Multi-way Communications: An Information Theoretic Perspective

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Abstract

Multi-way communication is a means to significantly improve the spectral efficiency of wireless networks. For instance, in a bi-directional (or two-way) communication channel, two users can simultaneously use the transmission medium to exchange information, thus achieving up to twice the rate that would be achieved had each user transmitted separately. *Multi-way communications* provides an overview on the developments in this research area since it has been initiated by Shannon. The basic two-way communication channel is considered first, followed by the two-way relay channel obtained by the deployment of an additional cooperative relay node to improve the overall communication performance. This basic setup is then extended to multi-user systems. For all these setups, fundamental limits on the achievable rates are reviewed, thereby making use of a linear high-SNR deterministic channel model to provide valuable insights which are helpful when discussing the coding schemes for Gaussian channel models in detail. Several tools and communication strategies are used in the process, including (but not limited to) computation, signal-space alignment, and nested-lattice codes. Finally, extensions of multi-way communication channels to multiple antenna settings are discussed.

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1

Introduction

The foundation of information theory by C. E. Shannon in 1948 laid the cornerstone for one of the greatest –if not the greatest– revolutions of our time; the communications revolution. Shannon established the fundamentals of a theory that is responsible for making almost every aspect of our daily activities easier, including social, financial, and educational activities.

The evolution of communications from its beginning to date can be described as a chain-reaction. Applications that require communication were few in the beginning. Thus, communication networks back then supported low data rates. The availability of such networks motivated developing applications that exploit them. In turn, this leads to higher demand on data rates, and thus requires developing the networks to support higher rates; and the process repeats itself. Nowadays, our lives became strongly dependent on communications. A great deal of our daily activities are executed through mobile communications or the internet using a diverse range of devices.

This process requires studying all aspects of communications technology from theory to practice. One important aspect is the information theoretic aspect which provides the fundamental performance limits of a given network. Such limits are the ultimate goal of a practical network design, and are therefore of significant importance.

Since Shannon's days, there has been a great deal of research in information theoretic aspects of communication networks. Most of the focus in the beginning was on the point-to-point channel (P2P) [139], the multiple-access channel (MAC) [1, 96], the broadcast channel (BC) [16, 17, 44], and the interference channel (IC) [2, 21, 22, 62, 130].

There has also been a great deal of interest in cooperative communication with various types of cooperation. One of these types is feedback from the receivers to the transmitters. The first work on feedback is that by Shannon in 1956 [140]. Another one of the important types of cooperation in network information theory is cooperation through relaying. The basic model to study this problem is the 3-node relay channel (RC) which was first introduced in 1971 by van der Meulen [165] and several schemes for this network were developed by Cover and El Gamal [45]. Recent information-theoretic studies on RC's can be found in e.g. [85] and references therein. Relaying can be expected to be adopted in current and future wireless systems, as it has been introduced in the IEEE 802.16j (WiMAX) standard.

These works mainly focus on one-way communication, i.e., from one or more transmitters to one or more receivers. However, the most common kind of communication is two-way. That is, two nodes exchange information (audio, video, etc.) between each other in both directions, where a node is not either a source or a destination, but both. This kind of cooperative communication is known as two-way communication, or more generally multi-way communication. It is important at this point to note that the term 'multi-way' that appears in van der Meulen's famous survey [166] as well as Ahlswede's article [1] refers generally to multi-user communications. Although the Shannon's two-way channel [141] has been discussed in [166], it is put under the same umbrella with the MAC, BC, RC, and IC. The common factor in all these channels is that they are multi-user channels. Recently however, the term 'multi-way' has been used to refer to multi-user channels consisting of nodes which are simultaneously sources and destinations, which is the focus of this manuscript.

Multi-way communication can lead to significant improvement in the performance of communication networks if adopted. Take the P2P channel from node 1 to node 2 as an example. If a feedback link is present between node 2 and node 1, it was shown that this link does not increase the capacity of the channel [140], but can be used to reduce the complexity of the communication [132]. However, if the feedback link is used to send information in the opposite direction from node 2 to node 1 as in the two-way channel (TWC) [141], then the overall capacity of the channel can significantly increase. This can be seen for instance in the Gaussian TWC which decouples into two parallel channels [61], and hence, has an overall capacity that is double the capacity of the P2P channel with feedback. On the other hand, using a relay to forward information in both directions to the communicating nodes that want to exchange information in both directions is much better than using it as in the classical RC. Thus, the performance of the RC is enhanced by using the relay as a bi-directional relay. This fact has triggered many researchers to focus their attention on bi-directional relaying [13, 59, 109, 125], uncovering its potential, and highlighting its significance to both the practical and theoretical communities.

The main goal of this manuscript is to introduce the reader to the work done in the field of multi-way communications, and to highlight some interesting open problems in this field. To this end, we organize the manuscript as follows.

- **Chapter 2** discusses the two-way channel and extensions to multi-way channels.
- **Chapter 3** discusses the two-way relay channel, which is essentially similar to the two-way channel, but where communication is facilitated by a relay node.
- **Chapter 4** discusses the multi-pair two-way channel, which consists of multiple two-way relay channels coexisting in the same medium.
- **Chapter 5** discusses the multi-way channel, which is a the extension of the two-way relay channel to a multi-user case with

arbitrary information exchange, not necessarily pair-wise as in the multi-pair two-way channel.

- **Chapter 6** discusses extensions of the previous chapters, where nodes are equipped with multiple antennas (MIMO nodes).

Note that the two-way channel is the fundamental building block of multi-way communication networks. It models a scenario where two nodes use the same medium to communicate in both directions. This channel is introduced in Chapter 2 where outer and inner bounds on its capacity region are presented. The idea of adaptive coding is introduced in this chapter and discussed. Furthermore, some related work treating extensions to multi-way channels is summarized, with main focus on whether adaptive coding is required or not in such channels.

