Physical Layer Network Coding for Wireless Applications: A Survey

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Abstract Physical layer network coding is a relatively new paradigm in networking which exploits interference, instead of avoiding it, to significantly enhance network throughput, robustness, and security. It has been extensively studied for wired networks and wireless ad-hoc networks. In this paper, we provide a survey of this rapidly evolving area, summarize some recent results, and discuss potential benefits of network coding in modern wireless networks such as WiMAX, 3G Long-Term Evolution (LTE), and LTE-Advanced.

Key words Network Coding, Multi-Hop Relays, Link Adaptation, LTE, LTE-Advanced, WiMAX

1 Introduction

Consider a network of multiple nodes connected via point-to-point links. Further assume that data from a sending node to be transmitted to one or more receiving nodes. Traditionally, information is transmitted from the sending node to each destination node through one or more intermediate nodes acting as relays. In relay nodes, packets of data that are received on an input link are stored and a copy is forwarded to the next node en route to destination nodes. In this store-and-forward approach the output link is dedicated to transmitting one data packet at a time.

It was not until recently that this old paradigm in network data communication was reexamined [1], the concept of network coding introduced, and the advantage of network coding over store-and-forward was first demonstrated. Ever since its introduction, network coding has emerged as a topic of much interest in a number of application areas including wireless communications. The bulk of the literature on network coding deals with wired and wireless computer networks, especially local area networks. But the concept of network coding can be equally beneficial in metropolitan area networks too. The gains observed from the application of network coding in LAN are considerable and if they can be replicated in larger networks, such as the 802.16 WiMAX, the 3G long-term evolution (LTE) and the future LTE-advanced, it is well worth investigating the potential areas of applications in these systems.

In this paper, we describe the basics of network coding with the aid of examples. Then we discuss the benefits of network coding for the specific case of IEEE 802.16e standards, also known as WiMAX.

2 Network Coding

2.1 An Example

A simple example of relaying in a wireless network is shown in Figure 1. The example depicts two neighboring nodes, S1 and S2, of a communication network at a distance twice the wireless transmission range. A relay node R, is located midway between S1 and S2. The relay node can either receive or transmit one packet in each unit of time. In the first instance, we assume that the store-and-forward approach is used by the relay allowing S1 and S2 exchange one packet of data in four units of time. In the first two units of time, the relay receives one packet from each side. In the subsequent two units of time, it broadcasts the packets it received one packet per time unit.

Figure 2 shows the second instance of packets being relayed by R. But this time R adopts the network coding approach for achieving better network utilization. In this scenario, the first two units of time are taken by S1 and S2 for sending their packets to R. Next, the relay node combines the two packets, in this case by exclusive-OR $\oplus$, for broadcasting the resulting packet. Since both S1 and S2 nodes have knowledge of their respective transmitted packets, they can extract the packet intended for them from the received combine packet $a \oplus b$. This simple example demonstrates that a 25% increase in the throughput is achievable by applying network coding as compared with the store-and-forward method.

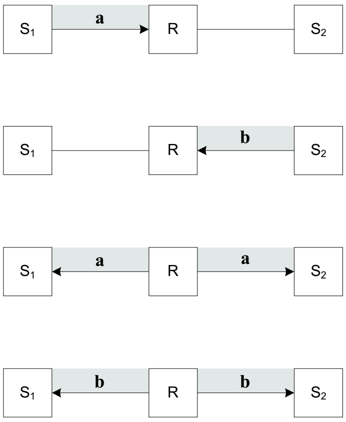

Figure 1: A store-and-forward relay takes four units of time to have S_1 and S_2 exchange data packets a and b.

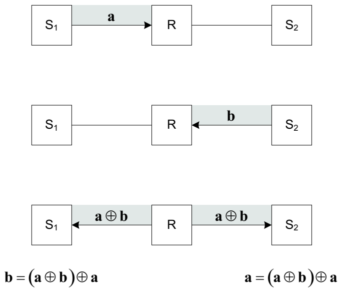

Figure 2: The relay applies network coding to combine the packets received from S1 and S2 before broadcasting the coded packet. The receiving nodes recover the original packets from the coded packet.

