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Distributed Coding in A Multiple Access Environment

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Full text available at: http://dx.doi.org/10.1561/1300000063

Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
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Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

Y. Tang, F. Heydaryan and J. Luo. *Distributed Coding in A Multiple Access Environment*. Foundations and Trends® in Networking, vol. 12, no. 4, pp. 260–412, 2018.

ISBN: 978-1-68083-469-7
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Foundations and Trends® in Networking

Volume 12, Issue 4, 2018

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Foundations and Trends® in Networking, 2018, Volume 12, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Contents

Distributed Coding in A Multiple Access Environment

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ABSTRACT

With the fast expansion of communication networks and the increasing dynamic of wireless communication activities, a significant proportion of messages in wireless networks are being transmitted using distributed protocols that feature opportunistic channel access without full user coordination. This challenges the basic assumption of long message transmissions among coordinated users in classical channel coding theory. In this monograph, we introduce channel coding theorems for the distributed communication model where users choose their channel codes individually. We show that, although reliable message recovery is not always guaranteed in distributed communication systems, the notion of fundamental limit still exists, and can indeed be viewed as an extension to its classical correspondence.

Due to historical priority of developing wireline networks, network architectures tend to achieve system modularity by compromising communication and energy efficiency. Such a

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Yanru Tang, Faeze Heydaryan and Jie Luo (2018), "Distributed Coding in A Multiple Access Environment", Foundations and Trends® in Networking: Vol. 12, No. 4, pp 260–412. DOI: 10.1561/1300000063.

choice is reasonable for wireline systems but can be disastrous for wireless radio networks. Therefore, to reduce efficiency loss, large scale communication networks often adopt wireless communication only at the last hop. Because of such a special structure, architectural inefficiency in wireless part of the network can be mitigated by enhancing the interface between the physical and the data link layers. The enhanced interface, to be proposed, provides each link layer user with multiple transmission options, and supports efficient distributed networking by enabling advanced communication adaptation at the data link layer. In this monograph, we focus on the introduction of distributed channel coding theory, which serves as the physical layer foundation for the enhanced physical-link layer interface. Nevertheless, early research results at the data link layer for the enhanced interface are also presented and discussed.

1

Introduction

A fundamental challenge in wireless networking is to efficiently share the open wireless channel among highly dynamic users. Classical information theory [20] and network theory [11] both have been investigating this key topic for half a century, but from two different angles and along two separate paths that have not yet converged [22].

Because wireless medium often needs to be shared among devices with tight bandwidth and power budgets, communication efficiency is a central concern in wireless systems. Classical information theory [20], particularly channel coding theory, addresses the "efficiency" concern by characterizing the fundamental performance limitation of a wireless channel, and this consequently provides design guidance for wireless systems to achieve or to approach the theoretical efficiency limits. However, information theory was originally developed in an environment when major wireless applications, such as mobile telephony and TV broadcast, only involved transmitting long messages to or from a small number of structured users. To achieve optimal efficiency, channel coding theory suggests that users in a communication party should jointly choose their channel codes, which includes the joint optimization of communication parameters such as information rate and transmission power [29][21][20]. This is termed the "coordinated" communication model in this monograph. Classical channel coding theory assumes that, so long as the messages are long enough and their corresponding coding schemes are optimized, overhead and possible inefficiency in coordinating the communication party should be negligible.

Wireless devices nowadays are often connected into communication networks which typically involve large numbers of users and a wide range of network functions. Modularized architecture is a crucial requirement for developing such large complex network systems [11]. Classical network theory addresses the "modularity" concern by proposing layered network architectures such as the open systems interconnection (OSI) model and its variations [96][69]. By partitioning communication functions into abstraction layers with clearly defined interfaces, OSI model allows system design and optimization to be focused on one or a small number of neighboring layers without the worry of how the outcome can fit into the general system. However, modularity usually does not come without a cost, and compromising low priority resources is a natural choice for achieving system modularity. Classical network theory was originally developed in an environment when the key demand was to connect computers to build the wireline internet infrastructure. For wireline systems, bandwidth of a network cable and communication power of a computer are relatively abundant. Consequently, classical network theory emphasizes the support of a wide range of communication functions in the design of layering interfaces and network protocols, but pays relatively less attention to the impact that the design proposals can have on communication efficiency of the involved systems.