Assume that the two communicating nodes in a TWC are physically separated, due to some obstruction or long distance between them. How can these nodes communicate? A potential solution is to use relay nodes to enable this communication. Deploying a relay node in the TWC leads to the so-called two-way relay channel. Chapter 3 introduces this channel and studies its capacity. In general, this channel models scenarios where two nodes communicate in both ways through a base-station or a satellite node. We use the linear-deterministic (LD) approach proposed by Avestimehr *et al.* [10] to capture the essence of the problem, and to determine a good transmission and relaying scheme for the Gaussian TWRC in terms of achievable rates. For the Gaussian channel, we study the performance of quantize-and-forward and compress-forward strategies at the relay. We analyze the achievable rate region and show that the cut-set bounds are achievable within a constant gap for all values of channel gains.

An interesting question one might ask is whether the treatment of the TWRC changes if multiples pairs of nodes are involved in the communication. Do the cut-set bounds remain tight? How does the coding scheme change? Chapter 4 discusses these issues by studying the capacity region of multi-pair TWRC (MP-TWRC). This network is an extension of the TWRC to a multi-user scenario with pair-wise message exchange. This problem is first examined in the context of the LD channel model. The capacity region of this network with two pairs of users when the relay is operating in the full-duplex mode is characterized. It is shown that the cut-set upper-bound is tight and the capacity region is achieved by a so-called divide-and-conquer relaying scheme. The insights gained from the LD network are then applied in the Gaussian MP-TWRC. The scheme in the LD channel translates to a specific superposition of lattice codes and random Gaussian codes at the source nodes and successive decoding at the destination nodes. This constitutes the main difference to the TWRC; the coding scheme consists of multiple layers of TWRC schemes decoded successively at the destinations. The achievable rate of this scheme with two pairs is analyzed and it is shown that for all channel gains it achieves the cut-set upper-bound within a constant gap.

The common factor between the TWRC and the MP-TWRC is that communicating nodes are grouped into pairs. What happens if these nodes are not grouped this way, but rather want to communicate in all directions? This scenario is studied in Chapter 5. The resulting network is called the multi-way relay channel (MWRC). This channel models networks consisting of multiple nodes communicating with each other in all direction through a centralized access network such as a cloud. The 3-user case, known as the Y-channel, is analyzed first. The capacity region of the LD Y-channel is characterized by using 3 modes of communication: bi-directional communication, cyclic communication, and uni-directional communication. Interestingly, it turns out that the cut-set bounds are not tight in this case, contrary to the TWRC and the MP-TWRC. Then, these communication modes are extended to the Gaussian Y-channel by using nested-lattice codes, and the capacity region of the Gaussian Y-channel is characterized within a constant gap. The sum-capacity of the K-user Y-channel is characterized afterwords within a constant gap as well. The multi-cast MWRC is also discussed in this chapter, which differs from the Y-channel in that nodes send common messages instead of private ones.

Finally, extensions of Chapters 2-5 are discussed in Chapter 6. This chapter mainly focuses on multi-antenna (MIMO) extensions of the TWRC, the MP-TWRC, and the MWRC, and highlights the main advances achieved in this aspect. MIMO communication is interesting since it allows harvesting spacial multiplexing gain, giving rise to higher achievable rates. This chapter further highlights open problems of interest in MIMO multi-way communication.

References

[1] R. Ahlswede. Multi-way communication channels. In *Proceedings of 2nd International Symposium on Information Theory*, pages 23–52, Tsahkadsor, Armenian S.S.R., Sep. 1971.

[2] R. Ahlswede. The capacity region of a channel with two senders and two receivers. *The Annals of Probability*, pages 805–814, 1974.

[3] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung. Network information flow. *IEEE Transactions on Information Theory*, 46(4):1204–1216, Jul. 2000.

[4] A. Alsharoa, F. Bader, and M.-S. Alouini. Relay selection and resource allocation for two-way DF-AF cognitive radio networks. *IEEE Wireless Communications Letters*, 2(4):427–430, Aug. 2013.

[5] A. Alsharoa, H. Ghazzai, and M.-S. Alouini. A genetic algorithm for multiple relay selection in two-way relaying cognitive radio networks. In *IEEE Vehicular Technology Conference*, Las Vegas, NV, Sep. 2013.

[6] A. Alsharoa, H. Ghazzai, and M.-S. Alouini. A low complexity algorithm for multiple relay selection in two-way relaying cognitive radio networks. In *IEEE International Conference on Communications*, Budapest, Jun. 2013.

[7] A. Alsharoa, H. Ghazzai, and M.-S. Alouini. Optimal transmit power allocation for MIMO two-way cognitive relay networks with multiple relays. *IEEE Wireless Communications Letters*, 3:30–33, 2013.

[8] A. Asadi, Q. Wang, and V. Mancuso. A survey on device-to-device communication in cellular networks. *pre-print arXiv:1310.0720v2*, Oct. 2013.

[9] A. S. Avestimehr, S. Diggavi, and D. Tse. A deterministic approach to wireless relay networks. *45th Annual Allerton Conference on Communication, Control, and Computing, Illinois, USA*, Sep. 2007.

[10] A. S. Avestimehr, S. Diggavi, and D. Tse. Wireless network information flow: A deterministic approach. *IEEE Transactions on Information Theory*, 57(4):1872–1905, Apr. 2011.

[11] A. S. Avestimehr and T. Ho. Approximate capacity of the symmetric half-duplex Gaussian butterfly network. In *Proceedings of the IEEE Information Theory Workshop (ITW)*, pages 311–315, Jun. 2009.

[12] A. S. Avestimehr, M. A. Khajehnejad, A. Sezgin, and B. Hassibi. Capacity region of the deterministic multi-pair bi-directional relay network. *IEEE Information Theory Workshop (ITW), Volos, Greece*, Jun. 2009.

