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An Approximation Approach to Network Information Theory

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Abstract

This monograph illustrates a novel approach, which is based on changing the focus to seek approximate solutions accompanied by universal guarantees on the gap to optimality, in order to enable progress on several key open problems in network information theory. We seek universal guarantees that are independent of problem parameters, but perhaps dependent on the problem structure. At the heart of this approach is the development of simple, deterministic models that capture the main features of information sources and communication channels, and are utilized to approximate more complex models. The program advocated in this monograph is to use first seek solutions for the simplified deterministic model and use the insights and the solution of the simplified model to connect it to the original problem. The goal of this *deterministic-approximation* approach is to obtain universal *approximate characterizations* of the original channel capacity region and source coding rate regions. The translation of the insights from the deterministic framework to the original problem might need non-trivial steps either in the coding scheme or in the outer bounds. The applications of this deterministic-approximation approach are demonstrated in four central problems, namely unicast/multicast relay networks, interference channels, multiple descriptions source coding, and joint source-channel coding over networks. For each of these problems, it is illustrated how the proposed approach can be utilized to approximate the solution and draw engineering insights. Throughout the monograph, many extensions and future directions are addressed, and several open problems are presented in each chapter. The monograph is concluded by illustrating other deterministic models that can be utilized to obtain tighter approximation results, and discussing some recent developments on utilization of deterministic models in multi-flow multi-hop wireless networks.

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1

Introduction

In his seminal paper [96], Shannon provided a complete solution to the fundamental limits of point-to-point communication, usually referred to as Shannon's channel coding theorem and Shannon's source coding theorem. Since the coding schemes allowed are of arbitrary block lengths, the original design problem is an infinite-dimensional optimization problem. Yet, the optimal solution, characterizing the fundamental limits of point-to-point communication, can be expressed as that of a finite-dimensional optimization problem ("single-letter" characterization). Moreover, for many specific channels and sources, this finite-dimensional optimization problem can be solved explicitly in closed form. This desirable feature is remarkable and almost unique among engineering fields, but it also sets a high standard for the information theory field.

A holy grail of information theory is to extend Shannon's point-to-point result to the network setting. The general network information theory problem is to analyze the fundamental limits of communication when multiple senders want to communicate with multiple receivers with the help of intermediate nodes. The first success came in the early 1970's, when Ahlswede [1] and Liao [57] independently provided a single-letter characterization of the capacity region of the multiple access channel. In this network, K users want

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to send information to a common receiver across a noisy channel. This result is rather general in the sense that it holds for an arbitrary number of users as well as arbitrary (memoryless) channel statistics. It led to much excitement in the field at that time. However, as it turned out, there have been essentially no other network information theory results of such generality since then. Most of the other results, for example, hold for only two users (such as the degraded message set problem for broadcast channels) or for a specific class of channel or source statistics (such as degraded broadcast channels). Even these results are few in number. Thus it is fair to say that we are still very far from solving the general network information theory problem, almost forty years after Ahlswede and Liao's discovery.

One of the critical ingredients to Shannon's seminal work was that of appropriately modeling the problem. The channel and source models in Shannon's work [96] are probabilistic, specified by the channel transition probability distribution, and the source probability distribution. This is a natural choice since the channels and sources we face in practice usually cannot be predicted in a sufficiently accurate manner, and probabilistic models best capture such uncertainties. The further simplification he introduced was to represent them as (discrete) memoryless channels and (discrete) memoryless sources. Though this is a simplification of reality, the success/impact of these ideas to practical systems demonstrated that it captured the essence of problem. However, Shannon's focus was on point-to-point channels and the natural question to ask is how to extend the models to networks, in a manner that still captures the essence of these problems. In addition to describing the nature of the sources and communication links, the network setting also requires a specification of the demand structure of the generated/required information. More specifically, the network model needs to identify the following:

- **Network connectivity structure:** this component abstracts the connections between various nodes, such as whether there exist communication channels between a set of nodes;

- **Source demand structure:** the component captures the source placement before and after the communication, *i.e.,* whether a particular source is present at a given node, whether it is to be reconstructed at a given node, whether in a lossless or lossy manner;

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- **Communication channels:** this component captures the dependence among various channel inputs and outputs for any given channel in the network, specifying the broadcast and interference signal interaction; the noisy communication model leads to a probabilistic model that is specified by a channel transition probability distribution;

- **Source generation structure:** this component captures the probabilistic structure of a given source and the dependency among different sources, which is usually specified by the joint probability distribution of the sources.

