Challenging Issues in Multimedia Transmission over Wireless Networks based on Network Coding

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Abstract—This paper considers the development of cooperative communication techniques for future wireless networks. To meet increasing throughput, delay and reliability demands, the future networks will have to rely on increased cooperation both among nodes and among protocol layers within a node. This requires a wide variety of knowledge, from theoretical issues such as graph theory or information theory, to issues at the physical and network layers, and to system and source levels. Recently, network coding has been proposed, providing a competitive solution to exploit all degrees of freedom offered by the wireless channel. Based on the solution of network coding, this paper focuses on two research directions: (i) source-aware network coding, which is about cross cooperation between the network layer and source level, and (ii) physical-layer network coding, which is about cross cooperation between the network and physical layers. The ultimate aim is to discuss issues related to practical design and implementation of wireless networks based on network coding for multimedia transmission.

I. INTRODUCTION

A. Cooperation in future wireless networks

A wireless ad-hoc network is decentralized and does not rely on pre-defined structure of the network such as routers or access points. To this end, each node in the network can help the network by retransmitting data to the other nodes. Information from the source to the destination is relayed through the intermediate nodes. This is known as cooperative communication or cooperation in short. Cooperation has been considered as one of the most interesting paradigms in future wireless networks. It involves two main ideas: (i) using relays to provide spatial diversity in a fading environment, and (ii) envisioning a collaborative scheme, where the relay also has its own information to send; so two terminals help one another to communicate by acting as relays for each other.

The motivation for studying such types of ad-hoc networks can be seen in various practical situations. Take the emergency situation as an example. In such a situation, either the classical networks are not working any more, or communication needs increase drastically in some region where it is almost non-existing. In this case, an ad-hoc network could be quickly deployed. Obviously, an extension of an existing network could be obtained with a reasonable cost using a mobile ad-hoc network (MANET)—a type of wireless ad-hoc networks—rather than modifying the infrastructure of the existing network. Other situations of interest include vehicle networks, extension of actual network coverage.

Such ad-hoc networks should be characterized by the following features: (i) cooperation should take place between users, (ii) the decisions should be distributed, (iii) cooperation should neither impair the security of the communication nor the security of the network, and (iv) the possible selfish behavior of users should be taken into account, as well as the conflicting interest of the various actors involved.

Obviously, cooperation among users is a key component of such networks. This has been recognized in various technical communities, and many papers can be found about cooperation at almost all levels of the communication network. At the network layer, “classical” routing (forwarding the data on a non interfering channel, through a specific path) has been studied extensively, and can also be used in the cooperation context. At the physical layer, cooperation takes place in the form of relaying by various means (amplify-and-forward, decode-and-forward, etc.). In this setting, the superimposition of signals in the wireless context is taken into account, as well as the diversity of the wireless channels. At the source level, cooperation takes place in the form of redundant representations, in which a small number of received representations provides a signal of given quality, and any additional one results in an improved quality. When the representations are not found at the same place, this results in some cooperation between nodes.

B. Network coding

Future wireless networks will require better spectral efficiency in order to meet the requirements of an increasing number of rate-hungry applications while facing the problem spectrum scarcity. Recently, Ahlswede et al. in [1] have proposed the concept of network coding (NC) at the network layer wherein, instead of only “store-and-forward” operations as in classical routing, intermediate nodes also perform additional computations, called coding. To this end, NC can be viewed as a form of cooperation at the network layer. It has been shown that NC offers a number of desired properties like resource efficiency, robustness and security.

By coding at the intermediate nodes, the information emitted from the sources is spread throughout the network, creating redundancy of information in the network. Intuitively, the coding mechanism allows the network to act as a sensing system that “senses the information” of the sources rather than “sensing
the packets” generated from the sources. Therefore, even when link failure occurs, the information redundancy allows the destination to decode the source information efficiently and robustly.

In the wireless context, embracing interference at the physical layer, NC is considered as a competitive solution to exploit all degrees of freedom offered by the wireless channel. The potential of NC for wireless communications is higher then in wired ones because of the broadcast characteristic of the channel and the dynamic nature of the topologies.

C. Multimedia transmission with network coding

The increasing demand for multimedia contents from receivers connected to wireless networks poses many difficulties when the bandwidth is constrained. NC allows to increase the amount of data transmitted over a given network in comparison with traditional routing, and thus constitutes an interesting alternative for the delivery of multimedia contents. It is then natural to pose the following problem: “How to transmit multimedia contents efficiently over a wireless network that is enabled by NC?”