[13] A. S. Avestimehr, A. Sezgin, and D. Tse. Capacity of the two-way relay channel within a constant gap. *European Transactions in Telecommunications*, 21(4):363–374, Apr. 2010.

[14] I.-J. Baik and S.-Y. Chung. Network coding for two-way relay channels using lattices. *Proceedings of IEEE International Conference on Communications, Beijing, China*, pages 3898–3902, May 2007.

[15] Z. Bar-Yossef, Y. Birk, T. Jayram, and T. Kol. Index coding with side information. *IEEE Transactions on Information Theory*, 57(3):1479–1494, Mar. 2011.

[16] P. P. Bergmans. Random coding theorem for broadcast channels with degraded components. *IEEE Transactions on Information Theory*, IT-19:197–207, 1973.

[17] P. P. Bergmans. A simple converse for broadcast channels with additive white gaussian noise. *IEEE Transactions on Information Theory*, IT-20:279–280, 1974.

[18] H. Boche and M. Schubert. *Duality theory for uplink downlink multiuser beamforming.* EURASIP Book Series on Signal Processing and Communications. Hindawi Publishing Corporation, Smart Antennas - State-of-the-Art ed., 2005.

[19] S. Boyd and L. Vanderberghe. *Convex optimization.* Cambridge University Press, 2004.

[20] V. R. Cadambe and S. Jafar. Interference alignment and the degrees of freedom for the K user interference channel. *IEEE Transactions on Information Theory*, 54:3425–3441, Aug. 2008.

[21] A. B. Carleial. A case where interference does not reduce capacity. *IEEE Transactions on Information Theory*, IT-21(1):569–570, Sep. 1975.

[22] A. B. Carleial. Interference channels. *IEEE Transactions on Information Theory*, 24(1):60–70, Jan. 1978.

[23] A. Chaaban, H. Maier, and A. Sezgin. The degrees-of-freedom of multi-way device-to-device communications is limited by 2. In *IEEE International Symposium on Information Theory (ISIT)*, Jan. 2014.

[24] A. Chaaban, K. Ochs, and A. Sezgin. The degrees of freedom of the MIMO Y-channel. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Istanbul, Jul. 2013.

[25] A. Chaaban and A. Sezgin. The capacity region of the linear shift deterministic Y-channel. In *IEEE International Symposium on Information Theory (ISIT)*, pages 2457–2461, St. Petersburg, Jul. 31-Aug. 5 2011.

[26] A. Chaaban and A. Sezgin. On the generalized degrees of freedom of the Gaussian interference relay channel . *IEEE Transactions on Information Theory*, 58(7):4432–4461, Jul. 2012.

[27] A. Chaaban and A. Sezgin. Signal space alignment for the Gaussian Y-channel. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, pages 2087–2091, Cambridge, MA, Jul. 2012.

[28] A. Chaaban and A. Sezgin. The approximate capacity region of the Gaussian Y-channel via the deterministic approach. *IEEE Transactions on Information Theory*, 61(2):939–962, Feb. 2015.

[29] A. Chaaban, A. Sezgin, and A. S. Avestimehr. On the sum capacity of the Y-channel. In *Proceedings of 42nd Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, Nov. 2011.

[30] A. Chaaban, A. Sezgin, and A. S. Avestimehr. Approximate sum capacity of the Y-channel. *IEEE Transactions on Information Theory*, 59(9):5723–5740, Sep. 2013.

[31] A. Chaaban, A. Sezgin, and D. Tuninetti. Achieving net feedback gain in the linear-deterministic butterfly network with a full-duplex relay. *Ahlswede Festschrift, Lecture Notes in Computer Science (LNCS) (arXiv:1207.6540)*, 7777:167–208, 2013.

[32] M. Chen and A. Yener. Interference management for multiuser two-way relaying. *Proceedigs of IEEE Annual Conference on Information Systems and Sciences, Princeton, NJ*, Mar. 2008.

[33] M. Chen and A. Yener. Multiuser two-way relaying for interference limited sytems. *Proceedings of IEEE International Conference on Communications, Beijing, China*, May 2008.

[34] M. Chen and A. Yener. Multiuser two-way relaying: detection and interference management strategies. *IEEE Transactions on Wireless Communications*, 8(8):4296–4305, Aug. 2009.

[35] Z. Cheng and N. Devroye. Multi-user two-way deterministic modulo 2 adder channels-When adaptation is useless. In *49th Annual Allerton Conference on Communication, Control, and Computing*, pages 434–438, Monticello, Sep. 2011.

[36] Z. Cheng and N. Devroye. On constant gaps for the two-way Gaussian interference channel. In *Proceedings of the Annual Allerton Conference on Communication, Control, and Computing*, Monticello, IL, Oct. 2012.

[37] Z. Cheng and N. Devroye. On the capacity of multi-user two-way linear deterministic channels. In *IEEE International Symposium on Information Theory (ISIT)*, pages 2092–2096, Cambridge, MA, Jul. 2012.

[38] Z. Cheng and N. Devroye. On constant gaps for the K-pair user two-way Gaussian interference channel with interaction. In *Proceedings of the IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Austin, TX, Dec. 2013.

[39] Z. Cheng and N. Devroye. The degrees of freedom of the K-pair-user full-duplex two-way interference channel with and without a MIMO relay. In *IEEE International Symposium on Information Theory (ISIT)*, Jul. 2014.

[40] Z. Cheng and N. Devroye. Two-way networks: when adaptation is useless. *IEEE Transactons on Information Theory*, 60(3):1793–1813, Mar. 2014.

[41] H. Chung, N. Lee, B. Shim, and T. Oh. On the beamforming design for MIMO multipair two-way relay channels. *IEEE Transactions on Vehicular Technology*, 61(7):3301–3306, 2012.

[42] E. Ciftcioglu, Y. Sagduyu, R. Berry, and A. Yener. Cost-delay tradeoffs for two-way relay networks. *IEEE Transactions on Wireless Communications*, 10(12):4100–4109, Dec. 2011.

