IEEE Information Theory Society Newsletter

Vol. 60, No. 4, December 2010 Editor: Tracey Ho ISSN 1045-2362

Editorial committee: Helmut Bölcskei, Giuseppe Caire, Meir Feder, Joerg Kliewer, Anand Sarwate, and Andy Singer

President's Column

Frank R. Kschischang

Volunteering: the practice of working on behalf of others without payment for time and services.

The IEEE Information Theory Society runs on the efforts of its volunteers. From those who serve on the Society's committees (the Conference Committee, the Fellows Committee, the Awards Committee, the Student Committee, the Outreach Committee, the Online Committee and many other committees), to the Board of Governors, to the organizers of Symposia, Workshops, and Summer Schools, to the officers of local Chapters, to the Distinguished Lecturers, to the Editor-in-Chief, Publications Editor, Newsletter Editor and Associate Editors, to the reviewers of papers, the list of those who serve the Society in some capacity is a long one. In fact, there are over 90 distinct names on the list of committee-members alone, and I would venture that many readers of this column have served as a Society volunteer in some capacity at some point. On behalf of the Society, I thank you for your efforts! And if you haven't yet enjoyed the privilege of serving as an ITSoc volunteer, I would encourage you to seize the opportunity when it arises.

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Eigenfactor^{tm}: a rating of the (purported) total importance of a scientific journal (see www.eigenfactor.org).

All bibliometric measures that attempt to boil the influence, impact, and "importance" of a scientific journal down to a single number should be treated with a healthy degree of skepticism. Nevertheless, members of the Information Theory Society may be interested to know that the IEEE Transactions on Information Theory currently ranks *first* among all journals in electrical engineering, computer science and applied mathematics in Eigenfactor^{tm} score. Eigenfactor assigns a score to a journal based on the number of times articles from the journal published in the past five years have been cited in the present year, giving higher weight (in a manner similar to Google's PageRank algorithm) to citations arising from journals that are themselves highly cited. Journal self-citations (references from articles in a journal to another article in the same journal) are not counted. Unlike the so-called "Impact Factor," which measures citations in a given year to articles published in the previous two years only, the Eigenfactor score has a longer window over which "impact" is measured. Nevertheless, with a "cited half-life" of over 9 years (meaning that half of the citations to the Transactions in a given year are to articles that were published more than 9 years before), even a five-year citation window may fail to properly recognize the influence of our venerable Transactions.

On June 30, Editor-in-Chief of the Transactions, Ezio Biglieri, reached the end of his term. Every paper submitted to the Transactions in the past three years was handled by Ezio—on the order of 2800 during his tenure as EiC. Under Ezio's careful stewardship, the Editorial Board of the Transactions grew from 26 Associate Editors to over 40 today, requiring a significant recruitment effort. Ezio's service to the Society as EiC was recognized with a special award at the Austin Symposium, and I am sure that everyone is grateful for his efforts.

Ezio's successor, Helmut Bölcskei, assumed the position of EiC on July 1st. To assist him with various issues of policy, appointment of Associate Editors, and other matters that arise in the running of the Transactions, Helmut has, with the approval of the Board of Governors, appointed an Executive Editorial Board, consisting of Dave Forney, Shlomo Shamai, Alexander Vardy, and Sergio Verdú. Clearly the Transactions is in very good hands.

As I mentioned in the March Newsletter, despite the high quality of the papers published in the Transactions, the lengthy "sub-to-pub" (the length of time between submission and publication of a paper) remains a concern. Of course I am not advocating sacrificing the quality of reviews, but I do suggest that there is significant margin to reduce review times. The transfer of our paper-handling operation to ScholarOne Manuscripts will likely smooth out certain logistical and

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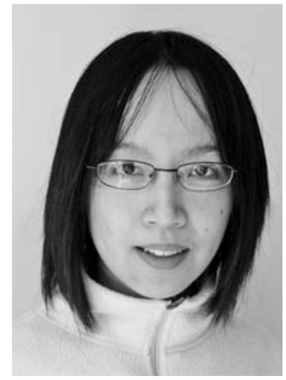
From the Editor

Tracey Ho



Dear IT Society members,

In this packed year-end issue, we have Frank Kschischang's last column as IT Society President. Please join me in expressing thanks for his immeasurable leadership and vision over this year. A warm welcome also to Giuseppe Caire as next year's IT Society President, and congratulations to Norman Beaulieu on winning two prestigious awards. Other articles in this issue include summaries of the 2010 ISIT plenary talks by Abbas El Gamal and Anthony Ephremides, and updates from WITHITS, the Online Committee and the IT Student Committee as well as a report on the Third Annual School of Information Theory.

As a reminder, announcements, news and events intended for both the printed newsletter and the website, such as award announcements, calls for nominations and upcoming conferences, can be submitted jointly at the IT Society website http://www.itsoc.org/, using the quick links "Share News" and "Announce an Event". Articles and columns that do not fall into the above categories should be e-mailed to me at tho@caltech.edu, with a subject line that includes the words "IT newsletter". The deadlines for the next few issues are:

Issue	Deadline
March 2011	January 10, 2010
June 2011	April 10, 2010
September 2011	July 10, 2010

Please submit ASCII, LaTeX or Word source files; do not worry about fonts or layout as this will be taken care of by IEEE layout specialists. Electronic photos and graphics should be in high resolution and sent as separate files.

I look forward to your contributions and suggestions for future issues of the newsletter.

Tracey Ho

IEEE Information Theory Society Newsletter

IEEE Information Theory Society Newsletter (USPS 360-350) is published quarterly by the Information Theory Society of the Institute of Electrical and Electronics Engineers, Inc.

Headquarters: 3 Park Avenue, 17th Floor, New York, NY 10016-5997.

Cost is $1.00 per member per year (included in Society fee) for each member of the Information Theory Society. Printed in the U.S.A. Periodicals postage paid at New York, NY and at additional mailing offices.

Postmaster: Send address changes to IEEE Information Theory Society Newsletter, IEEE, 445 Hoes Lane, Piscataway, NJ 08854.

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administrative procedures, and this may have a small impact. Any *significant* reduction in sub-to-pub will, however, require a change in culture: certain reviewers (me included, unfortunately) will need to start reading the paper *before* receiving the first reminder; certain associate editors will need to remember that a second (or third) review is not always mandated if the authors have faithfully implemented required changes; certain authors will need to remember that a positive first review is not an indefinite "reservation" to publish at their leisure. ScholarOne Manuscripts gives the Editor-in-Chief and the Associate Editors the ability to gather various performance statistics; it is conceivable that reviewers and associate editors will in the future be given an annual "report card," comparing their responsiveness with the general distribution.

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It has been a distinct privilege to serve as the 2010 President of the IEEE Information Theory Society. I am particularly grateful to have been able to work with a singularly dedicated group of officers, committee chairs, and many other volunteers that keep the Society running smoothly. I very much look forward to working with next year's officer group: Senior Past President Andrea Goldsmith, President Giuseppe Caire, First Vice President Muriel Médard, and our newest officer, Second Vice President Gerhard Kramer. The present group of Society officers has benefitted greatly from the sagacity of outgoing Senior Past President Dave Forney, who deserves a special note of thanks.

As always, if you would like to get more involved in the activities of the Society or share your comments, please contact me at frank@comm.utoronto.ca.

Scholar One Website for IEEE Transactions on Information Theory has gone live

New paper submissions to the IEEE Transactions on Information Theory should from now on be to http://mc.manuscriptcentral.com/t-it. Papers submitted under Pareja will be continued to be handled in Pareja. For comments, suggestions for improvements, and questions please contact

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Editor-in-Chief
IEEE Transactions on Information Theory

IT Society Member Honored

Dr. Norman C. Beaulieu, Professor and iCORE Research Chair in Broadband Wireless Communications at the University of Alberta has been awarded the 2010 Reginald Aubrey Fessenden Silver Medal "for outstanding contributions in wireless communication theory" by IEEE Canada, as well as the 2010 Canadian Award for Telecommunications Research (CATR), a career award that recognizes outstanding Canadian researchers as demonstrated by their impact on telecommunications research.

His major research contributions include the development of what is now termed the "Beaulieu Series", a method to compute error rates, outage and coverage in communications systems with inter-symbol and co-channel interference, practical diversity system design analysis, analysis and understanding of decision feedback equalizers, development of an improved Nyquist pulse, where its application to OFDM systems is now a Motorola-owned patent, as well as the development, in collaboration with Damen and El Gamal, of threaded algebraic space-time (TAST) codes, which have been patented and incorporated into the IEEE 802.16e (WiMax) standard. He is Fellow of IEEE, Fellow of the Royal Society of Canada, Fellow of the Engineering Institute of Canada, and Fellow of the Canadian Academy of Engineering, and has previously won the IEEE Communications Society Edwin Armstrong Achievement Award and the AST Leadership Foundation's Outstanding Leadership in Alberta Technology Award.

The Historian's Column

Anthony Ephremides

Periodically this column recognizes an external contributor and bestows upon him/her the coveted title of Honorary Historian. It is a distinct pleasure to so recognize today Ezio Biglieri, who hereby joins the ranks of Honorary Historians with the likes of Toby Berger, Jim Maney and others who over the years made similar contributions.

Ezio has drawn attention to the fact that, alongside their serious research contributions, many of our members display also a whimsical side full of eccentricity, humor, and lightness. He starts with recalling how Jack Van Lint (now deceased), while giving a talk at the banquet of the 1970 ISIT, referred to the dish of "pea-log-pea" and to the "digestive noise" it may produce. He then points to Bob McEliece who developed a superb substitution of lyrics for a famous Beatles song and included the famous refrain "ob-la-di p-log-p" in a number of performances in which he actually sang the song to critical acclaim.

Subsequent examples, of course, abound. During the 2008 JWCC (Joint Workshop on Communications and Coding), known also as workshop on Wine and Coding, Dave Forney, as chair session, introduced the speakers through use of, so-called, Clerihews (which are awkward and clumsy "limerick-like" poetic concoctions).

For example, the introduction of Ezio (who was in fact the very first speaker) went like this:

> Ezio Biglieri
> Connoisseur Extraordinary
> with Ephremides and Verdú
> he shows us all what to do.

On another occasion, the multi-talented Sol Golomb offered true limericks, like

> A message with content and clarity
> is gotten to be quite a rarity.
> To prevent the terror
> of serious error
> use bits of appropriate parity

or, like

> Delight in your algebra dressy
> but take heed from a lady name Jessie
> who spoke to us here
> of her primitive fear
> that good codes just might be messy

in reference to Coding Theorist Jessica McWilliams. These are all examples of a certain sort of playfulness that Shannon himself displayed through his fascination with juggling and other amusing endeavors. And talking about endeavors, here is the crowning example provided by Ezio, actually authored by himself, through his "nom de plume" of F.Y. Endeavor. It is titled:

> "60-word Shamelessly Adulatory
> Onomastic Double Acrostic"

It was delivered on the occasion of Dave Forney's celebration of his 60th birthday in 2000, dubbed the "Forneyfest".

> **D**eus ex machina of Information Theor**Y**
> **A**cademic of Engineering and Shannon Awarde**E**
> **V**ice President of Motorola in Bosto**N**
> **E**ditor-in-Chief and Merciless Reviewe**R**
> **F**ormalizer of the Coding Discipline to**O**
> **O**rganizer of Symposia and Colloquia thereo**F**
> **R**elentless modem builder, Fellow of IEE**E**
> **N**ot inferior to Shannon or Kotelinko**V**
> **E**xpounder of Turbocodes to Americ**A**
> **Y**ou achieved more than anybody di**D**

Some might say that Ezio stretched language, grammar, and syntax here, and they would be right. Others might say that the compilation of accolades reads awkward and asymmetric. They would be right, too. In fact what Ezio did here was to apply a modern version of the principle of Prokroustis. The latter was a villain of Greek Mythology who was positioned along the lonely path leading from ancient Athens to Corinth. He had a bed of fixed size and he would intercept every rare pedestrian who would come by his way and force him to lie on the bed. If the victim fell short in filling the length of the bed, Prokroustis would stretch his limbs to make him fit snugly. If on the other hand the victim was longer than the bed, the infamous bandit would chop-off the excess length. As it happens, Prokroustis was eventually eliminated by Theseus. Wishing upon Ezio no such fate (besides, we don't have modern versions of Theseus today), we wish to salute him for coming forward with these gems of wit that simply confirm that Information Theoretic have multiple talents.

In fact, upon reading the diverse talents attributed to Dave, what came to my mind was the inscription outside the house of Oscar Wilde in Dublin that described the distinctions of William Wilde (Oscar's father) who was actually the household chief. It read something like:

> Aural and Opthalmic Surgeon
> Historian, Biographer, Statistician,
> Topographer, Explorer, …

and several other endeavor descriptions that I jotted on a piece of paper that, unfortunately, I subsequently lost. Forgive my temptation to indulge in Ezio's writings but, as Oscar Wilde said "the only way to get rid of temptation is to succumb to it"!

Throughput and Capacity Regions

Plenary talk presented at the 2010 IEEE International Symposium on Information Theory, Austin, Texas, USA.

Anthony Ephremides

It is fair to say that one of the major challenges faced today by Information theorists is to extend the formidable power of the Theory of Shannon to Communication Networks [1]. Shannon himself had expressed skepticism about the extension and hinted that to do that "new ideas" would be needed. The success story of the single-link communication paradigm has found only moderate possibilities in multi-user systems. The AWGN (Additive White Gaussian Noise) model has been the solid anchor around which the search for the extension has resided for the last several decades. Even the cases of the point-to-point fading wireless channel or the most elementary versions of the two-by-two interference channel have defied attempts to reveal their capacities.

At the same time, in a way analogous to the situation in the first half of the twentieth century, when chaos was reigning in the efforts to understand the point-to-point communication process, today's network systems, i.e., the Internet, Local Area Networks, Cellular and Ad Hoc Wireless Networks are actually being built and operated and are changing our lives, yet without any clue as to their ultimate capabilities. So, it is high time to "bridge the gap".

In addition to differences in the minds of researchers concerning the methodological approach to this question, there is also a philosophical dichotomy. Purists on the side of traditional Information Theory insist that the fundamental model that captures the point-to-point communication process is sacrosanct and remains the true (and only?) approach to the multi-user case. At the same time, under the pressure of design improvements that are needed in the existing world of networks there is a growing interest in exploring alternative models. Without taking sides on this dichotomy, I tried in my June 2010 lecture to present our current knowledge of points of contact between these two views.

The focus of the present discussion centers on transmission *rates*. That is, what are the maximum achievable communication rates in multi-user systems? These rates are known as *capacities* in the Information Theoretic parlance and *throughputs* in the Networking community. Before elaborating on their relationship, it is important to highlight a highly important distinction in the modeling of communication systems. Do we care about our source model or not? By this I mean, do we care about whether the transmitter sits on top of an unlimited reservoir of data or whether it receives sporadic randomly generated data in real time from its surrounding physical sources?

In the first case, that is when the volume of available data at the source is infinite, delay does not matter. Then, the single-minded objective is to assess the highest rates at which data can be delivered to its destinations. We note that in the multi-user case these rates are actually rate regions of vector-valued rates. Let us call this case, the *saturated source* case, and the resulting rate measures the *saturated capacity* or *throughput* regions.

In the second case, we need to require that the rate at which the source actually generates (or receives from exogenous entities) its data must be, on average, equal to the rate with which it delivers them through the network channel to its destinations. Otherwise, the system lives through a transient phase at the ultimate end of which it converges to the saturated case.

