Analytically Evaluating the Impact of Wireless Channel Behavior on an Energy-Efficient Rate-Controlled Video Transmission System

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Abstract**—The challenging goal for the scientific community in the next future is to provide energy-efficiency for telecommunications networks. However, making a network device green can cause performance deterioration. Extending a previous work, in this paper we propose a cross-layer approach for the energy-efficient transmission of multiplexed rate-controlled multimedia streams over wireless channels. In particular, we have introducean Energy-Efficient ARQ protocol, which is able to exploit the wireless channel correlation. Moreover, using an analytical model of the system, we present a deep analysis on the impact of the wireless channel behavior on the performance of the proposed scheme.**

I. Introduction

The realization of very complex widespread wireless networks has been supported, in the last decade, by the advances in wireless transmission technology and has favored the enormous diffusion of portable computers and new generation cellular phones. In this context, mobile access to multimedia applications such as on-demand streaming to mobile devices is one of the most exciting services for next generation networks [1]. At the same time, in the last few years power consumption has become very relevant in our life, and there is EU-wide incentive to reduce carbon dioxide emissions by 20 % before year 2020. More in deep, 3 % is expected to come from the ICT sector and a major role in "greening" telecommunications will be played by wireless networking technologies. For this reason, if up to now the main goal of research and industrial work in telecommunications has been to maximize performance, or reduce energy consumption in mobile devices to lengthen their battery life, the challenge in the next future will be to realize green telecommunications networks, and specifically wireless devices that present the highest energy consumption coefficient per transmitted bit, among all the networking devices.

In this perspective a significant amount of works have been done in recent years to make both wired ([3], [2]) and wireless transmissions energy efficient [4], [5]. More specifically, in wireless networks the most part of them have been devoted to save energy in low-power battery devices, with the aim of increasing their lifetime [6], [7]. Since the launch of 3G access, mobile networks are a major consumer of electricity, and with LTE mobile operators have to prepare for even further increases in power consumption per base station. The energy bill of current deployed wireless networks is already more than significant, surpassing the 20 % of the operating costs for some of them. Thus, means to lower the energy consumption of wireless networks are very valuable. Unfortunately, the power amount necessary for efficient and reliable transmissions makes wireless network devices, like wireless routers and network interfaces, the most critical devices to be optimized. Therefore, greening a wireless network device can cause performance deterioration. It is widely accepted that a good way to improve performance from the network level to the application level is to use a cross-layer approach [8]. However, it is challenging to maintain perceived Quality of Service (QoS) acceptable when energy saving strategies are implemented.

Energy consumed for efficient wireless transmissions is strongly related to techniques for maintaining reliable communications over noisy channels, such as forward error correction (FEC) and automatic repeat request (ARQ). However, the channel-state unaware behavior makes both FEC and traditional ARQ techniques energy inefficient. For this reason, some channel-adaptive link layer protocol ideas, such as GBN-ARQ and SR-ARQ based on channel probing [9], and ARQ based on stochastic learning automaton [10], have been proposed earlier.

Now a challenging task for a successful deployment of mobile video services is to focus at the same time both power consumption at the transmission level and quality of service (QoS) at the application level, with the aim of providing system designers with a tool for achieving a tradeoff between these two above opposite targets. With this in mind, in a previous work [11] we have addressed an energy efficient cross-layer video transmission system over wireless channels consisting of both a channel-adaptive ARQ-based protocol and an adaptive video transmission system. The whole system is therefore adaptive in both video source coding and ARQ transmission. More specifically, we have proposed a new version of the SW-ARQ, in the following referred to as Energy-Efficient ARQ (EE-ARQ), in order to exploit the correlation of the wireless channel behavior, so minimizing transmission when the channel state is bad. In addition, in order to compensate transmission bandwidth reduction due to the energy saving policy, a Rate Controller has been introduced to follow a feedback law to control the encoding rate of the sources. In this paper, using an analytical model of the system, we evaluate the impact of the wireless channel behavior on the performance of the whole system.

