High-Speed Wireless LANs: Modeling and Simulation of Enhanced ARQ Strategies

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ABSTRACT

This paper focuses on improved error control schemes for high-speed wireless digital communications. The main objective is a better quality support for real-time services, such as video, when using wireless mobile digital networks.

In view of that, and besides the schemes already standardized, a novel error control mechanism is proposed. This new mechanism relies mainly in the use of Hybrid Automatic Repeat reQuest (HARQ) error control schemes and differentiated error robustness transmission modes. In this sense, when implementing this new technique, some of the capabilities offered by modern Wireless Local Area Networks (WLANs) are significantly better utilized.

To make the performance analysis of the proposed error control mechanism, and corresponding comparison with existing systems, it was developed a system simulation environment, together with other computational tools. Analysis for diverse radio channel conditions, from AWGN modeling to Gilbert-Elliot modeling, has been done and some examples are subsequently presented.

The simulation results show that this new strategy greatly improves the performance of real-time services, fulfilling the requirement of limited delays and enabling higher data rates.

Keywords: High-speed wireless LANs, Error control, Hybrid ARQs, Sequence Numbers protection, Modeling and Simulation, Performance analysis.

1. INTRODUCTION

At present, communications in high-speed wireless mobile networks have to deal with considerable varying transmission and service requirement conditions, often needing complex radio modulations and error control functions.

Indeed, in today's high bit rate Wireless LAN standards, as the IEEE 802.11 version "a" [1] and the High Performance Radio Local Area Network Type 2 (HIPERLAN/2) [2], there is a considerable need to enclose error control functions with appropriated suitability for the radio medium.

From a user plane protocol layering perspective, the error control functions are usually implemented by means of Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) mechanisms in, respectively, the Physical (PHY) and the Data Link Control (DLC) layers.

For those WLANs, both operating at 5 GHz bands, a FEC technique is associated with an Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme, enabling differentiated error robustness transmission modes (data rates from 6 to 54 Mbit/s).

Beyond FEC, an ARQ mechanism can also be used in the DLC layer. But, despite the "natural" appropriateness of ARQ for delay-tolerant communications, such as typical data services, ARQ mechanisms may also be used for delay-constrained applications. This is nowadays possible due to the high-speed and short-range communication characteristics of high-speed WLANs.

Early examples of the intended use of mobile broadband digital communications, involving real-time services, can be found in [3, 4]. Some of this research helped standardization bodies to tune their definitions in relation to the error control functions.

To the development of the work presented hereafter, it was important to follow the activity undertaken by ETSI/BRAN ("Broadband Radio Access Networks") project in its HIPERLAN/2 standard, much particularly in the DLC layer [5].

For this layer, it was defined a group of error control modes, trying to fulfill, as much as possible, the quality requirements of any kind of service, be it real-time or not.

These modes are identified as "acknowledged", "repetition" and "unacknowledged" modes, being the "acknowledged" the only one applying an ARQ technique, but in a restricted pure detection and plain copy packet retransmission scheme.

This last fact implies that, even using FEC and ARQ, the efficiency and/or global quality of "acknowledged" wireless communications may be significantly low when used by some demanding real-time services and radio operating conditions are not favorable.

Aware of the limitations of the standard implementation, particularly when thinking in audio/visual delay-constrained services, several work assumptions were therefore established and developed [6]. Major ones are related with ARQ mechanism enhancements and the way they are implemented either using current protocol specifications or proposing minor changes.

To fully evaluate and characterize proposed error control enhancement strategies, it was developed a system model and a simulation environment which have allowed the testing of different configurations, under diverse radio conditions, deriving in a large set of simulation results. A small selection of these results is presented in this paper.

2. NOVEL HYBRID ARQ SCHEME STRATEGY

It is known that an ARQ scheme can range from a pure detection and plain copy packet retransmission (standard ARQ) to a detection/correction and redundancy packet retransmission (Type III Hybrid ARQ). Indeed, if feasibly implemented, the most powerful schemes are the Type II/III HARQs, both using concatenated inner and outer codes.