[43] M. Costa. Writing on dirty paper. *IEEE Transactions on Information Theory*, 29(3):439–441, May 1983.

[44] T. Cover. Broadcast channels. *IEEE Transactions on Information Theory*, 18(1):2–14, 1972.

[45] T. M. Cover and A. El-Gamal. Capacity theorems for the relay channel. *IEEE Transactions on Information Theory*, 25(5):572–584, Sep. 1979.

[46] T. M. Cover and J. Thomas. *Elements of information theory*. Wiley Series in Telecommunications and Signal Processing, 2nd edition, 2006.

[47] D. Dash, A. Khoshnevis, and A. Sabharwal. An achievable rate region for a multiuser half-duplex two-way channel. In *Allerton*, pages 2092–2096, Monticello, Sep. 2010.

[48] G. Dueck. The capacity region of the two-way channel can exceed the inner bound. *Information and Control*, 40(3):258–266, 1979.

[49] A. El-Gamal and M. Costa. The Capacity Region of a Class of Deterministic Interference Channels. *IEEE Transactions on Information Theory*, IT-28(2):343–346, Mar. 1982.

[50] U. Erez and R. Zamir. Achieving 1/2 log(1 + SNR) on the AWGN channel with lattice encoding and decoding. *IEEE Transactions on Information Theory*, 50(10):2293–2314, Oct. 2004.

[51] R. H. Etkin, D. N. C. Tse, and H. Wang. Gaussian interference channel capacity to within one bit. *IEEE Transactions on Information Theory*, 54(12):5534–5562, Dec. 2008.

[52] T. Gaarder and J. K. Wolf. The capacity region of a multiple access discrete memoryless channel can increase with feedback. *IEEE Transactions on Information Theory*, IT-21:100–102, 1975.

[53] R. S. Ganesan, H. Al-Shatri, A. Kuehne, T. Weber, and A. Klein. Pair-aware interference alignment in multi-user two-way relay networks. *IEEE Transactions on Wireless Communications*, 12(8):3662–3671, Aug. 2013.

[54] R. S. Ganesan, T. Weber, and A. Klein. Interference alignment in multi-user two way relay networks. In *Proceedings of the 73rd IEEE Vehicular Technology Conference*, Yokohama, May 2011.

[55] M. Gastpar, A. Lapidoth, Y. Steinberg, and M. Wigger. Feedback can double the prelog of some memoryless gaussian networks. *arXiv:1003.6082v2 [cs.IT]*, 2012.

[56] L. Ghabeli and M. S. Derpich. Approaching the capacity of two-way Gaussian relay channel with relay private messages. In *IEEE International Symposium on Information Theory (ISIT)*, 2014.

[57] T. Gou, S. A. Jafar, S.-W. Jeon, and S.-Y. Chung. Aligned interference neutralization and the degrees of freedom of the $2 \times 2 \times 2$ interference channel. *IEEE Transactions on Information Theory*, 58(7):4381–4395, Jul. 2012.

[58] D. Gündüz, A. Goldsmith, and H. V. Poor. MIMO Two-way Relay Channel: Diversity-Multiplexing Tradeoff Analysis. In *Proceedings of Asilomar 2008*, Asilomar, USA, 2008.

[59] D. Gündüz, E. Tuncel, and J. Nayak. Rate regions for the separated two-way relay channel. In *Proceedings of the 46th Annual Allerton Conference on Communication, Control, and Computing*, pages 1333–1340, Urbana-Champaign, IL, Sep. 2008.

[60] D. Gündüz, A. Yener, A. Goldsmith, and H. V. Poor. The multi-way relay channel. *IEEE Transactions on Information Theory*, 59(1):51–63, Jan. 2013.

[61] T. S. Han. A general coding scheme for the two-way channel. *IEEE Transactions Information Theory*, 30(1):35–44, 1984.

[62] T. S. Han and K. Kobayashi. A new achievable rate region for the interference channel. *IEEE Transactions on Information Theory*, IT-27(1):49–60, Jan. 1981.

[63] M. Hasna and M. Alouini. End-to-end performance of transmission systems with relays over rayleigh-fading channels. *IEEE Transactions on Wireless Communications*, 2(6):1126–1131, Nov. 2003.

[64] C. Hausl and J. Hagenauer. Iterative network and channel decoding for the two-way relay channel. *Proceedings of IEEE International Conference on Communications, Istanbul, Turkey*, Jun. 2006.

[65] C. Hausl, O. I. scan, and F. Rossetto. Resource allocation for asymmetric multi-way relay communication over orthogonal channels. *Eurasip Journal on Wireless Communications and Networking*, 20, 2012.

[66] X. He and A. Yener. A new outer bound for the secrecy capacity region of the Gaussian two-way wiretap channel. In *Proceedings of the IEEE International Conference on Communications*, Cape Town, South Africa, May. 2010.

[67] X. He and A. Yener. Gaussian Two-way Wiretap Channel with an Arbitrarily Varying Eavesdropper. In *IEEE Globecom*, 2011.

[68] X. He and A. Yener. The role of feedback in two-way secure communications. *IEEE Transactions on Information Theory*, 59(12):8115–8130, Dec. 2013.

[69] A. P. Hekstra and F. M. J. Willems. Dependence balance bounds for single-output two-way channels. *IEEE Transactions on Information Theory*, 35:44–53, 1989.

[70] A. Høst-Madsen and J. Zhang. Capacity bounds and power allocation for wireless relay channels. *IEEE Transactions on Information Theory*, 51(6):2020–2040, Jun. 2005.

[71] C. Huang, S. A. Jafar, and V. R. Cadambe. Interference alignment and the generalized degrees of freedom of the X channel. *IEEE Transactions on Information Theory*, 58(8):5130–5150, Aug. 2012.