Taking the above general view, the point-to-point communication problem considered by Shannon has the latter two components to be non-trivial and probabilistic, yet the first two components to be extremely simple. One way of modeling the network problem is to consider in generality all the four components. Given the complexity of tackling such a general problem, most of the works in multiuser information theory traditionally considered special structures for the network connectivity and source demand structures while still maintaining the probabilistic modeling. A notable exception is the problem studied by Ahlswede et. al. in [4], which abandons the probabilistic model for the communication channels/source generation and focuses on the first two components of demand structure; in fact, the channels in the network are completely clean, operating just as bit pipes, and the sources are independent messages. Yet, even in this network consisting of clean channels, one remarkable aspect revealed in [4, 56] is that non-trivial coding (coined *network coding*) has to be performed in order to achieve the capacity for a non-trivial (multicast) demand structure. However, even with this simplification, the capacity region for *arbitrary* demand structure is still unknown. Going further, since most of practical channels and sources are unpredictable, the important question following the original work in [4, 56] is whether those ideas can be extended to noisy (probabilistic) channels and to include more general sources, and thus the field of network coding starts to converge with conventional multiuser information theory in the past ten years.

Given the above discussion, it is clear that communication problems in the network setting pose two kinds of difficulties: the first kind of difficulty is largely caused by the noisy (probabilistic) nature of the channels and the

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sources, which was the sole difficulty faced by Shannon in solving the point-to-point communication problem; the second kind of difficulty is largely caused by the interaction between communication entities, which is unique in the network setting. One of the motivations of our work is to think about network problems with these components in mind, and develop meaningful (yet tractable) models for which we can characterize network information flow rates. Moreover, these models should allow one to give fundamental insights to network communication problems that arise in practice. In order to do this, we need to understand the special classes of sources, channels and demand structures that can arise in practice.

A class of channels and a class of sources that have received much attention are linear Gaussian channels with quadratic cost constraint and Gaussian sources with quadratic distortion measure respectively. Not only are these models practically relevant for applications such as wireless and sensor networks, the physically meaningfulness of their structures gives some hope that Gaussian problems are easier to solve than the general case. Indeed, as is well-known, the capacity of the point-to-point Gaussian channel and the rate-distortion function of the Gaussian source are known in closed form. Can this luck help us make more progress in Gaussian network problems than in the general case? The answer is yes for broadcast channels. While the capacity region of the general broadcast channel is open even in the case of two users, the capacity region of Gaussian broadcast channels with arbitrary number of users is known. However, it seems that the luck ran out rather quickly as most Gaussian network problems are still open. Examples are interference channels (even the two-user case is open), relay networks (even the single-relay channel is open), multiple description and distributed lossy source coding (both open for more than 2 users). So it seems that Gaussian network problems are not too much easier than the general ones. However, they do give structure that we aim to capture in simplified models for the channel/source specification.

In this monograph we advocate a sequential approach to make progress on the network communication problem. In order to do this, we simplify the channel (and source) model to capture the essence of the network communication problem. In point-to-point channels, the only source of uncertainty for communication was the noise, modeled through a probabilistic channel.

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However, in a network, uncertainty can arise due to signal interaction (broadcast, multiple access interference) and therefore as a first step we consider *deterministic* signal interaction for communication that attempts to *approximately* capture the noisy scenario[1]. The model approximation step however has to be done strategically, such that the essential characteristics of the original problem can be largely retained. For channel coding problems, we wish to retain the source demand structure, and to approximate the original noisy (probabilistic) channels and the network connectivity structure with deterministic channels and the corresponding (possibly slightly different) network connectivity structure. For source coding problems, we wish to retain the network connectivity structure, and to approximate the original probabilistic sources and the source demand structure with a new set of simplified sources and the corresponding (possibly different) source demand structure. Finally, for a joint source-channel coding problem, we may need to approximate most of the components in the network to reach a new model.

Approximating the noisy (lossy) problem by a noiseless (lossless) one not only allows us to first focus on the signal interaction, but more importantly, noiseless problems are often much easier than noisy problems. For example, while the general noisy broadcast channel problem is open, the deterministic broadcast channel is solved (independently by Pinsker [79] and Marton [61]); while the general lossy distributed source coding problem is open (even for two users), the lossless distributed source coding problem is solved (the celebrated Slepian-Wolf Theorem [104]). Perhaps with the intuition that studying deterministic networks can provide important insights, there were some efforts devoted to this approach in the early 1980s (see deterministic relay channel [6, 31], deterministic interference channel [32] among others). However, these vanguard approaches did not explicitly translate the implications of these results on deterministic networks to the noisy problems of interest.

