IEEE Information Theory Society Newsletter

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Annual IT Awards Announced

The main annual awards of the IEEE Information Theory Society were announced at the 2012 ISIT in Cambridge this summer.

Katalin Marton

Ezio Biglieri

- The 2013 Claude E. Shannon Award goes to Katalin Marton. She will give the Shannon Lecture at the 2013 ISIT in Istanbul, Turkey.
- The 2012 Claude E. Shannon Award was given to Abbas El Gamal in Cambridge. Abbas presented his Shannon Lecture on the Wednesday of the Symposium. If you wish to see his lecture again or were unable to attend, a videotape of the lecture will be posted on our Society website.
- The 2012 Aaron D. Wyner Distinguished Service Award goes to Ezio Biglieri.
- The 2012 IT Society Paper Award was given to Young-Han Kim for his paper "Feedback capacity of stationary Gaussian channels," IEEE Trans. Inf. Theory, vol. 56, no. 1, pp. 57–85, Jan. 2010.
- The 2012 IEEE Communications Society and Information Theory Society Joint Paper Award goes to two papers:

  1) A. G. Dimakis, P. B. Godfrey, Y. Wu, M. J. Wainwright, and K. Ramchandran, "Network coding for distributed storage systems," *IEEE Trans. Inf. Theory*, vol. 56, no. 9, pp. 4539–4551, Sep. 2010.

  2) M. Lentmaier, A. Sridharan, D. J. Costello Jr., and K. Sh. Zigangirov, "Iterative decoding threshold analysis for LDPC convolutional codes," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 5274–5289, Oct. 2010.

- The 2012 Chapter of the Year Award goes to the Finland Chapter.
- The 2012 ISIT Student Paper Awards were selected and announced at the banquet of the Cambridge Symposium. The winners were Thomas Courtade, Kartik Venkat, and Wei Yang.
- Several members of our community became IEEE Fellows or received IEEE Medals, please see our website for more information: www.itsoc.org/honors

The Claude E. Shannon Award honors "consistent and profound contributions to the field of information theory" and it is the most prestigious honor of our Society. Katalin Marton is the first female to receive the award. She received her doctoral degree from Eötvös Loránd University in Budapest, and she has worked at the Central Research Institute for Physics in Budapest and at the Alfréd Rényi Institute of Mathematics of the Hungarian Academy of Sciences. In our community, Katalin Marton is perhaps best known for her work on multiuser information theory, in particular for her fundamental contributions to the capacity of broadcast channels in the 1970s. She has also made important contributions to rate distortion theory in the 1970s, the entropy and capacity of graphs in the 1980s and 90s, and more recently to measure concentration. Her work on "How to encode the mod-2 sum of two binary sources" from 1979 with J. Körner has inspired much recent work on wireless relaying theory and strategies.

The Aaron D. Wyner Distinguished Service Award honors "individuals who have shown outstanding leadership in, and provided long-standing exceptional service to, the Information Theory Community". Ezio Biglieri has been selected as the recipient of this award for 2012. He has served three times on the Board of Governors, he served as our President in 1999, and he was the Editor-in-Chief of the IT Transactions from 2007–2010.

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From the Editor

Tara Javidi

Dear IT Society members,

This is a very dense issue: the two highlights are the summary by Shlomo Shamai of his 2011 Shannon lecture "From Constrained Signaling to Network Interference Alignment via An Information-Estimation Perspective" and the announcement of the annual IT Society awards (kindly prepared by Gerhard Kramer). Warmest congratulations to the award winners for all your achievements!

Following the President's column, we congratulate Professors Shlomo Shamai and Bin Yu for their election to the Israel Academy of Sciences and Humanities and the President-Elect of the Institute of Mathematical Statistics, respectively. All of us intellectually rely and depend on the IEEE Transactions on Information Theory. In the last issue of the newsletter, Helmut Bölcskei, the Editor-in-Chief of the Transactions kindly provided a careful and detailed report on the state of the IT Transactions. In this issue, we have a follow up note from him regarding an important BoG resolution. These are all of course are in addition to our popular and regular contributions by Tony Ephremides and Solomon Golomb.

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 also can be e-mailed to me at ITsocietynewsletter@ece.ucsd.edu with a subject line that includes the words "IT newsletter." The next few deadlines are:

Issue	Deadline
December 2012	October 10, 2012
March 2013	January 10, 2013
June 2013	April 10, 2013

Please submit plain text, 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 hear your suggestions and contributions for future issues of the newsletter.

