Towards Zero-Cost Retransmission through Physical-Layer Network Coding in Wireless Networks

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ABSTRACT

We propose ZEro Retransmission Overhead (ZERO), a novel retransmission scheme which virtually removes the overhead by the retransmission. In our scheme, when a sender retransmits a packet, it piggybacks a new packet. At the receiver side, once the retransmitted packet is correctly received, the receiver can use it for the decoding of the piggybacked packet. Our scheme is essentially a physical layer network coding scheme coupled with modulation. Simulation result shows that our scheme significantly outperforms the previous approaches.

Categories and Subject Descriptors: C.2.2 [Computer-Communication Networks]: Network Protocols

General Terms: Design, Performance

Keywords: Network Coding, Wireless Networks

1. INTRODUCTION

In wireless networks, packet losses are frequently incurred by a few bit errors. However, the majority correct bits are usually dropped together and the whole packet is retransmitted, which wastes network capacity. Recent works propose to utilize the corrupted packet to reduce the retransmission overhead [1, 2]. In Partial Packet Recovery (PPR) [2], the receiver measures confidence values for the correctness of each bit in decoding, and requests for retransmission of only those bits that are likely in error. In SOFT [1], the receiver stores the confidence values of the corrupted packet and combines it with the retransmitted packet, thereby improving packet reception probability.

In this paper, we propose an even better retransmission scheme which significantly reduces the retransmission overhead. Our scheme is essentially a network coding scheme that mixes multiple packets in the retransmission. When the sender retransmits a packet, it piggybacks a new packet. At the receiver side, once the retransmitted packet is correctly received, the receiver can use it for the decoding of the piggybacked packet. As a result, the bandwidth consumption by the retransmission can even be completely removed. Digital network coding such as XORing packets cannot achieve the same effect, as it loses information in the packet encoding process. Therefore, we propose a novel physical layer (baseband signal level) network coding coupled with modulation in which the information of the mixed packets are conserved after the encoding. Simulation result shows that our scheme achieves the median throughput gains of 670% and 60% compared with the traditional retransmission and SOFT, respectively.

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2. PROPOSED IDEA

We start with an illustrative example that shows how our scheme works. Consider the case that the sender has transmitted a packet α, but the receiver has failed to correctly receive it and stored α' which is the corrupted version of α. Suppose the sender has another packet β in its queue. In the next transmission, the sender transmits the mixed packet $\alpha \oplus \beta$, where $\oplus$ is our encoding method of two packets. When the receiver receives $\alpha \oplus \beta$, it first tries decoding of α by

$$F_1(\alpha', \alpha \oplus \beta) = \alpha.$$

If the receiver succeeds to decode α, it utilizes α for the decoding of β.

$$F_2(\alpha, \alpha \oplus \beta) = \beta.$$

In this case, two packets are delivered in two transmissions even though one packet is retransmitted, thereby the overhead by the retransmission being removed. Now, how can we design encoding method $\oplus$ and decoding function F_1 and F_2? If $\oplus$ is traditional network coding operation such as the bit-level XOR, the receiver cannot decode α by the combination of α' and $\alpha \oplus \beta$, as $\alpha \oplus \beta$ does not have enough information to correct the wrong bits of α'. Our scheme is baseband level network coding by which the mixed packet does not lose any information about α and β. It is coupled with modulation and detection schemes. Note that though we use a Binary Phase Shift Keying (BPSK) example in this paper, our scheme can be applied to any modulation which has equal energy symbol for each constellation (*e.g.*, M-ary PSK), at the least.

In order to describe the proposed idea, we first explain how a packet is transmitted over wireless channel. A wireless signal $s(t)$ can be represented as $s(t) = Ae^{jw_ct}$, where w_c is the carrier frequency. The received baseband signal r after down-conversion and matched filtering is $r = hs + n$, where h, s and n are the channel gain, the transmitted baseband signal and Additive White Gaussian Noise (AWGN) respectively. In BPSK, the transmitted signal has two possible constellation points: 1 and -1 which correspond to a bit 0 and 1, respectively. Maximal Likelihood (ML) decision rule of the received signal is

$$\hat{s} = \arg \min_{s \in \{s_1, s_2\}} |r - s|^2.$$

This rule decodes the bit as 0 if r is at the right side of the decision boundary, and 1 if left side (Figure 1(a)).

Now let us consider the method to generate the mixed packet $\alpha \oplus \beta$. In this packet, each signal contains the bit information of both α and β. Assuming that the original modulation is BPSK which has one bit information for each signal, a signal of the mixed packet contains two bits information: one from α and another from β. To carry one more bit in a signal, we add two constellation points j and $-j$, and map two bits for each constellation point as shown in Figure 1 (b) (the bits in the left and right box correspond to the bit of α and β, respectively). Considering that the bit error rate (BER) is proportional to the minimum distance between constellation points, one may argue that our encoding method reduces the reliability of the mixed packet. But as our decoding method utilizes α in the decoding of β, β is decoded without loss of decoding probability.