With the computing power of mobile devices and wireless sensors exceeding previous generation large computers, the demand of wireless networking applications is increasing at a dramatic pace. However, developments of advanced wireless networks still suffer from the lack of a theoretical foundation that addresses both concerns of "efficiency" and "modularity" simultaneously. Because classical information theory and network theory each only emphasizes one aspect of the concerns and ignores the other one that is equally important, the need of a unification of the two classical frameworks should be quite apparent [22].

Indeed, such a vision has been recognized for decades, as witnessed by a long list of publications ranging from cross layer utility optimizations [76][93][27] to understanding networking phenomena from information theoretic perspectives [31][60][5][56], from the milestone results on wireless network scaling law [38][39][92], to the celebrated development of fountain channel coding [15][54][74][70][88], and to the historical discovery of network coding [2][52][49][91][43]. These results investigated efficiency problems in various layers of the network architecture from different perspectives. However, not all the problems are specific to wireless networks and therefore are not necessarily among the list of pressing concerns due to the increasing demand of wireless networking. Most of the research results mentioned above also did not suggest explicit architectural revisions to address the corresponding efficiency problems.

The viewpoint that we are going to introduce in this monograph is unique in the following senses. The associated architectural problem lies in the physical and the data link layers. It is an efficiency bottleneck, but only for wireless part of the networks. Furthermore, the research investigations to be presented are motivated and centered around a particular proposal of interface enhancement between the physical and the data link layers. The proposal was originally suggested in [58][87] and then in [55], but has never been thoroughly presented and explained. Therefore, this monograph serves as the first rigorous, in a relative sense, introduction of the research vision and the corresponding research results.

1.1 The Single-hop Cellular Structure

Direct extensions of classical information theoretic and network theoretic frameworks to wireless networking have their own inherited challenges at the bottom two layers, especially when there is a lack of balanced respect to the efficiency and the modularity concerns. Understanding these challenges is essential for identifying the missing pieces needed for the potential unification of the classical frameworks.

On one hand, channel coding theory provides design guidance by characterizing performance limitations such as channel capacity of a communication system. While such efforts have been highly successful in single user [71][72][81] and structured multiuser systems such as multiple access [1][53][90][94] and broadcast systems [19][9][10][30][89], the picture does not look so bright when it comes to a general multiuser network. Deriving channel capacity or capacity region of a general multiuser system is often extremely challenging. Even if one can be confident about solving the capacity problems, an equally important concern is the assumption of the coordinated communication model which has infiltrated into many aspects of the channel coding problem formulations [22]. More specifically, because a wireless network often involves a significant number of users with dynamic short message transmissions, the assumption that all users can be fully coordinated with a negligible overhead is no longer justified in such an environment. Performance limitations obtained in classical channel coding theory provide little guidance to the design and optimizations of distributed and partially distributed communication systems, which are commonly seen in wireless networks [11].

On the other hand, while extending the existing network architecture to wireless systems appeared to be more practical, not all extensions can stand the test of time. With revisions to handle wireless-specific problems such as the hidden and the exposed nodes problems [7], wireless devices can be effectively connected to carry out networking functions. Such extension enabled the exponential growth of Wi-Fi networks [77], which belong to the class of single-hop wireless networks in the sense that either the transmitter or the receiver in each transmission is directly connected to a wireline network. In Wi-Fi networks, wireless routers and client devices are often organized into a cellular-type structure with each micro cell being managed by one router and with interference between different cells well controlled via channel or space separations. By scheduling communication activities within each cell, and exploiting multiple access, broadcast and multiple antenna communication techniques, communication efficiency can be managed at an acceptable level. However, when it comes to multi-hop wireless networks, such as multi-hop bluetooth networks [61] and WiMax networks [3], the stories are quite different. While wireless devices can be connected effectively, most of the proposed multi-hop wireless networks failed to become popular mainly due to their low communication efficiency. Although it is well known that the throughput of wireless systems often does not scale well [38][39][92], the fact that only Wi-Fi-type networks can sustain an acceptable level of efficiency is primarily due to the architectural design details that intentionally or unintentionally compromised bandwidth and energy efficiency of many of the wireless systems.