IEEE Information Theory Society Newsletter

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President's Column

Muriel Médard

The suitcase from the ISIT trip has been finally unpacked, the e-mails among colleagues to check this or that paper that was presented at ISIT are tapering down and there is finally some time to reflect. Several vignettes spring to mind—the beautiful memorial event for Tom Cover, dancing after the banquet, a favorite talk, the Shannon Lecture, children running around during the barbeque, getting a chance to catch up with a dear collaborator under the tent. The attendance but, most importantly, the energy at ISIT are a sure sign of the health of our Society. In between darting among sessions or, more often, different last-minute organizational trivia, I was delighted to see the many groups sitting under the big tent that formed the nexus of our conference. There one could observe our Society in action. Long-term collaborators or recent acquaintances were engaged in lively technical discussions, pointing to a paper displayed on a laptop screen, or scribbling for each other on the back page of the program. Senior researchers and students mingled around coffee. Surely creating the possibilities for such exchanges is at the core of our mission as a Society. The very healthy pipeline of proposals for future ISITs and for ITWs bodes well for many more conversations and wonderful memories of conferences.

Another of our core missions is of course our beloved Transactions. As you may see from the minutes of our Board of Governors' meeting immediately preceding ISIT, our transactions are very healthy from the point of view of their quality and relevance to the scientific community, but require great effort financially on the part of the Society. Our current costs for producing them are by far our single largest expense, owing mostly to our editing costs. We currently have opted for the heavy editing provided by IEEE, which is the most complete, but by far also the most costly of the editing services it offers. Many of our sister societies, in which many of us are active, such as the Signal Processing Society and the Communications Society, use alternative methods. Examples of such editing practices are the more economical lighter IEEE editing, or editing by society-hired personnel, or the use of freelancers. In the short term, our Society is exploring different approaches to manage our editing costs, particularly since our authors by and large now provide us always with fairly serviceable Latex files, in a way that maintains the quality of the transactions in a financially sustainable way. Planning for the long term, our Society is engaged in a much broader exercise to examine, from many different perspectives, how to maintain the health of our transactions. A committee headed by our Second Vice President, Abbas el Gamal, will provide a report to the Board of Governors during our meeting in September at ITW Lausanne.

I would like to conclude my column with an appeal to the members of our community to consider joining, as a mentor or mentee, our mentoring effort. Having started it while a member of the Board of Governors, this initiative is of course very dear to me. But beyond its inception I can attest, having been a mentor, to the wonderful experience of being able to follow closely, and in a constructive, helpful manner, the career of a junior colleague. I have been blessed with outstanding mentees—Aditya Ramamoorthy, Tara Javidi, Aylin Yener and Joerg Kliewer, who is now heading the mentoring effort with Elza Erkip. This effort exemplifies the investment our community makes in the careers of its junior members and our commitment to the future of our field.

2012 IEEE Information Theory Society Chapter of the Year Award

The IEEE Finland Section Communications and Information Theory Joint Societies Chapter received the 2012 IEEE Information Theory Society Chapter of the Year Award for their contribution to spreading the enthusiasm for open problems in Information Theory. The Communications Society Chapter has been existed for years. A few years ago an idea, mainly by Professor Markku Juntti, to establish an IT Society Chapter in Finland was introduced. Finally, early in the last year, 2011, the Joint Societies Chapter was established in Finland. Its first officers are PhD Harri Saarnisaari as Chair and PhD Marian Codreanu as Vice-Chair. The Joint Chapter continues the good traditions of the Chapter and tries to organize and support different related events inside Finland, but also internationally. A particular recent example is the Wireless Innovation between Finland and US program (WIFIUS, www.wifius.org) that at the moment includes several IT related projects led by members of the Chapter. The WFIUS program organized a summer school at the University of Oulu at the end of June. The Chapter is honored to receive the 2012 IEEE Information Theory Society Chapter of the Year Award and will continue to work on upgrading and expanding its efforts and activities. The Chapter uses the Web (www.cwc.oulu.fi/IEEE_COM19/) to announce different events to its members and larger audience.

IT Society Members Honored

Prof. Shlomo Shamai (Shitz) was Elected a Member of the Israel Academy of Sciences and Humanities

We are happy to announce that Distinguished Professor Shlomo Shamai (Shitz) was elected a member of the Israel Academy of Sciences and Humanities. He joins a distinguished group of leading information theorists which includes Prof. Moshe Zakai and Prof. Jacob Ziv.

Chartered by law in 1961, the Israel Academy of Sciences and Humanities acts as a national focal point for Israeli scholarship in both the natural sciences and the humanities. The Academy consists of approximately 100 of Israel's most distinguished scientists and scholars, who, with the help of the Academy's staff and committees, monitor and promote Israeli intellectual excellence, advise the government on scientific planning, fund and publish research of lasting merit, and maintain active contact with the broader international scientific and scholarly community.

Prof. Bin Yu has been Elected President-Elect of Institute of Mathematical Statistics

Professor Yu will serve a three-year term: one year as President-Elect (12-13), one year as President (13-14) and one year as Past President (14-15).

http://imstat.org/news/2012/06/19/1340124690475.html

The IMS is a leading international professional and scholarly society devoted to the development, dissemination, and application of statistics and probability. The Institute currently has about 4,500 members in all parts of the world. It owns the following premier journals in Statistics and Probability: Annals of Statistics, Annals of Probability, Annals of Applied Statistics, Annals of Applied Probability, Electronic Journal of Statistics and Electronic Journal of Probability.