Normally, for these types of HARQs, the outer code adopts a half-rate format (information and parity parts with equal number of bits) with a size suitable with transmitted packet payloads. The differentiation between information and parity parts is usually done by a type indication field (this functionality is henceforth identified as the *"Info/Parity indication"*).

When the radio channel is in a "good" condition, the half-rate format technique allows that only the transmission of the outer code information part is needed (together with packet control fields and protected by the inner code). But, at the reception, if the decoding of the inner code presents an unrecovered error it turns necessary to transmit the corresponding outer code parity part.

In order to combine the proper parts (it is assumed the Selective-Repeat method for the packet flow) the receiver needs to distinguish, with total certainty, between the information and the parity parts of the outer code codeword, as well the original packet Sequence Number (SN).

Hence, to exploit the better performance of Type II/III HARQs, it is absolutely fundamental to have error-free packet control information (the SN and the Info/Parity indication). Unfortunately, this is exactly one of the main difficulties associated with these HARQ types, specially when considering the presence of error in existing high-speed wireless mobile communications.

The current state of the art reflects these difficulties and, consequently, neither Type II nor Type III HARQ schemes were adopted in WLAN standards. Almost of the emphasis still goes to aspects (yet innovative [7, 8]) related with the performance improvement of plain packet retransmission schemes (pure detection or Type I HARQs).

To overcome this problem and simultaneously achieve significant improvements in the field of high-speed WLANs, an original contribution work took place resulting in the development of a novel error control mechanism.

Generally speaking, this one consists in a completely new protection method of the critical packet control information (SN and Info/Parity indication) required by Type II/III HARQs. For that purpose, it is proposed, in first place, the creation of *"forward direction SN lists"* to be carried on by channels using the most reliable PHY modes.

When applied at the DLC layer of a WLAN, such as HIPERLAN/2, for each established DLC connection, those lists contain the Sequence Numbers of the User-Protocol Data Units (U-PDUs) scheduled to be transmitted. The "forward direction SN lists" are then carried in the available "Short Transport Channels" which use lower but more "robust" bit rates (6 to 18 Mbit/s).

In second place, and concurrently, the bits corresponding to what was before a "normal" SN field are now occupied by an Info/Parity indication and by a header protection field. This new occupancy can take the entire DLC U-PDU field previously reserved for the SN.

This way it is possible to have a perfect knowledge of SNs and Info/Parity indications, thus enabling the operation of Type II/III HARQs under adverse conditions, but still exploiting their superior performance.

3. MODELING AND SIMULATION

Simulation models

In order to compare the various classic ARQ solutions with the proposed alternative solutions a flexible system model was developed with the aid of some computational and graphical simulation tools, such as the MATLAB/Simulink family of software products.

An example of the main level of a developed simulation model is shown in Figure 1. Three parts compose the main level. One is related with the communication system blocks (upper part of the figure). Another one has to do with the simulation initialization blocks (middle part of the figure). The third part is concerned with the blocks that collect and process information related to performance data (lower part of the figure).

The main level acts as one of the core parts of the simulation activity for each implemented simulator. Accordingly, to maintain identical conditions in the simulation of the different schemes, and apart from the radio channel model used, the main level was kept unaltered.

When testing the same error control mechanisms and ARQ scheme, simulation models for the two radio channels used only differ in the respective error implementation blocks. The Additive White Gaussian Noise (AWGN) memoryless channel is characterized by an equal error probability, when transmitting "zeros" or "ones", called the BER of the channel (BER_c).

As for the Gilbert-Elliot (GE) memory channel the parameterization choices are much wider than in the AWGN model. The GE model uses a two-state Markov chain called the "good" and the "bad" states (Markov processes are often used to model channels with memory [9]). Each state is characterized by a different channel bit error rate, BER_{good} and BER_{bad}, by an *occupancy mean time*, mt_{good} and mt_{bad}, and by a *state probability*, P_{good} and P_{bad}. The equivalent bit error probability is assumed as the weighted average channel BER calculated over BER_{bad} and BER_{good} ($BER_c = BER_{bad} \times P_{bad} + BER_{good} \times P_{good}$).