Because of the difficulties in extending classical theoretical frameworks, major network systems tend to use wireline networks as their backbone and to use wireless links only at the last hop. Wireless devices are often organized into a cellular-type structure to best exploit operational guidance from both classical information theory and classical network theory. In this monograph, we term this special structure the "single-hop cellular structure", as illustrated in Figure 1.1. There have been continuous demands and research efforts to extend wireless systems beyond the single-hop cellular structure [22][37]. However, most of these efforts face a clear dilemma. That is, while the inefficiency of the current network architecture limited its capability in supporting complex wireless network structures, a complete redesign of the network architecture is also in lack of a strong incentive because the current architecture does work reasonably well for the wireline part of

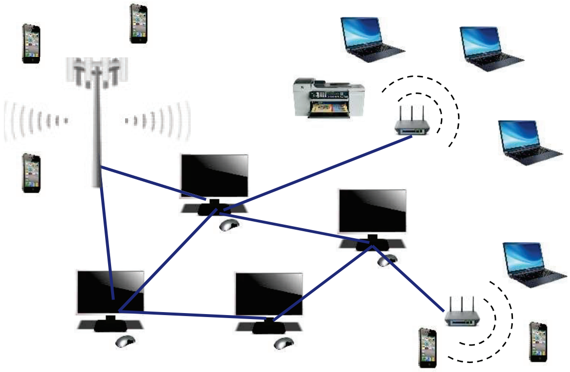

Figure 1.1: The single-hop cellular structure.

the networks. This dilemma does not necessarily imply that an ultimate unification of the classical theories will not happen. It does however suggest that consummation of the classical frameworks should be carried out in well motivated steps.

In the rest of the monograph, we will only consider wireless networks with the single-hop cellular structure due to its dominance in current wireless systems. Because a wireless channel usually has a much lower capacity than a wireline cable, with the objective of addressing the throughput bottleneck, we also choose to focus on the bottom two layers of the network, i.e., the physical and the data link layers. Note that once a data packet travels one hop into the wireline network, bandwidth and energy efficiency is no longer the primary concern, and hence research challenges at the higher layers become fundamentally different. Nevertheless, even with just two layers and a special network structure, the necessity of unifying information theory and network theory for wireless systems is still quite convincing.

1.2 The Missing Support of Distributed Communication

Data networks often have large numbers of bursty short messages that need to be disseminated in a timely manner [11][22]. Coordinating all users in a communication party in such an environment can be infeasible or expensive in terms of overhead. A significant proportion of the messages in current wireless networks are therefore transmitted using distributed communication protocols, where an individual user can adjust its communication parameters, such as a transmission/idling decision, without sharing such a decision with other users including its targeted receiver [58]. Such a communication model is incompatible with the joint coding design assumption of the classical channel coding theory. Distributed communication can also cause key issues that do not appear in a coordinated communication system. For example, without full user coordination, data packets transmitted from multiple users can experience collision at their receivers [60]. Collision detection and collision resolution therefore are core problems at the physical and the data link layers [11]. However, these problems are completely ignored in classical channel coding theory [20].

One may think that classical network theory and current network architecture provide reasonable support for distributed communication and networking at the bottom two layers. Unfortunately, this is true only for wireline systems when communication efficiency is not a key concern. Current layering architecture assumes that a link layer user can only determine whether a packet should be transmitted or not [11]. Other communication details are handled at the physical layer. In distributed communication when physical layer does not have full capability of joint channel code optimization, data link layer has to get involved into communication adaptation. A simple example is the collision resolution protocols such as the exponential backoff-based DCF protocol in IEEE 802.11 [12]. However, with each link layer user only having binary transmission/idling options, advanced wireless capabilities such as rate, power and antenna beam adaptations all become irrelevant at the data link layer. This can lead to a quite significant efficiency reduction in the throughput performance of a wireless system.