Annual IT Awards Announced

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He has further organized many conferences, symposia, workshops, and schools and continues to be a strong promoter of Information Theory. Needless to say, he is a recipient of many other prizes, including an IEEE Third-Millennium Medal and an IEEE Donald G. Fink Prize Paper Award. We are lucky to have such distinguished and dedicated members as leaders of our Society.

The Information Theory Society Paper Award is given annually "for an outstanding publication in the fields of interest to the Society appearing anywhere during the preceding two calendar years". The Awards Committee considered 9 nominations and recommended that the paper by Young-Han Kim on the "Feedback capacity of stationary Gaussian channels" from 2010 win the award. This paper solves a foundational problem that many other researchers could not over a period of several decades. The Board of Governors voted to accept the committee's recommendation at its annual meeting before ISIT in Cambridge. If you are curious to find out more about the selection procedure, please refer to the IT Society Bylaws at http://www.itsoc.org/people/organization

The IEEE Communications Society and Information Theory Society Joint Paper Award recognizes outstanding papers "appearing in any publication of the IEEE Communications Society or the IEEE Information Theory Society in the previous three calendar years". The Awards Committee was happy to receive a large number (15) of nominations this year. The 2012 Award went to two papers. The first was a 2010 paper on distributed storage by A. G. Dimakis, P. B. Godfrey, Y. Wu, M. J. Wainwright, and K. Ramchandran. The second was a 2010 paper on convolutional LDPC codes by M. Lentmaier, A. Sridharan, D. J. Costello Jr., and K. Sh. Zigangirov. Congratulations to all nine winners!

The 2012 Chapter of the Year Award was presented to the Finland Chapter at ISIT in Cambridge. The Membership and Chapters Committee selected the winner based on chapter-related activities during 2011 and 2012, including scientific events, student events, web presence, and recruiting efforts.

The ISIT Student Paper Award is a relatively new award of our Society that is intended to encourage and recognize student work. The Award is "given annually for up to three outstanding papers at the ISIT for which the student is the principal author and presenter". This year the ISIT Technical Program Committee assigned the Awards Committee 12 papers and presentations to judge. Our Bylaws specifies that the Awards Committee should announce the winner at the ISIT banquet. The decision was not an easy one as all student finalists did an excellent job of presenting their papers and answering questions. The three winners were Thomas Courtade for his paper "Multiterminal source coding under logarithmic loss" (co-author Tsachy Weissman), Kartik Venkat for the paper "Pointwise relations between information and estimation in Gaussian noise" (co-author Tsachy Weissman), and Wei Yang for the paper "Unitary isotropically distributed inputs are not capacity-achieving for large-MIMO fading channels" (co-authors Giuseppe Durisi and Erwin Riegler). Congratulations to the three winners!

Finally, at the annual Board of Governors meeting at ISIT, Abbas El Gamal proposed to create a new award to celebrate Tom Cover's legacy and to encourage future generations of Information Theory researchers and educators to follow Tom's example. The Board of Governors approved the creation of the Thomas M. Cover Dissertation award. The precise description of the award will be announced at a future date. The current model is to give the award to an original and innovative doctoral dissertation in any theoretical area in the information sciences, including but not limited to Shannon information theory, coding theory, learning theory, quantum information and computing, complexity theory and applications of information theory in probability and statistics. Please stay tuned for more information about this exciting new initiative.

The Historian's Column

Anthony Ephremides

Today's column is about technical clichés. It is quite amazing how certain practices take hold in many people's work and then enter a perpetuating cycle that fuels itself and persists without abating. There is really no logical explanation although there is **some** justification for their beginning.

Let me start with an example familiar to almost everyone. It is **Lena**. Do you remember her? She dominated the journals and conference proceedings in Communications, Signal Processing, Information Theory, and other disciplines for several decades. Lena, apparently, is a real person but her reaction to her astronomical technical fame is unknown. Also unknown is who (and why) used her picture for the first time to demonstrate image reconstruction techniques. She adorned countless pages with her alluring, sometimes demurring, expression and her wily twinkle under her folding hat. I remember I was fascinated by it but I did resist using it myself. I often imagined meeting her and offering her a drink. Would she be as mysterious as her picture suggested or would she be disappointingly ordinary? Her use in our community has certainly waned lately but she fed the imagination of untold numbers of researchers, students, and faculty alike.