[72] K.-S. Hwang, M. Ju, and M.-S. Alouini. On the outage performance of two-way amplify-and-forward relaying with outdated CSI over multiple relay network. In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, London, United Kingdom, Sep. 2013.

[73] K.-S. Hwang, M. Ju, and M.-S. Alouini. Outage performance of opportunistic two-way amplify-and-forward relaying with outdated channel state information. *IEEE Transactions on Communications*, 61(9):3635–3643, Sep. 2013.

[74] S. A. Jafar. Interference alignment: A new look at signal dimensions in a communication network. *Foundations and Trends in Communications and Information Theory*, 7(1):1–136, 2012.

[75] S. A. Jafar and S. Vishwanath. Generalized degrees of freedom of the symmetric Gaussian K user interference channel. *IEEE Transactions on Information Theory*, 56(7):3297–3303, Jul. 2010.

[76] F. Jelinek. Coding for and decomposition of two-way channels. *IEEE Transactions on Information Theory*, 10(1):5–17, Jan. 1964.

[77] J. Joung and A. H. Sayed. Multiuser two-way amplify-and-forward relay processing and power control methods for beamforming systems. *IEEE Transactions on Signal Processing*, 58(3):1833–1846, Mar. 2010.

[78] S. Katti, S. Gollakota, and D. Katabi. Embracing wireless interference: Analog Network Coding. *ACM SIGCOMM, Kyoto, Japan*, Aug. 27-31, 2007.

[79] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft. XORs in the air: practical wireless network coding. *ACM SIGCOMM, Pisa, Italy*, Sep., 11-15 2006.

[80] S. Kim, N. Devroye, P. Mitran, and V. Tarokh. Comparisons of bi-directional relaying protocols. In *Proceedings of the IEEE Sarnoff Symposium*, Princeton, NJ, Apr. 2008.

[81] S. Kim, B. Smida, and N. Devroye. Capacity bounds on multi-pair two-way communication with a base-station aided by a relay. *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Jun. 2011.

[82] S. Kim, B. Smida, and N. Devroye. Lattice strategies for a multi-pair bi-directional relay network. *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Aug. 2011.

[83] R. Knopp. Two-way radio network with a star topology. In *Proceedings of International Zurich Seminar*, Feb. 2006.

[84] G. Kramer. *Directed information for channels with feedback*. PhD thesis, Ph.D. dissertation, Swiss Federal Institute of Technology Zurich, 1998.

[85] G. Kramer, M. Gastpar, and P. Gupta. Capacity theorems for wireless relay channels. *Proceedings of the 41st Annual Allerton Conference on Communication, Control, and Computing*, Oct. 2003.

[86] G. Kramer and S. A. Savari. Cut sets and information flow in networks of two-way channels. In *IEEE International Symposium on Information Theory (ISIT)*, Jun.-Jul. 2004.

[87] K. Lee, N. Lee, and I. Lee. Achievable degrees of freedom on k-user y channels. *IEEE Transactions on Wireless Communications*, 11:1210–1219, Mar. 2012.

[88] K. Lee, N. Lee, and I. Lee. Achievable degree of freedom on K-user Y channels with heterogeneous messages. *IEEE Communications Letters*, 17(2):333–336, Feb. 2013.

[89] K. Lee, N. Lee, and I. Lee. Achievable degrees of freedom on mimo two-way relay interference channels. *IEEE Transactions on Wireless Communications*, 12(4):1472–1480, Apr. 2013.

[90] N. Lee and J. Chun. Signal space alignment for an encryption message and successive network code decoding on the MIMO K-way relay channel. In *IEEE International Conference on Communications*, Kyoto, Jun. 2011.

[91] N. Lee and J. Chun. Degrees of freedom for the MIMO Gaussian K-way relay channel: successive network code encoding and decoding. *IEEE Transactions on Information Theory*, 60(3):1814–1821, Mar. 2014.

[92] N. Lee and R. Heath. Multi-way information exchange over completely-connected interference networks with a multi-antenna relay. *http://arxiv.org/abs/1302.0749*, 2013.

[93] N. Lee and R. W. Heath. Degrees of freedom for the fully-Connected multi-way interference networks. In *IEEE International Symposium on Information Theory (ISIT)*, Istanbul, Jul. 2013.

[94] N. Lee and J.-B. Lim. A novel signaling for communication on MIMO Y channel: signal space alignment for network coding. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, volume 1, pages 2892–2896, Seoul, Jun. 2009.

[95] N. Lee, J.-B. Lim, and J. Chun. Degrees of freedom of the MIMO Y channel: Signal space alignment for network coding. *IEEE Transactions on Information Theory*, 56(7):3332–3342, Jul. 2010.

[96] H. H. J. Liao. *Multiple access channels.* PhD thesis, Department of Electrical Engineering, University of Hawaii, Honolulu, Sep. 1972.

[97] T.-K. Liu, W. Xu, X. Dong, and W.-S. Lu. Adaptive Power Allocation for Bidirectional Amplify-and-Forward Multiple-Relay Multiple-User Networks. In *IEEE Globecom*, pages 1–6, Miami, FL, Dec. 2010.

[98] H. Loeliger. Averaging bounds for lattices and linear codes. *IEEE Transactions on Information Theory*, 43(6):1767–1773, Nov. 1997.

[99] T. Lutz, C. Hausl, and R. Kötter. Bits through deterministic relay cascades with half-duplex constraint. *IEEE Transactions on Information Theory*, 58(1):369–381, Jan. 2012.

[100] M. Maddah-Ali, A. Motahari, and A. Khandani. Communication over MIMO X channels: interference alignment, decomposition and performance analysis. *IEEE Transactions on Information Theory*, 54(8):3457–3470, Aug. 2008.