When we do require a balanced input-output relationship, let us call the resulting (sustainable) rates, *stable capacity* and *stable throughput* regions. The precise mathematical way in which we define this notion of balance (called, *stability*) is actually of secondary importance. If we are willing to restrict our attention to a fairly general (but not the most general) class of traffic models, then almost all definitions of stability are equivalent and translate to "what-goes-in, must-come-out". In a single server queuing system (where service is the transmission of a piece of data over a given channel with known traditional Shannon capacity C bits/sec) this means that the arrival rate λ (or generation rate) at the source cannot exceed C (on average) and can have any value not exceeding C to guarantee stability.

One of the striking results in recent years has been that in such a single-link "stable" communication system, the stable Information-theoretic capacity, that is the rate at which *information* can be sent over the channel can be actually greater than C [2]. Let us not confuse "information" that is "communicated" over the channel with the actual data pieces (e.g. the packets) that the source receives, stores, and transmits at rate C. The relevant mental construct is known as "timing information" and the corresponding mental construct that consists of the real source, the channel, and the timing information, is known as a timing channel. Actually, the observation that any pauses and resumptions of activity by a source that receives (or generates) bursty traffic actually embody additional information goes back to 1976, when, under the guise of "overhead", this information was shown to be possibly huge and, in fact, could dominate the "actual" traffic [3].

If we now consider a multi-user system (for the sake of simplicity, let us just consider for the moment a 2-user multi-access channel), it is interesting to know what the corresponding *four* rate measures are. That is, what is the **saturated capacity region**, what is the **stable capacity region**, and what are the **saturated** and **stable throughput regions**? But we haven't yet discussed what we mean by throughput. In the case of the single-user (single-link) case this is not a different concept. However, in the multi-user case, it may be different.

The definition of throughput (unlike that of capacity) does not require the complex operational concept of coding theorems and mutual informations that are the components of the capacity measure. It simply counts "blocks" of information nuggets (from single-bits to huge multi-bit packets), it employs a channel model, for which the "primitive" transmission elements are just these blocks, and it attempts to specify the highest achievable rate of blocks per unit time at which they can be delivered to their destinations. Although the precise variables needed to carefully define throughput and capacity require systematic reconciliation, it is a straight-forward exercise to show that the stable throughput, the saturated throughput, and the saturated capacity are all equal in the single link case. As noted before, the stable capacity may be higher.

Returning to the two-user, multi-access case, we need to specify the channel model and the transmission rules. The simplest case that has been thoroughly (yet, non-trivially) studied is the so-called random access, collision channel. The "blocks" transmitted in a time unit ("slot") are packets and the channel is interference-limited to the exteme. This means that if both users attempt transmission in the same slot, their packets fail to be received, while if only one of them transmits in a slot, the transmission is successful.

This model is simple and has some subtle aspects that are often overlooked. Specifically, when a single user attempts transmission in a slot, the number of bits in it can be arbitrarily large. That is, in traditional terms, the collision channel has infinite capacity when only one user is present. This properly plays a crucial role in what we know about the rate measures for this channel. Under the rule of random access, each user in each slot decides independently whether to attempt transmission or not, provided there is at least one packet in its queue. User i attempts transmission with probability p(i) (and it receives exogenous traffic with rate λ_i packets-per-slot, in the stable case).

What we know for this system is that its stable throughput region is significantly larger than (that is, it strictly contains) the saturated throughput region [4]. In addition, we know it is concave and co-ordinate-convex. If we take the union of the set of such regions that correspond to different values of the p_i's, the resulting region is bounded in the positive quadrant of the (λ_1, λ_2) plane by the curve described by

$$\sqrt{\lambda_1} + \sqrt{\lambda_2} = 1$$

Both the stable and the saturated regions have exactly the same union. Hence, if the p_1, p_2 are not specified and fixed, the stable and the saturated throughput regions are exactly the same, although for fixed values of the p_i's they are not. Interestingly, and precisely because the collision channel has unlimited single-user capacity, the saturated Information theoretic capacity region of this channel (irrespective of the values of the p_i's) turns out to be also identical to the throughput region [5, 6]. This time the units of the rates are R_i bits/channel use, i = 1, 2 (since, otherwise, the unlimited, i.e. infinite, capacity of the channel, when a single user transmits, would lead to absurd conclusions) and the region is bounded by

$$\sqrt{R_1} + \sqrt{R_2} = 1$$

Nothing is known for this channel about its stable capacity region. It stands to reason that with the additional degree of freedom that timing provides, that capacity region would be larger. Of course, as soon as we migrate to multi-user systems, we must expect that the timing "opportunity" cannot be used entirely to embody additional information, since (at least partly) it must carry *overhead* information. This is also legitimate "additional" information but it is counted on the negative side of the ledger as it is constrained to convey logistical details that are not usually credited as transmitted "information" (perhaps erroneously so) in the conventional sense. They are however absolutely necessary for defining and specifying the operating rules of the system and are part of what we refer to as **protocols**.

How much farther can we go? There are some serious obstacles. The main difficulty in obtaining stable throughput regions lies in the analysis of interacting queueing systems. Unfortunately, for three or more users, tracking the dynamics of such queues gets too complicated. The main difficulty in obtaining saturated capacity regions lies in extending the Shannon-theoretic arguments and in proving the requisite coding theorems. An approach of some generality that has yielded some useful results so far in the direction od "bridging the gap", consists of generalizing the collision channel to a so-called channel with multi-packet reception capability. This is equivalent to the idea of simulataneous successful reception of signals from multiple users albeit at reduced individual rates. It is the outgrowth of multi-user detection theory and its use in CDMA systems. The model has become known as the "**packet erasure channel**" and it is fairly useful and moderately powerful as it can accommodate numerous practical situations.

The packet erasure channel model simply asserts that in every slot the packet of a user may reach its destination successfully with some probability, which is a decreasing function of the number of simultaneously transmitting other users. In its most general form, if the set of users in a multi-access channel is N, then for any subsets A and B of N, such that A contains B, we define the probability Q(A,B) as the probability that the users in B are successful given that the users in A attempt transmission. Clearly, to be physically meaningful, this model implies that Q is decreasing in the cardinality of A and in the cardinality of B.

For this channel model what we know is that the saturated throughput region coincides with the saturated capacity region under random access transmission rules. Furthermore, the stable throughput region (even though it is practically impossible to actually compute it) is equal to both of the preceding regions, provided a conjectured property holds. That property postulates that as two or more users become more aggressive in their attempt to access the channel (i.e., as they simultaneously increase their access probabilities), they end up achieving a marginal gain. It can be seen that whether they do or not is far from clear. On one hand, by being more aggressive, they increase their chances of getting their packets through. On the other hand, by so doing, they diminish their chances of being successful when they are simultaneously accessing the channel. This property is known as the **sensitivity monotonicity property** [7].

Nothing is known about the stable capacity region for this channel, but, again, it is natural to expect that it would be a region larger than the one for the saturated case, because of the timing degree of freedom.

It should be noted that the packet erasure model can be very useful in (at least, approximately) modeling systems in which the interference is treated as additive Gaussian noise (as, for example, in CDMA systems). Then the quantities Q(A,B) can be readily computed as the probabilities that the corresponding signal-to-interference-plus-noise-ratios (SINR) exceed a threshold that is a function of many things, but, notably an increasing function of the individual transmission bit-rates and a decreasing function of the target bit-error-rates. We do know that connecting packet lengths, bit-error, rate, and transmission rate is a formidable problem in Information Theory [8]. In multi-user systems it is a veritable "tabula rasa", that is nothing quantitative is known about their relationship. Nonetheless, for approximate calculations, one can even use (totally incorrectly, but with reasonable accuracy) the formula of R = log(1 + SINR) to relate the transmission rate to the threshold value of the SINR for zero error rate (implicitly assuming that, in the multi-user system, each user's link to the destination is an AWGN point-to-point channel).

The remark begs the next natural question, namely, what other, radically (perhaps) different rate measures could be useful in assessing ultimate capabilities of multi-user systems? Some recent encouraging developments point the way towards thinking outside the box. The notion of *transmission capacity*, not to be confused with transport capacity [9] (a concept that is interesting but not relevant to this discussion, despite the early excitement it created) is quite promising. It uses the concept of "outrage" (which is akin to that of packet erasure) as a tool for its definition and introduces the aspect of spatial distribution and density of the users in a wireless ad-hoc network. It is a new and different measure that tries to break free from the gridlock of the traditional approaches. It is too early to decide whether this particular measure (or some other alternative) will help yield a better understanding of the ultimate rate capabilities of real multi-user systems. What is certain is that some radically different thinking is required. The voluminous recent work (since the early '90's) or resource allocation (that includes the back-pressure algorithm and network utility maximization) [10,11] provides an alternative *and* complementary viewpoint towards the goal of meeting the "grand challenge" of "bridging the gap".

We should add that it is also important to develop means of handling "ultimate rate capabilities" of channels and networks that are time-varying and non-ergodic. Such are the networks and channels in most wireless applications. We do not have a clue about how to deal with them and we simply need to find a way to do that. For the moment it seems that the only way to deal with such objects is through the use of stochastic dynamic programming (which is a prohibitively difficult and abstruse tool).

In closing, I would like to point to some very recent work in which a traditional, strict coding theorem is provided for determining achievable rates in a multi-access channel in which the bursty users do *not* cooperate in jointly designing their codebooks. The standard Information-theoretic assumption is that sources can indeed cooperate in designing jointly their codebooks. In practical scenaria, such cooperation and joint coding is infeasible. Hence, it is important to fuse classical multi-access approaches with mechanisms of collision detection and retransmission. In [12] a new form of achievable rate region is defined within which reliable communication is possible, and outside of which reliable collision detection is achieved.

To conclude, it is fair to say that the "gap" is still "yawning". However, there is hope that it can be by-passed, if it cannot be bridged.

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Coding for Noisy Networks

Plenary talk presented at the 2010 IEEE International Symposium on Information Theory, Austin, Texas, USA.

Abbas El Gamal

Abstract: Network information theory aims to establish the limits on information flow in noisy networks and the coding schemes that achieve these limits. Although a general theory is yet to be developed, several coding schemes and bounds on the capacity have been developed. This article reviews these results with emphasis on two recently developed coding schemes—noisy network coding and compute–forward. The noisy network coding scheme generalizes compress–forward for the relay channel and network coding for noiseless networks and its extensions to erasure and deterministic networks to noisy networks. It outperforms an earlier extension of compress-forward to networks and achieves the tightest known gap to the cutset bound for multi-message multicast networks. Compute–forward is a specialized scheme for Gaussian networks. It is similar to decode–forward, except that weighted sums of codewords rather than individual codewords are decoded by the relays. To achieve higher rates than decode–forward, the scheme employs structured instead of random codes. Finally, directions for future work on coding for noisy networks are discussed.

I. Introduction

Over the past 40 years, there have been many efforts to extend Shannon's information theory to noisy networks with multiple sources and destinations. Although we may be far from a complete *network information theory*, several coding schemes that are optimal or close to optimal for some important classes of networks have been developed. This article is about these schemes. The focus will be on two recently developed coding schemes, *noisy network coding* and *compute–forward*. I will discuss how these two schemes relate and compare to the more well-known schemes of *decode–forward*, *compress–forward*, *amplify–forward*, and *network coding* and its extension to erasure and deterministic networks.

The noisy network model I consider is an N sender–receiver node discrete memoryless network (DMN) that consists of N sender alphabets $\mathcal{X}_j$, $j \in [1\colon N]$, N receiver alphabets $\mathcal{Y}_j$, $j \in [1\colon N]$, and a collection of conditional probability mass functions (pmfs) $p(y_1, \dots, y_N \mid x_1, \dots, x_N)$ that specify the probability of receiving the symbols $(y_1, \dots, y_N)$ when the input symbols $(x_1, \dots, x_N)$ are sent. Note that the *topology* of the network (if any) is defined through the structure of its conditional pmfs. Although this model is quite simple, it captures many key characteristics of real world networks, including noise, interference, multiple access, broadcast, relaying, and multi-way communication. The model includes noiseless, erasure, and deterministic networks as special cases and can be readily modified to include Gaussian networks and networks with state (including fast fading).

The network may be used to perform many different types of communication and distributed computing tasks. We focus on the multi-message multicast scenario in which each node has a single independent message and wishes to send it to a subset of the nodes. The problem is to find the *capacity region* of this network, that is, the closure of the set of rates at which the messages can be reliably transmitted to their intended receivers, and the *optimal coding scheme* that achieve it.

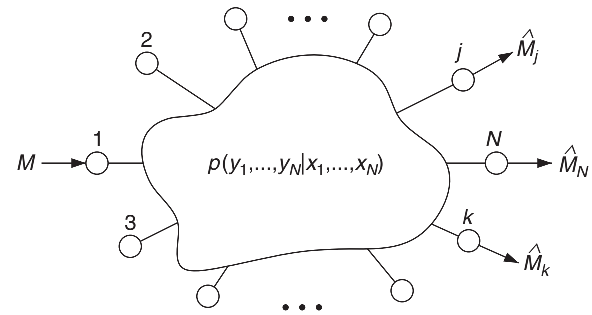

Figure 1. Discrete memoryless multicast network.

For simplicity of presentation we define the problem only for the single-message multicast setting depicted in Figure 1, where source node 1 wishes to send a message $M \in [1:2^{nR}]$ to a set of destination nodes $\mathcal{D} \subseteq [2:N]$ with the help of the rest of the nodes. To define the capacity, we assume Shannon's block coding setup with unlimited computational capabilities at the nodes and arbitrary coding delay.

A $(2^{nR}, n)$ multicast code for the DMN consists of:

- a message set $[1:2^{nR}]$,
- an encoder that assigns a symbol $x_{1i}(m, y_1^{i-1})$ to every $m \in [1:2^{nR}]$ and $y_1^{i-1} \in \mathcal{Y}_1^{i-1}$ for time $i \in [1:n]$,
- a set of relay encoders, where encoder $j \in [2:N]$ assigns a symbol $x_{ji}(y_j^{i-1})$ to every $y_j^{i-1} \in \mathcal{Y}_j$, $i \in [1:n]$, and
- a set of decoders, where decoder $k \in \mathcal{D}$ assigns an estimate $\hat{m}_k(y_k^n)$ to every $y_k^n \in \mathcal{Y}_k^n$.

We assume the message M to be uniformly distributed over the message set $[1:2^{nR}]$ and define the average probability of error as

$$P_e^{(n)} = \mathrm{P}\{\hat{M}_k \neq M \text{ for some } k \in \mathcal{D}\}.$$

A rate R is said to be *achievable* if there exists a sequence of $(2^{nR}, n)$ codes with $P_e^{(n)}$ that tends to zero as the block length n approaches infinity. The capacity C of the multicast network is the supremum of achievable rates. The capacity of the multicast network is not known in general. I will first present the cutset bound on the capacity. The rest of the article is focused on coding schemes for special and general noisy networks and corresponding lower bounds on the capacity.