And then there is … **Alice** and **Bob**. There are no pictures in this case and both of these individuals are … virtual. But their use in game theory and security analyses is more than widespread. It is not clear who is the "good" person and who is the "bad" one but they have dominated most illustrations of, indeed, very interesting problems. I imagine Alice to be something like Marilyn Monroe or Jane Mansfield. I do not know why but the name conjures up images of gorgeous blondes in my mind. As for Bob, I think of him as a colorless nerd who gets involved in these games reluctantly . There is no hint of romance in their relationship. They appear more like idiotic children or robots sending bits to each other or working up some form of mischief. They are everywhere and they are also becoming … nauseatingly familiar. Their use remains solidly widespread but it seems that it may have already crested. Familiarity breeds contempt. I can brag that I never invoked them in my papers or talks. Of course, they are often complemented by Eve. Not Eve of Paradise fame but rather a stand-in for an evil user, a villain. Her name suggests this clearly. She is the eavesdropper or the one who machinates and creates malware. If I would personify her I would probably use a standard depiction of a witch.

Which brings to me memories of … **Dimbo**. Who was Dimbo? Well, he is by now a rarity. He featured prominently in my high school book on introductory algebra. Algebra was the first course in English taught in my High School and we used an American book. This was the era of the beginnings of "new math", that basically aspired to teach everyone in a …"friendly" way without the abstruse and boring elements of rigor. Thus, all concepts of algebra would be demonstrated through the stumbling's of Dimbo, who was pictured in caricature sketches as a fat little boy with a puzzled (and dumb) expression.

So Dimbo would divide by zero and think nothing of it, he would only find one of the two roots of a quadratic equation, he could not distinguish between necessary and sufficient conditions, etc. Speaking of which, I must confess that my experiments in the classroom seem to suggest that more and more students today remind me of Dimbo. I often hypothesize that A implies B and then, later on purpose, I conclude A from B. Typically no alert student protests. I attribute this not to a reduction in natural intelligence but, rather, to a gradual shift from serial reasoning to parallel reasoning that has been brought about by the proliferating use of visual media. Thus "A" implies "B" is perceived as an association between A and B that is akin to equivalence. This is typical Dimbo behavior.

There are many such clichés into which more and more people slide. A much less offensive, and much more intellectual, example is the butterfly network of Network Coding fame. This one differs from the previous examples in that it is purely technical and insightful, just like the binary symmetric channel graph. But its continued use in more instances, than warranted, assigns to it a hue of a cliché. I must confess I have used it quite a bit myself, although lately I refrain from using it.

John Thomas, my advisor at Princeton, used to say that in the academic community we repeat ourselves a lot. He was right, no doubt. So let us resolve to use more diverse examples in our work. Let us replace Lena with Vladimir Putin, and let us drop Alice, Bob, and Eve in favor of Hillary, Amadeus, and Ulrica. It will be more fun. As for Dimbo we could perhaps use Laurel and Hardy or, even, G.W. Bush.

From Constrained Signaling to Network Interference Alignment via An Information-Estimation Perspective

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Abstract–This paper is based on the Shannon Lecture presented in August 2011, at ISIT2011, Saint Petersburg, Russia, and it presents a subjective overview of selected topics in Information Theory, Communications and Signal Processing taking an Information-Estimation perspective.

We first review basic Information-Minimum Mean Square Error (I-MMSE) relations and properties in Gaussian additive channels, and then address via this framework specific problems and results in: Nonlinear optimal filtering; Constrained signaling; Multiterminal models, touching upon broadcast, wiretap, and interference channels. Novel aspects in interference channels and interference alignment, are presented emphasizing the implications of I-MMSE expressions in the characterization of multiletter capacity regions.

Efficient codes for point-to-point, interference and relay channels and interference (disturbance) related problems are examined via the I-MMSE paradigm. A statistical physics view of I-MMSE related relations, is shortly mentioned as well as different other applications, implications and connections, such as the broadcasting strategy (variable-to-fixed channel coding), all motivated by the incremental channel decomposition.

Based on the overviewed framework, we emphasize specific research challenges in these areas motivated by the information-estimation perspective and we close with some generalizations and an outlook examining general channels and network information theoretic concepts.

1. Introduction

This paper is based on the material presented in the 2011 Shannon Lecture, at the IEEE Information Theory Symposium 2011, Saint Petersburg, Russia, on August 2011. It spans a wide spectrum of topics, emphasizing a common connecting line, namely the Information-Estimation perspective. Specifically, we adhere to the basic relation between mutual information and the minimum mean square (estimation) error [45], I-MMSE in short, in an effort to present a subjective overview of selected topics in a unified way. As in the Shannon Lecture, the topics chosen are mainly connected to research problems and results that the author has been and is involved in. By no means the material here, and neither the reference list can be considered as representative or reflecting the extremely rich spectrum of problems, models, results and literature that can be associated with an information-estimation paradigm. For the sake of conciseness, mainly basic concepts, results and observations, are provided, leaving details to the cited references. One of the central goals here is to point out specific research challenges, which again are motivated by the information-estimation relations. We use related prior and subsequent results in the information-estimation paradigm, for example: [33], [97], [145], [152] to point out relevant ideas, relations, as well as extensions and future challenges.