[101] H. Maier, A. Chaaban, and R. Mathar. Y-Δ product in 3-way Δ and Y-channels for cyclic interference and signal alignment. In *IEEE International Symposium on Information Theory (ISIT)*, Jun. 2014.

[102] H. Maier, A. Chaaban, R. Mathar, and A. Sezgin. Capacity region of the reciprocal deterministic 3-way channel via Delta-Y transformation. In *Proceedings of the 52nd Annual Allerton Conference on Communication, Control, and Computing*, Monticello , Illinois, Oct. 2014.

[103] I. Maric, R. Dabora, and A. Goldsmith. On the capacity of the interference channel with a relay. *Proceedings of IEEE International Symposium on Information Theory (ISIT), Toronto, Canada*, 2008.

[104] B. Matthiesen, A. Zappone, and E. A. Jorswieck. Resource allocation for energy-efficient 3-way relay channels. *IEEE Transactions on Wireless Communications*, Apr. 2015.

[105] H. B. Meeuwissen. *Information Theoretical Aspects of Two-Way Communication*. PhD thesis, TU Eindhoven, 1998.

[106] M. Mokhtar, Y. Mohasseb, M. Nafie, and H. El-Gamal. On the deterministic multicast capacity of bidirectional relay networks. In *IEEE Information Theory Workshop (ITW)*, Dublin, 2010.

[107] N. Naderializadeh and A. S. Avestimehr. ITLinQ: A new approach for spectrum sharing in device-to-device communication systems. *pre-print arXiv:1311.5527v1*, Nov. 2013.

[108] W. Nam, S.-Y. Chung, and Y. Lee. Capacity bounds for two-way relay channels. *Int. Zurich Seminar on Communications (IZS)*, pages 144–147, Mar. 12-14 2008.

[109] W. Nam, S.-Y. Chung, and Y. Lee. Capacity of the gaussian two-way relay channel to within 1/2 bit. *IEEE Transactions on Information Theory*, 56(11):5488–5494, Jul. 2010.

[110] K. Narayanan, M. P. Wilson, and A. Sprintson. Joint physical layer coding and network coding for bi-directional relaying. In *Proceedings of the 45th Annual Allerton Conference on Communication, Control, and Computing*, Illinois, USA, Sep. 2007.

[111] B. Nazer. Successive compute-and-forward. In *Proceedings of the 22nd International Zurich Seminar on Communication (IZS 2012)*, Zurich, Switzerland, Mar. 2012.

[112] B. Nazer and M. Gastpar. Compute-and-forward: harnessing interference through structured codes. *IEEE Transactions on Information Theory*, 57(10):6463–6486, Oct. 2011.

[113] T. Oechtering, C. Schnurr, I. Bjelakovic, and H. Boche. Broadcast capacity region of two-phase bidirectional relaying. *IEEE Transactions on Information Theory*, 54(1):454–458, Jan. 2008.

[114] T. J. Oechtering, R. F. Wyrembelski, and H. Boche. Optimal transmit strategy for the 2×1 MISO bidirectional broadcast channel. In *IEEE SPAWC*, pages 316–320, Recife, Brazil, Jul. 2008.

[115] L. Ong. Capacity results for two classes of three-way channels. In *Proceedings of the International Symposium on Communications and Information Technologies (ISCIT)*, Gold Coast, QLD, Oct. 2012.

[116] L. Ong and S. Johnson. The capacity region of restricted multi-way relay channels with deterministic uplinks. In *IEEE International Symposium on Information Theory (ISIT)*, pages 786–790, Cambridge, MA, Jul. 2012.

[117] L. Ong and S. Johnson. The capacity region of the restricted two-way relay channel with any deterministic uplink. *IEEE Communications Letters*, 16(3), Mar. 2012.

[118] L. Ong, S. Johnson, and C. M. Kellett. An optimal coding strategy for the binary multi-way relay channel. *IEEE Communications Letters*, 14(4):330–332, Apr. 2010.

[119] L. Ong, S. Johnson, and C. M. Kellett. The capacity region of multiway relay channels over finite fields with full data exchange. *IEEE Transactions on Information Theory*, 57(5):3016–3031, May 2011.

[120] L. Ong, C. M. Kellett, and S. Johnson. Functional-decode-forward for the general discrete memoryless two-way relay channel. In *IEEE ICCS*, pages 351–355, Singapor, Nov. 2010.

[121] L. Ong, C. M. Kellett, and S. Johnson. On the equal-rate capacity of the AWGN multiway relay channel. *IEEE Transactions on Information Theory*, 58(9):5761–5769, Sep. 2012.

[122] L. H. Ozarow. The capacity of the white Gaussian multiple access channel with feedback. *IEEE Transactions on Information Theory*, 30:623–629, Jul. 1984.

[123] A. J. Pierrot and M. Bloch. Strongly secure communications over the two way wiretap channel. *IEEE Transactions on Information Forensics and Security*, 6(3):595–605, Sep. 2011.

[124] P. Popovski and H. Yomo. Physical network coding in two-way wireless relay channels. In *IEEE International Conference on Communications*, pages 707–712, Glasgow, Jun. 2007.

[125] B. Rankov and A. Wittneben. Achievable rate regions for the two-way relay channel. *International Symposium on Information Theory (ISIT), Seattle, USA*, Jul. 9-14, 2006.

[126] B. Rankov and A. Wittneben. Spectral efficient protocols for half-duplex fading relay channels. *IEEE Journal on Selected Areas in Communications*, 25(2):379–389, Feb. 2007.

[127] J. Richter, C. Scheunert, S. Engelmann, and E. A. Jorswieck. Weak secrecy in the multiway untrusted relay channel with compute-and-forward. *IEEE Transactions on Information Forensics and Security*, 10(6):1262–1273, Jun. 2015.

[128] P. Rost. The two-way interference channel: towards a redesign of mobile communication systems. In *IEEE Vehicular Technology Conference Fall*, pages 1–5, San Francisco, CA, Sep. 2011.