To efficiently transmit multimedia contents through a wireless networks in a cross-layer design paradigm, the following points relating the source and the network must be taken into account: (i) the nature of the compressed multimedia data delivered by the sources such as variability of the rate, minimum quality requirements, constrained delivery delays, resilience to losses, and (ii) the characteristics of the various elements building up the network to adapt classical NC and decoding algorithms that were initially agnostic to the content of the packets coded together. In view of cross-layer design, given the type of multimedia content to be transmitted, how NC is performed at the network layer, adapting the particular multimedia content? In other words, source coding and NC should be jointly performed, and is called source-aware network coding (SNC).

Then, given an appropriate NC scheme has been implemented at the network layer for the corresponding multimedia content, how the information is further transmitted through the wireless physical layer more efficiently? Inspired by the advantages of NC, a similar adaptation at the physical layer, known as physical-layer network coding (PNC) was introduced by Zhang et al. in [2]. This can be realized based on the two-way relay channel model, which is common used in cooperative communications at the physical layer. The idea of PNC is motivated mainly by the broadcast nature of the wireless communications in addition to the ability of the physical layer to perform advanced coding schemes both on the bit and symbol levels. Most of the theories and techniques that have been developed for the straightforward NC can be adapted to PNC. Moreover PNC provides a larger number of degrees of freedom for the mixing functions which can result in additional interesting features. The cross-layer design of PNC requires information from the upper layers for mapping of NC to the physical layer.

Therefore, this paper aims to address issues that involve the development of NC in the whole protocol stack that cooperatively enhance the quality of multimedia transmission through the wireless network at both the network and physical layers.

II. MAIN DEVELOPMENTS IN NETWORK CODING

This section briefly reviews some main developments in network coding. When first introduced in 2000 [1], it is shown that the capacity of multicast networks under NC can be achieved by allowing intermediate nodes to mix the incoming information flows, rather than only store-and-forward packets as in “classical” routing. This result forms a breakthrough in network design. Historically, it is well-known that when multiple receivers need to simultaneously send data through a network, the resources must be shared and hence the individual data rates are reduced. With NC, each receiver can achieve the same rate as it is the sole node having access to the resources of the network.

The result in [1] does not show how to combine the incoming packets at each intermediate node. It has later been shown by Li et al. [3], [4] that linear NC suffices to achieve the capacity limit. In 2003, Koetter and Medard proposed to construct linear NC using an algebraic framework [5]; hence resorting the NC problem to solving a system of linear equations. The coefficients of the linear combinations in the above framework are however not easily known in advance, especially when the nature the network is dynamic and distributed. An answer to this problem was proposed in [6], by selecting these coefficients in a random manner; thus comes the name of random linear NC (RLNC). Therefore, RLNC is potential for practical design of future networks. This helps bridge from the theoretical study in [1] to practical design of network-coded future wireless networks.

III. SOURCE-AWARE NETWORK CODING

When considering the reliable broadcasting or multicasting of multimedia contents within an ad-hoc network, several constraints have to be satisfied so that quality requirements are met at the various receivers. The reconstructed multimedia contents have to be obtained with a minimum quality and usually with some constraints on the delivery delay. The quality of the streams received by receivers encountering similar channel conditions should be of the same order of magnitude. The delay when switching between various streams also has to be kept as small as possible. The mobility of the nodes has to be taken into account. All these constraints make the delivery of multimedia contents particularly challenging when considering networks with limited bandwidth.

Nevertheless, some properties of the compressed multimedia streams may facilitate information delivery. For example, multimedia contents are usually relatively robust against losses. Error concealment techniques, exploiting the temporal and/or spatial redundancy in the data to be decoded, may be used to mitigate for lost packets [7]. Recent source coders generate data streams which are scalable [8]; that is, they consist
of packets of various levels of importance. The reception of the most important packets allow the minimum quality requirement to be met, the reception of other packets improves the quality. In multiple-description coding [9], several complementary representations of the same content are generated. As soon as a single description is received, a reconstruction of the source is possible. Its quality increases when more descriptions are received. These approaches are traditionally combined which unequal error-protection channel codes or routing protocols providing some quality of service.

In the context of NC, the content of compressed multimedia packets has to be taken into account in order to maximize the quality at each receivers within the network, while satisfying the various above-mentioned constraints. Several issues may be raised when considering SNC (see, for examples, [10], [11]). Among the most important, one may cite the way to adapt NC to the importance of the data packets for the reconstructed multimedia content. Finding a trade-off between delivery delay and efficient NC is still difficult to obtain when accurately modeling the various components of the network. The robustness of NC techniques to losses and to transmission errors has also to be addressed. Finally, the way source coding and NC may be performed jointly has to be considered to improve the global throughput.