Simulation runs

As for the methodology for each simulation run, it has been decided that the transmitter had to transfer a predetermined number of packets to the receiver, using a DLC connection with an average constant capacity (expressed in number of time slots per MAC frame). Therefore, when using a certain physical mode, the available bandwidth in terms of bit rate is set by the product *frame usage percentage* × *PHY mode bit rate*.

For the results shown herein, it was assumed the utilization of 20% of the MAC frame (0.4 ms) and the use of a 54 Mbit/s physical mode. This results in DLC connections with a maximum gross rate of 10.8 Mbit/s.

For the AWGN channel model, the BER_c was specified in the range from 10^{-4} to 10^{-1}. For the GE model, its parameters were specified in order to get a similar range for the average BER_c.

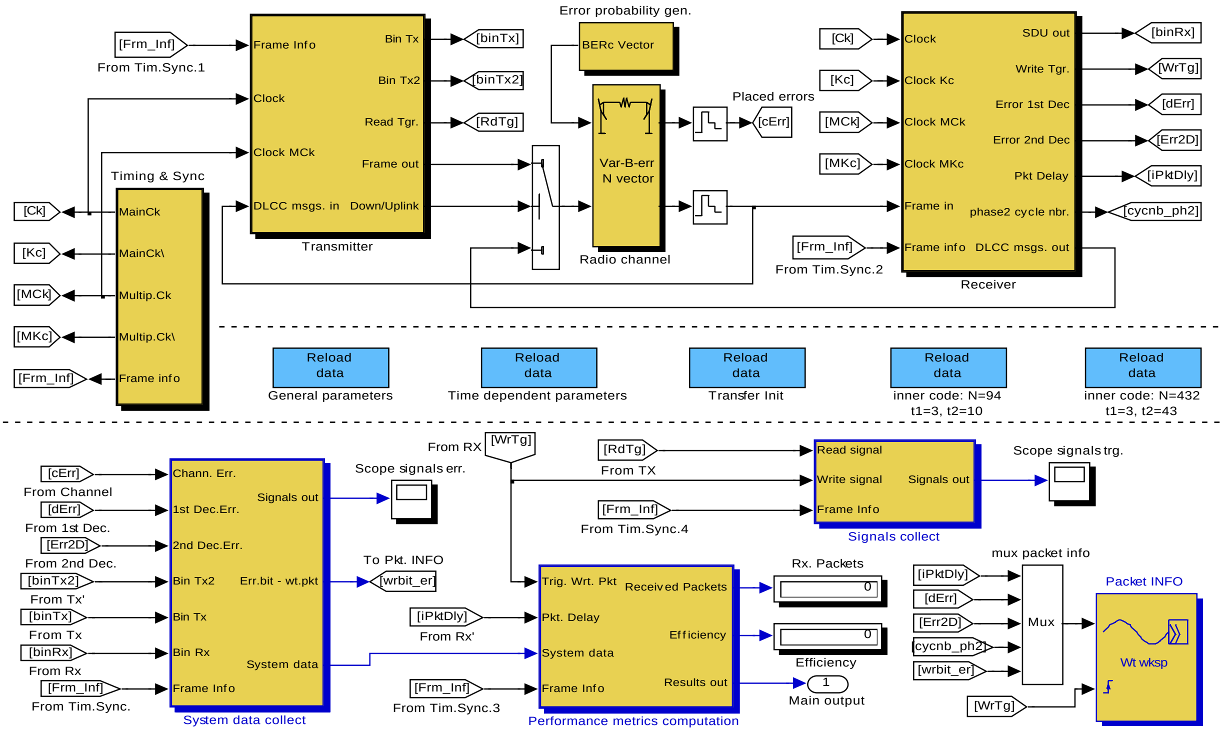


Figure 1. The main level of the simulation models.