II. Cutset Upper Bound

The cutset bound on the capacity of the multicast network is based on the simple observation that if the set of nodes is partitioned into a cut $(\mathcal{S}, \mathcal{S}^c)$ such that source node 1 is in $\mathcal{S}$ and destination node k is in $\mathcal{S}^c$ (see Figure 2), then the rate of information flow from node 1 to destination node k cannot exceed the rate of information flow from the set of inputs $X(\mathcal{S})$ in $\mathcal{S}$ to the set of nodes in $\mathcal{S}^c$ if

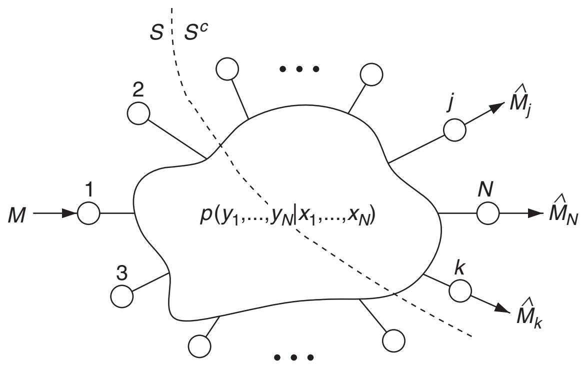

Figure 2. Illustration of a cut.

each subset is allowed to fully cooperate. The cutset bound is then obtained by taking the minimum of the information flow over all such cuts and over all destination nodes $k \in \mathcal{D}$, and then maximizing over all joint pmfs on $p(x^N)$.

Theorem 1 (Cutset Upper Bound [1]):

$$C \le \max_{p(x^N)} \min_{k\in\mathcal{D}} \min_{\mathcal{S}:1\in\mathcal{S},\, k\in\mathcal{S}^c} I(X(\mathcal{S});Y(\mathcal{S}^c)\,|\,X(\mathcal{S}^c)). \quad (1)$$

This cutset bound can be readily extended to DMNs with general message demand [2]. It is tight for several special classes of the noisy multicast network I defined, including:

- Point-to-point noisy channel [3].
- Noiseless unicast network [4].
- Classes of relay channels, including degraded and reversely degraded [5], semi-deterministic [6], [7], and relay channels with orthogonal sender components [8].
- Noiseless multicast networks [9].
- Erasure multi-message multicast networks [10].
- Deterministic multi-message multicast networks with no interference [11], [12] and when the functions are linear over a finite field [13].

The cutset bound was also shown to be tight to within a constant gap for some Gaussian networks [13], [14]. The bound, however, is not tight in general [15], [16] and can be tightened for multiple messages [17].

The rest of the article is divided into four parts. I will first review the three main coding schemes for the relay channel, namely decode–forward, compress–forward, and amplify–forward, and their extensions to networks. Next, I will review the independent line of work on network coding for noiseless networks and its extensions to erasure and deterministic networks. In the third part of the article, I will present the noisy network coding scheme, which is a recently developed scheme that includes compress–forward for the relay channel and network coding and its extensions as special cases, and extends these schemes to general noisy networks. Finally, I will describe the compute–forward scheme, which is a specialized scheme for Gaussian networks that uses structured instead of

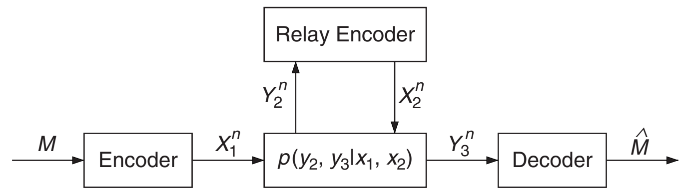

Figure 3. Discrete memoryless relay channel.

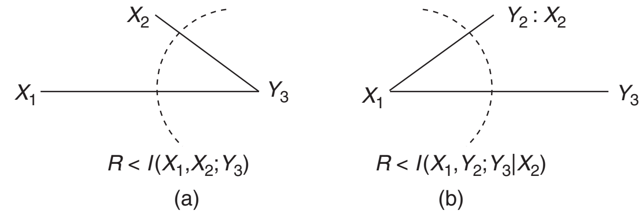

Figure 4. Interpretation of cutset bound for relay channel.

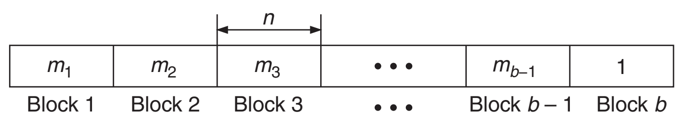

Figure 5. Block Markov scheme.

random coding. Along the way, I will compare the performance of these schemes using canonical examples of Gaussian network.

III. Relay Channel

The relay channel depicted in Figure 3 was first introduced by van der Meulen [18]. It is a 3-node DMN in which node 1 wishes to send a message M to destination node 3 with the help of relay node 2. The capacity of this simple DMN is not known in general.

The cutset bound in Theorem 1 simplifies to

$$C \le \max_{p(x_1,\,x_2)} \min\{I(X_1, X_2; Y_3), I(X_1; Y_2, Y_3\,|\,X_2)\}, \quad (2)$$

which is the minimum of two terms, a *cooperative multiple access* bound and a *cooperative broadcast bound* as depicted in Figure 4.

Next, I will discuss three basic relay channel coding schemes.

A. Decode–Forward

In the decode-forward scheme [5], the relay performs a "digital-to-digital" operation—it decodes the message and *coherently cooperates* with the sender to transmit it to the destination node. A *block Markov coding* scheme is used to send $b-1$ messages over b blocks each with n transmissions as depicted in Figure 5. At the end of block $j \in [1:b-1]$, the relay decodes the message M_j. Decoding at the receiver can be performed *backwards* after all b blocks are received [19], or sequentially using binning [5] or sliding-block decoding [20].

This scheme achieves the following lower bound on the capacity.

Theorem 2 (Decode-forward Lower Bound [5]):

$$C \ge \max_{p(x_1,\,x_2)} \min\{I(X_1, X_2; Y_3), I(X_1; Y_2\,|\,X_2)\}.$$

This lower bound differs from the cutset bound in (1) only in the absence of Y_3 in the broadcast term, and coincides with the cutset bound if the relay channel is *physically degraded* [5].

B. Compress–Forward

In the compress–forward scheme, the relay performs an "analog-to-digital" operation—the relay compresses its received signal and forwards the compression index to the destination node.

The original compress–forward scheme in [5] uses block Markov coding, where $b-1$ messages and sent in b n-transmission blocks. To communicate message M_j in block $j \in [1:b-1]$, the sender transmits the corresponding codeword. At the end of block j, the relay chooses a reproduction sequence $\hat{y}_2^n(j)$ of $y_2^n(j)$ from the compression codebook. Since $y_3^n(j)$ is correlated with $\hat{y}_2^n(j)$, Wyner–Ziv binning is used to reduce rate necessary to send $\hat{y}_2^n(j)$ to the destination node. The relay then sends the compression bin index to receiver in block $j+1$ via $x_2^n(j+1)$. At end of block $j+1$, the receiver decodes M_j *sequentially*:

1) It first decodes the compression bin index from which it finds $\hat{y}_2^n(j)$.

2) It then decodes M_j from $(\hat{y}_2^n(j), y_3^n(j))$.

This scheme achieves the following lower bound.

Theorem 3 (Compress–forward Lower Bound [5]):

$$C \geq \max_{p(x_1)p(x_2)p(\hat{y}_2 | y_2, x_2)} I(X_1; \hat{Y}_2, Y_3 | X_2), \tag{3}$$

where the maximum is over pmfs of the form $p(x_1)p(x_2)p(\hat{y}_2 | y_2, x_2)$ such that $I(X_2; Y_1) \geq I(Y_2; \hat{Y}_2 | X_2, Y_3)$.

This bound differs from the cutset bound in (2) in three ways:

- The lower bound has the same form as the broadcast bound in (2), but with Y_2 replaced by $\hat{Y}_2$.
- The lower bound has a condition instead of a second bound as in the cutset bound.
- The maximization in the lower bound is over product instead of joint pmfs over X_1, X_2.

C. Amplify–Forward

The third coding scheme for the relay channel is *amplify–forward* [21]. The scheme is developed for the AWGN relay channel depicted in Figure 6, where g_{21}, g_{31}, g_{32} are the channel gains and Z_2, Z_3 are additive Gaussian noise with normalized power 1. As usual, we assume power constraint P on each sender.

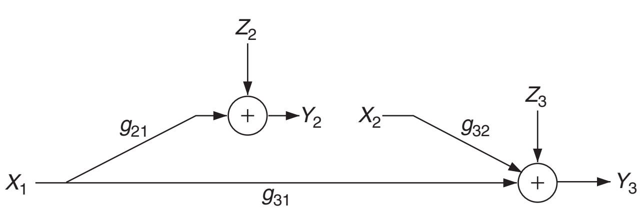

Figure 6. Gaussian relay channel.

In the the amplify–forward, the relay performs an "analog-to-analog" operation—it sends a scaled version of its previously received symbol $X_{2i} = aY_{2,i-1}$ for $i \in [1:n]$. The amplification factor a is chosen such that the relay sender power constraint is satisfied. This scheme reduces the relay channel to an inter-symbol interference channel with a closed form characterization of the capacity.

D. Comparison of the Schemes

To compare the above three schemes, consider the AWGN relay channel in Figure 6 with power constraint P on each sender. It can be shown that:

- The decode–forward rate is within 1/2 bit of the cutset bound.
- The compress–forward rate when evaluated using Gaussian X_1, X_2 and $\hat{Y}_2 = Y_2 + \hat{Z}$, where $\hat{Z}$ is Gaussian and independent of other channel random variables, is also within 1/2 bit of the cutset bound [22].
- The amplify–forward rate is within 1 bit of the cutset bound [22].
- Compress–forward always outperforms amplify–forward.
- Compress–forward also outperforms decode–forward when $g_{21}^2 < g_{31}^2$ or when $g_{21}^2 > g_{31}^2$ and $g_{32}^2 \geq g_{21}^2(1+g_{21}^2)/g_{31}^2 - (1+g_{31}^2)$. Decode–forward outperforms compress–forward otherwise.

E. Extensions to Multicast Networks

The above relay channel coding schemes can be extended to networks. In *network* decode-forward the message is decoded and forwarded along a path from the source node to each destination node using an appropriate subset of relays [11], [20], [23]. The resulting bound is tight for the single source unicast physically degraded network [11], [1]. The compress–forward scheme can also be extended to networks [23]. As in the original compress–forward scheme, this extension involves Wyner-Ziv binning and sequential decoding. Decode–forward of compression indices is used to enhance the performance of the scheme. Amplify–forward can be readily extended to Gaussian networks by having each relay send a scaled version of its previously received symbol. Later on, we compare the performance of these extensions to noisy network coding and compute-forward.

IV. Network Coding

In an independent line of investigation, network coding and extensions to erasure and deterministic networks have been developed. Consider a noiseless (wired) multicast network modeled by a weighted directed graph as depicted in Figure 7. The weights on the edges represent the capacities of the links of the network. Note that this model does not allow for broadcasting or interference. Also note that this model is a special case of the general DMN we defined earlier (simply replace each link by a noiseless DMC with the corresponding capacity). As before, we assume that node 1 wishes to send a message $M \in [1:2^{nR}]$ to a

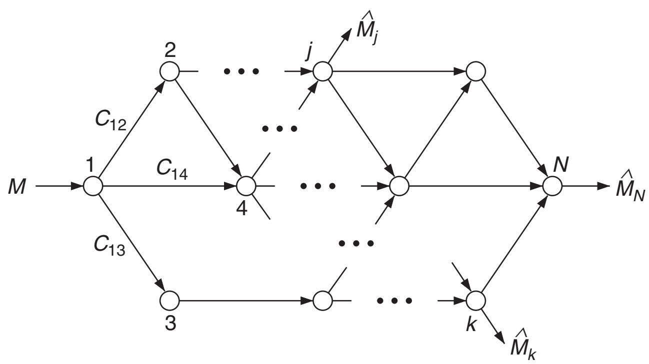

Figure 7. Noiseless multicast network.

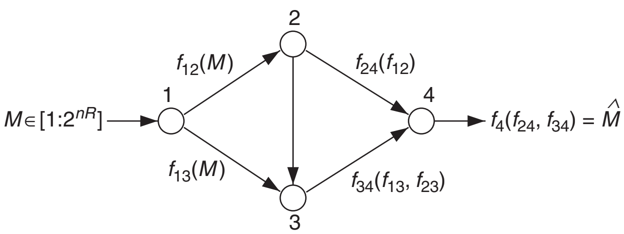

Figure 8. Acyclic noiseless network example.

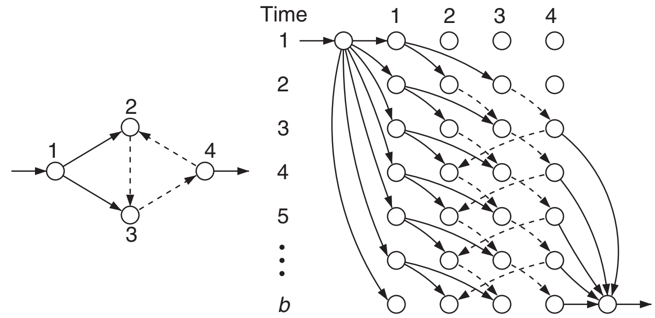

Figure 9. A cyclic network and its time-expanded acyclic network. The cycle $2 \to 3 \to 4 \to 2$ in the original network is unfolded to the paths $2(t) \to 3(t+1) \to 4(t+2) \to 2(t+3)$ in the time-expanded network.

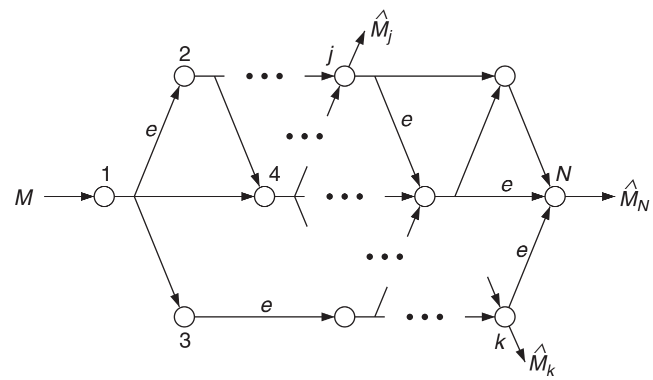

Figure 10. Wireless erasure multicast network.

set of destination nodes $\mathcal{D}$. Ford and Fulkerson [4] showed that the unicast capacity ($|\mathcal{D}| = 1$) coincides with the cutset bound and is achieved via routing. Ahlswede, Cai, Li, and Yeung [9] showed that the capacity of the general multicast case also coincides with the cutset bound, but is achieved using more sophisticated coding at the nodes.

Theorem 4 (Network Coding Theorem [9]):

$$C = \min_{k \in \mathcal{D}} \min_{\mathcal{S}:\, 1 \in \mathcal{S},\, k \in \mathcal{S}^c} C(\mathcal{S}).$$

The original proof of the network coding theorem was in two parts. The theorem is first proved for acyclic networks, where without loss of generality we can assume zero coding delay at the nodes. The block code is then specified by a set of mappings f_{jk} from incoming to outgoing edge indices as illustrated in Figure 8. The proof uses random codebook generation—the mappings $f_{jk} \in [1:2^{nC_{jk}}]$, $(j,k) \in \mathcal{E}$, and f_4 are randomly and independently generated, each according to a uniform pmf. The key step in the proof is to show that if the rate R is less than the cutset bound, then the end-to-end mapping is one-to-one with high probability. The proof is then extended to cyclic networks as follows. Since we cannot assume zero delay nodes in such networks, following the general problem setup in the Introduction, we assume unit coding delay at each node. The network is then unfolded into a *time-expanded* (acyclic) network as shown in Figure 9. The nodes in the network are replicated b times and auxiliary source and destination nodes are added. An edge is drawn between two nodes in consecutive levels of the time-expanded network if the nodes are connected by an edge in the original network. The auxiliary source node is connected to each copy of the original source node and each copy of a destination node is connected to the corresponding auxiliary destination node. Note that this time-expanded network is always acyclic. Hence, the random coding scheme for the acyclic network can be used. The key step in the proof is to show that for sufficiently large b, the cutset bound for the time-expanded network is roughly bC. Note that in this coding scheme the same message is sent over b transmission blocks using independent mappings. This crucial observation will be used later to generalize network coding and compress–forward to noisy networks.