First, in Section 2, we present the basic I-MMSE concepts and relations in a variety of Gaussian channels, scalar, vector, discrete and continuous in time. Then we go on to examine different properties of the minimum mean square (estimation) error (MMSE) achieved by the conditional mean operator. In Section 3, we highlight some signal processing aspects, namely the intimate connection between causal estimation (filtering) and non-causal estimation (smoothing) over a continuous time Gaussian channel. This connection within the classical non-linear filtering theory, was surprisingly derived via an information theoretic paradigm, and in fact no alternative technique has been reported so far. Section 4 focuses on constrained signaling, namely the ideal bandlimited Gaussian channel is studied with a peak-power limited input. The basic question addressed deals with the penalty associated with this constraint. While the results were reported in [111], here we take a retrospective I-MMSE view and mention other relevant studies.

Section 5 is devoted to some network (multiterminal) information theoretic models, for which the classical capacity regions can be deduced via the I-MMSE concepts, such as the Gaussian scalar broadcast channel [51]. The view is extended to parallel broadcast channels [20], while the general MIMO broadcast channel, the capacity region of which is known [149], is highlighted as a special timely challenge for the I-MMSE perspective. We also address the scalar Gaussian wiretap channel [51], and mention in short the I-MMSE methodology that led to closed form expressions of the secrecy capacity of the multiple-input-multiple-output (MIMO) wiretap channel under covariance input constraints [15]. The section is concluded by focusing on the Gaussian interference channel. Here new insights are developed by combining the I-MMSE paradigm with non-single letter capacity region characterization by first re-deriving the classical Sato bound [16]. The I-MMSE approach seems to provide further insights on specifying bounds on the capacity region of 'weak' interference channels and specific challenging problems are formulated. This section is concluded by skimming through novel results [160], which are based on the applications of notions as information-dimension [157], as well as the MMSE dimension [158] to provide an original perspective of interference-alignment on a Gaussian interference channel. Such an approach leads also to new observations and brings deeper insights into these timely concepts of interference alignment [55].

Section 6, is focused on implications of the information-estimation paradigm on the behavior of actual coding schemes. We review results that relate to optimal capacity achieving codes [101], and go on to consider recently reported results on the performance of 'bad' codes [10]. The notion 'bad' codes is used to describe point-to-point suboptimal codes on a Gaussian channel. These codes invoke however a diminished interference on other receivers [17], as is the situation in interference and certain relay channels. Indeed, when interference is measured by MMSE, [17] demonstrates via the I-MMSE relation that the Han-Kobayashi rate splitting strategy is optimal. This of course does not imply optimality in terms of achieving the capacity region of the interference channel, but in the model where disturbance is measured by the induced MMSE. Extensions of this approach to two and many MMSE constraints are reported in [17], [18] and [19] respectively. Further implications of the I-MMSE paradigm on other interference measures as the information disturbance [7] are also discussed.

Section 7 is devoted to applications, implications, connections and generalizations associated with the I-MMSE paradigm. First, we take a dual look of the incremental channel approach which is the central proof technique of the I-MMSE property [45], and that leads to a multilayered communications scheme. This is a central ingredient of variable-to-fixed channel coding [144] (the broadcast approach), which is used in Gaussian fading channels [116], [118], and also on fixed channels [146]. Inspired by the dual view of the incremental channel approach [45], we mention and reference a variety of applications related to vector Gaussian channels, such as intersymbol interference channels, either in time or in space, (resulting in classical Wyner type cellular model [163]) and others. Next in this section, we overview shortly different aspects that directly connect to the I-MMSE relation. First, we provide a statistical physics interpretation of this relation, emphasizing phase transition phenomena in reliable point-to-point and superposition codes [84]. Then, we skim over successful applications of the I-MMSE relation, mentioning the two dimensional intersymbol interference models [124], generalizations of the entropy-power-inequalities [47], [76] and others. This section ends with a generalized view of the I-MMSE principle, as applies to Poisson processes and channels [48], [4].

Section 8 terminates the paper with a concluding outlook. First, we examine general not necessarily Gaussian channels, following [45]. We review these results in view of a later contribution in [145] where a general divergence is expressed in terms of the difference between matched and mismatched MMSE expressions. We provide some operational meaning to the mismatched expressions by relating these to known lower bounds on achievable rates associated with mismatched decoding metric [30], [54], [83]. This concluding section ends by wondering whether the I-MMSE perspective could be useful in a variety of different timely information theoretic approaches, such as the 'approximate analysis' [133] demonstrating recently a remarkable success in a variety of multiterminal information theoretic problems.

