MULTIPLE ARQ PROCESSES FOR MIMO SYSTEMS

Haitao Zheng, Angel Lozano, Mohamed Haleem

Wireless Research Laboratory, Bell-Labs, Lucent Technologies, Holmdel, New Jersey, U.S.A.
Email: haitaoz, aloz, haleem@lucent.com

Abstract - We propose a new Automatic Retransmission reQuest (ARQ) scheme for MIMO systems with multiple transmit and receive antennas. The substreams emitted from various transmit antennas encounter distinct propagation channels and thus have different error statistics. Using per-antenna encoders, separating ARQ processes among the substreams results in a throughput improvement. Moreover, it facilitates the interference cancellation in certain MIMO techniques. Quantitative results from UMTS simulations demonstrate that the proposed multiple ARQ structure yields more than 30% gain in link throughput.

Keywords- MIMO, HARQ, UMTS, HSDPA

I. INTRODUCTION

Data transmission at the physical layer is always error-prone, especially in wireless environments. Error handling and recovery are implemented in terms of retransmitting corrupted data, often referred to as Automatic Retransmission reQuest (ARQ) [1]. Each transport block or packet is associated with a Cyclic Redundancy Check (CRC). Upon processing the packet, the receiver uses the CRC to validate the content. If the CRC fails, the receiver requests a retransmission. When user traffic is dominated by delay-tolerant applications, retransmissions become feasible and ARQ can provide dramatic improvements in throughput [2].

In MIMO architectures [3,4], multiple transmit and receive antennas are deployed to achieve higher data rates in comparison with single-antenna architectures. In conventional implementations, portions of each encoded packet are transmitted through each of the transmit antennas. If unaware of the presence of MIMO, HARQ simply attaches a single CRC to the packet with such CRC encompassing the data radiated from the various transmit antennas. We refer to this scheme as MIMO Single ARQ (MSARQ), as shown in Fig. 1.

II. SINGLE ENCODER VS. MULTIPLE ENCODERS

While, in order to approach capacity in rich multipath environments, the substreams radiated from the various transmit antennas should be uncorrelated [5], it may in practice be advantageous to jointly encode them. This has motivated a blossoming interest in the design of space-time (vector) codes [6]. Clearly, when the substreams are jointly encoded, they should share a single CRC.

At the same time, since the complexity of joint detection explodes as the number of transmit antennas grows large, there has also been strong interest in devising alternative approaches. One such approach is that of layered architectures, which incorporate multiple scalar encoders, one per transmit antenna. In these architectures, input data is de-multiplexed into multiple substreams, which are then separately encoded and radiated from the various transmit antennas (Fig. 2). At the receiver, the substreams are successively detected and cancelled [3,4]. Specifically, the information extracted from each substream is re-encoded, interleaved and modulated to construct a replica of the transmitted substream. This replica, combined with the channel response, is then subtracted from the overall received signal so that—if there are no errors—the interference contribution of this substream is removed. The complexity of these architectures increases more gracefully with the number of antennas. Furthermore, they can capitalize on existing scalar FEC formats. In fact, it has been shown that a layered architecture can approach the theoretical channel capacity if the data rates of the different transmit antennas are appropriately adjusted [8]. For the purpose of this contribution, however, the most relevant feature of a layered architecture is that it does not constraint the transmit
antennas to share a unique CRC. While it is possible to operate it as a MSARQ, it is also possible to arrange it so that each transmit antenna runs a separate CRC.

Notice that, since substreams transmitted from different antennas encounter distinct propagation channels, they have different error statistics. Using a typical channel propagation model with four transmit and four receive antennas [9], we observe that in more than 70% of error events (an error event occurs when any of the substreams contains an error), only the substreams from one or two transmit antennas are corrupted and thus require a retransmission (Fig. 3). However, upon an error event, an MSARQ receiver has to request a retransmission of the entire packet, because it relies on the single CRC over the whole packet. Re-transmitting substreams that have already been correctly received wastes throughput unnecessarily. Using multiple per-antenna encoders, it becomes possible to remove the constraint that the substreams radiated from multiple transmit antennas share a single ARQ process.

III. MULTIPLE ARQ FOR MIMO SYSTEMS

For per-antenna MIMO encoding architectures, we propose to employ multiple ARQ processes, one for each substream radiated from one transmit antenna or one group of antennas. This scheme is independent of the receiver processing algorithm and only requires that the receiver extracts substreams independently. We name this scheme as MIMO Multiple ARQ (MMARQ). As shown in Fig. 1, a CRC symbol is appended to each substream. At the receiver, each such substream is decoded and the associated CRC is used to validate the content. Multiple acknowledgment (NACK/ACK) indications are sent back to the transmitter, which decides whether to retransmit the substreams in error. We focus on high-speed downlink data transmission so that the overhead due to multiple CRC symbols is negligible. However, we need to consider the uplink signaling overhead due to multiple acknowledgements. For each ARQ process, NACK/ACK requires an overhead of 1 bit plus error protection redundancy. Here, the amount of ARQ feedback overhead scales with the number of transmitters. When the number of transmit antennas is large, grouping the antennas can reduce the signaling overhead.

