

# Multi-way Communications: An Information Theoretic Perspective

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## Multi-way Communications: An Information Theoretic Perspective

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## Abstract

Multi-way communication is a means to significantly improve the spectral efficiency of wireless networks. For instance, in a bi-directional (or two-way) communication channel, two users can simultaneously use the transmission medium to exchange information, thus achieving up to twice the rate that would be achieved had each user transmitted separately. *Multi-way communications* provides an overview on the developments in this research area since it has been initiated by Shannon. The basic two-way communication channel is considered first, followed by the two-way relay channel obtained by the deployment of an additional cooperative relay node to improve the overall communication performance. This basic setup is then extended to multi-user systems. For all these setups, fundamental limits on the achievable rates are reviewed, thereby making use of a linear high-SNR deterministic channel model to provide valuable insights which are helpful when discussing the coding schemes for Gaussian channel models in detail. Several tools and communication strategies are used in the process, including (but not limited to) computation, signal-space alignment, and nested-lattice codes. Finally, extensions of multi-way communication channels to multiple antenna settings are discussed.

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# 1

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## Introduction

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The foundation of information theory by C. E. Shannon in 1948 laid the cornerstone for one of the greatest –if not the greatest– revolutions of our time; the communications revolution. Shannon established the fundamentals of a theory that is responsible for making almost every aspect of our daily activities easier, including social, financial, and educational activities.

The evolution of communications from its beginning to date can be described as a chain-reaction. Applications that require communication were few in the beginning. Thus, communication networks back then supported low data rates. The availability of such networks motivated developing applications that exploit them. In turn, this leads to higher demand on data rates, and thus requires developing the networks to support higher rates; and the process repeats itself. Nowadays, our lives became strongly dependent on communications. A great deal of our daily activities are executed through mobile communications or the internet using a diverse range of devices.

This process requires studying all aspects of communications technology from theory to practice. One important aspect is the information theoretic aspect which provides the fundamental performance limits of

a given network. Such limits are the ultimate goal of a practical network design, and are therefore of significant importance.

Since Shannon's days, there has been a great deal of research in information theoretic aspects of communication networks. Most of the focus in the beginning was on the point-to-point channel (P2P) [139], the multiple-access channel (MAC) [1, 96], the broadcast channel (BC) [16, 17, 44], and the interference channel (IC) [2, 21, 22, 62, 130].

There has also been a great deal of interest in cooperative communication with various types of cooperation. One of these types is feedback from the receivers to the transmitters. The first work on feedback is that by Shannon in 1956 [140]. Another one of the important types of cooperation in network information theory is cooperation through relaying. The basic model to study this problem is the 3-node relay channel (RC) which was first introduced in 1971 by van der Meulen [165] and several schemes for this network were developed by Cover and El Gamal [45]. Recent information-theoretic studies on RC's can be found in e.g. [85] and references therein. Relaying can be expected to be adopted in current and future wireless systems, as it has been introduced in the IEEE 802.16j (WiMAX) standard.

These works mainly focus on one-way communication, i.e., from one or more transmitters to one or more receivers. However, the most common kind of communication is two-way. That is, two nodes exchange information (audio, video, etc.) between each other in both directions, where a node is not either a source or a destination, but both. This kind of cooperative communication is known as two-way communication, or more generally multi-way communication. It is important at this point to note that the term 'multi-way' that appears in van der Meulen's famous survey [166] as well as Ahlswede's article [1] refers generally to multi-user communications. Although the Shannon's two-way channel [141] has been discussed in [166], it is put under the same umbrella with the MAC, BC, RC, and IC. The common factor in all these channels is that they are multi-user channels. Recently however, the term 'multi-way' has been used to refer to multi-user channels consisting of nodes which are simultaneously sources and destinations, which is the focus of this manuscript.

Multi-way communication can lead to significant improvement in the performance of communication networks if adopted. Take the P2P channel from node 1 to node 2 as an example. If a feedback link is present between node 2 and node 1, it was shown that this link does not increase the capacity of the channel [140], but can be used to reduce the complexity of the communication [132]. However, if the feedback link is used to send information in the opposite direction from node 2 to node 1 as in the two-way channel (TWC) [141], then the overall capacity of the channel can significantly increase. This can be seen for instance in the Gaussian TWC which decouples into two parallel channels [61], and hence, has an overall capacity that is double the capacity of the P2P channel with feedback. On the other hand, using a relay to forward information in both directions to the communicating nodes that want to exchange information in both directions is much better than using it as in the classical RC. Thus, the performance of the RC is enhanced by using the relay as a bi-directional relay. This fact has triggered many researchers to focus their attention on bi-directional relaying [13, 59, 109, 125], uncovering its potential, and highlighting its significance to both the practical and theoretical communities.