The paper is structured as follows. Section II describes the proposed Green Adaptive Video Wireless Transmission system we consider in the rest of the paper. Section III

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introduces the Markov model of the system and defines the main performance parameters regarding both video encoding quality, queue, ARQ transmission and consumed power. In Section IV the model is then applied to a case study to evaluate the performance of a real case, and derive some guidelines on choosing the best parameter configuration according to the wireless channel characteristics. Finally, Section V concludes the paper.

II. System Description

In this section we will describe the *Green Adaptive Video Wireless Transmission* system we consider in the rest of the paper. It is constituted by a *Video Multiplexer* loaded by V *Adaptive Video Sources* connected to it through high-speed low-delay links. The *Video Multiplexer Queue* is served by a wireless channel with time-variant bit error rate (BER) behavior; channel losses are managed with the Automatic Repeat reQuest (ARQ) protocol. The wireless output link constitutes the system bottleneck. When channel conditions get worse, more retransmissions are needed and the Video Multiplexer queue length increases. In order to avoid congestion, video sources are adaptive, that is their emission bit rate is modified by a *Rate Controller* [12] located in the Video Multiplexer, according to the state of the Video Multiplexer Queue, with a mechanism described later in this section.

Adaptive Video Sources we are considering are any video sources that, according to a given feedback, can modify their encoding rate run time in order to change their emission rate [13], [14], [15]. Let $\underline{\Psi}$ be the encoding rate array, containing all the available emission bit rates of the video sources, and $\underline{\Omega}$ the quality array, containing the quality levels associated to the available emission bit rates, expressed in terms of peak signal to noise ratio (PSNR); let G be the number of encoding levels, that is, the cardinality of the sets $\underline{\Psi}$ and $\underline{\Omega}$.

Packets coming from video sources are subdivided in *ARQ blocks* of H bits to be managed by the ARQ protocol. These ARQ blocks are buffered in the Video Multiplexer Queue whose dimension, defined as the maximum number of blocks that can be accommodated in the queue and in the server facility, is K. Let C be the transmission rate on the wireless link, expressed in bits per second. Thus the time needed to transmit one ARQ block is $\Delta_{ARQ} = H/C$.

In the considered scenario the most appropriate version of ARQ is the stop-and-wait ARQ (SW-ARQ) because delays introduced by it are not too high, given that link propagation delays are negligible as compared to the ARQ block transmission time; on the other hand it ensures that packets are received at destination in the same order as they were sent by the transmitter.

In this paper we propose a modified version of the SW-ARQ protocol, in order to make it energy efficient. We will refer to this new protocol as EE-ARQ (Energy-Efficient ARQ). The motivation at the base of it is that the quality behavior of the underlying wireless transmission channel is a strongly-correlated stochastic process, that is, the same signal-to-noise ratio (SNR) level is maintained for a period that is very long as compared to the transmission duration of a single ARQ block. For this reason, if a transmission has failed, it is highly likely that an immediately successive attempt will follow the same sort. Starting from this consideration, we propose to use a retransmission policy where the transmission is attempted with a probability depending on the number of previous attempts. In such a way, the sender deduces the state of the channel and transmits more rarely when the channel is considered bad. More specifically, as in the classical SW-ARQ protocol, let ρ be the counter of transmission attempts already done for the same ARQ block ($\rho = 0$ when the block is transmitted for the first time). The counter ρ is incremented by one at each retransmission attempt, and reset to zero when a block is removed from the service facility because successfully transmitted or discarded because the maximum number of retransmissions, $s_{MAX}^{(R)}$, has been reached. According to the new EE-ARQ protocol, in a generic instant when the sender should transmit a block according to the classical SW-ARQ protocol, the transmission is attempted with a probability $\wp^{(Tx)}(\rho)$ depending on the number of previous attempts, ρ. It is defined as:

$$\wp^{(Tx)}(\rho) = \frac{1}{Tx_{law}(\rho)} \tag{1}$$

where $Tx_{law}(\rho)$ is the transmission law associated to the retransmission policy. In this paper we consider and analyze a retransmission policy similar to the exponential backoff adopted by IEEE 802.3 CSMA/CD protocol. More specifically, the transmission law, i.e. the denominator of the probability to attempt a transmission, increases exponentially with the number of previous attempts of retransmission. It is defined as:

$$Tx_{law}(\rho) = \gamma^{\rho}, \text{ with } \gamma \geq 1 \text{ and } \rho \in \{0, \ldots, s_{MAX}^{(R)}\} \tag{2}$$

Using this law allows the sender to deduce the state of the channel to transmit more rarely when the channel is bad. As we will see in Section IV, the choice of γ have a strong impact on the overall system performance in terms of both application quality and energy consumption.