Additionally, when simulating the use of a error correcting block code, such as BCH or RS, the detected errors may be accepted as corrected if their number is equal to or less than a certain programmable *"corrective action threshold"* (henceforth identified as λ).

The relationship between the corrective action threshold (λ), the detection range (*l*) and the correcting capability (t) of the code is set by the equation $2t = \lambda + l$ ($\lambda \le t$). This implies that the higher is λ the lower is the detection range of the code.

The relationship with the minimum Hamming distance (d) of the code can be devised from the well-known formula $d \ge 2t+1$, resulting in the formula $d \ge \lambda + l + 1$ ($\lambda \le t \le l$).

The λ corrective action threshold is applicable both to inner and outer codes (hereafter, the subscripts 1 and 2 will refer to DLC inner and outer codes, respectively). In the inner code, if λ_1 is set to zero that means the code will be only used to detect errors, hence the ARQ is a Pure detection and retransmission type. If λ_1 is set such as $1 \le \lambda_1 \le t_1$ then a Type I HARQ scheme is actually used.

4. SIMULATION RESULTS

Results for the AWGN memoryless channel

The first sets of simulation runs have used the AWGN memoryless channel for the modeling of the radio medium. Besides its simpler implementation when compared with the GE model, it provides an important initial behavior characterization of each ARQ scheme under discussion.

A representative sample of the results obtained with the AWGN channel can be found in Figure 2. In this figure, it is possible to observe the performance curves of simulated ARQ schemes, ranging from standard Pure detection (λ_1=0, CRC) till Type III ($1 = \lambda_1 < t_1$, $\lambda_2 < t_2$) HARQs using the enhanced ARQ strategy.

As predicted, the throughput efficiency reveals a clearly advantage of Type II/III HARQs. As for the residual BER, it is possible to see that a scheme set with appropriate corrective action threshold values can have a fairly good performance, up to significant BER_c values (see λ_1=1, λ_2=41, BCH-BCH).

For the average number of retransmissions per packet, it is possible to notice that, for Pure detection and Type I schemes, the average number of retransmissions suffers a continuing value increase from rather low values of BER_c. For Type II/III, the average number of retransmissions is kept below the value 1, up to a BER_c= 0.03, breaking only after that value.

Interesting to observe is the behavior of the standard deviation curves for Type II/III HARQs. After an increase up to value 0.5 (meaning, in this particular case, that approximately half of the total number of information packets go through in the first transmission and the other half requires one retransmission) a decrease occurs just to value zero. This indicates that all packets experience a number of retransmissions identical to the average. In this case, this means that the probability of occurring exactly one retransmission, for each information packet, is equal to 1.

Figure 3 shows the histograms relative to the number of retransmissions per packet, for considered ARQ schemes. For instance, in Pure detection or Type I HARQ, the use of the wireless communication link requires a lot of retransmissions for BER_c values larger than 0.007. On the contrary, in Type II/III HARQs, for a BER_c=0.02, all packets pass through requiring only one retransmission. Besides a better characterization of the communication link activity these histograms also highlight the supremacy of Type II/III HARQs.

