Chapter 1
Information Theoretical Limits on Cooperative Communications

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ABSTRACT

This chapter provides an overview of the information theoretic foundations of cooperative communications. Earlier information theoretic achievements, as well as the more recent developments, are discussed. The analysis accounts for full/half-duplex node, and for multiple relays. Various channel models such as discrete memoryless, additive white Gaussian noise (AWGN), and fading channels are considered. Cooperative communication protocols are investigated using capacity, diversity, and diversity-multiplexing tradeoff (DMT) as performance metrics. Overall, this chapter provides a comprehensive view on the foundations of and the state-of-the-art reached in the theory of cooperative communications.

INTRODUCTION

In traditional communication networks data transmission directly occurs between the transmitter and the receiver. No user solicits the assistance of another one. However, in a general communication network, there are many intermediate nodes that are available to help. For example in wireless networks, when one node broadcasts its messages, all nearby nodes overhear this transmission. Processing and forwarding these messages to the intended destination, system performance, whether it be throughput, lifetime, or coverage area, can be improved. To understand how much performance improvement can ideally be possible by this "cooperative" network, we need an information theoretical study. Such a study also elucidates how cooperation should take place and helps construct the backbone for future cooperative communication applications.

Figure 1. The three-terminal communication channel
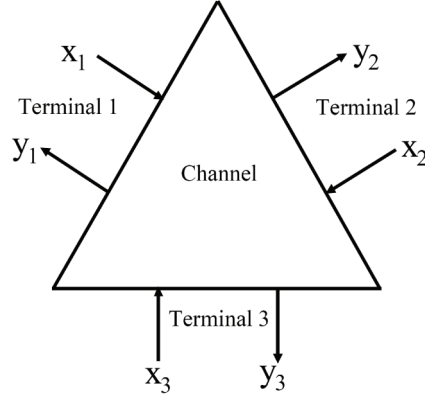
In information theory the idea of cooperation was first presented by van der Meulen (1971), which established the foundations of the *relay channel*. The relay channel is a three-terminal network, in which Terminal 1 (source) aims to transmit to Terminal 3 (destination) with the help of Terminal 2 (relay) as in Figure 1. The aim is to attain the highest communication rate from Terminal 1 to Terminal 3. In general the intermediate relay enhances communication rates of the direct link from Terminal 1 to 3.

To elaborate the idea of enhanced communication rates via relaying, here we introduce an example from (van der Meulen, 1971). Table 1 gives the channel output probabilities $P(y_2, y_3|x_1,x_2)$ conditioned on input pairs (x_1, x_2) when the destination is assumed to be silent $(x_3=0)$. Observe that if $x_2 = 1$, both y_2 and y_3 are equal to 1 no matter what x_1 is. Neither the relay, nor the destination can distinguish the correct x_1 and hence, communication rates between the source and the relay, and the source and the destination are equal to zero given $x_2 = 1$. When $x_2 = 0$, the channels between the source and the relay, and the source and the destination both become equivalent to a binary symmetric channel with crossover probability 1/2, whose capacity is also equal to zero. Hence, no direct communication is possible from the source to the relay, or from the source to the destination. However, non-zero communication rates from the source to the destination can be achieved with the help of the relay. Observe that if $x_2 = 0$ and the destination knows the channel output y_2, then the source can send 1 bit noiselessly to the destination. On the other hand, the destination can learn about y_2, if the relay helps the source and transmits its output signal after its own observation is complete. This information can be sent at rate 0.32 bits/channel use when x_1 is set to 0. By appropriate time division between these two strategies, (van der Meulen, 1971) proves that the capacity of this example channel is equal to 0.243 bits/channel use with vanishing error probability. As this example clearly shows, relaying can substantially increase achievable rates with respect to direct transmission.

The relay channel is essential to both wired and wireless networks. In wired networks many source and destination pairs are connected via intermediate relay nodes. In wireless networks, due to the *wireless broadcast advantage* idle nodes overhear nearby transmissions. These nodes can relay the information and contribute to achieving higher rates.

The capacity of the relay channel was calculated in (van der Meulen, 1971) only for some particular example channels. Guidelines for communication/relaying principles in a general relay channel were

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