As already observed so far, the task of the *Rate Controller* is to control the emission bit rate of the video sources with the target of maintaining the queue length as much constant as possible, avoiding situations in which the buffer empties or overflows due to some channel condition variations. To this purpose the Rate Controller periodically monitors the state s_Q of the Video Multiplexer Queue, defined as the number of ARQ blocks which are present in the queue and in the service facility; based on it, the Rate Controller implements a feedback law that determines at each time slot whether sending "rate-increase" or "rate-decrease" feedback messages to the video sources. In order to tune the system reaction time, the Rate Controller decides the number of sources that have to change their rates. More specifically, at each time slot, the Rate Controller first decides the kind of message to send to the video sources according to the state of the queue: when s_Q is less than $K/2$, it sends "rate-increase" messages, while it sends "rate-decrease" messages when s_Q is greater than $K/2$, where K has been defined as the maximum number of blocks that can be accommodated in the queue and in the server facility. No messages are sent when $s_Q = K/2$. Then the Rate Controller decides the number of sources that have to receive the above messages. This number is calculated as $\tilde{v}(s_Q) = \phi \cdot f_{law}(s_Q)$, where $f_{law}(s_Q)$ is the per-source feedback law mask, shown in Fig. 1.

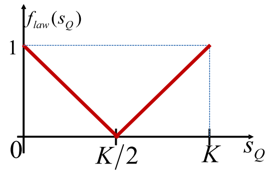


Fig. 1. Feedback law

The coefficient $\phi \in \{1, \cdots, V\}$ allows the Rate Controller to decide the maximum number of sources that can be contacted simultaneously.

Since the number $\tilde{v}(s_Q)$ may not be an integer, it is rounded to one of the closest integer values with probabilities proportional to its distance from them. So the final number of sources that have to change their rate is given by:

$$v(s_Q) = \begin{cases} \lfloor \tilde{v}(s_Q) \rfloor & \text{with probability: } 1 - \wp_V(s_Q) \\ \lfloor \tilde{v}(s_Q) \rfloor + 1 & \text{with probability: } \wp_V(s_Q) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where $\wp_V(s_Q) = \tilde{v}(s_Q) - \lfloor \tilde{v}(s_Q) \rfloor$, and $\lfloor x \rfloor$ indicates the maximum integer lower than or equal to x. The $v(s_Q)$ sources to be contacted are randomly chosen among the V sources loading the buffer, starting from the ones encoding at the highest bit rate if $s_Q \in \left]\frac{K}{2}, K\right]$, or from the ones encoding at the lowest bit rate, if $s_Q \in \left[0, \frac{K}{2}\right[$.

III. System Model

In this section we describe the Markov model the Green Adaptive Wireless Transmission system described in the previous section, and in the following indicated as Σ. For space problems, we limit to briefly introduce the model, referring the reader to [16] for details. As already said, it is a queueing system loaded by an aggregate of V video adaptive sources, and served by a wireless channel with the energy efficient EE-ARQ mechanism described so far. The model is defined by using the most general Markov-modulated process in the discrete-time domain, the Switched Batch Bernoulli process (SBBP) [17]. The so-called ARQ reaction period, indicated as Δ, and defined as the time needed to transmit an ARQ block and receive the relative ack on the wireless link, is used as the time slot.

