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Performance analysis of a cross-layered incremental redundancy hybrid automatic repeat request (CL IR-HARQ) mechanism

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The performance of Hybrid Automatic Repeat reQuest (HARQ) in wireless networks has been extensively studied in recent years. Most of the HARQ performance results reported in the literature have been based on cross-layer techniques making use of Media Access Control (MAC) and physical layer information. In contrast, we present a performance analysis of a cross-layer approach that uses MAC and Internet Protocol (IP) layer information to efficiently control packet retransmissions in wireless networks. Evaluation results (using performance metrics such as packet error rate, retransmission efficiency, delay) obtained at the IP layer, using a two-state Gilbert Elliott channel model, demonstrate the significant performance improvements of the (MAC-IP) cross-layer strategy.

1. Introduction

The ever-increasing need for higher data rates and multimedia services leads to stringent requirements on the bit rate that next-generation cellular wireless networks are expected to deliver. High variations of wireless channels' quality affect data delivery and retransmission mechanisms are proposed to deal with this major issue. Several past efforts have addressed this problem in the literature; however, it still remains a challenge for researchers to design reliable wireless communications systems to improve data delivery. As a result, the design of error control protocols becomes important. Two main error control coding classes are considered in the literature: (1) *Forward Error Correcting* (FEC) and (2) *Automatic Repeat reQuest* (ARQ). The use of FEC solution becomes useless in situations where the Signal-to-Noise Ratio (SNR) is high. To overcome this problem, adaptive FEC solutions have been proposed. However, with high time varying channels, many of the past proposed FEC solutions can incur high overheads. Automatic Repeat reQuest (ARQ) mechanisms have been used for quite some time in wireless communications. ARQ is a retransmission mechanism that is triggered upon receipt of Non-Acknowledgement (NAK) from the receiver side. However, the ARQ mechanism is not efficient in situations where the wireless channel quality is bad. To avoid FEC and ARQ drawbacks in wireless communications, a new class of error correction mechanisms has been introduced namely, Hybrid-ARQ (HARQ) mechanism, that combines FEC and ARQ mechanisms. HARQ adapts the coding rate according to the channel state and the retransmission mechanism upon receipt of a NAK.

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With pure ARQ mechanism, each data packet should be received correctly. With HARQ type II mechanism, the first transmission contains only payload information and parity bits, similarly to the classical ARQ. If error is detected, the second transmission will contain both of redundancy bits using FEC code and parity bits. If it is received with errors, error correction could be done by combining information received from the two transmissions. At the receiver side, erroneous data blocks are usually stored. Two main combination methods exist: Chase Combining HARQ and Incremental Redundancy HARQ (IR-HARQ). In our work, we use IR-HARQ. Different schemes and algorithms have been proposed for IR-HARQ and the most popular algorithm can be described as follows: the source data is first encoded by a mother code with rate k/n, and then punctured into (a) multiple blocks where each block will be sent in subsequent retransmission order until the source data packet is successfully decoded. If a retransmission is requested, additional selected parity bits are transmitted. At the receiver, the old and new received parity bits are combined to try recovering the source data.

Two other HARQ types exist: type I and type III. Type I is similar to the ARQ scheme but adds a fixed FEC code rate to the packet. With this mechanism, all redundancy bits are sent each time. The receiver tries to correct errors using firstly the FEC code and if it fails, the entire packet is discarded and a retransmission is requested. Type III is similar to type II IR-HARQ where systematic bits (i.e., information bits + Cyclic Redundancy Check (CRC) bits) are always included. The main difference between HARQ type I and HARQ type II mechanisms is that in type I, the transmission of the entire packet is repeated each time a retransmission is needed. However, in type II mechanism, subsequent retransmissions are performed and combined in some way with the packets previously received with errors. The way packets are combined at the receiver side defines the class of type II.

HARQ mechanisms have been extensively evaluated at the MAC layer. By leveraging the cross layer joint optimization paradigm, new HARQ mechanisms have been studied afterwards. Most of the HARQ performance results reported in the literature have been based on cross-layer techniques making use of the Media Access Control (MAC) and physical layer information. However, few research efforts have focused on analytical performance modeling at the network layer. In this paper, we present an analytical framework to analyze the performance of a HARQ mechanism that uses MAC and Internet Protocol (IP) layer information to efficiently control packet retransmissions in wireless networks. By doing so, we demonstrate the superior performance obtained when using such MAC-IP cross-layer strategy as compared to when not using it.

The remainder of this paper is organized as follows. Section 2 presents a brief summary of related works and contributions of this work. Section 3 describes the Hybrid ARQ mechanism that we have adopted as an example, while Section 4 illustrates Reed–Solomon (RS) codes and their use in the Hybrid ARQ mechanism. Section 5 describes the MAC-IP cross-layer IR-HARQ mechanism and the sender and receiver algorithms. The Gilbert-Elliott model and our analytical framework are described in Sections 5 and 6 respectively. Performance evaluation results are presented in Section 6. Finally, we make some concluding remarks in Section 7.

2. Related works and contributions of this work

In this paper, we present a cross-layer mechanism which operates between the MAC layer and the IP layer to apply incremental redundancy hybrid ARQ using Reed–Solomon codes (RS). We describe an analytical framework to analyze the performance of the mechanism. Other contributions which have previously investigated this research topic include [1–4], and more recently [5]. The main difference between our work and that of [5] is that we studied the cross-layered IR-HARQ approach over Gilbert-Elliott two-state-channel while [5] derived performance metrics for closed-form expressions of a larger class of ARQ and HARQ using Gaussian and fading Rayleigh channels with an additive white zero-mean Gaussian noise. Actually, in the work of [5], the authors had to approximate the computation of $p1(k)$ which is the probability that a packet is correctly received after k retransmissions whereas in our work, we derived analytically this probability considering Reed–Solomon codes. Chung and Tsai [4] presented a performance analysis of a multi-radio fast HARQ mechanism for delay-sensitive flows. Retransmission is based on the estimated channel quality and on the length of application data unit with Nakagami-m slow fading channels. The average link packet error probability is approximated but in our work this probability is analytically computed. The authors of [1,3] have presented analytical models to study selective repeat HARQ and ARQ mechanisms. A performance evaluation of SR HARQ is provided in [3] in terms of throughput, number of retransmissions, and delay for Reed–Solomon linear erasure block codes. Choi and Shin [2] presented an analytical derivation of throughput of adaptive HARQ schemes where the error control code and the frame length at the data link layer are used adaptively based on the channel conditions. RS and BCH codes are used. In our work, we only used RS codes, and the strategy of retransmission is different in that it is based on incremental redundancy and we require that a packet with uncorrectable errors can be retransmitted and the retransmitted packet is also re-decoded. Our contribution in this paper focuses on a specific cross-layer MAC-IP HARQ that uses the Incremental Redundancy technique. As we mentioned earlier, we consider the Gilbert-Elliott channel model (G-E) [6,7] using Reed–Solomon (RS) codes [8] to derive typical performance metrics analytically without relying on approximations (as most previous related works have done) and we obtain a good understanding of the behavior of a first MAC-IP cross-layered retransmission process in order to design more complex cross-layer techniques.

3. The CL IR-HARQ mechanism

In our performance analysis, we used the cross-layered IR-HARQ mechanism proposed in [5]. But it is worth pointing out this analysis can be applied to any other IR-HARQ