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Symbol-level reliable broadcasting of sensitive data in error-prone wireless networks

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HIGHLIGHTS

- A novel transmission approach based on the importance of symbols is considered.
- In the case of single packet, we propose an algorithm, and prove its optimality.
- We extend the proposed method to the case of multiple packets.
- We enhance the gain of the proposed method using symbol-level network coding.

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ABSTRACT

Reliable packet transmission over error-prone wireless networks has received a lot of attention from the research community. In this paper, instead of using simple packet retransmissions to provide reliability, we consider a novel retransmission approach, which is based on the importance of bits (symbols). We study the problem of maximizing the total gain in the case of partial data delivery in error-prone wireless networks, in which each set of bits (called symbols) has a different weight. We first address the case of one-hop single packet transmission, and prove that the optimal solution that maximizes the total gain has a round-robin symbol transmission pattern. Then, we extend our solution to the case of multiple packets. We also enhance the expected gain using random linear network coding. Our simulation results show that our proposed multiple packets transmission mechanism can increase the gain up to 60%, compared to that of a simple retransmission. Moreover, our network coding scheme enhances the expected total gain up to 15%, compared to our non-coding mechanism.

1. Introduction

Broadcasting schemes are widely used for disseminating data and control messages in wireless networks. However, the error-prone wireless links creates challenges in these networks. To handle these challenges, different mechanisms [6,30,19,28,20] have been proposed to provide reliability. In the case of numeric data, e.g., the captured information by sensor nodes, the importance of the data (numbers) decreases from the left (most significant bit) to the right (least significant bit). Therefore, any mechanism that addresses numeric data transmissions in a lossy environment should consider the weights of the bits. The problem of reliable transmission has received a lot of attention; however, to the best of our knowledge, nobody has studied the problem of transmitting symbols (a group of bits) with different weights.

In contrast to the previous works, in this paper, we propose a novel broadcasting approach in wireless networks which considers the importance of the symbols. Instead of providing reliable transmissions and guaranteeing a full delivery of the data, we are interested in maximizing the expected total gain of the destination nodes, with a fixed given number of symbol transmissions. In applications such as transmitting numeric data from a source node to a set of destination nodes, encountering an error in more important bits has a more negative impact, and with a given number of transmissions, it is more efficient to allocate more transmissions to the most important part of the data.

Fig. 1(a) shows an example, in which a packet with 2 symbols is transmitted to a destination node. The weights of the symbols s_1 and s_2 are equal to 2 and 1, respectively. Assume that the error-rate of the link is equal to 0.6. The window size for transmitting the packet is equal to 2 symbols, and after that, another packet

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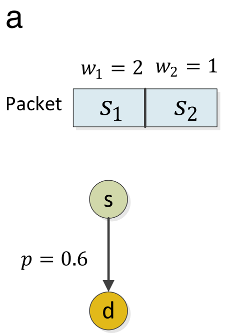

b

2 transmissions

x_1	x_2	Utility
2	0	1.28
1	1	1.2
0	2	0.64

3 transmissions

x_1	x_2	Utility
3	0	1.568
2	1	1.68
1	2	1.44
0	3	0.78

Fig. 1. Motivation example; (a) setting, (b) the choices with 2 and 3 transmissions.

will be ready for transmission. In this case, the traditional methods transmit each symbol once. Now, let us compute the expected gain. We represent the number of transmissions of symbols s_1 and s_2 as x_1 and x_2, respectively. Thus, the probability of successful delivery of symbols s_1 and s_2 is equal to $1 - p^{x_1}$ and $1 - p^{x_2}$, respectively. Consequently, the expected gain is equal to $w_1 \times (1 - p^{x_1}) + w_2 \times (1 - p^{x_2})$, where w_1 and w_2 are the weights of symbols s_1 and s_2. The possible distribution of 2 transmissions and their respective utilities are shown in Fig. 1(b). The figure shows that it is more efficient to allocate both of the transmissions to symbol s_1. Now assume that the window size is equal to 3 transmissions. Fig. 1(b) shows that the optimal solution is allocating 2 transmissions to symbol s_1, and 1 transmission to symbol s_2. It should be noted that if there is no deadline, then the optimal solution is a simple extension from the channel coding theory [5].