When the receiver receives $\alpha \oplus \beta$, it first tries to correct the corrupted bits in α' by maximal ratio combining (MRC) of α' and $\alpha \oplus \beta$, as SOFT [1] does. If the decoding of α is successful, the receiver decodes β with α and $\alpha \oplus \beta$. The mixed packet $\alpha \oplus \beta$ has more constellation points, and it makes the receiver more likely mistake in deciding the actually transmitted signal. But the decoded packet α gives us the prior knowledge about where the origin of the signal is. Figure 1(c) and 1(d) illustrate it. Suppose the bit of α is known to be 0. Then the receiver can find that the signal that the sender has chosen is either s_1 or s_3. Therefore, as shown in Figure 1 (c), the receiver has same decision boundary with BPSK for decoding of β. Similarly, it chooses $\hat{s}$ between s_2 and s_4 if the bit of α is 1. As a result, the decoding probability of the combined packet does not differ from that in the decoding of a native packet. This decoding rule can be written as follows:

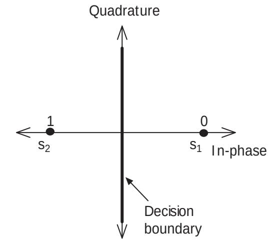
$$\hat{s} = \begin{cases} \arg\min_{s \in \{s_1, s_3\}} |r - s|^2 & \text{if } \alpha = 0, \\ \arg\min_{s \in \{s_2, s_4\}} |r - s|^2 & \text{if } \alpha = 1. \end{cases}$$

3. PERFORMANCE EVALUATION

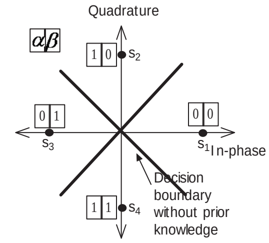
We compare the performance of our scheme with the traditional retransmission and downlink version of SOFT.In this simulation, we generate 300 source- destination pairs whose distance varies from 80m to 150m. We evaluate the normalized throughput after transmitting 1000 packets with the packet size of 1500 bytes. We assume Rayleigh fading channel, path-loss exponent 4, transmission power 20dBm and thermal noise power -63dBm. Figure 2 compares the CDFs of the normalized throughput for the three schemes. In this result, SOFT and our scheme have the minimum throughput 0.41 and 0.49, respectively, whereas 20% of links in traditional retransmission has zero throughput in the given setting. Moreover, our scheme far outperforms the traditional retransmission and SOFT in throughput. For instance, it achieves the median throughput gains of 670% and 60% compared with traditional retransmission and SOFT, respectively. Moreover, while the throughput of SOFT and the traditional retransmission is limited to 0.96, more than 20% of links in our scheme achieves throughput 1.

4. CONCLUSION

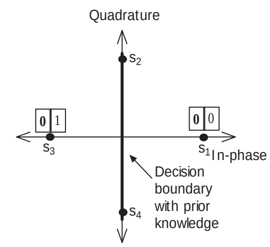
Retransmission is a fundamental tool to fight against bit errors, but its redundancy can significantly impair capacity.



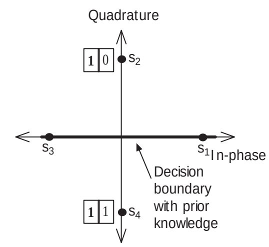
(a) Uncoded packet with BPSK modulation



(b) Coded packet without prior knowledge



(c) Coded packet with prior knowledge $\alpha = 0$



(d) Coded packet with prior knowledge $\alpha = 1$

Figure 1: Signal space and decision boundary with and without physical layer network coding

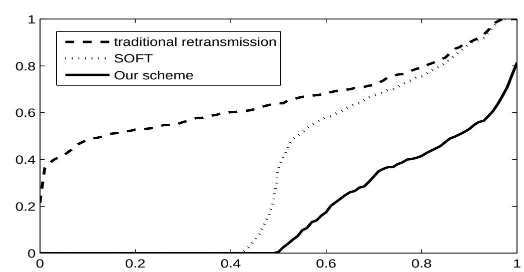


Figure 2: Throughput comparison

Our work is a network coding-based retransmission scheme that virtually removes the retransmission overhead by piggybacking a new packet to the retransmitted packet, without sacrificing the information content or the decoding probability. The performance evaluation result shows that our scheme significantly outperforms the traditional retransmission scheme and SOFT.

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