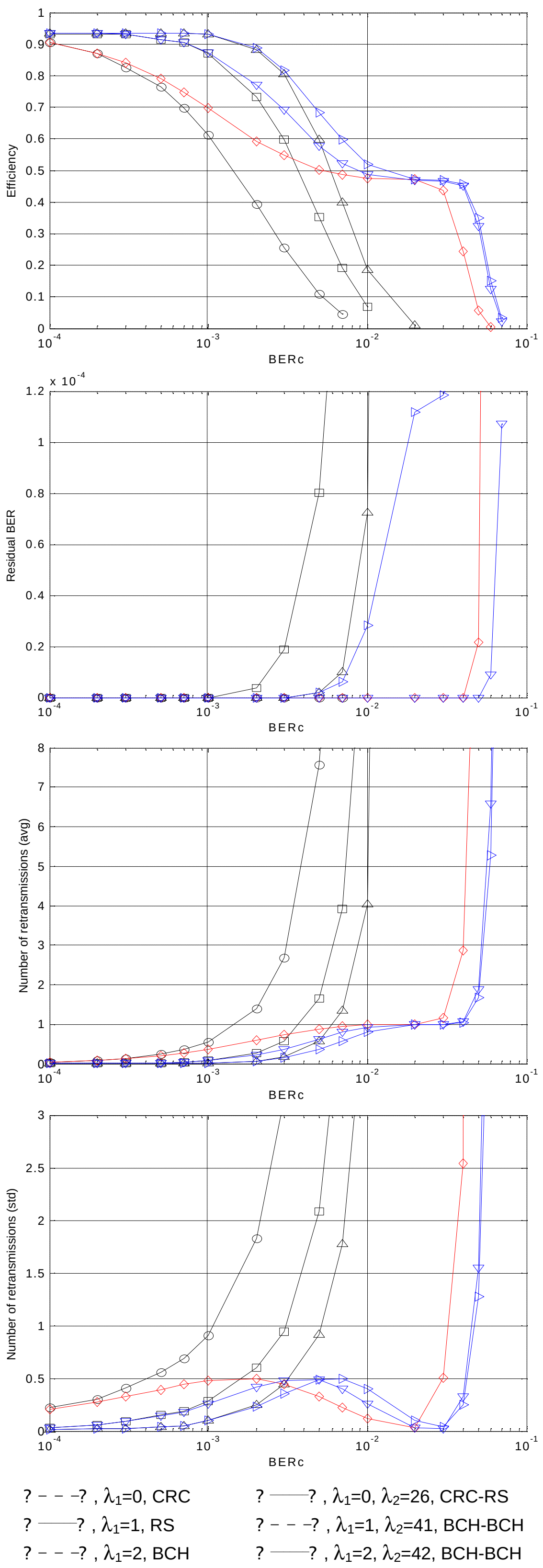
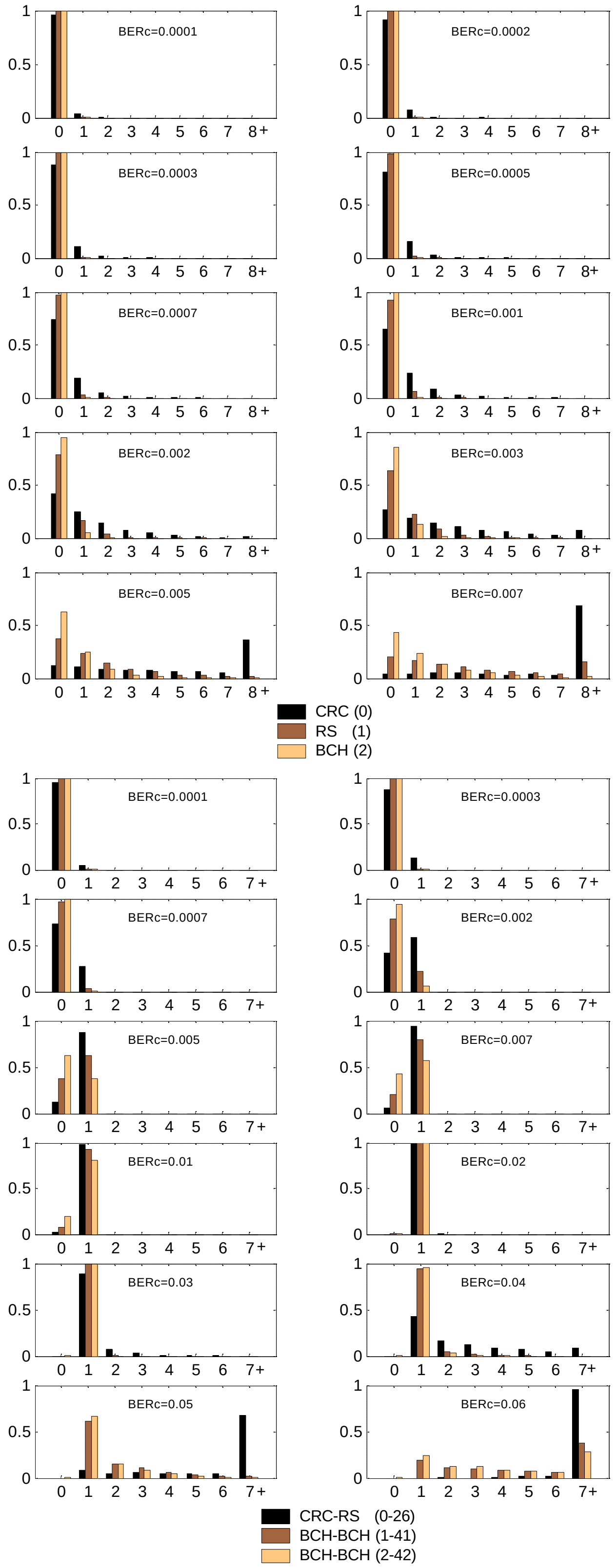


