to 6 dBs of gap from the Genie performance. PER prediction is slightly better having up to 5.5 dBs of gap from Genie performance. Both H and Λ based PER prediction perform tight to Genie based AMC with slightly better performance when adopting Λ.

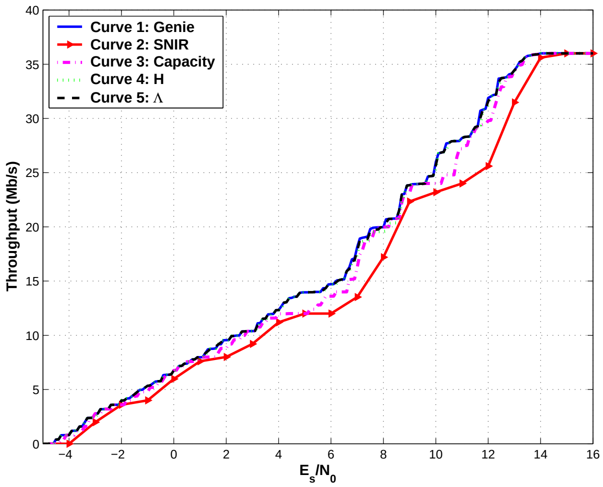

Fig. 1. OFDM turbo coded transmission with δ= 0. Curves 1,4 and 5 are almost identical.

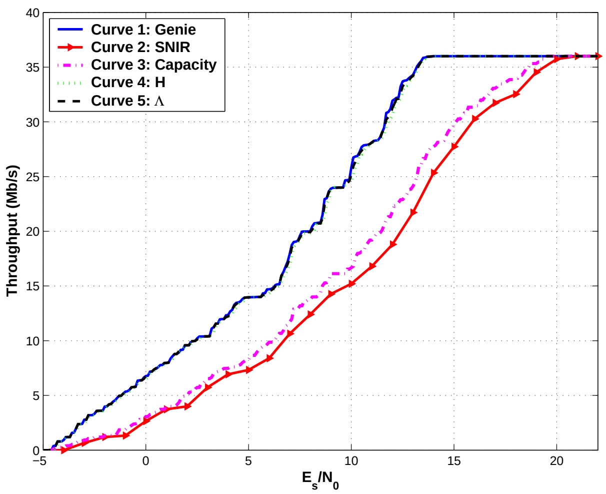

Fig. 2. OFDM turbo coded transmission with $\delta \in [-3, 3]$ dB. Curves 1,4 and 5 are almost identical.

IV. Conclusion

In this paper, PER prediction reliability is investigated for four prediction methods: SNIR, Capacity, and two link quality metrics exploiting the soft outputs of the turbo-decoder. The throughput performance obtained by an adaptive modulation and coding algorithm is assessed in a turbo-codes OFDM WLAN scenario. Quality of Service constraints are imposed in terms of target packet error rate and safety margin to avoid catastrophic link adaptation problems. It can be observed that the average throughput can be significantly increased by the metrics relying on the decoder soft outputs, and quasi ideal prediction can be reached.

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