[129] S. Saha and R. A. Berry. Symmetric K-user Gaussian interference channels: approximate sum-capacity via deterministic modeling. In *Proceedings of the 50th Annual Allerton Conference on Communication, Control, and Computing*, Monticello, Illinois, Oct. 2012.

[130] H. Sato. The capacity of the Gaussian interference channel under strong interference. *IEEE Transactions on Information Theory*, IT-27(6):786–788, Nov. 1981.

[131] A. Schad and M. Pesavento. Multiuser bi-directional communications in cooperative relay networks. In *IEEE CAMSAP*, pages 217–220, San Juan, Dec. 2011.

[132] J. Schalkwijk and T. Kailath. A coding scheme for additive noise channels with feedback- Part I: No bandwith constraint. *IEEE Transactions on Information Theory*, IT-12(2):172–182, Apr. 1966.

[133] J. P. M. Schalkwijk. The binary multiplying channel: A coding scheme that operates beyond Shannon's inner bound region. *IEEE Transactions on Information Theory*, 28(1):107–110, 1982.

[134] J. P. M. Schalkwijk. On an extension of an achievable rate region for the binary multiplying channel. *IEEE Transactions on Information Theory*, 29(3):445–448, May 1983.

[135] C. Schnurr, S. Stanczak, and T. J. Oechtering. Achievable rates for the restricted half-duplex two-way relay channel under a partial-decode-and-forward protocol. In *IEEE Information Theory Workshop (ITW)*, pages 134–138, Porto, May 2008.

[136] A. Sezgin, A. S. Avestimehr, M. A. Khajehnejad, and B. Hassibi. Divide-and-conquer: approaching the capacity of the two-pair bidirectional Gaussian relay network. *IEEE Transactions on Information Theory*, 58(4):2434–2454, Apr. 2012.

[137] A. Sezgin, M. Khajehnejad, A. S. Avestimehr, and B. Hassibi. Approximate capacity region of the two-pair bi-directional gaussian relay network. *IEEE International Symposium on Information Theory (ISIT), Seoul, Korea, Jun. 28- Jul. 3*, 2009.

[138] R. Shakeri, A. Taherpour, H. Khakzad, and T. Khattab. Optimal power allocation and relay selection in two-way multi-relay cooperative communication. In *IEEE Gulf Cooperation Council Conference & Exhibition*, Doha, Nov. 2013.

[139] C. E. Shannon. A mathematical theory of communication. *The Bell System Technical Journal*, 27:379–423, 623–656, 1948.

[140] C. E. Shannon. The zero error capacity of a noisy channel. *IRE Transactions on Information Theory*, 2(3):8–19, 1956.

[141] C. E. Shannon. Two-way communication channels. *Proceedings 4th Berkeley Symposium on Mathematical Statistics Probability, Berkeley, CA*, pages 611–644, 1961.

[142] M. Shaqfeh, A. Zafar, H. Alnuweiri, and M.-S. Alouini. Joint opportunistic scheduling and network coding for bidirectional relay channel. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Istanbul, Turkey, 2013.

[143] I. Shomorony and A. S. Avestimehr. Sum degrees-of-freedom of two-unicast wireless networks. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, St. Petersburg, Jul. 31-Aug. 5 2011.

[144] I. Shomorony and A. S. Avestimehr. Degrees of freedom of two-hop wireless networks: everyone gets the entire cake? In *Proceedings of the Annual Allerton Conference on Communication, Control, and Computing*, Monticello, IL, USA, Oct. 2012.

[145] I. Shomorony and A. S. Avestimehr. Two-unicast wireless networks: characterizing the degrees-of-freedom. *IEEE Transactions on Information Theory*, 59(1):353–383, Jan. 2013.

[146] D. Slepian and J. K. Wolf. Noiseless coding of correlated information sources. *IEEE Transactions on Information Theory*, IT-19:471–480, Jul. 1973.

[147] Y. Song and N. Devroye. List decoding for nested lattices and applications to relay channels. In *Proceedings of the 46th Annual Allerton Conference on Communication, Control, and Computing*, 2010.

[148] Y. Song and N. Devroye. Lattice codes for the Gaussian relay channel: Decode-and-forward and compress-and-forward. *IEEE Transactions on Information Theory*, 59(8):4927–4948, Aug. 2013.

[149] Y. Song, N. Devroye, H.-R. Shao, and C. Ngo. Lattice coding for the two-way line network. *IEEE Journal on Selected Areas in Communications*, 32(9):1707–1720, Sep. 2014.

[150] C. Suh and D. Tse. Feedback capacity of the Gaussian interference channel within 2 bits. *IEEE Transactions on Information Theory*, 57(5):2667–2685, May 2011.

[151] C. Suh, I.-H. Wang, and D. Tse. Two-way interference channels. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Istanbul, Turkey, 2013.

[152] R. Tandon and S. Ulukus. On dependence balance bounds for two way channels. In *41st Asilomar Conference*, pages 868–872, Pacific Grove, CA, Nov. 2007.

[153] K. K. Teav, Z. Zhendong, and B. Vucetic. Performance optimization of MIMO Y channels: interference alignment and signal detection. *IEEE Communications Letters*, 18(1):66–69, Jan. 2014.

[154] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu. Device-to-device communications in 5G cellular netowrks: Challenges, solutions, and future directions. *IEEE Communications Magazine*, pages 86–92, May 2014.

[155] E. Telatar. Capacity of multi-antenna Gaussian channels. *European Transactions on Telecommunications*, 10(6):585–596, Nov. 1999.

[156] Y. Tian and A. Yener. Signal space alignment and degrees of freedom for the two-cluster multi-way relay channel. In *IEEE International Conference on Communications in China*, pages 12–17, Beijing, Aug. 2012.