Achievability of the capacity of noiseless multicast networks was later established using *linear network coding* [24], [25]. In addition to being a more practical scheme, linear network coding achieves capacity error-free and using a finite block length.

A. Extensions to Erasure and Deterministic Networks

The network coding scheme has been extended in several directions, including to erasure networks [10] and deterministic networks [12], [13]. For example, consider a wireless multicast erasure network modeled by a hypergraph, where the packet sent over each hyperedge is erased at each node input independently with probability ϵ as depicted in Figure 10. The capacity of the network when the packet erasure pattern is available at the destination nodes coincides with the cutset bound and is achieved using network coding [10]. This result holds also for multi-message multicast networks, where the sources wish to send their messages to the same set of destination nodes.

Network coding has been extended to deterministic multicast networks in which the output at each node is a deterministic function of the inputs of all nodes as depicted in Figure 11. This model is a special case of the DMN that captures the effect of interference and broadcasting, but not noise.

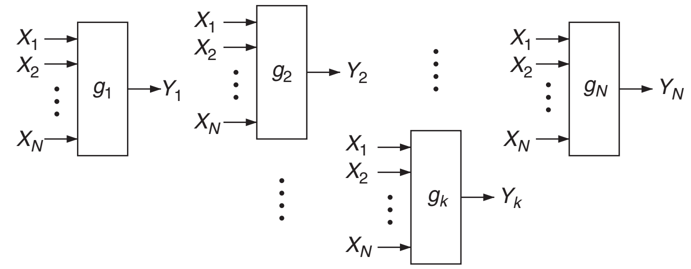

Figure 11. Deterministic network.

The capacity of the deterministic multicast network is not known in general. Since the network is deterministic, the cutset bound simplifies to

$$C \le \max_{p(x^N)} \min_{k\in\mathcal{D}} \min_{\mathcal{S}:1\in\mathcal{S},\, k\in\mathcal{S}^c} H(Y(\mathcal{S}^c)\,|\,X(\mathcal{S}^c)). \tag{4}$$

The following lower bound on the capacity is established by extending the network coding scheme.

Theorem 5 (Network Coding Lower Bound for Deterministic Networks [13]):

$$C \ge \max_{\prod_{j=1}^{N} p(x_j)} \min_{k\in\mathcal{D}} \min_{\mathcal{S}:1\in\mathcal{S},\, k\in\mathcal{S}^c} H(Y(\mathcal{S}^c)\,|\,X(\mathcal{S}^c)). \tag{5}$$

Note that the only difference between this bound and the cutset bound (4) is that the maximization is over product instead of joint pmfs on the inputs. Further, the lower bound coincides with the cutset bound in some special cases, including:

- If there is no interference [12], i.e., when $Y_k = (y_{k1}(X_1), \ldots, y_{kN}(X_N))$ for every $k \in [1:N]$.
- If the functions are linear over a finite field [13], i.e., $Y_k = \sum_{j=1}^{N} g_{jk} X_j$ for $g_{jk}, X_j \in \mathbb{F}_q$, $j \in [1:N]$, $k \in [1:N]$. This class of networks is interesting because they approximate Gaussian networks in high SNR.

The achievability proof of the lower bound (5) closely follows that for noiseless networks. It is again divided into two steps. In the first step, *layered* networks are considered (see Figure 12). Fix the product pmf $\prod_{j=1}^{N} p(x_j)$ that attains the bound (5). The codebook for each node j is randomly and independently generated according to this pmf. In particular each source node generates a codebook for its message, and each relay node generates a sequence $x_j^n(y_j^n)$ for each received sequence y_j^n. The key step in the proof is to show that if the rate R satisfies the lower bound, then the end-to-end mapping is one-to-one with high probability. The proof is then extended to non-layered networks by considering a time-expanded layered network with b blocks. It is then shown that if the rate bR is less than b times the lower bound in (5) for sufficiently large b, then the end-to-end mapping is one-to-one with high probability. The key to the proof for cyclic networks again is to send the same message b times using independent mappings.

V. Noisy Network Coding

The noisy network coding scheme [2] generalizes compress–forward and network coding and its extensions to noisy networks. The starting point for the development of this scheme is the following alternative characterization [26] of the compress–forward lower bound

$$C \ge \max_{p(x_1)p(x_2)p(\hat{y}_2\,|\,y_2,x_2)} \min\{I(X_1, X_2;Y_3) - I(Y_2;\hat{Y}_2\,|\,X_1, X_2, Y_3),\; I(X_1;\hat{Y}_2, Y_3\,|\,X_2)\}. \tag{6}$$

This characterization of the compress–forward lower bound is closer in form to the cutset bound (2) than the original characterization (3). More interestingly, it turns out to generalize more naturally to noisy networks, achieving strictly higher rates than the extension of compress–forward to networks in [23].

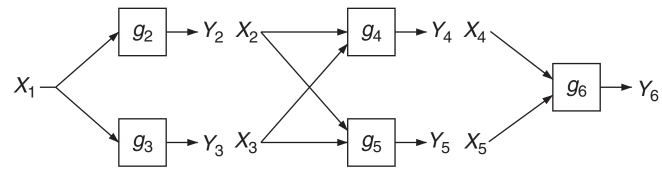

Figure 12. Example layered deterministic network.

Theorem 6 (Noisy Network Coding Theorem [2]):

$$C \ge \max \min_{k\in\mathcal{D}} \max_{\mathcal{S}\subseteq[1:N]:1\in\mathcal{S},\, k\in\mathcal{S}^c} (I(X(\mathcal{S});\hat{Y}(\mathcal{S}^c), Y_k\,|\,X(\mathcal{S}^c)) - I(Y(\mathcal{S});\hat{Y}(\mathcal{S})\,|\,X^N, \hat{Y}(\mathcal{S}^c), Y_k)), \tag{7}$$

where the maximum is over $\prod_{k=1}^{N} p(x_k)p(\hat{y}_k\,|\,y_k, x_k)$.

This lower bound includes as special cases the capacity of noiseless multicast networks [9], the lower bound on deterministic multicast networks [13], and the capacity of wireless erasure muticast networks [10].

The scheme shares features from both the original compress–forward scheme and the network coding scheme. The proof of achievability, however, is simpler and more general than that for network coding and applies directly to non-layered and cyclic networks without the need for time expansion. Each source node sends the same message b times. The relays use compress–forward but *without* Wyner–Ziv binning or requiring the compression indices to be correctly decoded! The decoders use *simultaneous* instead of sequential decoding. For simplicity, consider the proof for the relay channel.

Codebook generation: Fix $p(x_1)p(x_2)p(\hat{y}_2\,|\,y_2, x_2)$ that attains the lower bound. For each $j \in [1:b]$, we generate an independent codebook as follows:

1. Randomly and independently generate 2^{nbR} sequences $x_1^n(j, m)$, $m \in [1:2^{nbR}]$, each according to $\prod_{i=1}^{n} p_{X_1}(x_{1i})$.
2. Randomly and independently generate 2^{nR_2} sequences $x_2^n(l_{j-1})$, $l_{j-1} \in [1:2^{nR_2}]$, each according to $\prod_{i=1}^{n} p_{X_2}(x_{2i})$.
3. For each $x_2^n(l_{j-1})$, $l_{j-1} \in [1:2^{nR_2}]$, randomly and conditionally independently generate 2^{nR_2} sequences $\hat{y}_2^n(l_j\,|\,l_{j-1})$, $l_j \in [1:2^{nR_2}]$, each according to $\prod_{i=1}^{n} p_{\hat{Y}_2|X_2}(\hat{y}_{2i}\,|\,x_{2i}(l_{j-1}))$.

Encoding and decoding are explained with the help of the following table.

Block	1	2	3	...	$b-1$	b
X_1	$x_1^n(1,m)$	$x_1^n(2,m)$	$x_1^n(3,m)$	...	$x_1^n(b-1,m)$	$x_1^n(b,m)$
Y_2	$\hat{y}_2^n(l_1\|1), l_1$	$\hat{y}_2^n(l_2\|l_1), l_2$	$\hat{y}_2^n(l_3\|l_2), l_3$	...	$\hat{y}_2^n(l_{b-1}\|l_{b-2}), l_{b-1}$	$\hat{y}_2^n(l_b\|l_{b-1}), l_b$
X_2	$x_2^n(1)$	$x_2^n(l_1)$	$x_2^n(l_2)$	...	$x_2^n(l_{b-2})$	$x_2^n(l_{b-1})$
Y_3	$\emptyset$	$\emptyset$	$\emptyset$	...	$\emptyset$	$\hat{m}$

Encoding: To send the message m, the sender transmits $x_1^n(j, m)$ in block j. Upon receiving $y_2^n(j)$, the relay finds an index l_j such that $(\hat{y}_2^n(l_j\,|\,l_{j-1}), y_2^n(j), x_2^n(l_{j-1}))$ are jointly typical. The relay sends $x_2^n(l_j)$ in block $j+1$.

Decoding: At the end of block b, the receiver finds the unique index $\hat{m}$ such that $(x_1^n(j,\hat{m}), \hat{y}_2^n(l_j\,|\,l_{j-1}), x_2^n(l_{j-1}), y_3^n(j))$ is jointly typical for all $j \in [1:b]$ and some $(l_1, l_2, \ldots, l_b)$.

The analysis for the probability of error and extensions of the proof to noisy networks can be found in [2].

A. Extension to Noisy Multi-message Multicast Networks

The noisy network coding theorem readily extends to DM multi-message multicast networks, where each node $k \in [1:N]$ wishes to send a message M_k to a set $\mathcal{D}_k \subseteq [1{:}N]/\{k\}$ of destination nodes.

Theorem 7 (Multi-message Multicast Noisy Network Coding Lower Bound [27]):

Let $\mathcal{D} = \bigcup_{k=1}^N \mathcal{D}_k$. A rate tuple $(R_1, \ldots, R_N)$ is achievable for the DMN if for some joint pmf $\prod_{k=1}^N p(x_k)p(\hat{y}_k\,|\,y_k, x_k)$ such that

$$\sum_{k\in\mathcal{S}} R_k < \min_{k\in\mathcal{S}^c\cap\mathcal{D}} (I(X(\mathcal{S});\hat{Y}(\mathcal{S}^c), Y_k\,|\,X(\mathcal{S}^c)) - I(Y(\mathcal{S});\hat{Y}(\mathcal{S})\,|\,X^N, \hat{Y}(\mathcal{S}^c), Y_k)) \quad (8)$$

for all $\mathcal{S} \subseteq [1:N]$ with $\mathcal{S}^c \cap \mathcal{D} \neq \emptyset$

It can be shown that this theorem includes results on erasure and deterministic multi-message multicast networks [10], [28] as special cases.

The above bound can be extended to multi-message multicast Gaussian networks, where the received vector at the nodes for input X^N is given by

$$Y^N = GX^N + Z^N,$$

where G is the network gain matrix and the additive noise Z^N is i.i.d. $\mathrm{N}(0,1)$. We assume power constraint P on every sender X_j, $j \in [1:N]$. The noisy network coding can be extended to this case by first extending it to DMN with input costs and then applying the discretization procedure described in [2].

The optimal distribution on the inputs and the auxiliary random variables is not known. Assuming Gaussian signals, i.e., $X_j \sim \mathrm{N}(0,P)$, and $\hat{Y}_j = Y_j + \hat{Z}_j$, where $\hat{Z}_j \sim \mathrm{N}(0,1)$, the noisy network coding bound (8) reduces to

$$\sum_{j\in\mathcal{S}} R_j < \frac{1}{2}\log\left|I + \frac{P}{2}G(\mathcal{S})G(\mathcal{S})^T\right| - \frac{|\mathcal{S}|}{2}.$$

Now, the cutset bound is upper bounded as

$$\sum_{j\in\mathcal{S}} R_j \le \frac{1}{2}\log\left|I + \frac{P}{2}G(\mathcal{S})G(\mathcal{S})^T\right| + \frac{|\mathcal{S}|}{2}\log 3.$$

By loosening these two bounds further, we can show that the noisy network coding lower bound is within 0.63 N bits/transmission of the cutset bound. This improves upon previous gap results in [13], [28].

For specific Gaussian networks we can obtain tighter bounds and can compare the performance of noisy network coding to other schemes.

Example (Two-Way Relay): The AWGN two-way relay channel is a 3-node Gaussian network. The outputs for inputs X_1, X_2, X_3 are

$$Y_k = \sum_{j\neq k} g_{kj} X_j + Z_k, \quad k = 1, 2, 3,$$

where the additive noise Z_k are i.i.d. $\mathrm{N}(0,1)$. We assume power constraint P on every sender. Consider the multi-message multicast setting in which node 1 wishes to communicate message M_1 to node 2 and node 2 wishes to communicate message M_2 to node 1. Node 3 acts as a relay to help communicating the two messages.

This example of a multi-message multicast network has been studied by several groups who compared the performance of decode–forward, compress–forward, and amplify–forward [29], [30]. In Figure 13, we compare these previous results to the noisy network

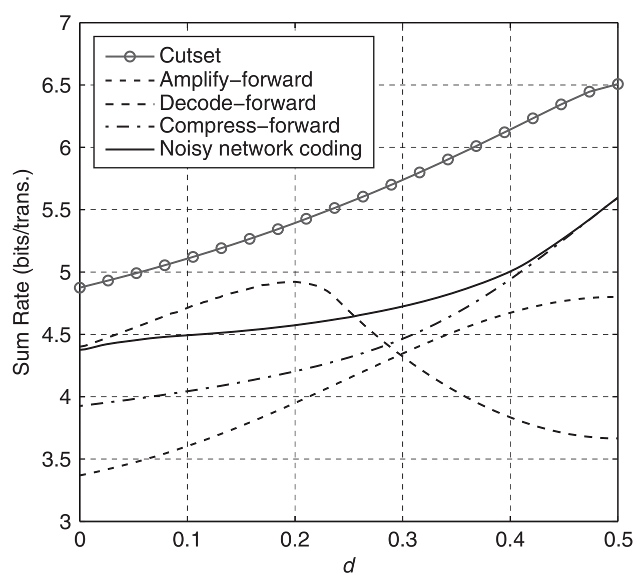

Figure 13. Comparison of bounds for AWGN 2-way relay. Nodes 1 and 2 are unit distance apart and node 3 is distance $d \in [0, 1]$ from node 1 along the line between nodes 1 and 2; $g_{13} = g_{31} = d^{-3/2}$, $g_{23} = g_{32} = (1-d)^{-3/2}$.

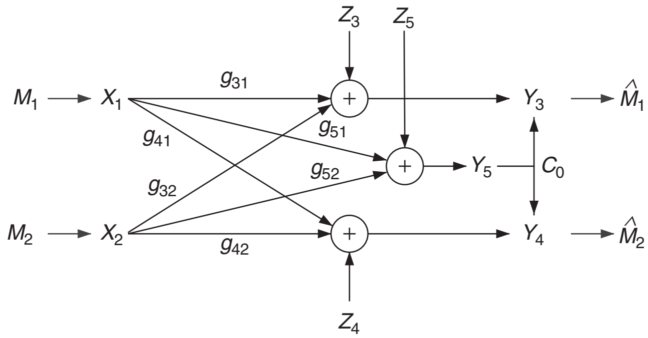

Figure 14. AWGN interference relay channel.