In particular, one of the critical steps advocated in this monograph is to use the insights and the solution of the simplified model and connecting it to the original problem. This leads us to the concept of *approximate characterizations* of the channel capacity region and source coding rate regions. By

[1] In [105], it is mentioned that Shannon had an unpublished work "Systems which approach the ideal as $P/N \to \infty$," March 1948, which pre-dated [96], where he studied the high-SNR behavior of Gaussian channels. This could be an early insight of Shannon into the deterministic approach.

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finding the optimal solution for the communication problem in the approximate (deterministic) model, we look for insights and techniques that can be used on the original probabilistic channels or sources (through some possibly non-trivial translations).

The kind of approximation we seek is to be *universal* in that its gap to optimality can depend on the problem structure, but not the particular parameters of the scenario. For example, in the noisy network communication problem, we do *not* want the approximation gap to depend on the noise level (or "signal-to-noise" ratio) or channel strengths; though it could depend on the overall network structure. Similarly, in the lossy data compression problem, we do not want the approximation gap to depend on the particular distortion level desired. The form of the approximation could be either additive (capacity within "constant number of bits") or multiplicative (capacity or distortion approximated to within a "constant factor").

To summarize, the approach we advocate has two levels of approximation, and it consists of four main steps:

- Model approximation: *noisy* channel coding problems are approximated by *noiseless* problems; lossy source coding problems are approximated by *lossless* problems.

- Analysis: analyze the simplified problem, and possibly find complete solutions for them.

- Translation: translate new insights and techniques, and use them to find new schemes and/or outer bounds to the original probabilistic problem.

- Approximate characterization: derive a worst-case gap of the performance of the proposed scheme to optimality, universal for all values of the channel parameters, yielding a universal approximate characterization of the capacity region or the rate region.

Approximate solutions to information theory problems are not new. However, they are by and far isolated results, each with its own proof technique. What distinguishes the approach we advocate here from these results is that it is a systematic approach with two levels of approximation that can be applied to *many* problems, as we shall discuss in this monograph.

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Though the approach above is general, we focus largely on one class of channels and one class of sources, namely linear Gaussian channels with quadratic cost constraint and Gaussian sources with quadratic distortion measure respectively. Not only are these models practically relevant for applications such as wireless and sensor networks, the models themselves have canonical properties that we hope to exploit (like linearity, quadratic cost/distortion etc.). Therefore, further simplification of the Gaussian model to deterministic (lossless) should retain some of the essence of the original noisy (lossy) model. This suggests that a natural approximate model should be almost linear, and as we shall see, indeed this kind of approximation is very insightful for the Gaussian problems. In fact the approximation of real numbers with binary expansions turns out to be a very useful interpretation/approximation tool for Gaussian problems.

Before we illustrate the approach in more detail, we address a few natural questions that can arise about this program. One fundamental question is what the approximate characterizations seek to achieve. The utility of the deterministic/approximation approach is to evaluate which information transmission/compression techniques are universally (approximately) efficient, and therefore give guidelines to engineering design. These might yield new coding techniques that arise from the deterministic approach or be more salutary in showing that existing techniques are (provably) quite good. Though ideally one would like an exact characterization in terms of a finite dimensional optimization problem, this approximation approach gives guidelines of what we are "fighting for" (for the last bit of efficiency or much more?). This kind of philosophy has been successfully applied in computer science (approximation algorithms) and queueing theory (fluid limit of traffic). Moreover, interpreting the approximations should be done carefully with respect to the regimes of interest. For example, the kind of universal approximation we seek becomes relatively more accurate when the noise is small compared to the signals (interference-limited or low-noise regime). So while the worst-case gap (universal approximation) holds for all parameter ranges, the performance gap is more meaningful in the low-noise regime where the achievable rates are high. The dual statement for source coding is that the approximation using this approach becomes relatively more accurate when the target distortion levels are small and the required rates are high.

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In this monograph, we will illustrate this approach and demonstrate its application to four central problems in network information theory: (1) Relay networks, (2) Interference channels, (3) Multiple descriptions problem , and (4) Joint source-channel coding over networks. We will conclude the monograph by discussing other deterministic models that can be utilized to obtain tighter approximation results, and some recent developments on utilization of deterministic models in multi-unicast multi-hop wireless networks.

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