Figure 2. Performance of standard and enhanced ARQ schemes on AWGN channels: throughput efficiency, residual BER and number of retransmissions per packet (average and standard deviation).



Sign "+": means a number of retransmissions equal or larger than the number preceding it

Figure 3. Histograms of the number of retransmissions per packet for standard and enhanced ARQ schemes (AWGN channels): Pure detection and Type I HARQs (above), and Type II/Type III HARQs (below).

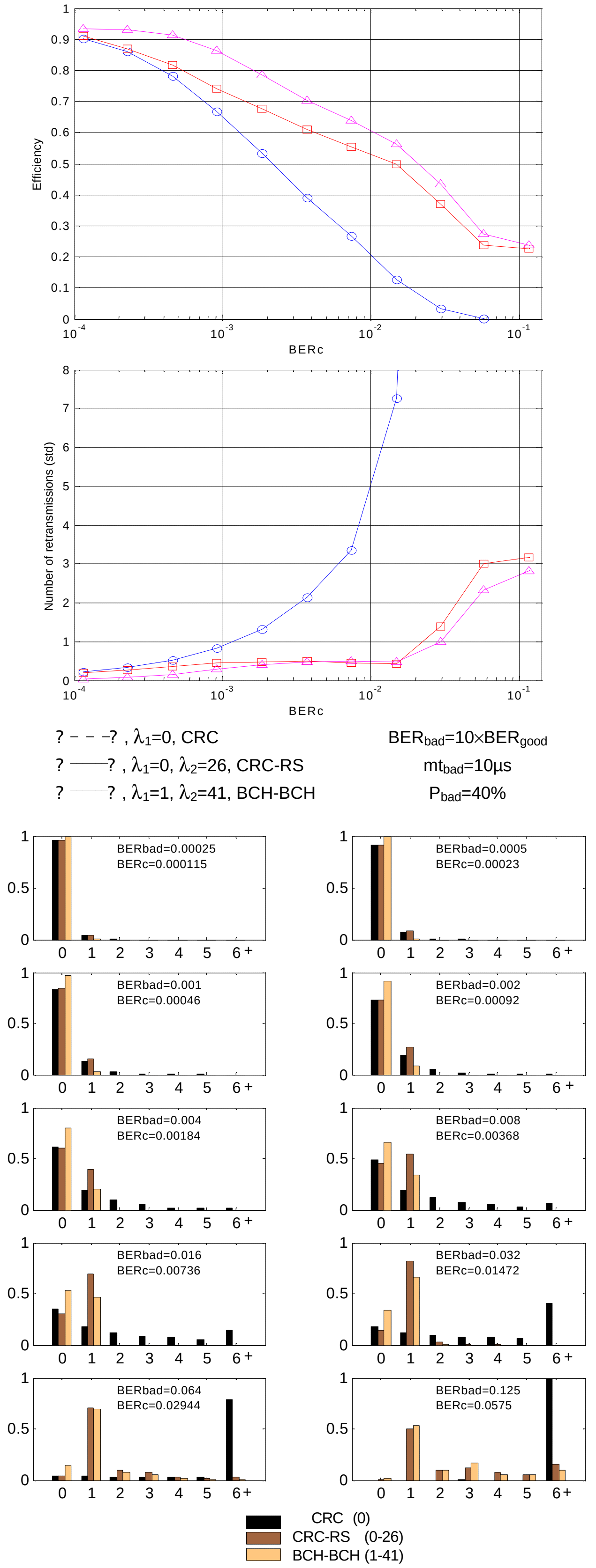


Figure 4. Performance curves and histograms of the number of retransmissions per packet in a GE channel with $\mathrm{BER}_{\mathrm{bad}}$=10´$\mathrm{BER}_{\mathrm{good}}$, $\mathrm{mt}_{\mathrm{bad}}$=10μs and $\mathrm{P}_{\mathrm{bad}}$=40%.

Results for the GE memory channel

As for the GE memory channel an extensive set of results, for various conditions of the radio channel, have been obtained using diverse ARQ and coding schemes. Two selected examples of those simulation results, including small and large channel variations in terms of BER, are depicted in Figures 4 and 5.

The performance curves and the histograms, concerning a GE channel characterized by a relatively small $\mathrm{BER}_{\mathrm{bad}}/\mathrm{BER}_{\mathrm{good}}$ ratio ($\mathrm{BER}_{\mathrm{bad}} = 10\mathrm{BER}_{\mathrm{good}}$), a "bad" state mean time $\mathrm{mt}_{\mathrm{bad}} = 10$μs and a "bad" state probability $\mathrm{P}_{\mathrm{bad}} = 40\%$, are shown in Figure 4.

Figure 5 presents similar outcomes, but for a GE channel with a $\mathrm{BER}_{\mathrm{bad}} = 100\mathrm{BER}_{\mathrm{good}}$, a $\mathrm{mt}_{\mathrm{bad}} = 1$μs and a $\mathrm{P}_{\mathrm{bad}} = 20\%$. Note that, in order to get a better awareness of simulation results, the GE channel histograms display both actual simulated $\mathrm{BER}_{\mathrm{bad}}$ values as well corresponding $\mathrm{BER}_{\mathrm{c}}$ values.