Let us define the following processes: 1) the *queue drain process* of this system, $N(p)$, representing the number of ARQ blocks removed from the system in the p-th slot; 2) the emission process of the Adaptive Source aggregate, $W(p)$, representing the number of ARQ blocks sent to the queue from the source aggregate during the p-th slot. A complete description of the system Σ at the p-th slot requires a two-dimensional Markov chain, whose state in the generic p-th slot is defined as $\underline{S}^{(\Sigma)}(p) = \left(\underline{S}^{(W)}(p), \underline{S}^{(S)}(p)\right)$, where:

- $\underline{S}^{(W)}(p)$ is the state of the underlying Markov chain of the adaptive source aggregate emission process $W(p)$. It is a vector of G elements; the g-th element, for $g \in \{1, ..., G\}$, represents the number of sources using the g-th encoding level for the frame to be encoded in the p-th slot;
- $\underline{S}^{(S)}(p)$ is the state of the Markov chain of the queueing system process; it is a two-dimensional Markov chain defined as $\underline{S}^{(S)}(p) = \left(S^{(Q)}(p), \underline{S}^{(N)}(p)\right)$ where:
    - ○ $S^{(Q)}(p) \in \{0, ..., K\}$ is the queue state, i.e. the number of ARQ blocks in the queue and in the server facility at the p-th slot;
    - ○ $\underline{S}^{(N)}(p)$ is the state of the Markov chain characterizing the queue drain process $N(p)$; it is defined as $\underline{S}^{(N)}(p) = \left(S^{(R)}(p), S^{(C)}(p)\right)$, where $S^{(R)}(p)$ and $S^{(C)}(p)$ are the retransmission state and the channel state, respectively.

Now, by solving the system Markov chain as shown in [16], we can derive the following main QoS parameters:

- $\overline{psnr}$, defined as the mean peak signal-to-noise ratio characterizing the encoding process of the video sources;
- $\wp_{Loss_{ARQ}}$, defined as the loss probability due to the fact that some ARQ blocks have been retransmitted for a number of times greater than the maximum limit $s^{(R)}_{MAX}$;
- $\wp_{QueueNotEmpty}$, defined as the probability the buffer is not empty.

Assuming that video sources are enough adaptive, the two above metrics, $\wp_{Loss_{ARQ}}$ and $\wp_{QueueNotEmpty}$, can be used to quantify the capacity of the system to maximize link utilization when the channel gets better quality, and avoid losses when the channel get worse. For example, the loss probability can be used to find the minimum acceptable channel quality that avoids buffer saturation, given a minimal video bitrate.

In order to evaluate the energy saving amount introduced by the proposed protocol, from the analytical model we derive the total power consumption as follows:

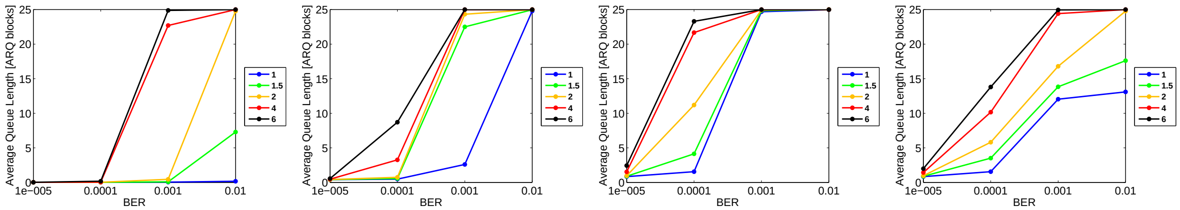
$$\overline{\mathcal{P}} = \overline{\mathcal{P}}_{Tx_{SUCCESS}} + \overline{\mathcal{P}}_{Tx_{FAILURE}} + \overline{\mathcal{P}}_{IDLE} \tag{4}$$

where $\overline{\mathcal{P}}_{Tx_{SUCCESS}} = \mathcal{P}_{Tx} \cdot \wp_{Tx_{SUCCESS}}$, $\overline{\mathcal{P}}_{Tx_{FAILURE}} = \mathcal{P}_{Tx} \cdot \wp_{Tx_{FAILURE}}$, and $\overline{\mathcal{P}}_{IDLE} = \mathcal{P}_{IDLE} \cdot \wp_{IDLE}$ represent the power consumed during a successful transmission, a failed transmission and an ARQ transmitter IDLE state (corresponding to a state when the transmitter is idle because the queue is empty, or the EE-ARQ algorithm imposes the transmitter to not transmit in order to save power). The terms $\mathcal{P}_{Tx}$ and $\mathcal{P}_{IDLE}$ are input parameters, representing the power consumed in one slot to transmit an ARQ block or to be in the IDLE state, respectively. The terms $\wp_{Tx_{SUCCESS}}$, $\wp_{Tx_{FAILURE}}$ and $\wp_{IDLE}$ are the probabilities of a successful transmission, a failed transmission and a transmitter IDLE state, respectively.