2. The I-MMSE Relation

2.1. Basic I-MMSE Relation

The relation between the average mutual information (I) and the minimum mean square error (MMSE) over Gaussian channels has been reported in [45]. In its simplest form for scalar variables, the channel output Y is given by

$$Y = \sqrt{\mathrm{snr}}\,X + N, \tag{2.1}$$

where X is the input random variable and N is the additive standard Gaussian noise. The signal-to-noise ratio is designated by snr. We designate by $I(X;Y)$ the average mutual information between X and Y and the MMSE is denoted by:

$$\mathrm{mmse}(X|Y) = \mathrm{mmse}(X:\mathrm{snr}) = \mathrm{mmse}(\mathrm{snr}) = E(X - E(X|Y))^2. \tag{2.2}$$

The elegant relation in [45] states:

$$\frac{d}{d\mathrm{snr}} I(X;Y) = \frac{1}{2}\mathrm{mmse}(X:\mathrm{snr}). \tag{2.3}$$

For example, consider the Gaussian case where $X \sim \mathcal{N}(0,1)$ is a standard normal variable. In this case the conditional mean estimator is given by

$$E(X|Y) = \frac{\sqrt{\mathrm{snr}}}{1+\mathrm{snr}}Y \tag{2.4}$$

and the respective MMSE equals

$$\mathrm{mmse}(X:\mathrm{snr}) = E\left(X - \frac{\sqrt{\mathrm{snr}}}{1+\mathrm{snr}}Y\right)^2 = \frac{1}{1+\mathrm{snr}}. \tag{2.5}$$

The relation (2.3) is verified by noting that:

$$I(X;Y) = I_g(\mathrm{snr}) \triangleq \frac{1}{2}\log(1+\mathrm{snr}). \tag{2.6}$$

For the symmetric binary case where $X = X_b = \pm 1$ with equal probability $(1/2)$ it can be verified that (2.3) is satisfied where

$$\mathrm{mmse}(X:\mathrm{snr}) = 1 - \int_{-\infty}^{\infty} \frac{e^{-y^2/2}}{\sqrt{2\pi}} \tanh(\mathrm{snr} - \sqrt{\mathrm{snr}}\,y)\, dy \tag{2.7}$$

and

$$I(X;Y) = I_b(\mathrm{snr}) = \mathrm{snr} - \int_{-\infty}^{\infty} \frac{e^{-y^2/2}}{\sqrt{2\pi}} \log\cosh(\mathrm{snr} - \sqrt{\mathrm{snr}}\,y) dy. \tag{2.8}$$

The mmse and I expressions as functions of snr are depicted in Fig. 2.1

Five different proofs are stated in [45] where the central one is based on the incremental channel principle to be further discussed. The other proofs exploit respectively, De Bruijn's identity; the direct approach motivated by multiple-access-channel (MAC) interpretation; a geometric property of the output likelihood ratio; and the causal continuous time setting using Duncan's classical relation [33].

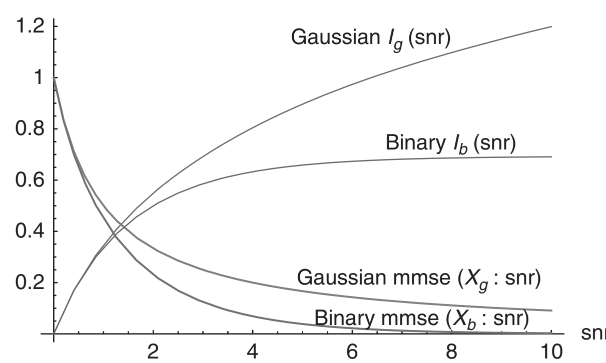

Fig. 2.1. Mutual information (*I*) and minimum mean square error (mmse) relations for Gaussian and binary inputs.

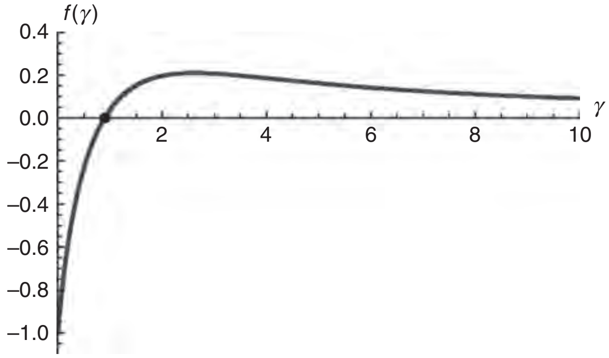

Fig. 2.2. A typical behavior of $f(\gamma)$, where X is equiprobable binary $\pm\sqrt{2}$.

2.2. Crossing Properties of the MMSE

An interesting property of the MMSE relation is the single-crossing property established in [51].