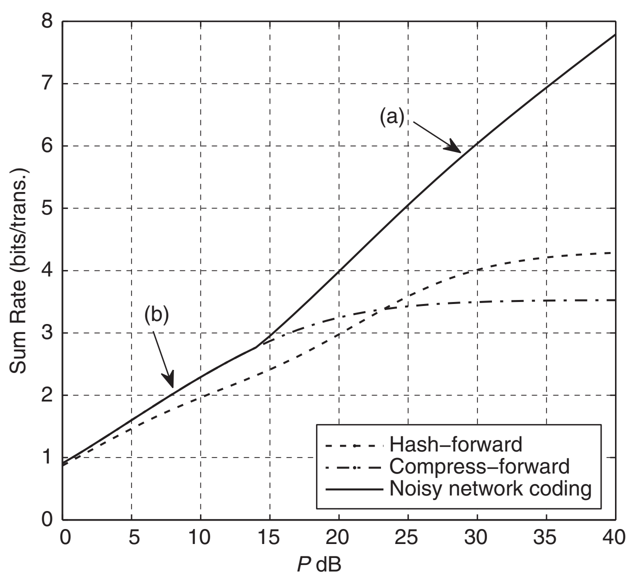

Figure 15. Comparison of schemes for AWGN interference relay channel for $g_{31} = g_{42} = 1$, $g_{41} = g_{32} = g_{51} = 0.5$, $g_{52} = 0.1$, $C_0 = 1$. The (a) segment of the plot for the noisy network coding is when interference is treated as noise, and (b) is when each receiver decodes both messages.

coding bound. Note that noisy network coding strictly outperforms the extensions of compress–forward and amplify–forward, and outperforms decode–forward when the relay is sufficiently far from both destination nodes.

More generally, it can be shown that the sum-rate achieved by noisy network coding is within 1.5 bit/transmission of the cutset bound, while the sum-rate gap for the other schemes is *unbounded* (as $P \to \infty$).

B. Extension to Multi-unicast Networks

Noisy network coding can be extended to other message demands [31]. For example, consider an N-node DM multi-unicast network in which node 1 wishes to communicate message M_1 to node 3 and node 2 wishes to communicate message M_2 to node 4. The rest of the nodes act as relays. Using noisy network coding, we can view this network as an *interference channel* with senders X_1 and X_2, and respective receivers $(Y_3, \hat{Y}_5, \hat{Y}_6, \ldots, \hat{Y}_N)$ and $(Y_4, \hat{Y}_5, \hat{Y}_6, \ldots, \hat{Y}_N)$. Hence, we can use well-known coding schemes for the interference channel, including

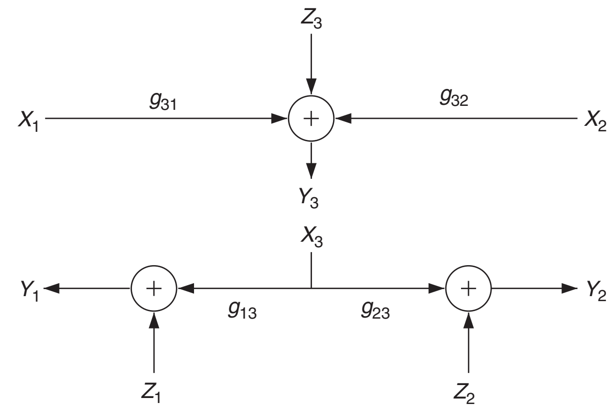

Figure 16. AWGN two-way relay with no direct links.

- treating interference as noise, where each receiver decodes only its message, or
- simultaneous non unique decoding, where each receiver decodes both messages without requiring correct decoding of the other message.

To illustrate the combination of noisy network coding with interference channel coding schemes, consider the following.

Example (Interference Relay): The AWGN interference channel with a relay is a 5-node network. As shown in Figure 14, the outputs

$$Y_k = g_{k1}X_1 + g_{k2}X_2 + Z_k, \quad k = 3, 4, 5,$$

where the noise Z_k, $k = 1, 2, 3$, are i.i.d. $\mathrm{N}(0, 1)$. Again assume power constraint P on each sender. In addition, there is a noiseless broadcast link with capacity C_0 from node 5 to nodes 3 and 4.

In [32], extensions of compress–forward and hash–forward [7] are compared. In Figure 15, we compare these results to noisy network coding with different interference channel coding schemes. Note that noisy network coding uniformly outperforms the other schemes.

C. Summary

In summary, noisy network coding generalizes compress–forward and network coding and its extensions to noisy networks and can be readily extended to general multi-message networks. Noisy network coding strictly outperforms earlier extensions of compress–forward to networks and can outperform extensions of decode–forward and amplify–forward. Further, it achieves the tightest known gap to the cutset bound for Gaussian multi-message multicast networks, while other schemes have arbitrarily large gap as demonstrated by the two-way relay example. The noisy network coding scheme also demonstrates that simultaneous decoding can achieve higher rates than sequential decoding. The achievability proof demonstrates that proving achievability for a general DMN can be more straightforward, easier, and cleaner than for special cases such as noiseless, deterministic, and Gaussian networks. Thus, although the interest in the information theory community is focused mainly on Gaussian networks because of their relevance to wireless

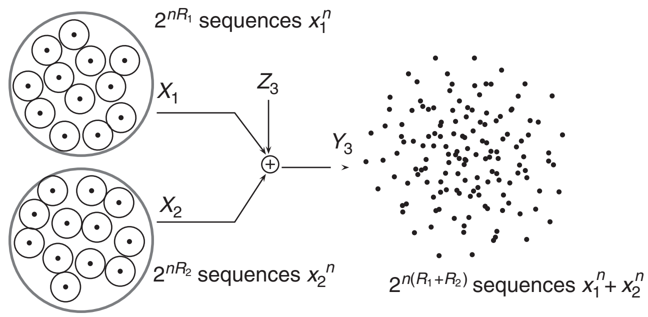

Figure 17. Using Gaussian codes there is a one-to-one correspondence between the individual codewords and their sum.

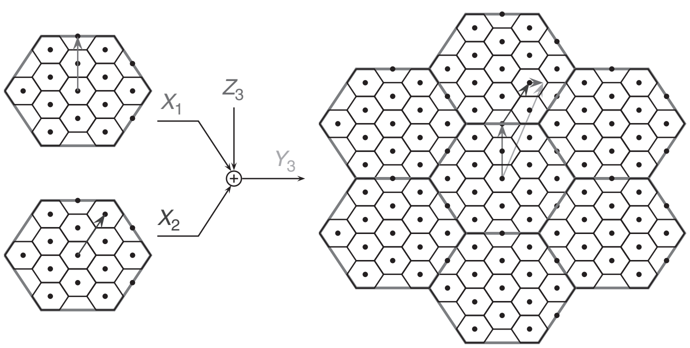

Figure 18. Using lattice codes, sum of every two codewords is a codeword. The sum can be decoded provided the individual rate is sufficiently low.

networks, we should still consider DMNs when developing new coding schemes.

VI. Compute–forward

The coding schemes I discussed so far use random codebook generation. It turns out that one can do better by using lattice or structured codes. This important observation builds on an early result by Körner and Marton on distributed lossless computing. Consider a doubly symmetric binary source (DSBS) (X_1, X_2), where $X_1, X_2 \sim \text{Bern}(1/2)$ and $X_1 \oplus X_2 = Z \sim \text{Bern}(p)$. The sources are separately encoded and sent to a decoder over noiseless links. The decoder wishes to losslessly compute their mod-2 sum Z. By the Slepian–Wolf theorem, any sum rate greater than $H(X_1, X_2) = 1 + H(p)$ can be achieved. On the other hand, if we use the *same* random linear code, any sum rate greater than $2H(p)$, which is the smallest possible rate, can be achieved. This shows that using the same linear code can outperform random coding (binning).

The compute–forward scheme is developed for Gaussian networks and builds on a wealth of previous work on lattice codes (see [33] for a review of this work). To illustrate this scheme, consider the AWGN two-way relay network with no direct links depicted in Figure 16. In the decode-forward scheme, the relay decodes both messages and broadcasts them (or their sum) to the source-destination nodes. In compute–forward, the relay decodes $g_{31}X_1^n + g_{32}X_2^n$ instead. Since node 1 knows X_1^n, it can compute X_2^n from $g_{31}X_1^n + g_{32}X_2^n$. Similarly, node 2 knows X_2^n, so it can compute X_1^n from $g_{31}X_1^n + g_{32}X_2^n$.

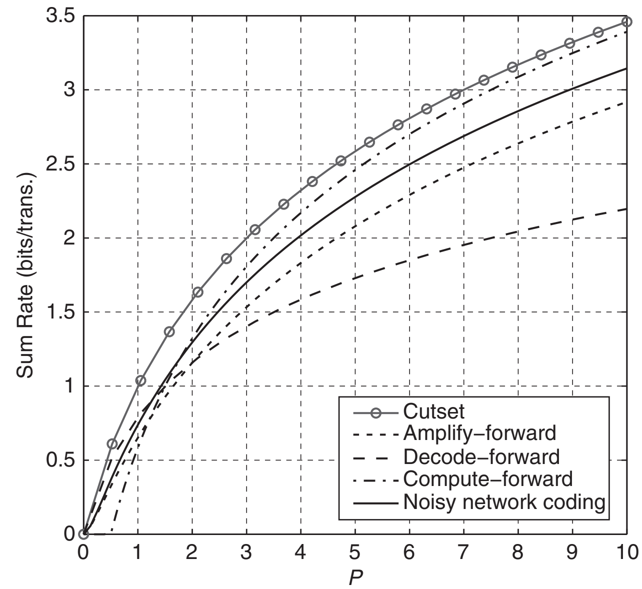

Figure 19. Compute–forward can outperform other schemes ($g_{31} = g_{32} = 1$ and $g_{13} = g_{23} = 2$).

Using Gaussian random codes, however, compute–forward reduces to decode–forward because the sum of every two Gaussian generated codewords uniquely determines the individual codewords with high probability (see Figure 17). However, if we use the same lattice code instead [34], [35], the weighted sum of two codewords is a codeword (many details are skipped here) as illustrated in Figure 18. This relaxes the requirement for decoding the weighted sum and thus the transmission rates from nodes 1 and 2 can be increased.

Figure 19 compares the achievable sum-rates for compute–forward to amplify–forward, decode–forward, and noisy network coding. Note that except at low power P, compute–forward outperforms these other schemes. More generally, it can be shown that compute–forward achieves sum-rate within 0.58 bit of the cutset bound [36], while noisy network coding achieves within 1 bit of the cutset bound for this case. The rest of the schemes have unbounded gap to the cutset bound. Noisy network coding and decode–forward can outperform the implementation of compute–forward in [36] in certain channel gain regimes as illustrated in Figure 20.

VII. Conclusion

I discussed two recently developed coding schemes for noisy networks:

- Noisy network coding is a general purpose scheme that yields a single-letter lower bound on capacity, and naturally generalizes both compress–forward and network coding to noisy networks.

- Compute–forward is a specialized scheme for Gaussian networks. It uses structured instead of random coding to reduce the rate of the combined signal at each relay and hence makes it possible for the relay to decode the combined signal without decoding each message.

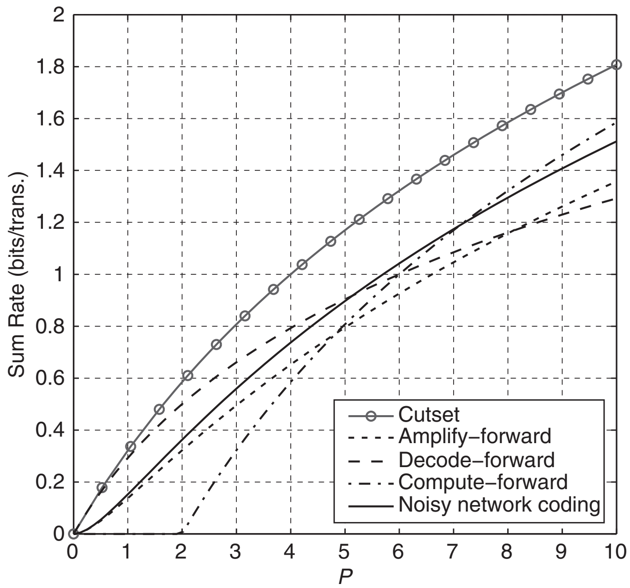

Figure 20. Compute–forward does not always outperform other schemes ($g_{31} = g_{32} = 0.5$ and $g_{13} = g_{23} = 1$).

I showed that these two schemes can outperform previously developed coding schemes over canonical Gaussian networks.

There are many possible directions for future work in this area.

- To explore applications of noisy network coding to wireless networks. This involves developing practical codes and implementing simultaneous decoding.
- To find a general single-letter characterization for achievable rates using compute–forward. At present, single-letter characterizations exist only for small examples.
- Compute–forward may be viewed as a structured decode–forward. It would be interesting to explore the use of structured codes in noisy network coding. The difficulty again is to find a single-letter characterization.
- We have seen that decode–forward can outperform noisy network coding. It would be interesting to explore ways to combine the two schemes along the lines of the combination of partial decode–forward and compress–forward for the relay channel in [5].

In conclusion, we may be a long way from finding the optimal coding scheme for noisy networks, but there has been much progress toward achieving this goal.

VIII. Acknowledgments

I would like to thank Young-Han Kim, Sung Hoon Lim, and Sae-Young Chung for providing the examples and general feedback on this article, and Michael Gastpar for providing input on the compute–forward scheme. I would like to thank Suhas Diggavi for several fruitful discussions. I would also like to thank Bernd Bandemer, Yeow-Khiang Chia, and Han-I Su for help on preparing the article. The work on noisy network coding was partially supported under DARPA ITMANET.

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GOLOMB'S PUZZLE COLUMN™

Derangements and Beyond

Solomon W. Golomb

On a rainy day, n people enter a restaurant and check their umbrellas. When they leave, the umbrellas are returned at random. How many of the $n!$ permutations of the umbrellas result in no people getting their own umbrellas back?

A permutation with no one-cycles (the above situation) is called a *derangement*. (Another meaning of "derangement" is *insanity*!) It is well-known that the number $d(n)$ of derangements on n objects is given by

$$d(n) = n! \sum_{k=0}^{n} \frac{(-1)^k}{k!} = \{n!/e\}$$

where e is the base of natural logarithms, and $\{x\}$ denotes the integer closest to the real number x. (This formula is usually proved by an inclusion/exclusion argument.)

Show the following:

1) $d(n) \equiv (-1)^n \pmod{n}$, all $n > 1$.

2) $d(n) \equiv 0 \pmod{n-1}$, all $n > 1$. (Give both a numerical proof and a combinatorial proof.)

3) $d(n) \equiv (-1)^n \pmod{n-2}$, all $n > 2$.

4) $d(n) = nd(n-1) + (-1)^n$, all $n > 1$.

Next,

5) Obtain an exact expression for $z(n)$, the number of permutations on n objects with no 2-cycles. (When n people attend a company party where each person brings a gift, and the gifts are redistributed to the guests at random, $z(n)$ is the number of permutations on the n gifts where no two people, x and y, end up having exchanged gifts with each other; but it *does* allow people getting back the gifts they themselves brought.) *Hint*: Use inclusion/exclusion.