IV. Numerical results

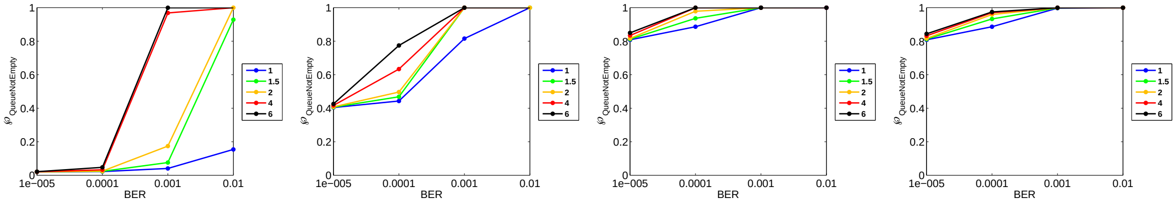
In this section we numerically evaluate the cross-layer approach proposed for the Green Adaptive Video Wireless Transmission system. The evaluation will be carried out in terms of both quality of service and power saving, with the purpose of deducing some design guidelines on the choice of the best EE-ARQ protocol parameter, according to the given requirements specified in terms of QoS and power saving.

In the following we consider a video sequence in CIF format (352 x 288 pixels), related to a documentary captured from the BBC International Television, and encoded using the vcodec mpeg2video with the ffmpeg encoder. We have applied $G = 3$ different encoding levels ($\underline{\Psi} = \{10, 200, 400\}$kbit/s). The correspondent PSNR values are:



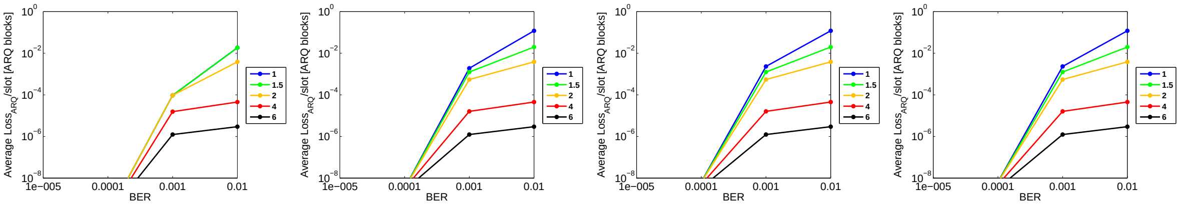
(a) CBR($\Psi = 10kB/s$) (b) CBR($\Psi = 200kB/s$) (c) CBR($\Psi = 400kB/s$) (d) Controlled Rate

Fig. 2. Average Queue Length



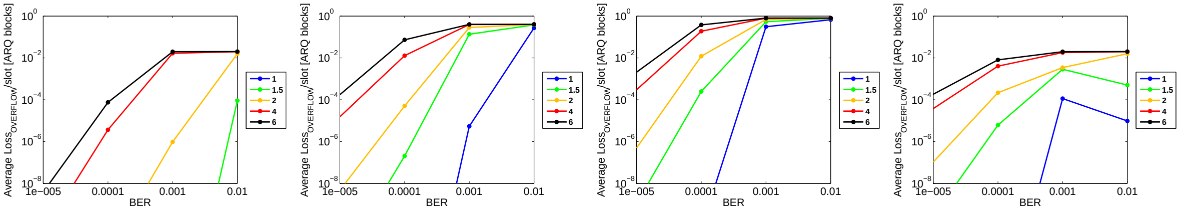
(a) CBR($\Psi = 10kB/s$) (b) CBR($\Psi = 200kB/s$) (c) CBR($\Psi = 400kB/s$) (d) Controlled Rate