For example, let us consider a multiple access system with K homogenous users and a single receiver. Assume unit channel gain from each user to the receiver, and additive Gaussian noise with zero mean and variance N_0. Assume that each user has a transmission power of P. From classical channel coding theory [20], we know that, if each user encodes its own message at a rate of $\frac{1}{2}\log_2\left(1+\frac{P}{N_0}\right)$ bits/symbol, then reliable message recovery is only possible if the users transmit sequentially. Sum rate of the system therefore is upper bounded by the single user channel capacity of $C_1 = \frac{1}{2}\log_2\left(1+\frac{P}{N_0}\right)$ bits/symbol, irrespective of the user number K. Alternatively, if users transmit in parallel with an individual rate of $\frac{1}{2K}\log_2\left(1+\frac{KP}{N_0}\right)$, then sum rate of the system can approach the sum channel capacity of $C_K = \frac{1}{2}\log_2\left(1+\frac{KP}{N_0}\right)$ bits/symbol, which grows unboundedly in K. A similar conclusion applies to the same system with a distributed communication model as well. Assume that each user has bursty short messages and cannot afford the overhead of joint coding optimization. If each message is encoded at a rate only slightly less than C_1[1], then sum rate of the system

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[1] Note that the rate needs to be smaller than C_1 in order to support reliable decoding with a finite codeword length [28].

is upper bounded by C_1 bits/symbol. Alternatively, if messages arrive with a statistics such that on average $\tilde{K}$ users should have messages to transmit at any moment, then it is generally beneficial to encode each message at a rate close to $\frac{1}{2\tilde{K}}\log_2\left(1+\frac{\tilde{K}P}{N_0}\right)$ to support parallel transmissions from up to $\tilde{K}$ users. However, because traffic statistics is unknown at the design stage of a protocol and may also vary in time, in the case of distributed communication, maintaining a high throughput efficiency requires users to have reasonable flexibility of adapting their communication parameters, such as communication rate, at the data link layer. Such a capability is not supported by the physical-link layer interface in the current network architecture.

1.3 An Enhanced Physical-Link Layer Interface

The nature of distributed communication implies that communication parameters cannot be jointly and fully optimized at the physical layer. However, system traffic at the data link layer may still be more or less stationary. To improve communication efficiency, data link layer should exploit advanced wireless capabilities to adapt transmission schemes accordingly, and this needs to be done under the constraint of maintaining a layered (or modularized) network architecture.

To achieve such an objective, we propose an enhancement to the physical-link layer interface [55]. In the enhanced interface, each link layer user can be equipped with multiple transmission options as opposed to the binary transmission/idling options. Different transmission options may correspond to different communication settings such as different power, rates or antenna beams. We generally assume that each link layer user should have a handful of possibly device-dependent transmission options. To maintain the layered architecture, under the distributed communication model, we assume that link layer protocol should inform the physical layer whether a message needs to be transmitted, and if so, which transmission option should be used. Such decisions are not controlled or optimized at the physical layer. We assume that a physical layer receiver should decode the message only if a pre-determined error probability threshold can be met [11][55]. Otherwise the receiver should report collision to the data link layer. At the data link layer, we assume that a user can only choose from the list of provided transmission options, as opposed to being able to adapt the communication parameters arbitrarily.

While the interface enhancement appears to be minor, it involves key research questions whose answers cannot be found in the classical frameworks. At the physical layer, due to possible lack of user coordination, reliable message delivery cannot always be guaranteed. However, it is a fundamental requirement in the layered architecture that any message forwarded to the data link layer must be reliable [11]. Furthermore, because transmission decisions are made at the data link layer, i.e., they are not controlled by a physical layer protocol, any assumption of such a control, such as information rate optimization, may not be valid in physical layer channel coding. With these constraints, whether the notion of fundamental limit still exists for a distributed communication system is a key question that needs to be answered. In Sections 2 and 3 of this monograph, we will show that not only the notion of channel capacity still exists for a distributed system, it can indeed be viewed as an extension to the corresponding result in classical channel coding theory. Meanwhile, at the data link layer when a user is equipped with multiple transmission options, one needs to understand how packet transmission schemes should be adapted in response to the events of transmission success and packet collision. In existing link layer protocols, when only a single transmission option (plus an idling option) is available, a common practice in response to packet collision is to reduce the packet transmission probability of each user [42][11][12]. From classical channel coding theory, we know that a more efficient approach could be reducing the communication rate of each user [20]. However, while transmission options with different power and rate combinations may be available, there is no guarantee that the ideal option should be on the list. Furthermore, different link layer networks may also have different utility optimization objectives. Whether a general link layer distributed medium access control framework exists to optimize transmission schemes under these constraints is an important question that needs to be answered. Although we are not yet able to provide rigorous answers to this question, in Section 4, we present early research results to show that a stochastic approximation framework could be a good starting point to investigate the corresponding link layer problems.

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