6) Give an asymptotic expression for your result in Problem 5.

Note that any two rows of an $n \times n$ Latin square ($n > 1$) are derangements of each other, and $d(n)$ is the number of ways to fill in the $2 \times n$ "Latin rectangle" $\begin{pmatrix} 1 & 2 & 3 & \ldots & n \\ x_1 & x_2 & x_3 & \ldots & x_n \end{pmatrix}$,

where $(x_1, x_2, \ldots, x_n)$ is a permutation of $(1, 2, \ldots, n)$, and $x_i \neq i$ for all i, $1 \leq i \leq n$.

We now consider $3 \times n$ "Latin rectangles", written in standard form as $\begin{pmatrix} 1 & 2 & 3 & \ldots & n \\ x_1 & x_2 & x_3 & \ldots & x_n \\ y_1 & y_2 & y_3 & \ldots & y_n \end{pmatrix}$, where $(x_1, x_2, \ldots, x_n)$ and $(y_1, y_2, \ldots, y_n)$ are permutations of $(1, 2, \ldots, n)$, where $x_i \neq i$, $y_i \neq i$, $x_i \neq y_i$, for all i, $1 \leq i \leq n$, and $1 < x_1 < y_1 \leq n$. We call such a pattern a *trerangement*, and let $t(n)$ be the number of $3 \times n$ Latin rectangles in standard form (i.e. the number of trerangements on n objects.)

7) Can every $3 \times n$ trerangement be extended (by adjoining rows) to form an $n \times n$ Latin square, for all $n \geq 3$? (Prove or disprove.)

8) Find the values of $t(3)$, $t(4)$, and $t(5)$.

9) Can you find an exact expression for $t(n)$, for all $n \geq 3$?

continued on page 20

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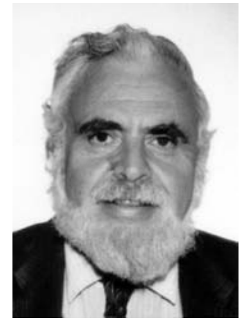
Seating Arrangements Solutions

Solomon W. Golomb



1) *Perfect* seating arrangements for $n + 1$ people are known to exist for all $n \geq 2$ *except* for $n = 3$ and $n = 5$. (See Reference 1.)

2) Here is an example of a *perfect* seating arrangement for 8 people ($n = 7$):

0	1	2	3	4	5	6	7
0	2	7	5	3	6	4	1
0	3	5	1	7	6	2	4
0	4	3	1	6	5	7	2
0	5	2	6	1	4	7	3
0	6	3	7	4	2	1	5
0	7	1	3	2	5	4	6

3) As the above example shows, a *perfect* seating arrangement with $n + 1$ people, ignoring the "all 0's" column, need not be a Latin square. (Only the columns headed by 1 and by n must be permutations, since "person 0" must have all distinct neighbors both on the right and on the left.)

4) If $n + 1$ is prime, the $n \times (n + 1)$ multiplication table modulo $n + 1$ will always provide an *ideal* seating arrangement ($n \geq 2$), as in:

$n + 1 = 3$

0	1	2
0	2	1

$n + 1 = 5$

0	1	2	3	4
0	2	4	1	3
0	3	1	4	2
0	4	3	2	1

$n + 1 = 7$

0	1	2	3	4	5	6
0	2	4	6	1	3	5
0	3	6	2	5	1	4
0	4	1	5	2	6	3
0	5	3	1	6	4	2
0	6	5	4	3	2	1

5) and 6) The following *ideal* seating arrangement for $n + 1 = 9$ people shows that $n + 1$ need not be prime:

0	1	2	3	4	5	6	7	8
0	2	4	1	6	3	8	5	7
0	3	1	5	2	7	4	8	6
0	4	6	2	8	1	7	3	5
0	5	3	7	1	8	2	6	4
0	6	8	4	7	2	5	1	3
0	7	5	8	3	6	1	4	2
0	8	7	6	5	4	3	2	1

A "zig-zag construction", of the type described in Reference 1, can be used to obtain ideal circular seating arrangements for $2n + 1$ people, for all $n \geq 1$.

7) and 8) As disclosed in Reference 1, there are 736 *perfect* seating arrangements, for $n + 1 = 7$ people, in "standard form"; and there are 466,144 *perfect* seating arrangements, for $n + 1 = 8$ people, in "standard form."

In Reference 1, the $n \times n$ portion of the table for a *perfect* seating arrangement is called a *Tuscan square*. It is conjectured that Tuscan squares which are not Latin squares exist for all $n \geq 6$; and all 466,144 examples at $n = 7$ are non-Latin. Applications are mentioned to frequency hopping patterns for communications and radar, and to experimental designs in statistics.

If n people are to be seated along a line as at a lunch counter (with two end-seats) rather than a circle, neighborliness in the fewest rounds is again obtained from the rows of an $n \times n$ Tuscan square (without the adjoined 0's). If all n rows are used, then in n rounds each person x has every person y on the right exactly once, and on the left exactly once. (Also, x will be seated at each end of the row exactly once.) If the Tuscan square, with n even, has $n/2$ rows that are the mirror reversals of the other $n/2$ rows, then we can seat the n people along a line in $n/2$ rounds such that each person x has every person y as a neighbor (either left or right) exactly once, and is seated at an end exactly once.

Acknowledgment. This column resulted from interesting discussions with Richard Hess.

Reference 1. "Tuscan Squares – A New Family of Combinatorial Designs," Solomon W. Golomb and Herbert Taylor, *Ars Combinatoria*, **20 – B** (1985), pp. 115–132.

Derangements and Beyond *continued from page 18*

10) Some sets of n letters can be anagrammed (i.e. permuted) to form a trerangement of three English words. (For example, from {E, I, M, T} we can form $\begin{pmatrix} EMIT \\ ITEM \\ TIME \end{pmatrix}$, with no repeated letter in any column.

Find trerangements into English words from each of the following sets of letters.

a) {A, E, L, S, T};

b) {E, A, P, R, S};

c) {E, I, P, R, S, T};

d) {E, I, M, O, P, R, S};

e) {A, E, G, I, L, N, R, T}

Third WITHITS Annual Event

Tara Javidi

The third WITHITS annual event took place on the 16th of June, 2010, during the International Symposium of Information Theory (ISIT), Austin, Texas. The organizers of this event added a grain of playful and witty mystery to their poster design by withholding the specific content of the event: the poster's information was limited to the photos of Prof. G. Wornell from MIT, Prof. A. El Gamal from Stanford, Prof. B. Hajek from UIUC and Prof. A. Orlitsky from UCSD, under a visible WITHITS logo, framed by photos of various woman dignitaries, with a title that read, "Yes, she can" and "Learn who is their favorite woman." The poster reminded me of a recent New York Times op-ed called "Feminism of the Future Relies on Men" which (not entirely convincingly nonetheless passionately) argued that it is men who can and should battle gender disparity and promote gender equity explicitly.

Opening the event, Professor Christina Fragouli, from EPFL and one of the organizers, explained that this was going to be the first "non-technical" event at ISIT with a technical content! Four well-known and highly respected male members of the IT society were asked to give a short 10 minute presentation about the work of a woman in information theory or a related field; someone whose work most affected their work or whose story appealed to them the most. Christina explained that the organizers' motivation was to celebrate and promote the significant technical contributions by women in our field.

With the list of prolific authors and brilliant presenters, it was no surprise that the presentations were technically rich, inspiring, and entertaining. Perhaps less expected was the diversity of the talks in the selection of the scholar whose work was being presented, in the nature of the presented work/scholarship, and in the speaker's style of presentation. In fact, the sole point of unity seemed to be the sincerity, creativity, and the dedication each speaker put into the preparation of their presentation and brought to the event!

The first speaker was Professor Abbas El Gamal from Stanford University who talked about the life (briefly) and work of Katalin Marton (in length). Professor El Gamal catalogued a detailed list of Marton's high impact and well known papers relevant to Information Theory, organized in 7 categories from the broadcast channel to the capacity of graphs. Very much in line with his interest in teaching and pedagogy, Professor El Gamal proceeded to go through the simpler proof of the Blowing-Up Lemma by Marton. Listening to Professor El Gamal's clear restatement of the proof, I was reminded of why Information Theory fascinates and inspires so many of us! Professor El Gamal then ended his presentation with a slide in which he specifically reviewed and celebrated Marton's impact on his own work.

The second speaker was Professor Bruce Hajek from the University of Illinois, Urbana Champaign. Professor Hajek spoke about Catherine Doléans-Dade in whose "dream course on martingale calculus" the young Bruce Hajek learned more than he ever learned in any other class. Professor Hajek catalogued Doléans-Dade's work on the theory of predictable compensators and Doléans' significant contributions to the calculus of martingles while reviewing the history of advances in this field. The narrative effectively situated Doléans' contributions within the larger context of mathematical scholarship. In contrast, Professor Hajek-visibly moved and emotional-ended with Doléans' life story (she passed away in 2004) whose turns and twists eventually displaced this accomplished woman mathematician out of the established world of mathematics!

Professor Greg Wornell from MIT presented his "her-storical" findings about the legendary Hedy Lamarr (Hedwig Eva Maria Kiesler). The talk focused on Lamarr's personal life in three acts, the last one of which detailed the story of the US patent No. 2292387, which for the first time disclosed the invention of the frequency-hopped spread spectrum for secret communications. Lamarr's story, reconstructed and narrated by Professor Wornell, is a true story of eclectic ambitions and uninhabited enthusiasm. Professor Wornell's presentation was a celebration of someone who did not make the "safe" choices, did not hesitate to take risks and managed to make it work. This was also an example of how we are impacted by creativity "outside" our field.

Last but not least, Professor Alon Orlitsky from the University of California, San Diego spoke. Professor Orlitsky explained his interest in looking at the contributions and the impact of those closest to him. In an unexpected way, and with no prior coordination, Professor Orlitsky's choice in placing and celebrating the work of women with whom he has interacted closely seemed to perfectly address Professor Hajek's presentation about the past generation's displacement and neglect. In a by now familiar Orlitsky-ish introduction, he proceeded to sift through his many women information theorist friends/collaborators (a stunning majority of women in the field!), he arrived at a coin flip between Emina Soljanin and Serap Savari whose outcome favored the latter. Professor Orlitsky carefully detailed Savari's contributions in arithmetic coding, sending distributions in quantum communication, multi-source network coding, and capacity approximation. He ended his presentation with a more involved description of Savari's award winning work on fix-free codes.

It is truly hard to believe the amount of information and sincere commitment that each presenter conveyed in his very short 10 minute presentation. Though some source coding technique was likely utilized, it was still telling of the time and effort the speakers each had put out of their very busy schedule in preparing these talks. The slides are available at http://withits.epfl.ch/events/2010isit.

The event was spontaneously followed by a discussion and coffee among WITHITS members regarding future events as well as the goals and actions of the group.

Recent Activities of the IT Student Committee

Bobak Nazer, Salim El Rouayheb, and Aylin Yener

Greetings from the Student Committee. We have had an active summer with multiple events at ISIT and Allerton. Our panel at ISIT this year was entitled "Recipes for a Good Talk." We were fortunate to have Massimo Franceschetti (UCSD), Emina Soljanin (Bell Labs), Emre Telatar (EPFL), Venu Veeravalli (UIUC), and Aaron Wagner (Cornell) share a few pages from their respective cookbooks.

We also were happy to host another productive student roundtable research discussion. Thanks very much to the following students for leading a discussion:

- Viveck Cadambe: Interference Alignment
- Satashu Goel: Security and Networking
- Pulkit Grover: Complexity and Energy
- Yashodhan Kanoria: Game Dynamics on Networks
- Oliver Kosut: Secrecy
- Paolo Minero: Capacity Scaling of Ad Hoc Networks
- Parimal Parag: Networking/Delay
- Eren Sasoglu: Polar Codes
- Rajiv Soundararajan: Joint Source Channel Coding
- Changho Suh: Distributed Storage
- Ravi Tandon: Feedback for Multi-User Channels
- Ye Tian: Deterministic Models

We continued our ISIT tradition of handing out t-shirts to student attendees. Thanks very much to Mustapha El Halabi for desiging the t-shirt. We are also grateful to Pulkit Grover for photographing the ISIT student events.

Also during ISIT, the Student Paper Award- first proposed by the Student Committee and presented for the fourth time in Austin- was awarded to five students. Congratulations to

- **Jayadev Acharya** (UCSD) for his paper "On Reconstructing a Sequence from its Subsequence Compositions," (co-authored with Hirakendu Das, Olgica Milenkovic, Alon Orlitsky, Shengjun Pan)
- **Yashodhan Kanoria** (Stanford) for his paper "On the deletion channel with small deletion probability," (co-authored with Andrea Montanari)
- **Arya Mazumdar** (UMD) for his paper "Codes in Permutations and Error Correction for Rank Modulation," (co-authored with Alexander Barg)
- **Benjamin Kelly** (Cornell) for his paper "Universal Hypothesis Testing in the Learning-Limited Regime," (co-authored with Thitidej Tularak, Aaron Wagner, Pramod Viswanath)
- **Yury Polyanskiy** (Princeton) for his paper "Variable-length coding with feedback in the non-asymptotic regime," (co-authored with H. Vincent Poor, Sergio Verdu)

We also would like to congratulate all the students whose papers were candidates for the Best Student Paper award.

The student committee, as usual, also held an event at Allerton. This year we tried a new event: a quiz game on Information Theory (what else!) based on the quiz show Jeopardy. The categories were "Capacity Regions", "Shannon Lecturers", "Codes", "IT Paper Awards", and "ISIT Locations". We had a lot of fun and would like to try this event again in the future.

As always, we are always looking for new volunteers. Please feel free to contact Salim salim@eecs.berkeley.edu or Bobak bobak@ece.wisc.edu if you are interested.

Report on the Third Annual School of Information Theory

Aylin Yener and Gerhard Kramer

The Third Annual School of Information Theory was held at USC on August 5–8 with 178 students in attendance. The School is an educational initiative whose main purpose is to provide a venue where graduate students can meet to discuss research, form friendships and collaborations, and learn how to actively and socially participate in scientific research. The students present themselves and their work in a friendly environment, interact with well-known senior scientists, and exchange ideas. While the core topic is information theory, related topics in mathematics, physics, biology, and networking are welcome.

Jack Wolf enjoying the Padovani Lecture.

Past schools were held at Penn State University and Northwestern University in 2008 and 2009, respectively. The school experienced a 76% growth in the number of student attendees over the past three years: 101 students in 2008, 141 students in 2009, and 178 students in 2010. We also had 6 speakers, 6 co-organizers, and 11 guests, so the total number of attendees this year was over 200. In fact, we had 239 student applicants; many students had to cancel their application due to lack of travel funds or visa issues.