[157] Y. Tian and A. Yener. Degrees of freedom optimal transmission for the two-cluster MIMO multi-way relay channel. In *IEEE International Conference on Communications*, pages 3344–3348, Budapest, Jun. 2013.

[158] Y. Tian and A. Yener. Degrees of Freedom for the MIMO Multi-way Relay Channel. *IEEE Transactions on Information Theory*, 60(5), May 2014.

[159] R. Timo, G. Lechner, L. Ong, and S. Johnson. Multi-way relay networks: orthogonal uplink, source-channel separation and code design. *IEEE Transactions on Wireless Communications*, 61(2):753–768, Feb. 2013.

[160] D. Tse and P. Viswanath. *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[161] K. Tutuncuoglu, B. Varan, and A. Yener. Energy harvesting two-way half-duplex relay channel with decode-and-forward relaying: Optimum power policies. In *International Conference on DSP*, Fira, Jul. 2013.

[162] K. Tutuncuoglu, B. Varan, and A. Yener. Optimum transmission policies for energy harvesting two-way relay channels. In *IEEE International Conference on Communications*, Budapest, Jun. 2013.

[163] K. Tutuncuoglu and A. Yener. Multiple access and two-way channels with energy harvesting and bi-directional energy cooperation. In *ITA Workshop*, San Diego, CA, Feb. 2013.

[164] P. Ubaidulla, M.-S. Alouini, and S. Aissa. Multi-pair cognitive two-way relaying and power allocation under imperfect CSI. In *IEEE Vehicular Technology Conference*, Dresden, Jun. 2013.

[165] E. van der Meulen. Three-terminal communication channels. *Ad. Appl. Pmb.*, 3:120–154, Sep. 1971.

[166] E. van der Meulen. A survey of multi-way channels in information theory: 1961-1976. *IEEE Transactions on Information Theory*, 23(1):1–37, Jan. 1977.

[167] R. Vaze and R. W. Heath. Capacity scaling for MIMO two-way relaying. In *Proceedings of International Symposium on Information Theory (ISIT)*, Nice, France, 2007.

[168] R. Vaze and R. W. Heath. Optimal amplify and forward strategy for two-way relay channel with multiple relays. In *Proceedings IEEE Information Theory Workshop (ITW)*, pages 181–185, Volos, Jun. 2009.

[169] R. Vaze and R. W. Heath. On the capacity and diversity-multiplexing tradeoff of the two-way relay channel. *IEEE Transactions on Information Theory*, 57(7):4219–4234, Jul. 2011.

[170] C. Wang. Beyond One-Way Communication: Degrees of Freedom of Multi-Way Relay MIMO Interference Networks. *arXiv:1401.5582*, Jan. 2014.

[171] C. Wang, H. Chen, Q. Yin, A. Feng, and A. F. Molisch. Multi-user two-way relay networks with distributed beamforming. *IEEE Transactions on Wireless Communications*, 10(10):3460–3471, Oct. 2011.

[172] G. Wang, W. Xiang, , and J. Yuan. Outage performance for compute-and-forward in generalized multi-way relay channels. *IEEE Communications Letters*, 16(12):2099–2102, Dec. 2012.

[173] M. P. Wilson, K. Narayanan, H. D. Pfister, and A. Sprintson. Joint physical layer coding and network coding for bidirectional relaying. *IEEE Transactions on Information Theory*, 56(11):5641–5654, Nov. 2010.

[174] A. Wyner and J. Ziv. The rate-distortion function for source coding with side information at the decoder. *IEEE Transactions on Information Theory*, IT-22(1):1–10, Jan. 1976.

[175] R. F. Wyrembelski, T. J. Oechtering, I. Bjelakovic, C. Schnurr, and H. Boche. Capacity of Gaussian MIMO bidirectional broadcast channels. In *IEEE International Symposium on Information Theory (ISIT)*, pages 584–588, Toronto, Canada, Jul. 2008.

[176] L.-L. Xie. Network coding and random binning for multi-user channels. In *Proceedings of the 10th Canadian Workshop Information Theory*, 2007.

[177] H.-J. Yang, Y. Choi, N. Lee, and A. Paulraj. Achievable sum-rate of MU-MIMO cellular two-way relay channels: lattice code-aided linear precoding. *IEEE Journal on Selected Areas in Communications*, 30(8):1304–1318, Sep. 2012.

[178] L. Yang, K. Qaraqe, E. Serpedin, and M.-S. Alouini. Performance analysis of amplify-and-forward two-way relaying with co-channel interference and channel estimation error. In *IEEE Wireless Communications and Networking Conference*, pages 3710–3714, Shanghai, Apr. 2013.

[179] R. Zamir. Lattices are everywhere. In *4th Annual Workshop on Information Theory and its Applications (ITA)*, La Jolla, CA, Feb. 2009.

[180] A. Zewail, Y. Mohasseb, M. Nafie, and H. El-Gamal. The deterministic capacity of relay networks with relay private messages. In *IEEE Information Theory Workshop (ITW)*, Sevilla, Sep. 2013.

[181] A. Zewail, Y. Mohasseb, M. Nafie, and H. El-Gamal. The deterministic multicast capacity of 4-node relay networks. In *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Istanbul, Turkey, Jul. 2013.

[182] M. Zhang, H. Yi, H. Yu, H. Luo, and W. Chen. Joint optimization in bidirectional multi-user multi-relay MIMO systems: non-robust and robust cases. *IEEE Transactions on Vehicular Technology*, 62(7):3228–3244, Sep. 2013.

[183] Z. Zhang, T. Berger, and J. P. M. Schalkwijk. New outer bounds to capacity regions of two-way channels. *IEEE Transactions on Information Theory*, 32:383–386, 1986.

[184] Z. Zhao, Z. Ding, M. Peng, W. Wang, and K. K. Leung. A special case of multi-way relay channel: When beamforming is not applicable. *IEEE Transactions on Wireless Communications*, 10(7):2046–2051, Jul. 2011.