Let

$$f(\gamma) \triangleq (1+\gamma)^{-1} - \mathrm{mmse}(X:\gamma) \tag{2.9}$$

designate the difference in terms of (2.9) of MMSE between a standard Gaussian and any other input X. If X is not standard Gaussian the function $f(\gamma)$ has at most one zero. Namely, if $f(\mathrm{snr}_0)=0$, then (i) $f(0)\le 0$; (ii) $f(\gamma)$ is strictly increasing on $\gamma\in[0,\mathrm{snr}_0]$; (iii) $f(\gamma)>0$ for every $\gamma\in(\mathrm{snr}_0,\infty)$; and, (iv) $\lim_{\gamma\to\infty} f(\gamma)=0$.

A typical behavior of $f(\gamma)$ is depicted in in Fig. 2.2. The very same properties of $f(\gamma)$ persists if the estimation of X is based also on another variable U, [51] namely

$$f(\gamma) = (1+\gamma)^{-1} - \mathrm{mmse}(X:\gamma|U), \tag{2.10}$$

where

$$\mathrm{mmse}(X;\gamma|U) = E_U[\mathsf{E}(X-E(X|Y,U))^2|U] = E(X-E(X|Y,U))^2. \tag{2.11}$$

2.3. I-MMSE: The Vector Case

The I-MMSE relation holds similarly for the vector case. Let $\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{N}$ designate the input, output and standard Gaussian noise vectors respectively, where

$$\boldsymbol{Y} = \sqrt{\mathrm{snr}}\cdot \boldsymbol{HX}+\boldsymbol{N} \tag{2.12}$$

and where $\boldsymbol{H}$ stands for the channel matrix. For $\mathsf{E}\|\boldsymbol{X}\|^2<\infty$, we have [45]

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{dsnr}} I(\boldsymbol{X};\sqrt{\mathrm{snr}}\,\boldsymbol{HX}+\boldsymbol{N}) &= \frac{1}{2}\mathrm{mmse}\,(\boldsymbol{HX}|\sqrt{\mathrm{snr}}\,\boldsymbol{HX}+\boldsymbol{N})\\ &= \frac{1}{2}\mathrm{mmse}(\mathrm{snr}) = \frac{1}{2}E\|\boldsymbol{HX}-\boldsymbol{H}\mathsf{E}\{\boldsymbol{X}|\boldsymbol{Y}\}\|^2\\ &= \frac{1}{2}\mathrm{tr}[E\{(\boldsymbol{X}-E(\boldsymbol{X}|\boldsymbol{Y}))(\boldsymbol{X}-E(\boldsymbol{X}|\boldsymbol{Y}))^\top\}\boldsymbol{H}^\top\boldsymbol{H}].\end{aligned} \tag{2.13}$$

For the Gaussian input case, where $\boldsymbol{X}$ is Gaussian vector with standard iid components, relation (2.13) is verified by the standard estimation results,

$$\boldsymbol{E}\{(\boldsymbol{X}-\boldsymbol{E}(\boldsymbol{X}|\boldsymbol{Y}))(\boldsymbol{X}-\boldsymbol{E}(\boldsymbol{X}|\boldsymbol{Y}))^\top\} = (\boldsymbol{I}+\mathrm{snr}\,\boldsymbol{H}^\top\boldsymbol{H})^{-1} \tag{2.14}$$

and

$$I(\boldsymbol{X};\boldsymbol{Y}) = \frac{1}{2}\log\det(\boldsymbol{I}+\mathrm{snr}\,\boldsymbol{H}^\top\boldsymbol{H}). \tag{2.15}$$

Extensions and generalizations of the basic I-MMSE relations and properties in discrete time are by now well established. Naming a few as follows:

- Gradient of the mutual information in a vector Gaussian channel [97];
- Mutual information expressed for general channels, via input estimates [98];
- Mismatched estimation and relative-entropy expressions [145] to be further addressed in the following;
- I-MMSE properties, applications and implications [51], [100], [159];
- Relations to directed information (and hence, feedback channels) [61].
- Pointwise I-MMSE relations [139].

2.4. I-MMSE: The Continuous-Time Channel

The I-MMSE relations hold and are in particular interesting for continuous time Gaussian channels [45]. Here we have

$$Y_t = \sqrt{\mathrm{snr}}\,X_t + N_t, \qquad t\in[0,T], \tag{2.16}$$

where X_t designates a real valued input process that satisfies $\int_0^T \mathsf{E}X_t^2\,\mathrm{d}t<\infty$, and where N_t is the standard additive white Gaussian noise. The received signal is designated by Y_t and as before, snr stands for the signal-to-noise scaling ratio parameter.

The average mutual information is designated by

$$I(\mathrm{snr}) = \frac{1}{T}I(X_0^T;Y_0^T), \tag{2.17}$$

where Z_a^b denotes the process Z_t, $a\le t\le b$.