A. Layered and multiple-description network coding

One of the approaches for transmitting multimedia contents over the network based on network coding is the multiple-description network coding (MDNC), combining multiple-description source coding for multimedia sources and network coding. The problem of using multiple-description codes to maximize a weighted average distortion at several sink nodes of a network has been addressed using routing in [12]. Multiple-description codes combined with appropriate routing are shown to be more efficient than linear broadcast codes [13]. The performance of the proposed schemes with NC have been considered in [14]. A suboptimal algorithm is proposed, the main idea of which is to build, as for layered coding, one subgraph per description and to perform NC within each subgraph considered as independent of the others.

Another approach is the layered network coding (LNC), combing layered source coding for and network coding. One of the characteristics of layered source coding is that low-priority layers are useless unless all higher-priority layers have been received. Protocols allowing different classes of services, such as DiffServ or MPLS, are the standard solutions to perform routing of packets with various importance. An alternative approach is considered in [15]–[17] where NC is used by performing first a rate allocation among the various nodes of the network depending on their capacities and on the rate requirements of the various layers. For each layer, a subgraph of the original graph describing the network is build, taking into account only the nodes able to receive this layer. Classical NC of the packets in each layer is then performed for each of the generated subgraphs.

In both LNC and MDNC, an integer linear programming problem has to be solved to build the various subgraphs. For that purpose, the knowledge of the topology of the whole network is required, and thus the solution may only be obtained in a centralized manner. Distributed algorithms may be interesting, since NC may be done in a totally decentralized way. The protocol aspects of the problem have not been addressed, too. Another issue comes from the fact that NC has to be performed at the upper layers of the protocol stack, since contents of packets may be identified, for example, mainly from the RTP headers. NC at upper layers induces a processing delay at each node of the network which is important to take into account when building the various subgraphs. Finally, the robustness to variations of the topology of the network and of the rate within each layer has also to be taken into account.

B. Joint source-network-channel coding/decoding

In the context of peer-to-peer content storage and distribution, random NC has been shown to be more robust against packet losses than traditional forward error correction, see for example [18]. In wireless networks, packet losses are usually due to transmission errors corrupting the received packet. Some error-detection mechanism is put at work to detect these errors, and to drop erroneous packets, even if there are very few errors.

Joint source-channel decoding (JSCD) techniques [19] aim at exploiting soft information provided by channel decoders in conjunction with redundancy present in the protocol stack and in the source bitstream to correct packets with few errors, and thus improve the throughput. Very few results have been considered in the context of joint decoding of network-coded packets. In [20], channel soft information has been considered to improve the decoding of network codes in the context of a relayed communication. The residual redundancy of the source bitstream, or the redundancy introduced when performing multiple-description NC may be efficiently exploited to build joint source-network-channel decoders.

Additional problems should be considered in a joint approach for source-network-channel coding/decoding in multi-hop and cooperative wireless networks. An important open problem is to determine what should be done at intermediate nodes in an error-prone environment. In this situation, intermediate nodes play the role of relays. Most studies have retained the assumption that the relay only transmits if it decodes correctly (decode-and-forward relying method aided by strong error correction codes at the relay). An interesting topic is to find strategies for the case that decoding failures happen at the relay (NC with noisy relay), or different and more sophisticated relying methods are employed. Some preliminary studies are available in [21] and [22] for the multiple-access relay channel. Furthermore, most studies and methods available so far have analyzed simplified network topologies (for examples, with two or three mobile stations on the multiple-access relay channel or one relay for the two-way relay channel) [21]. The analysis of multi-hop wireless networks and more general network topologies appears to be
an important and unexplored research field [23]. In particular we are interested in the problem of finding a protocol for achieving an efficient network topology in the case of real-time multimedia streaming over mobile ad-hoc networks. Even though this problem has several common features with peer-to-peer location and routing, the additional parameters of MANETs make traditional wired solutions unfit to this case. Moreover the current trend in this kind of problems is to drop the traditional layered approach typical of network protocols to move towards a cross-layer design [24]. Therefore, an efficient routing protocol should be inherently designed for the ad-hoc wireless case, exploiting the intrinsic broadcast property of the medium, and should be conceived with a cross-layer approach. Other important and open research issues are represented by the reference scenario with correlated sources [25] and realistic multipath propagation conditions for distributed multi-hop networks [26].

IV. PHYSICAL-LAYER NETWORK CODING

In a NC setting, the outputs of each node are calculated from the content of the input links by means of “mixing” functions. These functions are applied on the bits of the error free packets delivered by the MAC or upper layers. Several theoretical frameworks have been proposed to assess the network capacity region [5], [27] and to design NC schemes. Most of these frameworks are based on mature theories like graph theory and algebraic geometry. Using these tools, it has been shown that the capacity region of the network can be simply achieved by means of random linear functions [3]. Moreover, through an appropriate design of these functions we are able to bring numerous interesting properties to the network like self error recovery, secrecy and immunity against security attacks [28], [29]. In practice many control data are exchanged in order to establish the protocol which is responsible of the communication between the nodes of a network (in direct physical link or through many relays). The first step when a node is switched on is to discover the direct environment to have knowledge about direct neighbors. Then and depending on the using protocol, a partial or complete view of the topology is imported to all the nodes of the network. This information is held by control information as “hello” messages in IP networks and is necessary to calculate appropriate mixing functions. Most of protocols and technique that have been developed so far are designed for IP-level NC.

Physical-layer network coding (PNC) has been proposed to use NC schemes in the physical layer of wireless devices [2]. It was intended is to extend the classical NC techniques investigated for MAC and IP level to physical layer processing. This will potentially offer a larger number of degrees of freedom. However, it requires to address new cross-layer problems which range from low level synchronization to high level packet recombination protocols [30], [31]. Implementation of PNC involves several practical issues as will be addressed next.

A. Channel knowledge, neighbor discovery

The PNC operates on the received analog signals. Because of the wireless channel nature, these signals are a mix of other signals radiated by other devices. In order to mix these signals with its own symbols, accurate channel state information and neighboring knowledge are required for each node. Consequently, this information should be provided by upper layer mechanisms. It is well known that such mechanisms sacrifice a considerable amount of bandwidth resources. Usually a compromise needs to be made between the information accuracy provided by these protocols and the spectral efficiency enhancements they provide. Such compromise will be one of the most important issues in PNC. Besides channel state information and neighborhood discovery should also be considered. In fact these parameters become more and more important for a large number of applications. While some initial work on imperfect CSI has been proposed in NC [32], neighbor discovery is still an open issue.

B. Synchronization

This issue is specific to PNC. In fact, the received symbols correspond to the superposition of multiple signals radiated by other terminals. Because of propagation delays, these signals cannot be fully synchronized. One possible approach to ensure synchronization between the received symbols is the use orthogonal frequency division multiplexing (OFDM) modulation with adequate cyclic prefix (CP). The CP length should account for the propagation delay of the farthest interesting node. A short CP will allow to recombine signals from near nodes only. The signals of the other terminals will be considered as noise. On another hand, longer CP will allow to distinguish a large number of signals which could exceed the number of degrees of freedom available at the receiver side. That is, the physical layer synchronization have to be jointly designed with synchronization messages and protocols in upper layers in a cross-layer framework. Synchronization has just been addressed in the context of PNC [33] and this result can be good starting points for further investigation on NC synchronization.

C. Protocols and header definition for PNC

Like bit-level NC, PNC needs additional control messages and header information in order to allow a node to “de-mix” the superposed signals and to re-encode them with its own symbols for the next transmission. Furthermore, the encoding node needs to know the missing information of other peers in addition to their joint processing capabilities. Such kind of information have to be propagated by means of cross-layer protocols combined with adequate header information. Joint design of packets headers and the encoding/decoding protocols should be investigated in order to minimize high level decoding and to fully exploit the physical-layer processing.

D. PNC aware physical layer modes

Multiple-Input-Multiple-Output (MIMO) processing is competitive approach to increase the spectral efficiency of wireless
communications. It allows to multiplex several streams in the same time frequency resource block and also to harden the wireless link by relying on diversity recombination. Another attractive capability of MIMO processing is to mitigate the interference between several wireless nodes operating in the same area. This feature can be leveraged in network coding context by creating independent input or output links. In this case, the MIMO processing can be used to imitate a wired network where all input/output links are independent of each other. This configuration is even better than wired networks since the links can be created and destroyed dynamically. The potential gains of practical MIMO physical layer schemes should be investigated in the context of NC combined with appropriate MAC protocols.

V. Conclusion

In view of cross-layer design for cooperative communications to transmit multimedia contents, this paper considers the development of wireless ad-hoc networks based on network coding. In particular, two open directions are discussed. The first direction is source-aware network coding that designs network coding at the network layer that can help to transmit multimedia contents efficiently. The second direction is physical-layer network coding which exploits various degrees of freedom of the wireless medium. Various issues involved have been discussed, especially practical aspects at both network layer and physical layer. A recent implementation of OFDM-based PNC [33] can be an interesting foundation for a practical implementation of network-coded future wireless networks for multimedia transmission.

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REFERENCES


