Network Coding Applications

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Abstract

Network coding is an elegant and novel technique introduced at the turn of the millennium to improve network throughput and performance. It is expected to be a critical technology for networks of the future. This tutorial deals with wireless and content distribution networks, considered to be the most likely applications of network coding, and it also reviews emerging applications of network coding such as network monitoring and management. Multiple unicasts, security, networks with unreliable links, and quantum networks are also addressed. The preceding companion deals with theoretical foundations of network coding.

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1

Introduction

The emergence of network coding has brought about a metamorphosis in thinking about network communication, with its simple but important premise that in communication networks, we can allow nodes to not only forward but also process the incoming independent information flows.

Today, ten years after the emergence of the first example of network coding the butterfly network, a lot is already known about network coding, in particular for the case of network multicast. Network multicast refers to simultaneously transmitting the same information to multiple receivers in the network. The fascinating fact that the original network coding theorem brought was that the conditions necessary and sufficient for unicast at a certain rate to each of these receiver are also necessary and sufficient for multicast at the same rate, provided the intermediate network nodes are allowed to combine and process different information streams.

In the first part of the tutorial [24], we examined in detail the case of network multicast, mainly from a theoretical point of view. We argued that network coding can and has been studied within a number of different theoretical frameworks, in several research communities, most notably Information Theory and Computer Science. The choice of framework a researcher makes most frequently depends on his/her background and preferences. However, one may also argue that each network coding issue (e.g., code design, throughput benefits, complexity) should be put in the framework in which it can be studied the most naturally and efficiently.

The goal of the second part of the tutorial, is to depart from the multicast scenario, and discuss how ideas from network coding can have impact on a number of new applications.

Today, more and more researchers and engineers ask what network coding is, what its benefits are, and how much it costs to design and operate networks implementing network coding. At this point, we do not have complete answers to these questions even in the case of network multicast. For example, the minimum network operating costs required to achieve maximum throughput are not known in general in terms of the code alphabet size and the number of routers required to code. (Multicast in networks with two sources and arbitrary number of receivers is almost completely understood.)

Even less is known in the arguably practically more important case of multiple unicasts, where we do not have a good understanding of the theoretical limits and on how to achieve them. Today, not even the throughput benefits of coding have been completely characterized. Although there are directed graph instances where the network coding throughput increase is proportional to the number of nodes in the graph, we are yet to find an undirected graph instance where network coding offers any benefits. Another transmission scenario for which benefits of coding are not fully understood are networks with non-uniform demands. Studying general traffic patterns is complicated from the fact that optimal solutions may require exponential alphabet sizes and nonlinear operations. We discuss such issues in Section 5.

Also, work is just beginning to address the problem of disseminating correlated information over network coded systems, and more generally the problem of distributed source coding. Such connections between source coding and network coding is one of the topics that we will not cover in this tutorial.

The Microsoft's Avalanche system has sparked the interest in using network coding for content distribution. Various tests and measurements have been carried out on experimental P2P systems, and results together with numerous observed advantages of using network coding were reported (see Section 3). Fine-tuning this approach for specific applications, such as video on demand, and developing a theory that would completely support the experimental evidence, is still missing.

Network coding allows to take advantage of the broadcasting capabilities of the shared wireless medium to provide benefits in terms of bandwidth, transmission power, and delay, as we will argue in Section 4. Clearly to warranty the deployment of such techniques, the required processing of data within the network needs to have low complexity and power consumption. MIT's COPE demonstrated that even when coding operations are confined to simple binary additions obeying some additional constraints, there are still gains to be had in terms of throughput and efficiency of MAC layer protocols. The first approaches on wireless network coding ignored the interference of multiple broadcast transmissions at a receiver. One can show that such strategies can incur significant losses in terms of achievable rates. Physical layer network coding was a first attempt to remedy this. Very recently, a linear deterministic model was developed that captures the interactions between the signals in a wireless network, and was shown that for such models one can obtain an information-theoretic max-flow min-cut result. Wireless and sensor networks provide vast opportunities for applications of network coding, and numerous and diverse problems are beginning to receive attention, ranging from techniques such as cross layer design over issues such as fairness and delay, to untuned radios and distributed storage.

Another line of recent work deals with networks in which some edges are in a certain way compromised. The information carried by such edges may be deleted, altered, or observed by an adversary whose information gain we would like to limit. Information may also be lost due to channel errors. Usually, no assumption is made on the choice of such edges, but their number is limited. Network codes can be designed for such networks, although some throughput has to be sacrificed to accommodate for compromised edges. The maximum achievable throughput is known for most of such scenarios, and it depends on the size of the affected edge set. Algorithms for designing error-correcting, attack resilient, and secure network codes have also been proposed, and we discuss some of them in Sections 6 and 7. Very recently an elegant approach to error correction was introduced based on the use of subspaces. For some cases however, more related to security, the codes we have today require huge alphabet size and are in general too complex to implement. Thus design of practical codes is of interest. In general, combining network coding with security is an area with many interesting open questions. Information theoretic tools have also been useful here to characterize achievable rates, for, up to now, specific sets of networks with lossy links.

These days we are beginning to see network coding ideas being put to use in problems other than increasing throughput in networks with multiple users. There is evidence that network coding may be beneficial for active network monitoring, as well as passive inference of link loss rates. Interestingly, in a system employing randomized network coding, the randomly created linear combinations implicitly carry information about the network topology, that we can exploit toward diverse applications. Use of network coding techniques can help to increase rates of multicast switches, leverage the efficiency of databases, and reduce on-chip wiring. We briefly discuss such applications in Section 9.

The network coding butterfly has even reached quantum information theorists (see Section 8). If we recall that in multicast communications networks, large throughput gains are possible with respect to their (physical) transportation or fluid counterparts because classical information can be processed in a way that physical entities cannot, an interesting question to ask is whether anything can be gained by allowing processing of quantum information at nodes in quantum networks. Although physical carriers of quantum information can be processed in certain ways determined by the laws of quantum mechanics, two operations essential in classical information networking, replication (cloning) and broadcasting, are not possible. However, approximate and probabilistic cloning as well as different types of compression of quantum states are possible, and have been used in attempts to find a quantum counterpart of network coding.

The reason that network coding continues to be a very active field is clearly due to the benefits it promises to offer. As we mentioned earlier, we discuss in Section 4 how network coding can help to better exploit shared resources such as wireless bandwidth, and to conserve scarce resources, such as battery life. Moreover, it can offer benefits in terms of *reliability* against channel errors and *security*, as we discuss in Sections 6 and 7, respectively. Although all these are important, perhaps the most interesting benefits of network coding might manifest in situations where the topology dynamically changes, and operation is restricted to distributed algorithms that do not employ knowledge about the network environment. This is the topic of the following Section 2.

We hope that the research effort in the area of network coding will continue to increase, bringing new exciting results and applications, and making the results described in this tutorial very fast outdated.

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