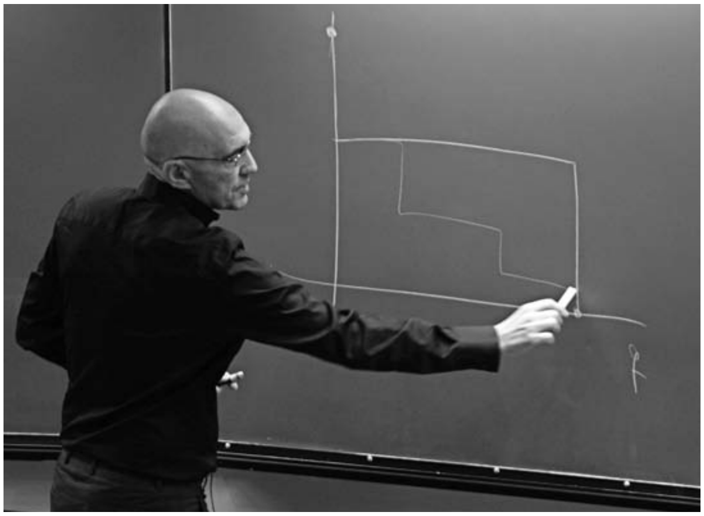
The School format has courses given by distinguished scientists followed by student poster presentations. The six lecturers this year were Jack Wolf (UCSD) who posed and answered the question of whether an information theorist can be happy in a center for information storage, Andrea Goldsmith (Stanford) who explained how wireless channels and networks work, Emmanuel Candès (Stanford) who spoke about the information theory of data matrices, Alon Orlitsky (UCSD) who lectured on probability estimation for large alphabets, Sergio Verdú (Princeton) who read and explained Shannon's 1948 paper, and Rüdiger Urbanke (EPFL) who helped us understand codes that approach capacity. Jack Wolf's lecture was the 2010 IEEE Information Theory Society Padovani Lecture and we were honored to have Roberto Padovani (Qualcomm) present to introduce Jack who was Roberto's Ph.D. advisor.

As usual, student participation was a requirement for attendance: every student introduced his or her work in the form of a short (1-minute) talk as well as a poster presentation. The poster sessions were lively and interactive; the discussions continued long after the sessions concluded. Many students took advantage of Sergio Verdú's homework assignment to read Shannon's 1948 paper and write about what surprised them the most. The feedback was substantial, insightful, and deep.

The social program included a pizza dinner on Wednesday, August 4, a "pie-and-burger" picnic on Thursday (veggie burgers too!), lunches and dinners every day, and a speaker & organizer dinner on Friday. Thank you to Urbashi Mitra for organizing a party at her home for our guests and the local Los Angeles faculty on August 4.

Many people helped to make the 2010 School a success. Michelle Effros (Caltech) and Tracey Ho (Caltech) put the poster program together, Alex Dimakis (USC) and Mike Neely (USC) organized t-shirts and lecture halls, Sriram Vishwanath (UT Austin) served as Treasurer, and Matthieu Bloch (Georgia Tech) managed the web site. We were particularly lucky to have Anita Fung and Gerrielyn

Group photo in front of the USC Physical Education Building on a sunny Friday afternoon.


Sergio Verdú explaining Shannon's paper.

Ramos, USC Communication Sciences Institute assistants, taking excellent care of the food, registration, housing, and posters. Thank you to Bobak Nazer (Univ. Wisconsin, Madison) for being our photographer.

USC faculty and students enthusiastically supported the school. USC EE Department Head Sandy Sawchuk helped to organize the lecture hall and video equipment. Binh Tran of the USC Distance Education Network provided the video equipment and training. USC EE tech-savvy students Hassan Ghozlan, Kung-Chuan Hsu, and Rahul Urgaonkar operated the equipment. Many more USC EE students helped with the event: Marjan Baghaie, Ozgun Bursalioglu, Prasanta Ghosh, Joshua Gunn, Song-Nam Hong, Hoon Huh, Dileep Kalathil, Jeong Gon Kim, Ching-Yi Lai, Chih-Ping Li, Angeliki Metallinou, Bill Ntranos, Krishnakumar Raman, Peyman Razaghi, Arash Saber Tehrani, Feng Wan, Bo Xiao, and Daphney-Stavroula Zois. Thank you all!

The 2010 School was made possible by financial support from several institutions. In particular, the IEEE Information Theory Society, the U.S. Army Research Laboratory (ARL), the National Science Foundation (NSF), and the USC Ming Hsieh Institute provided substantial support. In fact, the support from the USC Ming Hsieh Institute was rather special: its very first grant! The School also received funding from USC Electrical Engineering, Northwestern University—Master of Science in Information Technology Program, Rice University—Center for Multimedia Communication, Texas A&M University—ECE Department, Penn State—Networking and Security Research Center, The University of Texas at Austin—Wireless Networking and Communications Group, the University of Notre Dame, Princeton University, and Roberto Padovani.

As usual, a year of planning culminated in a few short and exciting days. The idea of organizing a summer school came about in 2006 and we are both so very thrilled to see the continuing growth in student numbers and the excitement that future schools generate with our Society's members. Volunteers have already come forward to organize the School over the next three years. The 2011 plans are underway with our very capable organizer Sriram Vishwanath. We look forward to next year's School!

In the meantime, we invite you to browse the 2010 School website http://www.itsoc.org/school for photographs, student posters, lecture slides, video recordings, and more. Enjoy!

IEEE Information Theory Society Board of Governors Meeting

June 13, 2010 Austin, TX

Aria Nosratinia

Attendees:

Costas Georghiades, Nihar Jindal, Giuseppe Caire, Alexander Barg, Prakash Narayan, Bruce Hajek, Helmut Bölcskei, Michelle Effros, David Forney, Li Peng, Narayan Santhanam, Aylin Yener, Muriel Médard, Ezio Biglieri, Christina Fragouli, Frank Kschischang, Sergio Verdú, Emina Soljanin, Paul Siegel, Martin Bossert, Rolf Johannesson, Gerhard Kramer, Daniel Costello, Hans-Andrea Loeliger, Antony Ephremides, Alon Orlitsky, Vladimir Blinovsky, Maxim Chuyashkin, Todd Coleman, Aria Nosratinia, Andrea Goldsmith (by phone).

The meeting was called to order at 12:30 hours by the Society President Frank Kschischang, who greeted the members of the board.

1) The agenda was approved by consent, including the minutes of the previous BoG meeting in La Jolla.

2) Vince Poor made a brief presentation, seeking the support of the society for a book on non Gaussian statistical communication theory. David Middleton, who passed away last year, finished 10 chapters. IEEE intends to publish it, Leon Cohen is the editor, and Vince Poor will write a foreword. The IEEE press is asking if the IT society is willing to sponsor this project. Little commitment is required from the society, primarily advertising to the IT society membership at fairly low cost. In return, ITsoc members can purchase the book at reduced rate, or society can get a fraction of the royalties. The motion to support this book was approved.

3) The society president Frank Kschischang presented his report, outlining that the society is in good shape, both financially as well as in terms of activities. This is reflected in the agenda today. He mentioned that a book in

German has been written about Claude Shannon and his life and activities.

Martin Bossert added that this book is the enlarged version of the dissertation of a historian from the University of Munich who was able to get input from Shannon's daughter for the writing of the book. Many documents related to the work of Shannon were confidential up to a few years ago but only recently opened by the US government, and are reproduced in the book. However the book is a historical account, not a technical one. Jim Massey has made very positive remarks about the book. The author is apparently working on an English translation.

4) The Treasurer's report was presented by the IT Treasurer, Nihar Jindal. The finances of the society are improving. Operating surplus has been $491k and investment returns $764k. Reserves at end of 2009 are approximately $3M. Reserve to expense ratio was approximately 1.7, well above the IEEE minimum of 0.5. The budget for 2010 and 2011 was presented. ITsoc has been running a consistent operating surplus, but the trends on many important items are out of the control of the society, e.g. IEEExplore, and fluctuate quite a bit. In the last meeting, there were some concerns about declining print revenues, but the treasurer does not believe this to be very worrisome. The worries about losing the subscriptions of non-member entities is relieved in part by IEEE offering electronic subscription for them.

   The long term outlook is not bad, as there are significant degrees of freedom in controlling costs in the face of potentially declining revenues. In particular transactions editing costs and member print subscription fees, which are currently heavily subsidized, can be adjusted as needed.

5) The report of Nominations and Appointments Committee was presented by David Forney. The following slate of candidates for the BoG were put forward, all of whom agreed to serve if elected: Erdal Arikan, Alexander Barg, Joao Barros, Michelle Effros, Elza Erkip, J. Nicholas Laneman, Amin Shokrollahi, David Tse, Alexander Vardy, Emanuele Viterbo, En-Hui Yang, Aylin Yener. In addition an opportunity was given for further nominations by the BoG members, and Mahesh Varanasi was nominated. It was mentioned that it is better if the candidates try to go through the Nominations and Appointment Committee, even though direct nomination is allowed by the bylaws. It was also mentioned that the bylaws as they stand may be a product of the time when nominations were done in a much less formal way, while now we have a 5-person Nominations and Appointment Committee, and perhaps the changing of this bylaw should be considered. David Forney moved for the BoG to approve the slate of candidates, and the motion was approved unanimously.

   The annual meeting is the only time the EiC can be elected. The search was started last year. Helmut Bölcskei was considered and he has agreed to serve if appointed. His appointment was approved unanimously by the BoG.

6) The election for next year's officers was taken under consideration. Giuseppe Caire was nominated as a candidate for president. For 1st vice president Muriel Médard was nominated as a candidate. Alex Grant and Gerhard Kramer were nominated as candidates for 2nd vice president. All candidates were approved unanimously.

7) Ubli Mitra was nominated for liaison to the Signal Processing society. Frank Kschischang moved to approve this appointment, and the motion passed unanimously.

8) The Publications Committee report was presented by Ezio Biglieri. The EiC handover is scheduled for July. The submission system handover is scheduled for Fall 2010. The senior IEEE editor handover was in Spring 2010. We have 44 associate editors, up from 26 in June 2007. We need to appoint new associate editors. Appointments were delayed until S1M is in place. To be approved by BoG: Yossi Steinberg (at large), Tomohiko Uyematsu and Wei Yu (Shannon Theory) and Tsachy Weissman (Shannon Theory and Source Coding). The motions for the appointment of each of the editors was carried.

   The projected page count is greater than 6100. A number of special issues are published or in the making, including "information theory in molecular biology and neuroscience in Feb. 2010.

   The ad-hoc committee appointed to organize the transition to ScholarOne are Alex Grant and Adriaan van Wijngaarden. The handover is scheduled for fall 2010. For a while, pareja and ScholarOne will coexist. 113 out of 149 IEEE journals use ScholarOne (S1M). This system also generates data that is useful for the management of the journal. This is used in part for the 5-year review. Our review will be upcoming in the next year. Currently the articles are stored by S1M, but this will soon move to IEEE. S1M uses software for automatic detection of plagiarism. Submissions from authors in prohibited list are automatically identified.

   A "Best editorial practices" document has been issued, with the goal of reducing the sub-to-pub time and making the review process more homogeneous across editors. A version of it was published in the IT Newsletter.

   Our average sub-to-pub time in July 2010 was 83 weeks, with a median of 78 weeks. This is an improvement compared to the last year.

   The issue of open-access publication has been looked at by IEEE. The idea is instead of paying to read, one must pay to publish. The cost is currently between $800 to $3000. Two IEEE publications have gone to a hybrid model, but it is unclear that the open access or hybrid model is sustainable. Several members of the BoG were of the opinion that paying for publication has serious problems, in particular, it will put a filter on publication based on wealth or funding situation.

   The IT Society Newsletter is to be made available via Xplore. The issue will appear as a single file and search function will not be available. Rollout is scheduled for 2011.

   IEEE wants to abandon paper-based formatting and numbering in favor of single-article publication. This means that the sequential page numbers, volumes, etc. will be eliminated.

The new author gateway is scheduled to be operational in October. This will enable the authors to observe the status of their article through the publication process.

9) The report of the Awards Committee was presented by the committee chair Giuseppe Caire. The committee was responsible for Comsoc/ITsoc paper award, the IT best paper award, and the ISIT best student paper award. The 2010 Comsoc/ITsoc paper award goes to: "Coding for errors and erasures in random network coding," by R. Koetter and F. Kschischang. The 2010 IT society paper award goes to: "Channel polarization: a method for constructing capacity-achieving codes for symmetric binary-input memoryless channels" by E. Arikan. The report and the recommendation of the report were supported by the vote of the BoG.

   The ITsoc nomination for the BBVA Frontiers of Knowledge Award for Information and Communication Technologies was Dr. Andrew Viterbi. This nomination was endorsed by the IEEE Signal Processing Society and IEEE Communications Society.

   Giuseppe Caire indicated that the ISIT best student paper award is not yet in the bylaws, and there is no clearly understood procedure to run the award. This year there were 250 self-nominated papers with no pre-selection or consistent recommendation from the TPC regarding the student paper awards. The Awards Committee selected 43 papers to be further considered. The session chairs of these papers have been asked to provide feedback about the presentation quality, and the Awards Committee will also attend as many as possible. The large number of papers after the cutoff presents difficulties, and it is desirable that more pre-filtering be done by the TPC.

   The discussions in general re-affirmed the importance and continuation of the ISIT best student paper award. The motion was made to formally codify the best student paper award in the society by-laws. The motion was carried by a majority vote.

   The suggestion was made that instead of "best paper award" it can be named "outstanding paper award," in recognition of the fact that strict ordering of the quality of conference papers is difficult.

10) The Online Committee report was presented by Nick Laneman. More people are being involved in the committee, and also the Online Committee is working with other committees. No significant request for funding is expected for the next year. Some statistics from the web site were presented. The web site traffic is growing, the development is continuing, and the committee is evolving.

   The photo carousel is generating a large amount of traffic, so if any of the committees have activities that they want to highlight, they might consider this.

   Another issue is advertising on the web site, on which the Online Committee would like to get the sense of the BoG. It was mentioned that there would be additional work in managing sponsorships and advertising.

   A software is being used that allows the construction of "sub-sites." One example of it is the summer school. Although the Online Committee is not currently in a position to absorb, e.g., a conference, but that capacity may soon come into existence, and this will give the conference organizers the option of erecting their web site inside the IT society web site.

11) The incoming Editor-in-chief, Helmut Bölcskei, presented some thoughts on the editorial practices. Some ideas from the structure of the journal "Annals of Statistics" were presented. Several ideas were discussed, including: recruiting tenured editors from academia, recruiting senior editors who have served before, training sessions for new editors. Comments were made on the transition to ScholarOne. Some of the transition difficulties include: system flagged actions, provision for special issues, and the ability of the editors to set review deadlines in a case-by-case basis. The pros and cons of having a dedicated editorial assistant, who will send some personalized notifications and tend to specific requests by authors and associate editors, was discussed.

   An idea was presented for an executive editorial board (EEB) consisting of several senior, highly recognized people in the field, to be appointed by the BoG on a rotating basis, to work closely with the EiC regularly. One of the EEB members will be designated to fill in during any absence or vacation of EiC. The EEB helps in finding new AEs, help AEs that under-perform, deals with plagiarism cases, and handles appeals and complaints. The EEB also helps in fast-rejecting papers, identifying topics and authors for tutorial/survey/condensation papers, identifies papers for awards, and identifies topics and guest editors for special issues.

12) The Student Committee report was presented by Aylin Yener. A new networking event was introduced at CISS, geared towards graduating students looking for jobs, which was attended by approximately 100 students. Two events are planned for ISIT: a round table research discussion and a panel discussion on "recipes for good talks." An update was presented on the progress of the summer school of information theory, Aug. 5–8, 2010. In 2008 and 2009, the format of the summer school consisted of three lectures each lasting 4.5 hours. The new format this year consists of six 2-hour lectures. The school was registered with IEEE as a conference, and ITsoc has confirmed its sponsorship. The applicant number shows a 50% increase over the previous year, and an effort was made to accommodate all applicants. So far, 193 have confirmed that they will attend. The total estimated budget is approximately $70k, the majority of which is for accommodations and food.