The main goal of this manuscript is to introduce the reader to the work done in the field of multi-way communications, and to highlight some interesting open problems in this field. To this end, we organize the manuscript as follows.

- **Chapter 2** discusses the two-way channel and extensions to multi-way channels.
- **Chapter 3** discusses the two-way relay channel, which is essentially similar to the two-way channel, but where communication is facilitated by a relay node.
- **Chapter 4** discusses the multi-pair two-way channel, which consists of multiple two-way relay channels coexisting in the same medium.
- **Chapter 5** discusses the multi-way channel, which is a the extension of the two-way relay channel to a multi-user case with

arbitrary information exchange, not necessarily pair-wise as in the multi-pair two-way channel.

- **Chapter 6** discusses extensions of the previous chapters, where nodes are equipped with multiple antennas (MIMO nodes).

Note that the two-way channel is the fundamental building block of multi-way communication networks. It models a scenario where two nodes use the same medium to communicate in both directions. This channel is introduced in Chapter 2 where outer and inner bounds on its capacity region are presented. The idea of adaptive coding is introduced in this chapter and discussed. Furthermore, some related work treating extensions to multi-way channels is summarized, with main focus on whether adaptive coding is required or not in such channels.

Assume that the two communicating nodes in a TWC are physically separated, due to some obstruction or long distance between them. How can these nodes communicate? A potential solution is to use relay nodes to enable this communication. Deploying a relay node in the TWC leads to the so-called two-way relay channel. Chapter 3 introduces this channel and studies its capacity. In general, this channel models scenarios where two nodes communicate in both ways through a base-station or a satellite node. We use the linear-deterministic (LD) approach proposed by Avestimehr *et al.* [10] to capture the essence of the problem, and to determine a good transmission and relaying scheme for the Gaussian TWRC in terms of achievable rates. For the Gaussian channel, we study the performance of quantize-and-forward and compress-forward strategies at the relay. We analyze the achievable rate region and show that the cut-set bounds are achievable within a constant gap for all values of channel gains.

An interesting question one might ask is whether the treatment of the TWRC changes if multiples pairs of nodes are involved in the communication. Do the cut-set bounds remain tight? How does the coding scheme change? Chapter 4 discusses these issues by studying the capacity region of multi-pair TWRC (MP-TWRC). This network is an extension of the TWRC to a multi-user scenario with pair-wise message exchange. This problem is first examined in the context of the LD channel model. The capacity region of this network with two

pairs of users when the relay is operating in the full-duplex mode is characterized. It is shown that the cut-set upper-bound is tight and the capacity region is achieved by a so-called divide-and-conquer relaying scheme. The insights gained from the LD network are then applied in the Gaussian MP-TWRC. The scheme in the LD channel translates to a specific superposition of lattice codes and random Gaussian codes at the source nodes and successive decoding at the destination nodes. This constitutes the main difference to the TWRC; the coding scheme consists of multiple layers of TWRC schemes decoded successively at the destinations. The achievable rate of this scheme with two pairs is analyzed and it is shown that for all channel gains it achieves the cut-set upper-bound within a constant gap.

The common factor between the TWRC and the MP-TWRC is that communicating nodes are grouped into pairs. What happens if these nodes are not grouped this way, but rather want to communicate in all directions? This scenario is studied in Chapter 5. The resulting network is called the multi-way relay channel (MWRC). This channel models networks consisting of multiple nodes communicating with each other in all direction through a centralized access network such as a cloud. The 3-user case, known as the Y-channel, is analyzed first. The capacity region of the LD Y-channel is characterized by using 3 modes of communication: bi-directional communication, cyclic communication, and uni-directional communication. Interestingly, it turns out that the cut-set bounds are not tight in this case, contrary to the TWRC and the MP-TWRC. Then, these communication modes are extended to the Gaussian Y-channel by using nested-lattice codes, and the capacity region of the Gaussian Y-channel is characterized within a constant gap. The sum-capacity of the  $K$ -user Y-channel is characterized afterwards within a constant gap as well. The multi-cast MWRC is also discussed in this chapter, which differs from the Y-channel in that nodes send common messages instead of private ones.

Finally, extensions of Chapters 2-5 are discussed in Chapter 6. This chapter mainly focuses on multi-antenna (MIMO) extensions of the TWRC, the MP-TWRC, and the MWRC, and highlights the main advances achieved in this aspect. MIMO communication is interest-

ing since it allows harvesting spacial multiplexing gain, giving rise to higher achievable rates. This chapter further highlights open problems of interest in MIMO multi-way communication.

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