Fig. 3. Probability of NOT empty Queue



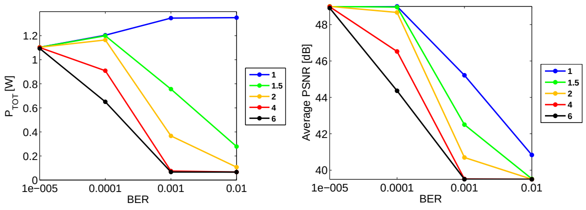
(a) CBR($\Psi = 10kB/s$) (b) CBR($\Psi = 200kB/s$) (c) CBR($\Psi = 400kB/s$) (d) Controlled Rate

Fig. 4. Average losses for exceeding the maximum allowed number of retransmissions $s^{(R)}_{MAX}$ of the same ARQ block



(a) CBR($\Psi = 10kB/s$) (b) CBR($\Psi = 200kB/s$) (c) CBR($\Psi = 400kB/s$) (d) Controlled Rate

Fig. 5. Average losses due to buffer overflow



(a) Controlled Rate (b) Controlled Rate

Fig. 6. Power Consumption and Average PSNR in the Rate Controlled case ($t_{GOOD} = 10^{-3}s$)

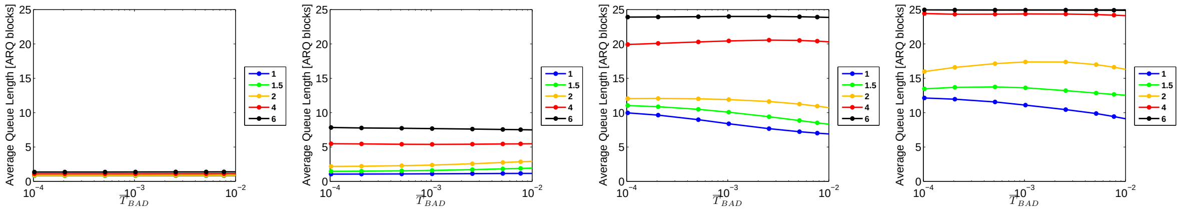
$\underline{\Omega} = \{39.5, 46.0, 49.0\}$ dB. In both the analyses we have set the number of sources to $V = 10$, and the buffer size to $K = 25$ ARQ blocks. Each ARQ block is constituted by $H = 512$ bits, the maximum number of retransmissions is $s^{(R)}_{MAX} = 7$. We consider a Rate Controller with the V-shaped feedback mask in Fig. 1, and we set the parameter $\phi = 1/V$ in such a way that only one source at time is requested to change its encoding rate.

As far as the wireless transmission side is concerned, we used a channel bitrate C of 5Mb/s; therefore the slot duration is $\Delta_{ARQ} = H/C = 0.1$ms. According to [18], we assumed that the wireless interface consumes a power of $\mathcal{P}_{Tx} = 1350$ mW during transmission, and $\mathcal{P}_{IDLE} = 66$ mW when it is idle.

In order to evaluate the impact of the channel behavior on the whole system performance, we have carried out two different analyses: the first one aims at evaluating the impact of the BER, while the second one considers the influence of the channel BER time correlation. Both the analyses have been done for five different values of the parameter $\gamma \in \{1, 1.5, 2, 4, 6\}$. Of course, the case of $\gamma = 1$ coincides with the classical ARQ technique, while the higher γ, the less aggressive the transmitter on the wireless channel in presence of losses.

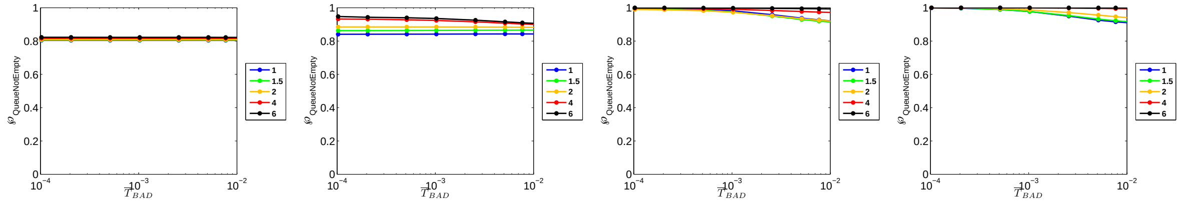
In the first analysis we have taken a channel that introduces a constant BER. The analysis is done against the introduced BER. In order to evaluate the ability of our system to adapt to different channel situations, we present results for both the cases of CBR (Constant Bit Rate) encoding sources and RC (Rate Controlled) sources, i.e. sources using the proposed Rate Controller.