With MSARQ, interference cancellation and HARQ are typically performed independently of each other. With MMARQ, however, they can be combined advantageously such that, for each substream, the interference cancellation is performed after HARQ operation. More precisely, the reliability of the decoded data is much higher after HARQ and, thus, using such data to reconstruct the signal replicas used for interference cancellation reduces error propagation dramatically.

IV. UMTS-HSDPA SIMULATION

In this section, we compare the performance of MSARQ and MMARQ in the context of UMTS High-Speed Downlink Packet Access (HSDPA) [7]. In HSDPA, users are time-multiplexed in short frames. A scheduler determines which user is served at each frame and the entire HSDPA code space is assigned to the scheduled user. Hence, the transmit signal consists of a superposition of orthogonal codes (see Fig. 2.) There is no power control and the base station adjusts the transmit rate based on feedback from the mobile terminals.
The performance metric is the single-user Over The Air (OTA) throughput, which is defined as the ratio of the number of the correctly received information bits and the transmission time [7] when the entire channel is allocated to a single user. OTA represents the peak net throughput that can be delivered to a user. The following settings are used in the simulation:
- Frequency-flat fading.
- Pedestrian speed (3 Km/hr).
- 70% of transmit power dedicated to HSDPA.
- 10 out of 16 orthogonal codes dedicated to HSDPA.
- 3.33-ms frame.
- Channel: perfectly known at receiver or simulated channel estimation error.
- HARQ scheme: chase combining, N=3 channel Stop And Wait (SAW), 2 frame ACK feedback, 16-bit CRC per process.
- 4 uncorrelated transmit and 4 uncorrelated receive antennas.
- 8 Modulation and Coding Schemes (MCS) employing turbo codes with varying rates and symbol repetition [4]: QPSK rate ¼ repeated 4 times, QPSK rate ¼ repeated 2 times, QPSK rate ¼, QPSK rate ½, QPSK rate ¾, 16-QAM rate ½, 16-QAM rate ¾.

The substreams are decoded according to a fixed order and the MCS of each antenna is separately controlled based on SINR feedback from the receiver [8]. The mapping between SINR and MCS at each antenna is adjusted to maximize the throughput while maintaining some target Frame Error Rate (FER) measured prior to HARQ operation. When this target FER is small (<5%), the probability of retransmission is low and there is no large gain with any kind of ARQ. As the target FER increases, the probability of retransmissions grows and there is a considerable gain with MMARQ. Hence, we optimize the FER to maximize the OTA.

Our initial simulation assumes an ideal environment with perfect channel estimation and perfect uplink feedback. We first examine the advantage of combining HARQ with interference cancellation by comparing the substream error performance of MMARQ and MSARQ. MSARQ performs interference cancellation and HARQ independently, so that the interference from any corrupted substream cannot be eliminated even if the substream is later fully recovered through HARQ. As shown in Fig. 4, such inefficiency yields higher substream error rate. The OTA throughput is shown in Fig. 5, where MMARQ achieves 26-40% improvement compared to MSARQ. Both the combined operation and the multiple ARQ structure contribute to the throughput improvement. In order to quantify the gain due to multiple ARQ structure, we also simulate the OTA throughput of an improved version of MSARQ where the receiver performs interference cancellation twice, one before HARQ operation and one after. This structure is referred to as MSARQ with IC. We see that the gain of multiple ARQ is 10-20%. The ergodic Shannon capacities for one-transmit one-receive and 4-transmit 4-receive systems are also shown in the same figure as references.
binary error of 6%, which can corrupt both the SINR feedback and the NACK/ACK indication(s). Fig. 6 illustrates the OTA throughputs of MMARQ, MSARQ and MSARQ with IC. The degradations due to the imperfect environment are 10-18% for MMARQ, 17-32% for MSARQ and 16-24% for MSARQ with IC. Relatively, MMARQ is less sensitive to estimation noise and feedback error. Overall, MMARQ outperforms MSARQ by 30-45%, while the gain due to multiple ARQ increases to 15-25%.

![Fig. 6 OTA throughput of MMARQ, MSARQ and MSARQ with interference cancellation in a realistic environment with imperfect channel estimation and imperfect uplink feedback.](image)

V. CONCLUSION

We have proposed a new ARQ scheme for MIMO schemes in which substreams radiated from different antennas are encoded separately. Conventionally, a single ARQ process is applied to each data packet. Upon an error event, all constituent substreams—including those that have already been correctly received—are retransmitted. In contrast, the proposed scheme separates ARQ process among the substreams. We have quantified the gains of the new scheme within the context of UMTS high-speed downlink data access. We first consider an ideal environment with perfect channel estimation and uplink feedback, where MMARQ improves the OTA throughput by 25-40%. We then perform the simulation in a realistic environment based on the assumptions of imperfect channel estimation and possibly corrupted uplink feedback. Such uncertainty leads to higher FER, and HARQ becomes a major technique for efficient error control and recovery. Hence, MMARQ is even more favorable where the performance improvement increases to 30-45% compared to that of MSARQ. It should be pointed out that the results presented here are based on the assumption of flat fading, where the substreams display independent error statistics. Frequency-selective fading may change this conclusion and this problem is currently under investigation.

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