13) A proposal for the 2011 winter school for information theory in Barcelona was presented by Ezio Biglieri. The organizing committee and the proposed instructors were introduced. A projected financial outline of the operation of the winter

school in Barcelona was outlined. The requested funds from the ITsoc is approximately 8,000 euros. The anticipated participation includes 50 students. The expected registration fee is 200 euros per person. There is a week-long program, with 3 hours of lectures every morning, and 3 hours of student presentations in the afternoon, with one afternoon off. The motion for providing 8,000 euros for the winter school was carried.

14) The report of the Chapters and Membership Committee was presented by Muriel Médard. Many of our chapters are very active. The chapter of the year award goes to the Russia chapter in light of many significant events with good attendance. There are two new chapters: South Africa and Vancouver. There are some challenges, including getting the chapters to post their activities on our web site. Also the utilization of the Distinguished Lecturers program has been an issue. It has been proposed to collect some best practices from active chapters, and identify the underlying issues in under-performing chapters.

    Our membership is slightly on the decline, with some signs of recovery. Student membership is particularly encouraging.

15) The report of WITHITS was presented by Christina Fragouli. Some statistics about membership and (co)authorship of papers was presented. WITHITS has organized an event at ISIT 2010.

16) The Conference Committee report was presented by Bruce Hajek. There is a board-approved transition in this committee. Martin Bossert will start serving after this meeting; the BoG thanked Alex Grant, the out-going member, for his services.

    A revised budget for ISIT 2011 was presented. The motion for approval of the revised budget was carried.

    The proposal for ISIT 2014 in Honolulu, Hawaii, was presented by Anders Host-Madsen. The proposed general chairs are Anders Host-Madsen, Venu Veeravalli, and Aleksander Kavcic. Several options for the conference venue were presented. The Conference Committee recommended the BoG to approve the proposal for ISIT 2014 in Hawaii. The motion for the approval of the venue was carried.

    The report from ISIT 2010 is that everything is going well. ISIT 2012 and 2013 are progressing according to plan. The upcoming workshops are Dublin and Paraty. There are no other workshops on the horizon, and the Conference Committee welcomes proposals for ITWs.

    The motion for society sponsorship of NetCogs 2011 was carried.

17) Frank Kschischang presented the report for the Wyner and Shannon Awards Committee. The committee enquired the sense of the BoG regarding the issue of a joint Shannon award in the hypothetical case where two persons have made most or all of their contributions jointly. The general sentiment was that this is not consistent with the nature of the Shannon award.

18) Bruce Hajek requested input from the BoG regarding the issue of a potential decrease of the percentage of IEEE members elevated to fellow each year (currently set to 0.1% of the membership). The opinions expressed were that the standard of the ITsoc is very high and it would not be appropriate to raise that bar any higher, but also some dissatisfaction was expressed that the standard for elevation to fellow does not seem to be uniform across IEEE societies.

19) The meeting was adjourned at 17:50 hours.

Workshop Report: Information Theory & Coding Workshop at Sharif University of Technology

Farokh Marvasti and M J Emadi

For the first time an Information Theory & Coding Workshop was organized by Advanced Communications Research Institute (ACRI) and Center of Excellence in Multi-access Communications of EE Dept at Sharif University of Technology on June 30th of 2010.

The main purpose of this workshop was to introduce new research results of the students and academic staff. In this one-day workshop there were two guests; Prof. Ezio Biglieri, the former Editor-in-chief of IEEE Transaction on Information Theory, and Prof. Parastoo Sadeghi from Department of Information Engineering, the Australian National University. The presentations were as follows:

Introduction by Prof Farokh Marvasti, Director of Advanced Communications Research Institute.

Trends in Information Theory, Prof. E. Biglieri, Editor-in-chief of IEEE Trans. on Information. Theory.

Achievable Rate Regions for Interference and Cognitive Radio Channels, *Dr.Hodtani, EE Dept., Ferdowsi Univ. of Mashhad.*

State-Dependent Relay Channel with Private Messages with Partial Causal and Non-Causal Channel State Information, B. *Akhbari, EE Dept., Sharif Univ. of Tech.*

On the Capacity of Causal Cognitive Interference Channel With Delay, *M. Mirmohseni, EE Dept., Sharif Univ. of Tech.*

On the Capacity Bounds for CDMA Systems, Prof F Marvasti, *Dr. K. Alishahi, S.Dashmiz, P. Paad, M. Mansouri, and H. Shafinia, EE Dept., Sharif Univ. of Tech.*

On Coding for Coded Coperative Data Exchange, **Guest Speaker:** *Prof. P Sadeghi, Dept of Information Eng, Australian national University.*

Optical Orthogonal Code Design, *M. Alem, EE Dept., Sharif Univ. of Tech.*

Fountain Codes and their Applications to Optical Systems, *M. Karimi, EE Dept., Sharif Univ. of Tech.*

On the Capacity Bounds for Broadcast Networks, *S. Salehkalaibar, EE Dept., Sharif Univ. of Tech.*

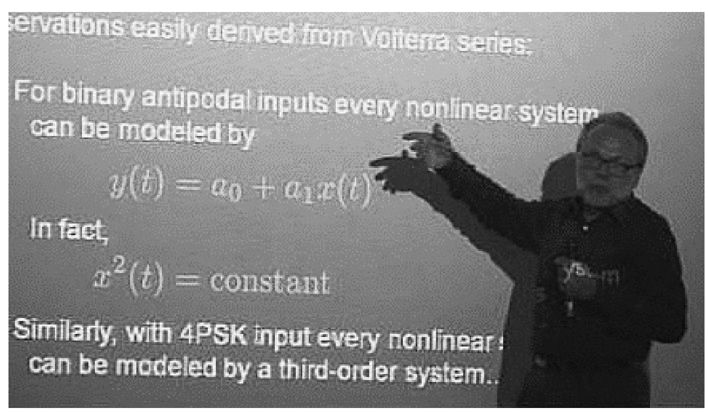
Secret Key Sharing in Multiple Access Source and Channel Models, *S. Salimi, EE Dept., Sharif Univ. of Tech.*

Cognitive Interference Channel with Two Confidential Messages, *Ghanizadeh, EE Dept., Shahed Univ.*

Prof. E. Biglieri's Research Activities

Closing Session, Prof. *E. Biglieri and P. Sadeghi*

In the closing session, Prof. E. Biglieri and Prof. P. Sadeghi expressed that the quality of the presented research on information theory and coding in the workshop was far beyond their expectations and they were impressed by the command of English and the quality of students in the EE department of Sharif University of Technology. The ACRI labs that participated in this workshop were Information Theory, Wireless Communications, Optical Communications, and Signal Processing. Labs directed by Profs, MR Aref, M Nasiri-Kenari, JA Salehi and F Marvasti, respectively.



Positions Available

Positions of Postdoctoral Fellows and Research Associates are open at the Institute of Network Coding (INC) of The Chinese University of Hong Kong (CUHK). Initial appointments are typically for two years, and the commencing date is flexible.

Applicants should have a strong research record in network coding related areas, including theory, applications, or implementation.

For further information please visit the INC home page at http://www.inc.cuhk.edu.hk or contact Raymond Yeung at whyeung@ie.cuhk.edu.hk

Updates from the Online Committee

Since the official launch of the new infrastructure in 2008, many features have been added to the itsoc website. While early improvements were targeted towards easier maintenance, the latest add-ons have been developed to make more content easily accessible to the IT community. In particular,

- The website now supports mathematical expressions. Contributors can use LaTeX syntax to include sophisticated equations in webpages (http://www.itsoc.org/people/committees/online/example-latex-page). This feature will allow newsletter articles to be published online and will encourage contributors to submit briefs surveys or tutorials on specific topics.
- Media resources (slides and videos of Shannon lectures, ISIT keynotes, or School of Information Theory lectures) can now be stored as "Lectures", a customized object that makes it easy to sift though the numerous resources archived over the years (http://www.itsoc.org/school/lecture-files/wolf). The Online Committee is actively working to convert all existing resources to this new format.

Several enhancements are already lined up and will be released in the next few months. This includes:

- Improved Lecture objects with embedded videos, which will eventually replace the media server media.itsoc.org.
- Additional support for conference websites, which will allow conference organizers to integrate their website seamlessly within www.itsoc.org.

After 4 years of dedicated service as Chair of the Online Committee, Nick Laneman will step down in January 2011 and will be replaced by Matthieu Bloch. During his tenure, Nick oversaw the development and successful launch of the website infrastructure. The Online Committee expresses his sincere gratitude to Nick for his leadership and vision and looks forward to many years of continued website enhancements.

With many exciting new features planned down the road, the Online Committee welcomes any member to join the Online Committee.. Volunteers should contact Matthieu Bloch directly (matthieu.bloch@ece.gatech.edu).

The Online Commitee

The 2011 International Symposium on Network Coding (NetCod 2011) will be held in Beijing, China from July 25-27, 2011

(which is one week before the IEEE International Symposium on Information Theory 2011 in Saint Petersburg)

We invite original, previously unpublished papers and research contributions in the area of network coding. Both mature and early stage results are welcome. Specific topics of interests include (but are not limited to) the following:

- Shannon theory for network coding
- Network code constructions and algorithms
- Joint source coding and network coding
- Joint channel coding and network coding
- Resource optimization for network coding
- Robustness, energy, or delay aspects of network coding
- Security and error correction for network coding
- Wireless network coding Implementation aspects of network coding
- Network coding applications Network Coding for Internet Communications
- Network Coding for Distributed Storage

Authors should prepare a Portable Document Format (PDF) version of their manuscripts for submission. Submitted papers will be reviewed by experts in the field and must be no longer than 6 pages, using the standard IEEE style for conference papers.

Important Dates

Paper Submission Deadlines: Feb 22, 2011

Acceptance Notification: April 18, 2011

For more information, please contact the General Chair or TPC Co-Chairs

Homepage: http://netcod2011.org/

General Chair
Yixian Yang
Beijing University of Posts and Telecommunications, China

TPC Co-chairs
Zhen Zhang
University of Southern California
Terence Chan
University of South Australia

CANADIAN SOCIETY OF INFORMATION THEORY
SOCIÉTÉ CANADIENNE DE THÉORIE DE L'INFORMATION

The 2011 Canadian Workshop on Information Theory

Kelowna, British Columbia, Canada
May 18-20, 2011

First Call For Papers

The 12th Canadian Workshop on Information Theory (CWIT) will be held on the campus of the University of British Columbia Okanagan, Kelowna, British Columbia in the scenic Okanagan Valley from Wednesday May 18 to Friday May 20, 2011. Papers in (but not exclusive to) the following fields of research are solicited:

- Shannon Theory
- Application of Information Theory
- Multiuser Information Theory
- Quantum Information Processing
- Coding Theory and Practice
- Coded Modulation
- Data Compression and Source Coding
- Communication Systems
- Cooperative Communication
- Cryptology and Data Security
- Information Theory and Statistics
- Signal Processing
- Pattern Recognition and Learning
- Sequences and Complexity
- Multi-terminal Information Theory
- Data Networks
- Detection and Estimation
- Cognitive Radio

Authors wishing to have papers considered for the workshop should electronically submit their full papers (maximum four pages) in PDF format by **January 15, 2011** through EDAS (http://edas.info/index.php) using the standard IEEE two-column format. Accepted papers will be published on IEEE Xplore website and in the proceedings of the workshop. Paper acceptance will be announced on March 15, 2011. Authors of papers accepted for the workshop will be requested to submit a four-page camera-ready paper no later than April 1, 2011.

For the first time, Canadian Society of Information Theory (CSIT) will sponsor a School of Information Theory immediately prior to or after the CWIT 2011. The goal of the School of Information Theory is to bring graduate students and senior researchers together to participate in a stimulating and informative tutorial program related to information theory and its applications.

Coference inquiries regarding the workshop should be addressed to either of two workshop co-chairs:

Dr. Robert Schober
Dept. of Electrical and Computer Engineering
University of British Columbia
Vancouver BC V6T 1Z4
Phone: 604-822-3515
Fax: 604-822-5949
Email: rschober@ece.ubc.ca

Dr. Julian Cheng
School of Engineering
University of British Columbia Okanagan
Kelowna BC V1V 1V7
Tel: 250-807-8808
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Email: julian.cheng@ubc.ca

For more information on CWIT 2011, please visit :
http://cwit2011.ok.ubc.ca/

2011 IEEE Winter School of Information Theory
March 14-18,
Barcelona, Spain

The 2011 IEEE Winter School of Information Theory will take place in Barcelona between the 14th and the 18th of March. Jointly organized by UPF (Universitat Pompeu Fabra) and by CTTC (Centre Tecnològic de Telecomunicacions de Catalunya), and officially sponsored by the IEEE Information Theory Society, the 11th of the biennial winter school continues its tradition to provide opportunities for graduate students to meet, present their research, and get advice from distinguished professors in their areas.

In addition to their function as instructors, the invited professors will also be giving special tutorials on selected topics. This year's instructors are

Prof. Helmut Bölcskei (ETH Zürich)
Prof. Gerhard Kramer (Technische Universität München)
Prof. Emre Telatar (EPFL Lausanne)
Prof. Daniel P. Palomar (Hong Kong University of Science & Technology)
Prof. Baltasar Beferull-Lozano (Universitat de València)

The number of participants is limited. Priority will be given to early registrations. The cost for students (including shared accommodation) will be around 200 Euros. Registration will open in mid-December 2010, please follow the website:http://www.dtic.upf.edu/~afaridi/WinterSchool

The general co-chairs of this year's winter school are Angel Lozano (UPF) and Xavier Mestre (CTTC), and the technical chair is Ezio Biglieri (UPF). The web development and the promotion of the event is handled by Azadeh Faridi (UPF) and Deniz Gündüz (CTTC), and Vanesa Daza (UPF) is responsible for the local arrangements.

Conference Calendar

DATE	CONFERENCE	LOCATION	WEB PAGE	DUE DATE
December 6–10, 2010	2010 IEEE Global Communications Conference (GLOBECOM 2010)	Miami, FL	http://www.ieee-globecom.org/	Passed
January 8–14, 2011	14th Workshop on Quantum Information Processing (QIP 2011)	Singapore	http://qip2011.quantumlah.org/	Passed
February 6–11, 2011	2011 Information Theory and Applications Workshop	San Diego, CA	http://ita.ucsd.edu/workshop.php	By invitation
March 23–25, 2011	45th Annual Conference on Information Sciences and Systems (CISS 2011)	Baltimore, MD	http://ciss.jhu.edu/	January 5, 2011
April 10–15, 2011	IEEE INFOCOM 2011	Shanghai, China	http://www.ieee-infocom.org/	Passed
May 9–13, 2011	WiOpt 2011	Princeton	www.wiopt.org	December 23, 2010
May 14–17, 2011	2011 IEEE Vehicular Technology Conference (VTC2011-Spring)	Budapest, Hungary	http://www.ieeevtc.org/vtc2011spring/	Passed
June 5–9, 2011	IEEE International Conference on Communications (ICC 2011)	Kyoto, Japan	http://www.ieee-icc.org/	Passed
June 20–22, 2011	2011 IEEE Communication Theory Workshop	Sitges, Catalonia, Spain	http://www.ieee-ctw.org	TBD
July 31–August 5, 2011	2011 IEEE International Symposium on Information Theory (ISIT 2011)	St Petersburg, Russia	http://www.isit2011.info	February 10, 2011
October 16–20, 2011	2011 IEEE Information Theory Workshop (ITW 2011)	Paraty, Brazil	http://www.fee.unicamp.br/itw2011/	April 10, 2011

Major COMSOC conferences: http://www.comsoc.org/confs/index.html