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Implementation of physical-layer network coding☆,☆☆

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ABSTRACT

This paper presents the first implementation of a two-way relay network based on the principle of physical-layer network coding (PNC). To date, only a simplified version of PNC, called analog network coding (ANC), has been successfully implemented. The advantage of ANC is that it is simple to implement; the disadvantage, on the other hand, is that the relay amplifies the noise along with the signal before forwarding the signal. PNC systems in which the relay performs XOR or other denoising PNC mappings of the received signal have the potential for significantly better performance. However, the implementation of such PNC systems poses many challenges. For example, the relay in a PNC system must be able to deal with symbol and carrier-phase asynchronies of the simultaneous signals received from multiple nodes, and the relay must perform channel estimation before detecting the signals. We investigate a PNC implementation in the frequency domain, referred to as FPNC, to tackle these challenges. FPNC is based on OFDM. In FPNC, XOR mapping is performed on the OFDM samples in each subcarrier rather than on the samples in the time domain. We implement FPNC on the universal soft radio peripheral (USRP) platform. Our implementation requires only moderate modifications of the packet preamble design of 802.11a/g OFDM PHY. With the help of the cyclic prefix (CP) in OFDM, symbol asynchrony and the multi-path fading effects can be dealt with simultaneously in a similar fashion. Our experimental results show that symbol-synchronous and symbol-asynchronous FPNC have essentially the same BER performance, for both channel-coded and non-channel-coded FPNC systems.

1. Introduction

In this paper, we present the first implementation of physical-layer network coding (PNC) on the software radio platform. We believe this prototyping effort moves the concept of PNC a step toward reality. Our implementation work also exposes and raises some interesting issues for further research.

PNC, first proposed in [1], is a subfield of network coding [2] that is attracting much attention recently. The simplest system in which PNC can be applied is the two-way relay channel (TWRC), in which two end nodes A and B exchange information with the help of a relay node R in the middle, as illustrated in Fig. 1. Compared with the conventional relay system, PNC could double the

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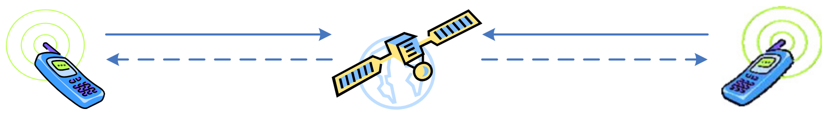

Fig. 1. System model for physical-layer network coding.

throughput of TWRC by reducing the needed time slots for the exchange of two packets from four to two [1]. In PNC, in the first time slot, end nodes *A* and *B* send signals simultaneously to relay *R*; in the second phase, relay *R* processes the superimposed signals and maps them to a network-coded packet for broadcast back to the end nodes. From the network-coded packet, each end node then makes use of its self-information to extract the packet from the other end node [1,3,4].

Prior to this paper, only a simplified version of PNC, called analog network coding (ANC) [5], has been successfully implemented. The advantage of ANC is that it is simple to implement; the disadvantage, on the other hand, is that the relay amplifies the noise along with the signal before forwarding the signal, causing error propagation.

To the best of our knowledge, the implementation of the original PNC based on XOR mapping as in [1] has not been demonstrated, even though it could have significantly better performance. A reason is that the implementation of XOR PNC poses a number of challenges. For example, the relay must be able to deal with symbol and carrier-phase asynchronies of the simultaneous signals received from the two end nodes, and the relay must perform channel estimation before detecting the signals.

This paper presents a PNC implementation in the frequency domain, referred to as FPNC, to tackle these challenges. In particular, FPNC is based on OFDM, and XOR mapping is performed on OFDM samples in each subcarrier rather than the samples in the time domain. We implement FPNC on the universal soft radio peripheral (USRP) platform. Our implementation requires only moderate modifications of the packet preamble design of 802.11 a/g OFDM PHY. With the help of the cyclic prefix (CP) in OFDM, symbol asynchrony and the multi-path fading effects can be dealt with in a similar fashion. Our experimental results show that symbol-synchronous and symbol-asynchronous FPNC have nearly the same BER performance for both channel-coded and non-channel-coded FPNC.

As far as we know, [6] is the first paper that proposes the use of OFDM for PNC. Besides discussing various issues related to the application of OFDM in PNC, it presented a theoretical analysis on applying OFDM in PNC systems to deal with the OFDM sample asynchrony problem. To tackle sample offset, the authors proposed to sample at the midpoint of the two optimal sampling points of the respective end nodes (i.e., the two adjacent peals of the matched filter output). This was considered as the best compromise. However, for real systems operating with OFDM, the sampling positions are often not important. We show in Section 2.1 that the the time-domain sampling position, in fact, has little effect on the frequency domain samples we need, since the pulse shape of the time-domain samples of OFDM is closer to a *sinc* waveform than a rectangular waveform.

Challenges

In the following, we briefly overview the challenges of PNC, and the implementation approaches taken by us to tackle them:

Asynchrony

There are two possible implementations for PNC: synchronous PNC and asynchronous PNC. In synchronous PNC, end nodes *A* and *B* have the uplink channel state information (CSI). They perform precoding and synchronize their transmissions so that their signals arrive at relay *R* with their symbols and carrier phases aligned. For high-speed transmission, such tight synchronization is challenging; in addition, timely collection of CSI is difficult in fast fading scenarios.

Asynchronous PNC is less demanding. It does not require the two end nodes to tightly synchronize and precode their transmissions. In particular, knowledge of the uplink CSI is not needed at the two end nodes. The simplicity at the end nodes comes with a cost. Without precoding and synchronization of the two end nodes, their signals may arrive at the relay with symbol and carrier-phase misalignments. A key issue in asynchronous PNC is how to deal with such signal asynchrony at the relay [7,8].

This paper focuses on the implementation of asynchronous PNC. To deal with asynchrony, our FPNC implementation makes use of OFDM to lengthen the symbol duration within each subcarrier. Then, independent XOR PNC mapping is performed within each subcarrier. OFDM splits a high-rate data stream into a number of lower-rate streams over a number of subcarriers. Thanks to the larger symbol duration within each subcarrier, the relative amount of dispersion caused by the multipath delay spread is decreased. The OFDM symbols of the two end nodes become more aligned with respect to the total symbol duration, as illustrated in Fig. 2. In particular, if the relative symbol delay is within the length of the CP, the time-domain misaligned samples will become *aligned* in the frequency domain after *DFT* is applied. This property will be elaborated later in Section 2.

Channel estimation

For good performance of asynchronous PNC, the relay must have the knowledge of the uplink CSI. This has been the assumption in many prior works on PNC (e.g., [1,6]). This means that the relay will need to estimate the channel gains. Most channel estimation techniques for the OFDM system assume point-to-point communication in which only one channel needs to be estimated. In PNC, the relay needs to estimate two channels based on simultaneous reception of signals (and preambles) from the two end nodes. This poses the following two problems in PNC that do not exist in point-to-point communication: