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

Nguyen Linh-Trung, Vo Nguyen Quoc Bao, Pierre Duhamel, Mérouane Debbah

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

Nguyen Linh-Trung*, Vo Nguyen Quoc Bao†, Pierre Duhamel‡, Mérouane Debbah§

*Fac. Electronics and Telecommunications, VNU University of Engineering and Technology, Hanoi, Vietnam

†Dept. Telecommunications, Posts and Telecommunication Institute of Technology, Ho Chi Minh city, Vietnam

‡Signals and Systems Laboratory, CNRS/SUPELEC, Gif-sur-Yvette, France

§Alcatel-Lucent Chair on Flexible Radio, SUPELEC, Gif-sur-Yvette, France

linhtrung@vnu.edu.vn; baovnq@ptithcm.edu.vn; pierre.duhamel@lss.supelec.fr; merouane.debbah@supelec.fr

***Abstract*—To meet increasing throughput, delay and reliability demands, future wireless networks will have to rely on increased cooperation both among nodes and among protocol layers in 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. A potential solution is the recently proposed network coding because it offers a number of desired properties such as resource efficiency, robustness and security. This paper focuses on two research directions for multimedia transmission over wireless networks based on network coding: (i) source-aware network coding and (ii) physical-layer network coding. These directions follow the cross-layer framework in designing the communication protocol stack. Challenging issues which are related to the practical design of network-coding enabled wireless networks are addressed and discussed.**

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 other nodes. Information from the source to the destination is relayed by intermediate nodes. This is known as *cooperative communication* or cooperation in short. Cooperation has been considered 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 wherein two terminals help each other to communicate by acting as relays while each terminal also has its own information to send.

The motivation for studying such types of ad-hoc networks can be seen in various practical situations. For example, in an emergency situation, either the existing network in the underlying area fails or the number of communication requests in the network increases drastically above the capability of the existing network. In this case, an ad-hoc network could be quickly deployed. Obviously, the existing network could be extended with a reasonable cost by 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 of distributed manner, (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 and has been recognized at almost all layers of the communication network. For example, at the application layer, 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. At the network layer, traditional 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.

B. Network coding

Future wireless networks will require better spectral efficiency in order to meet the demand of an increasing number of rate-hungry applications. Recently, *network coding* (NC) has been proposed by Ahlswede et al. in [1] at the network layer. Instead of performing only "store-and-forward" operations as in traditional routing, intermediate nodes in NC also perform additional computations (coding) on the incoming data and then forward the coded information. In this sense, NC can be considered a form of cooperation at the network layer. It has been shown that NC offers a number of desired properties such as 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 source information in the network. Intuitively, the coding mechanism enables the network to act as a sensing system which "senses the information" of the sources rather than "sensing the packets" generated by the sources. Therefore, even when link failure occurs, the redundant information allows efficient and robust decoding of the source information at the destination.

In the wireless context, NC embraces interference at the physical layer and, hence, is considered 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 the amount of data transmitted over a given network to be increased 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 question: "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 various components building up the network to adapt to NC, and the 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 to the particular multimedia content? In other words, source coding and NC should be jointly performed. This is referred to in this paper as *source-aware network coding* (SNC).

Then, given that 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. Moreover, PNC provides a larger number of degrees of freedom for the coding 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 involving the development of NC at both the network and physical layers that altogether enhance the quality of multimedia transmission through wireless networks.

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 the packets as in traditional routing. This result sets 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 constructing linear NC using an algebraic framework [5], reverting 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 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 the loss of 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 receiver 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 seek for 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 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 and MPLS, are the standard solutions for performing routing of packets with various levels of 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 manner. The protocol aspects of the problem have also not been addressed. 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 [18]. In wireless networks, packet losses are usually due to transmission errors which corrupt 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 to exploit the soft information provided by channel decoders in conjunction with the redundancy present in the protocol stack and in the source bitstream in order to correct packets with a few errors, and thus improve the throughput. Very few results have been considered in the context of joint decoding of network-coded packets. The channel soft information has been considered in [20] 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 for building 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, the 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 relaying method aided by strong error correction codes at the relay). An interesting topic is to find strategies for the case that decoding fails at the relay (NC with noisy relay), or different and more sophisticated relaying 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 for 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 the traditional wired solutions unfit to this case. Moreover, the current trend in this kind of problems is to move toward 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 output of each intermediate node of the network is calculated from the content of the input links by means of a combining function. Such a function is applied on the bits of the error free packets delivered by the link layer or upper layers. Several theoretical frameworks have been proposed to assess the capacity region of the network [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 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 for the communication between the nodes, either in direct physical links or through many relays. When a node is switched on, the first step is to discover the direct environment in order to have knowledge about direct neighbors. Then, depending on the protocol in use, a partial or complete view of the topology is imported to all the nodes of the network. This information is held by the control information as “hello” messages in IP networks and is necessary for calculating appropriate mixing functions. Most of protocols and techniques that have been developed so far are designed for NC at the network layer.

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 traditional NC techniques investigated for the network layers 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, such a signal is a combination of signals radiated by other devices. In order to combine these signals with its own symbols, accurate channel state information (CSI) and neighboring knowledge are required for each node in the network. Consequently, this information should be provided by upper layer mechanisms. It is well known that these mechanisms sacrifice a considerable amount of bandwidth resources. A compromise usually needs to be made between the accuracy of information and the enhancement of spectral efficiency provided by these protocols. Such a compromise will be one of the most important issues in PNC. While some initial work on imperfect CSI has been proposed in PNC [32], neighbor discovery is still an open issue.

B. Synchronization

The received symbols correspond to the superposition of multiple signals radiated by other terminals. These signals cannot be fully synchronized due to propagation delays. One possible approach to ensure synchronization between the received symbols is the use orthogonal frequency devision 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 allows the recombination of signals from only nearby nodes; signals from other terminals are considered noise. On another hand, a longer CP allows the distinguishing of a large number of signals that could exceeds the number of degrees of freedom available at the receiver side. Therefore, synchronization at the physical layer should be jointly designed with that at upper layer in a cross-layer framework. PNC synchronization has just been addressed in [33] and this result can be a good starting point for further investigation.

C. Protocols and header definition for PNC

Like NC at the network layer, PNC needs additional control messages and header information for allowing a node to “de-mix” the superimposed signals and then 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 a competitive approach for increasing the spectral efficiency. It allows the multiplexing of several streams in the same time frequency resource block and also the hardening of 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 capability can be leveraged in NC 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 framework for cooperatively transmitting multimedia contents, this paper considers the development of source-aware network coding and physical-layer network coding. Various issues involved have been discussed, especially practical aspects at both the network layer and the physical layer. A recent implementation of an OFDM-based PNC prototype by Lu et al. [33] can be an interesting foundation for the practical implementation of NC-enabled future wireless networks for multimedia transmission.

Acknowledgment

This work was supported by the Ministry of Science and Technology of Vietnam, under project number 39/2012/HD/NDT, and by the French DIGITEO organization.

References

[1] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, July 2000.

[2] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical-layer network coding," in *Proc. 12th Annual Int. Conf. Mobile Computing and Networking (MobiCom '06)*. New York, NY, USA: ACM, 2006, pp. 358–365.

[3] S. Li, R. Yeung, and N. Cai, "Linear network coding," *IEEE Trans. Inf. Theory*, vol. 49, no. 2, pp. 371–381, Feb. 2003.

[4] S.-Y. R. Li, Q. T. Sun, and Z. Shao, "Linear network coding: Theory and algorithms," *Proc. IEEE*, vol. 99, no. 3, pp. 372–387, 2011.

[5] R. Koetter and M. Medard, "An algebraic approach to network coding," *IEEE/ACM Trans. Netw.*, vol. 11, no. 5, pp. 782–795, 2003.

[6] T. Ho, M. Medard, R. Koetter, D. R. Karger, M. Effros, J. Shi, and B. Leong, "A random linear network coding approach to multicast," *IEEE Trans. Inf. Theory*, vol. 52, no. 10, pp. 4413–4430, 2006.

[7] W.-Y. Kung, C.-S. Kim, and C.-C. Kuo, "Spatial and temporal error concealment techniques for video transmission over noisy channels," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 16, no. 7, pp. 789 –803, july 2006.

[8] T. Schierl, H. Schwarz, D. Marpe, and T. Wiegand, "Scalable extension of H.264/AVC," ISO/IEC JTC1/SC29/WG11 MPEG2004/M10569/S03, Tech. Rep., mar 2004.

[9] C. Tillier, T. Petrisor, and B. Pesquet-Popescu, "A motion-compensated overcomplete temporal decomposition for multiple description scalable video coding," *EURASIP J. Image and Video Proc.*, vol. 2007, p. 12 pages, 2007.

[10] A. Markopoulou and H. Seferoglu, "Network coding meets multimedia: Opportunities and challenges," *IEEE MMTC E-Letter*, vol. 4, no. 1, pp. 12–15, 2009.

[11] E. Magli and P. Frossard, "An overview of network coding for multimedia streaming," in *Int. Conf. Multimedia and Expo*, Cancun, Mexico, 2009, pp. 1488 –1491.

[12] X. Wu, B. Ma, and N. Sarshar, "Rainbow network flow of multiple description codes," *IEEE Trans. Inf. Theory*, vol. 54, no. 10, pp. 4565–4574, 2008.

[13] T. M. Cover, *Elements of Information Theory*, 2nd ed. Wiley-Interscience, 2005.

[14] M. Shao, X. Wu, and N. Sarshar, "Rainbow network how with network coding," in *Proc. Network Coding Workshop*, Hongkong, 2008.

[15] N. Sundaram, P. Ramanathan, and S. Banerjee, "Multirate media stream using network coding," in *43rd Annual Allerton Conf. Communication, Control, and Computing*, 2005.

[16] X. Chenguang, X. Yinlong, Z. Cheng, W. Ruizhe, and W. Qingshan, "On network coding based multirate video streaming in directed networks," in *IEEE Int. Conf. Performance, Computing, and Communications*, april 2007, pp. 332 –339.

[17] Y. Wu, "Distributing layered content using network coding," in *SECON Workshops '08*, june 2008, pp. 1 –4.

[18] H. Balli, X. Yan, and Z. Zhang, "Error correction capability of random network error correction codes," in *IEEE Int. Symp. Info. Theory*, june 2007, pp. 1581 –1585.

[19] P. Duhamel and M. Kieffer, *Joint source-channel decoding: A cross-layer perspective with applications in video broadcasting*. Academic Press, 2009.

[20] C. Hausl and J. Hagenauer, "Iterative network and channel decoding for the two-way relay channel," in *IEEE Int. Conf. Communications*, vol. 4, june 2006, pp. 1568 –1573.

[21] S. Yang and R. Koetter, "Network coding over a noisy relay : A belief propagation approach," in *IEEE Int. Symp. Info. Theory*, june 2007, pp. 801 –804.

[22] G. Zeitler, R. Koetter, G. Bauch, and J. Widmer, "Design of network coding functions in multihop relay networks," in *Int. Symp. Turbo Codes and Related Topics*, sept. 2008, pp. 249 –254.

[23] J. Kliewer, T. Dikaliotis, and T. Ho, "On the performance of joint and separate channel and network coding in wireless fading networks," in *IEEE Int. Work. Info. Theory for Wireless Networks*, july 2007, pp. 1–5.

[24] E. Setton, T. Yoo, X. Zhu, A. Goldsmith, and B. Girod, "Cross-layer design of ad hoc networks for real-time video streaming," *IEEE Wireless Commun. Mag.*, vol. 12, no. 4, pp. 59 – 65, aug. 2005.

[25] J. Del Ser, P. Crespo, B. Khalaj, and J. Gutierrez-Gutierrez, "On combining distributed joint source-channel-network coding and turbo equalization in multiple access relay networks," in *IEEE Int. Conf. Wireless and Mobile Computing, Network and Communications*, 2007.

[26] M. Renzo, F. Graziosi, and F. Santucci, "A comprehensive framework for performance analysis of cooperative multi-hop wireless systems over log-normal fading channels," *IEEE Trans. Commun.*, vol. 58, no. 2, pp. 531–544, 2010.

[27] R. W. Yeung, *Information Theory and Network Coding*. Springer, 2008.

[28] R. Koetter and F. R. Kschischang, "Coding for errors and erasures in random network coding," *IEEE Trans. Inf. Theory*, vol. 54, no. 8, pp. 3579–3591, Aug. 2008.

[29] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, M. Medard, and M. Effros, "Resilient network coding in the presence of byzantine adversaries," *IEEE Trans. Inf. Theory*, vol. 54, no. 6, pp. 2596 –2603, June 2008.

[30] S. C. Liew, S. Zhang, and L. Lu, "Physical-layer network coding: Tutorial, survey, and beyond," *Physical Communication*, May 2012.

[31] B. Nazer and M. Gastpar, "Reliable physical layer network coding," *Proc. IEEE*, vol. 99, no. 3, pp. 438–460, 2011.

[32] H. Gacanin, T. Sjodin, and F. Adachi, "On channel estimation for analog network coding in a frequency-selective fading channel," *EURASIP Journal on Wireless Communications and Networking*, 2011.

[33] L. Lu, TaotaoWang, S. C. Liew, and S. Zhang, "Implementation of physical-layer network coding," *Physical Communication*, 2012.