Finding the importance of a data is application specific. As another example, consider a multi-layer (multi-resolution) video [21,27,7]. In multi-layer video coding, each video is divided into a base layer and a set of enhancement layers. The base (first) layer is required to watch the video. In contrast, the enhancement layers can increase the quality of the video. However, a layer is not useful without the layers with a smaller index. In this case, the layers with a smaller index are more important than the layers with a greater index. In order to assign weights to the different layers, we can measure the effect (quality enhancement) of adding a layer to the layers with a smaller index and consider it as the weight of that layer.

In this work, we answer the following question. How should we distribute the transmissions to different symbols with unequal importance in order to maximize the total expected gain? While answering this question, we have the following contributions:

- In contrast to previous works, which study the problem of reliable packets or symbol level transmission, we study the problem of maximizing the total gain in the case of partial data delivery.
- In the case of single packet transmission to multiple destinations with homogeneous channel conditions, we propose an algorithm to find the optimal solution, and prove its optimality. This algorithm assigns the transmissions to the symbols in a set of round-robin iterations.
- We also propose an optimal algorithm for the case of transmitting a single packet to multiple destinations with heterogeneous channels.
- We extend the proposed single packet transmission algorithms to the case of multiple packets, and use the advantage of random linear network coding to enhance the expected gain.
- We show that network coding does not necessarily increase the gain, and we find the condition that network coding results in more gain than the non-coding mechanism.

The rest of this paper is organized as follows. Section 2 reviews the related work and describes linear network coding. In Section 3, we provide the problem definition and the setting. We propose our mechanisms for the case of transmitting a single packet in Section 4. In Section 5, we extend our proposed mechanism to the case of transmitting multiple packets, and we boost the gain of the proposed method using linear inter-packets network coding. We discuss the implementation issues in Section 6, and evaluate the proposed mechanisms through simulations in Section 7. Section 8 concludes the paper.

2. Related work and background

2.1. Reliable transmission

Certain mechanisms, such as feedback messages, can be applied in error-prone wireless networks to provide reliability. Automatic Repeat reQuest (ARQ) is one of the most frequently used approaches for addressing this challenge [6]. Nevertheless, ARQ imposes overhead, since it requires transmitting many feedback messages, especially for the case of multi destination nodes. Hybrid-ARQ approaches [30,25], which combine FEC (Forward Error Correction) with ARQ, are proposed to solve this problem. The RMDP approach, which is a complex method, [25] uses Vandermonde [24] code and ARQ to ensure reliability.

Using rateless (fountain) codes [19,28,20] is an efficient way to provide reliability without using feedback messages. In these schemes, the source node can generate and transmit an unlimited number of encoded packets until each destination node receives enough encoded packets to retrieve the original packets. In this scheme, the destination nodes need to collect a sufficient number of encoded packets, regardless of which packets have been lost. Assuming that the number of original packets is k, the number of sufficient coded packets that need to be received is $N = (1 + \epsilon)$ [19], where ϵ is a small number and shows the overhead of the rateless codes. Note that ϵ is independent of the reliability of the links. It can be shown that as $k \to \infty$, the overhead goes to zero [2]. Therefore, rateless codes are very efficient for transmitting a large number of packets, but are inefficient for transmitting a small number of packets. As a result, rateless codes are not appropriate for delay-sensitive applications, such as our problem, which needs small batches of packets.

2.2. Network coding

Network coding (NC) [11,3,23,12] is introduced in [1] for wired networks, to solve the bottleneck problem in single multicast problem. It is shown in [15] that linear network coding achieves the capacity for the single multicast session problem. The authors in [13] provide a useful algebraic representation of the linear network coding problem. *Random linear network coding* is proposed in [9], and it is shown that randomly selecting the coefficients of the coded packets, achieves the capacity asymptotically, with respect to the finite field size.

In random linear network coding, coded packets are the random linear combination of the original packets over a finite field. The coded packets are in the form of $\sum_{i=1}^{k} \alpha_i \times P_i$, where P and α are the packets and random coefficients, respectively. Using random linear network coding, the source node generates and transmits random coded packets and their respective random coefficient vector. The destination nodes are able to decode the coded packets once they receive k linearly independent coded packets. The decoding process is done using Gaussian elimination for solving a system of linear equations. Using this scheme, the destination nodes can send just one acknowledgment message to stop the source node