2.2 Linear Network Code

Physical implementation of network codes incurs processing delay at the nodes. It is therefore desirable that the coding mechanism inside a network code be implemented by simple and fast circuitry. For this reason, network codes that involve only linear mappings are of particular interest. Consider a node which has packets $p_1, p_2, \cdots, p_n$ for transmission. These packets can be from one or several sources. For convenience we assume that all packets have the same size of L bits. Each packet p_i is partitioned into symbols $\{p_{i,k}|k = 1, 2, \cdots, L/s\}$ consisting s successive bits. With linear network coding, outgoing packets, each denoted by x consists of symbols x_k where each is a linear combination of the symbols from the original packets. This means:

$$x_k = \sum_{i=1}^{n} c_i p_{i,k} \tag{1}$$

Here $\mathbf{c} = [c_1, c_2, \cdots, c_n]$ is the encoding vector, and $\mathbf{x} = \left[x_1, x_2, \cdots, x_{L/s}\right]$ is the information vector both defined in Galois Field GF(2^s).

The example of Figure 2 is a linear network code with symbols from GF(2) and the encoding vector $\mathbf{c} = [1, 1]$. For decoding of the m-th received packet, we assume that it contains the encoding vector $\mathbf{c_m}$ in addition to the information vector $\mathbf{x_m}$. In order to recover the original packets $p_1, p_2, \cdots, p_n$, the receiving node needs to solve the system of equations:

$$\mathbf{x}_m = \sum_{i=1}^{n} c_{m,i} p_i \tag{2}$$

for the set unknowns $\{p_i|i = 1, \cdots, n\}$.

3 Potential Benefits of Network Coding

3.1 Higher Throughput

A key result of network coding is that it can increase the capacity of a network for multicast traffic. For example, consider the network shown in Figure 3 and taken from [2]. The vertices in the directed graph of Figure 3 represent nodes, and the edges of the graph represent point-to-point channels. Assume that there are M sending nodes, and N receiving nodes. All receivers are interested in receiving all sources. Now, if the source rates are such that each receiver can decode all sources when it is the only receiver in the network, then with an appropriate choice of linear coding coefficients, the network can support all receivers simultaneously ([1][3]).

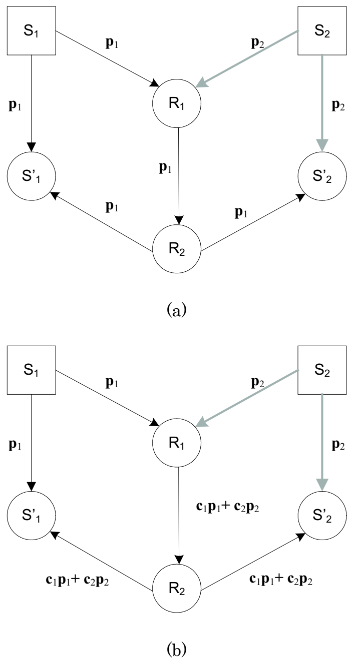

Figure 3: An example of how network coding can improve throughput; (a) store-and-forward relaying (b) network coding approach.

In Figure 3, S_1 and S_2 multicast to both S'_1 and S'_2. For simplicity assume that all links have normalized capacity equal to unity. In Figure 3(a), where store-and-forward approach is adopted, the capacity of the link between nodes R_1 and R_2 is shared for transmitting the packets from both sources. In this case, S'_1 receives packets from S2 at half the rate it does from S1. As such, both receiving nodes can receive at 150% of the link capacity. With network coding, however, the packets from both sending nodes are combined on the link from R_1 to R_2. As such, S'_1 receives packets from both sending nodes with the same rate. Thus, the achievable rates are 200% for each receiving node. This is equivalent to each receiving node using the network for its sole use. The throughput benefits of network coding are also achievable for unicast communications. Consider again Figure 3 but assume now that source S_1 transmits to destination S'_2 and S_2 to S'_1. With network coding we can send at rate 100% of the link capacity to each receiver, while without, we can only send at rate 50% to each receiver.