First we evaluate the average queue length and the probability of queue not empty. From Fig. 2 we can see the average queue length increases as the source encoding bit rate increases, whereas the feedback mechanism allows to reduce the average queue length (Fig. 2(d)), by adjusting the encoding bit-rate of sources according to the state of the channel. On the other hand, Fig. 3(d), shows that



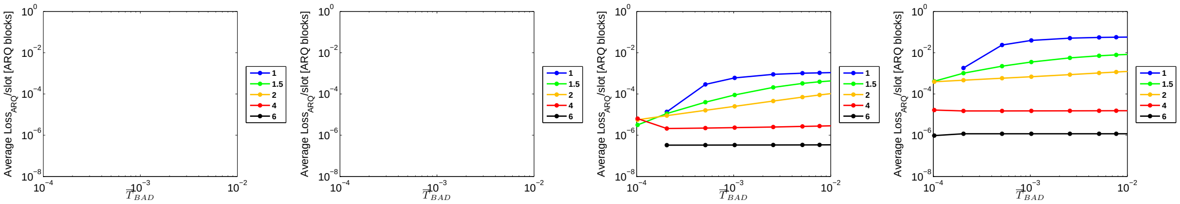
(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 7. Average Queue Length



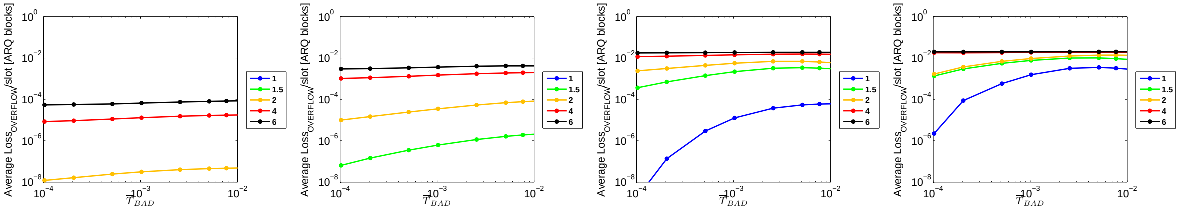
(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 8. Probability of NOT empty Queue



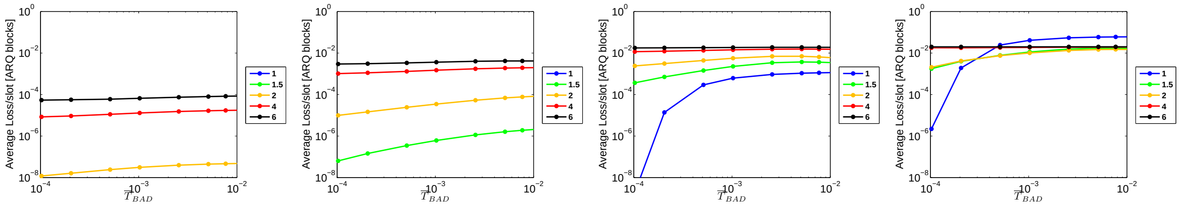
(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 9. Average losses for exceeding the maximum allowed number of retransmissions $s_{MAX}^{(R)}$ of the same ARQ block



(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 10. Average losses due to buffer overflow



(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 11. Average total losses

the probability of queue not empty is always almost 1, meaning that the rate control facility of the proposed system allows sources to fully utilize the channel, i.e. no waste of bandwidth is produced by the mechanism.

