Physical Communication 6 (2013) 4–42

Contents lists available at SciVerse ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

Physical-layer network coding: Tutorial, survey, and beyond ☆

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ARTICLE INFO

Article history:
Received 25 April 2011
Received in revised form 4 March 2012
Accepted 3 May 2012
Available online 11 May 2012

Keywords:
Physical-layer network coding
Network coding
Two-way relay channel
Wireless networks

ABSTRACT

The concept of physical-layer network coding (PNC) was proposed in 2006 for application in wireless networks. Since then it has developed into a subfield of network coding with wide implications. The basic idea of PNC is to exploit the mixing of signals that occurs naturally when electromagnetic (EM) waves are superimposed on one another. In particular, at a receiver, the simultaneous transmissions by several transmitters result in the reception of a weighted sum of the signals. This weighted sum is a form of network coding operation by itself. Alternatively, the received signal could be transformed and mapped to other forms of network coding. Exploiting these facts turns out to have profound and fundamental ramifications. Subsequent works by various researchers have led to many new results in the domains of (1) wireless communication, (2) information theory, and (3) wireless networking. The purpose of this paper is fourfold. First, we give a brief tutorial on the basic concept of PNC. Second, we survey and discuss recent key results in the three aforementioned areas. Third, we examine a critical issue in PNC: synchronization. It has been a common belief that PNC requires tight synchronization. Recent results suggest, however, that PNC may actually benefit from asynchrony. Fourth, we propose that PNC is not just for wireless networks; it can also be useful in optical networks. We provide an example showing that the throughput of a passive optical network (PON) could potentially be raised by 100% with PNC.

1. Introduction

The concept of physical-layer network coding (PNC) was originally proposed in [1] as a way to exploit the network coding operation [2,3] that occurs naturally in superimposed electromagnetic (EM) waves. It is a simple fact in physics that when multiple EM waves come together within the same physical space, they add. This additive mixing of EM waves is a form of network coding, performed by nature. Alternatively, the additive network coding operation can be transformed and mapped to other forms of network coding after reception. Exploiting these facts turns out to have profound and fundamental ramifications.

In many wireless communication networks today, interference is treated as a destructive phenomenon. When multiple transmitters transmit radio waves to their respective receivers, a receiver receives signals from its transmitter as well as from other transmitters. The radio waves from the other transmitters are often treated as interference that corrupts the intended signal. In Wi-Fi networks, for example, when multiple nodes transmit together, packet collisions occur and none of the packets can be received correctly.

As originally proposed in [1], PNC was an attempt to turn the situation around. By exploiting the network coding operation performed by nature, the "interference" could be put to good use. In a two-way relay channel (TWRC), for example, by allowing the two end nodes to transmit simultaneously to the relay and not treating this

☆ This is an Invited Paper.

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doi:10.1016/j.phycom.2012.05.002

as collision, PNC can boost the system throughput by 100% [1].

To our knowledge, the same idea as PNC for application in TWRC was also independently proposed in [4]. Ref. [1], however, went beyond TWRC to discuss the application of PNC in general network topologies. In addition, the implications of PNC for MAC (medium access control) protocols and network-layer designs were also discussed in [1]. The potential benefit of network coding taking into account the characteristics of the multiple-access channel was investigated in [5] from an information-theoretic angle. Unidirectional multicast communication was the focus in [5], whereas bidirectional unicast communication was the focus in [1,4]. In [1,4,5], the relay maps the weighted sum of the simultaneously received signals to another form of network coding before relaying the information. Ref. [6] proposed and implemented a simple version of PNC called Analog Network Coding (ANC) in which the weighted sum is simply amplified and forwarded. The same idea was proposed for application in the satellite network in an earlier paper in 1998 [7]. In this article, we will broadly refer to all the above schemes that exploit simultaneous reception of signals to effect network coding operations as PNC schemes.

Since 2006, many researchers have made contributions that advance the understanding of PNC. The flavors of the research fall into three general categories: (1) communication-theoretic studies; (2) information-theoretic analyses; and (3) network and protocol designs. PNC raises many new interesting issues on each of the three fronts. For example, an interesting issue from the communications standpoint is the extent to which synchronization of the simultaneous transmissions by multiple transmitters to a receiver is required in a PNC system. An interesting information-theoretic issue is the extent to which the cut-set bound on the information capacity can be approached when PNC is applied to TWRC. Interesting networking issues include how to apply PNC in a network setting with many sources and destinations, and how to design multiple-access protocols to exploit the fact that not all interferences are bad in a wireless network operated with PNC.

The purpose of the present paper is fourfold. First, we give a brief tutorial on the basic concept of PNC and related key issues. Second, we survey and discuss recent results on the above three fronts. Third, we examine a critical issue in PNC: synchronization. It has been a common belief that PNC requires tight synchronization. We present some recent results suggesting that PNC may actually benefit from asynchrony. Fourth, we put forth the idea of "optical PNC". We provide an example showing that the throughput of a passive optical network (PON) could potentially be raised by 100% with optical PNC. Our target audience includes new entrants in the area, as well as researchers and engineers that need to see the bigger picture of PNC.

Throughout this article, the term "capacity" is used in the information-theoretic sense. That is, by "capacity", we mean information-theoretic capacity in which a data rate below the capacity can be achieved with arbitrarily low error probability with channel-coded packets of large length. The term "throughput" is used in the networking sense. In a network, the modulation, the maximum packet length, the channel code, and many other design parameters may have been fixed. Given a signal-to-noise ratio, the data rate on a link, or its throughput, may be lower than the information capacity. Unless otherwise stated, when discussing "throughput" in the networking context, we assume that the system is designed to have low packet error rates so that packet errors can be ignored: this could be achieved by incorporating a sufficiently large power margin.

The remainder of this paper is organized as follows. Section 2 is a brief tutorial introducing the basic concept of PNC and overviewing various issues arising from PNC. Section 3 goes into the details of communication-theoretic studies of PNC. Results on asynchronous PNC and channel-coded PNC are discussed. Section 4 overviews some information-theoretic results of PNC and examines their implications. Section 5 considers MAC and network layer issues arising from PNC. In Section 6, we propose the idea of optical PNC. We conclude this paper in Section 7 by presenting some worthwhile future directions for PNC research.

2. A brief tutorial of PNC

The easiest way to illustrate the concept of PNC is through TWRC. TWRC is a three-node linear network in which two end nodes, nodes 1 and 2, want to communicate via a relay node *R*. There is no direct signal path between nodes 1 and 2. An example is a satellite network in which nodes 1 and 2 are the ground stations, and the relay *R* is the satellite.

The half-duplex constraint is often imposed on wireless communication systems to ease engineering design. With the half-duplex constraint, a node cannot transmit and receive at the same time. This means that the relay in TWRC cannot receive from node 1 or node 2 and transmit to them at the same time. A corollary is that each packet from node 1 to node 2 (and similarly, each packet from node 2 to node 1) must then use up at least two time slots to reach its destination. Thus, the best possible packet exchange throughput is two packets for every two time slots, one in each direction.

In the following, we examine the number of time slots needed for nodes 1 and 2 to exchange one packet with each other in various systems. In particular, we show that PNC can achieve the upper bound throughput of two packets every two time slots.

To proceed quickly to our discussion in a tutorial style, here we opt for a "bottom-up" approach in which notations are defined when they are first used. Readers who prefer a "top-down" approach are referred to the Appendix for the formal definitions of the TWRC system model and the collection of related notations. Throughout this paper, we use the uppercase letter to denote a packet and the corresponding lower-case letter to denote a symbol within the packet. For example, S_1 is a packet, and s_1 is a symbol within the packet.