3.2 Enhanced Robustness

Another benefit of network coding is improved robustness in packet transmission. Network coding takes information packets and produces encoded packets, where each encoded packet contains information from all the data packets. Provided a sufficient number of encoded packets are received, the transmitted data packets can be retrieved.

In the example of Figure 1, assume that S_1 and S_2 may move out of range at random and without notifying the node R. If the relay node R broadcasts a (or b), the transmission might be completely wasted, since the intended destination might not be able to receive. However, if the R broadcasts $a \oplus b$, the transmission will bring new information to the active nodes.

4 WiMAX Network Coding: Two Examples

We give two examples of the benefits of network coding in WiMAX. Although our examples are focused on the use of network coding in WiMAX, these can be extended to systems such as LTE and LTE-Advanced because of similarities.

4.1 Multi-Hop Relays

In this subsection, we provide a design example [?] to demonstrate the advantages of network coding in multi-hop relaying. The scenario illustrated in Figure ?? can be related to part of a WiMAX network that consists of three stations: base station S_1, relay station R, and subscriber station S_2. In this scenario, node R is a customer premise equipment. We assume that a number of connections have been established that traverse the path S_1-R-S_2 and vice-versa because node S_1 and S_2 do not locate in the coverage area of each other. We also assume for simplicity that there is only one class of traffic. To enable network coding, we can partition a frame in the time domain into slots, which can be naturally supported in WiMAX. Note that multiple connections can share the same slot if they share the same next hop node. For the example we introduced previously, node S_1 can combine all data toward node S_2, and node S_2 can combine all data toward S_1. With the same reasoning provided for the examples of Figures 1and 2, it is easy to see that traditional multi-hop relaying in WiMAX would require four time slots for the exchange of data between the base station and the user equipment. On the other hand, with network coding, the number of required time slots is reduced to three. This would require that receiving nodes decode the received block of data in the network layer.

4.2 Link Adaptation

Adaptive coding and modulation (AMC) is a useful feature of WiMAX that allows the transmission rate be adapted to time-varying channel conditions. However, effectiveness of AMC is limited by the timeliness and accuracy of the channel state information (CSI) from the receiver. In order, to improve the effectiveness of AMC, it is complimented at the physical layer of WiMAX by Hybrid Automatic Retransmission reQuest (HARQ). This is a variant of the ARQ error control protocol, combining ARQ with Forward Error Correction (FEC). However, HARQ incurs overhead with its retransmissions and ACK/NACK packets leading to decreased throughput. In addition, in handover and multi-hop transmission modes in WiMAX, a mobile station is able to establish connections with several uplink nodes through different sub-channels. In these cases, HARQ is not able to fully utilize the wireless bandwidth, as it is designed for a point-to-point channel. Here HARQ is independently performed on individual links, incurring additional overhead. In [5], the effectiveness of network coding in WiMAX in comparison with HARQ has been investigated. In this case, a MAC-layer protocol has been designed by employing random network coding, rather than the traditional HARQ at the physical layer. It has been demonstrated that random network coding offers robust and stable transmission. With network coding, should a packet be lost, subsequent packets contain the information carried in the lost packet. Therefore, random network coding has been shown to be able to adapt the rate of data transmission to match the available bandwidth in time-varying wireless channel conditions. In addition, the mobile station is able to enjoy data transmissions from several upstream nodes concurrently with random network coding, in which case the wireless medium is fully utilized. Specifically, it has been shown in [5] network coding can achieve 10% throughput gain as compared with HARQ on single-hop transmissions. More significantly the throughput variance was reported to have reduced by 50% leading to more stable data rates. Throughput gains of 65% and 35% were reported for handover and multi-hop scenarios, respectively, with similar reductions in throughput variance.

5 Conclusions

Network coding offers advantages over the traditional store-and forward routing approach. Although the benefits of network coding in local area networks have been investigated, its application in wider area networks such as WiMAX, LTE, and LTE-advanced is mostly unexplored. In this paper, we explained the fundamentals of network coding and presented some examples of usefulness of this approach in WiMAX. These examples showed significant advantages of network coding over its traditional counterparts that it warrants investigating areas in the 3G LTE and LTE-Advanced systems where network coding can be applied.

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