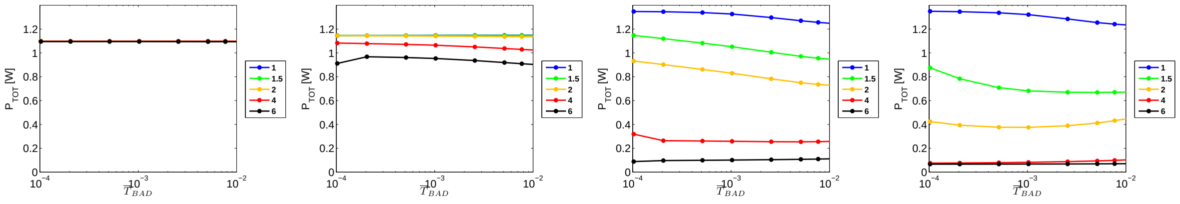
Fig. 4 shows that losses for exceeding the maximum allowed number of retransmissions, $s_{MAX}^{(R)}$, of the same ARQ, are not affected by the presence of the Rate Controller. However, the presence of the EE-ARQ, as expected, allows us to reduce the number of such losses with respect to the case of traditional ARQ (which is represented by the case with $\gamma = 1$).

Fig. 5 shows that losses due to the buffer overflow increase when the source bitrate increases, whereas the rate controller is able to adjust the source sending rate according to the channel and buffer conditions so reducing losses (Fig. 5(d)).

Finally Fig. 6 shows the power consumption and the average PSNR in the case of rate controlled source. We can see that the EE-ARQ is able to reduce the power consumption with respect to the traditional ARQ, while the performance degradation remain acceptable.

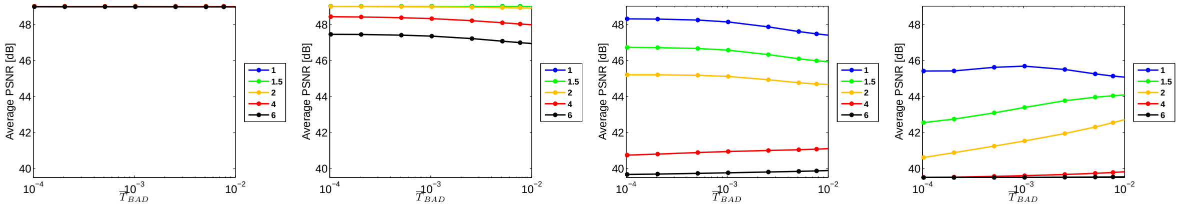
The second analysis we have carried out through the proposed analytical model regards the impact of the correlation properties of the channel on the performance of the whole system. To this purpose we have considered the case of $\overline{T}_{BAD} = \overline{T}_{GOOD}$. Fig. 7 shows the average queue length as function of $\overline{T}_{BAD}$.

Regardless to the specific value of the BER in the BAD state, the average queue length is not affected by the correlation of the channel. However, when channel



(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 12. Power consumption



(a) $BER = 10^{-5}$ (b) $BER = 10^{-4}$ (c) $BER = 10^{-3}$ (d) $BER = 10^{-2}$

Fig. 13. Average PSNR

conditions get worse (Fig. 7(c) and Fig. 7(d)), the choice of higher values of the γ parameter determines an increase of the average queue length. Consequently, the average loss due to the buffer overflow lightly increases (Fig. 10), but at the same time, the loss due to the ARQ mechanism decreases (Fig. 9), so the average total loss is not heavily affected by the choice of γ (Fig. 11). Additionally, Fig. 12 and Fig. 13 show that great power saving can be achieved thanks to the EE-ARQ, without heavily affecting the QoS.

V. CONCLUSIONS

In this paper, we have evaluated the impact of the wireless channel behavior on the performance of a cross-layer approach, proposed by the same authors in [11], for the transmission of multiplexed rate-controlled multimedia streams over wireless channels. More specifically the Energy-Efficient ARQ (EE-ARQ) protocol allows to exploit the wireless channel correlation, so minimizing transmission when the channel state is bad. In addition, in order to compensate transmission bandwidth reduction due to the energy saving policy, a Rate Controller controls the encoding rate of the sources, according to a given feedback law. The evaluation of the impact of the channel behavior on the performance of the whole system has been carried out by using an analytical model of the system. the numerical analysis has been done against the BER introduced by the wireless channel and its correlation properties.

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