Despite the noteworthy differences, in terms of used parameters, between these two examples, the analysis of both situations reveals a consistent performance gain of the implementation using enhanced HARQ mechanisms, over the standard ARQ scheme. Even so, as shown in Figures 4 and 5, that gain is more or less extent depending on the simulated radio link conditions (i.e., the parameter values used to characterize the GE channel).

5. CONCLUSIONS

When considering possible methods to introduce error protection mechanisms in high performance wireless mobile communications none of the two usual ARQ schemes (standard Pure detection and Type I Hybrid) is appropriate. The combined effects of channel fading and multipath signal propagation are such that these schemes require a considerable number of retransmissions, making it difficult to timely combat the errors generated.

Type II/III HARQ schemes are very efficient schemes but for communications under adverse conditions there is no mechanism to guarantee their normal operation, which makes it impracticable. Hence, one of the central line actions has been finding techniques that enable Type II/III HARQs to operate almost normally, even in considerably unfavorable circumstances.

In order to guarantee their normal operation in WLAN communications, it has been proposed to convey the very important packet control information (i.e., the Sequence Numbers and the Info/Parity indications) using a method that provides a much superior protection, but requiring almost no modification to current specifications.

As for the SN information, usually located in the packet header, it is proposed that before actual packet transmissions a "forward direction SN list" should be created, for each DLC connection, and conveyed by the most reliable physical modes already defined for the 5 GHz WLANs.

As for the Info/Parity indication, it is proposed to convey it directly in the packet header, together with its necessary protection.

Using the method new allocations, the packet control information protection is significantly increased making feasible the use of Type II/III HARQ schemes with their recognized advantages.

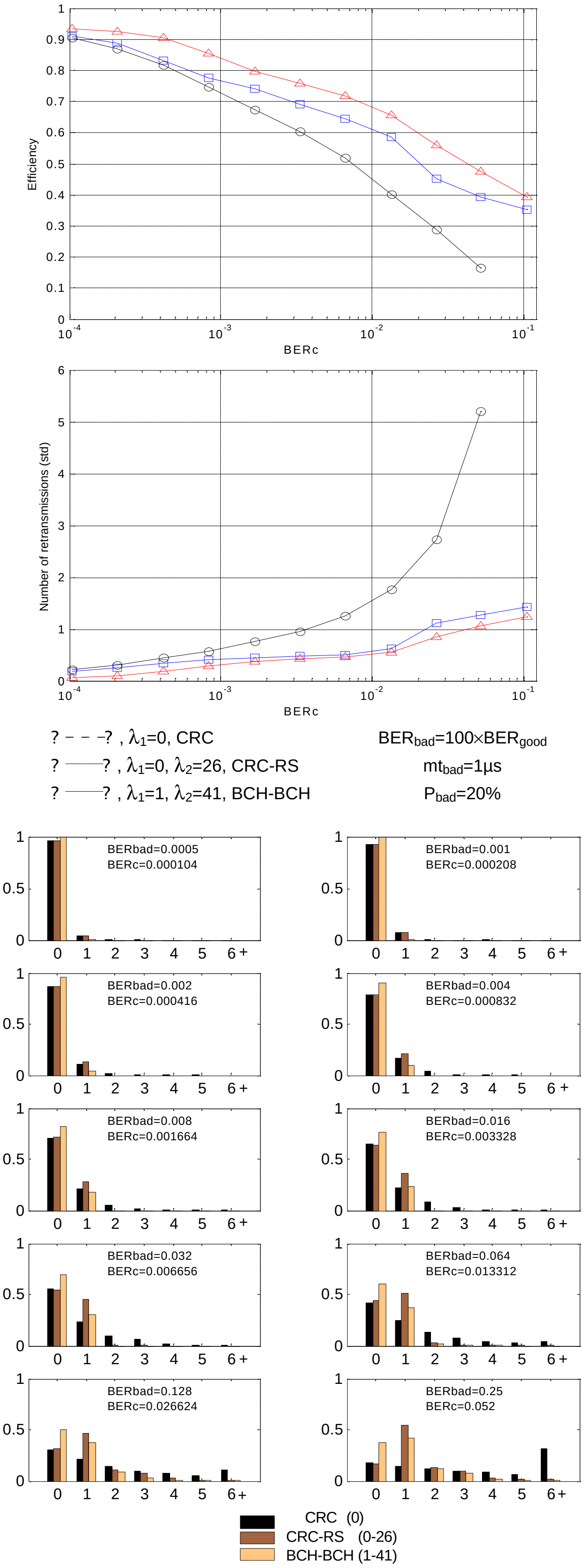


Figure 5. Performance curves and histograms of the number of retransmissions per packet in a GE channel with BER$_{bad}$=100´BER$_{good}$, mt$_{bad}$=1μs and P$_{bad}$=20%.

The characterization of the effective performance gains, between standard ARQs and HARQs using the proposed new strategy, is achieved performing a substantial number of simulations using different parameterization choices for radio channel conditions, including nominal bit rates and MAC frame usage.

The results obtained show, invariably that enhanced Type II/III HARQ schemes always achieve a better performance than other ARQ schemes. This is particularly obvious when the radio channel is characterized by a high BER (from 10^{-3} to 10^{-2}).

For real-time services where some moderate error occurrence is yet tolerable, such as typical delay-constrained audio/video services, it has been shown that implementing a Type III HARQ, as proposed, is an excellent solution since it provides extra throughput efficiency within a large BER range.

Moreover, it has been seen that a Type III HARQ scheme, together with the novel strategy, is able to operate over high BER channels for which a Pure detection ARQ scheme is no longer feasible.

6. REFERENCES

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