The causal (filtering) and non-causal (smoothing) optimal estimators are respectively $\mathsf{E}\{X_t|Y_0^t\}$ and $\mathsf{E}\{X_t|Y_0^T\}$ and the corresponding MMSE per unit time expressions are:

$$\mathrm{cmmse}(\mathrm{snr}) = \frac{1}{T}\int_0^T \mathsf{E}(X_t-\mathsf{E}\{X_t|Y_0^t\})^2\mathrm{d}t, \tag{2.18}$$

$$\mathrm{mmse}(\mathrm{snr}) = \frac{1}{T}\int_0^T \mathsf{E}(X_t-\mathsf{E}\{X_t|Y_0^T\})^2\mathrm{d}t. \tag{2.19}$$

The intimate I-MMSE relation in [45] reads here,

$$\frac{\mathrm{d}}{\mathrm{dsnr}}I(\mathrm{snr}) = \frac{1}{2}\mathrm{mmse}(\mathrm{snr}) \tag{2.20}$$

and it complements the classical relation [33]

$$I(\mathrm{snr}) = \frac{\mathrm{snr}}{2}\mathrm{cmmse}(\mathrm{snr}). \tag{2.21}$$

By comparing (2.20) and (2.21) we find

$$I(\text{snr}) = \frac{\text{snr}}{2}\text{cmmse}(\text{snr}) = \frac{1}{2}\int_0^{\text{snr}} \text{mmse}(\gamma)d\gamma. \tag{2.22}$$

Let X_t be a Gaussian zero mean stationary process with power spectral density $S_X(f)$. In this case we have [122]

$$I(\text{snr}) = \frac{1}{2}\int_{-\infty}^{\infty} \log[1 + \text{snr}\, S_X(f)]df. \tag{2.23}$$

The classical MMSE results due to [155] reads

$$\text{mmse}(\text{snr}) = \int_{-\infty}^{\infty} \frac{S_X(f)}{1+\text{snr}S_X(f)}df \tag{2.24}$$

and the filtering MMSE is due to [164]

$$\text{cmmse}(\text{snr}) = \frac{1}{\text{snr}}\int_{-\infty}^{\infty} \log(1+\text{snr}S_X(f))df \tag{2.25}$$

verifying thus the general relation (2.22) in the Gaussian case.

3. Reflections in Signal Processing

Rewriting (2.22) provides a general elegant relation between the filtering (causal) and smoothing (non-causal) MMSE expressions

$$\text{cmmse}(\text{snr}) = \frac{1}{\text{snr}}\int_0^{\text{snr}} \text{mmse}(\gamma)d\gamma. \tag{3.1}$$

Somewhat surprising is the fact that this relation has emerged via an information-theoretic mechanism, and not by methods of the well established and mature fields of filtering (linear or nonlinear) and estimation theory. In particular, the expressions are convenient and elegant for stationary processes, where we take $T \to \infty$ and have

$$\text{mmse}(\text{snr}) = \mathsf{E}\{(X_t - \mathsf{E}\{X_t|Y_{-\infty}^{\infty}\})^2\} \tag{3.2}$$

$$\text{cmmse}(\text{snr}) = \mathsf{E}\{(X_t - \mathsf{E}\{X_t|Y_{-\infty}^{t}\})^2\}. \tag{3.3}$$

For Gaussian stationary processes the expressions $\text{mmse}(\text{snr})$ and $\text{cmmse}(\text{snr})$ are given by (2.24) and (2.25) respectively. Another less obvious example is the random telegraph process, that is a stationary Markov, two state $X_t = \pm 1$ having iid, exponentially distributed, inter-transition durations, of transition rate ν. The filtering and smoothing errors are given by expressions (3.4) [165] and (3.5) [156] respectively, and have been derived separately with a 20 years gap:

$$\text{mmse}(\text{snr}) = \frac{\displaystyle\int_{-1}^{1}\int_{-1}^{1} \frac{(1+xy)\exp\left[-\frac{2\nu}{\text{snr}}\left(\frac{1}{1-x^2}+\frac{1}{1-y^2}\right)\right]}{-(1-x^2)^2(1-y^2)^3}dxdy}{\left[\displaystyle\int_1^{\infty} u^{\frac{1}{2}}(u-1)^{-\frac{1}{2}}\exp\left(\frac{-2\nu u}{\text{snr}}\right)du\right]^2} \tag{3.4}$$

$$\text{cmmse}(\text{snr}) = \frac{\displaystyle\int_1^{\infty} u^{-\frac{1}{2}}(u-1)^{-\frac{1}{2}}\exp\left(\frac{-2\nu u}{\text{snr}}\right)du}{\displaystyle\int_1^{\infty} u^{\frac{1}{2}}(u-1)^{-\frac{1}{2}}\exp\left(\frac{-2\nu u}{\text{snr}}\right)du}. \tag{3.5}$$

This indeed demonstrates the importance in filtering theory of such a classical relation (3.1) which has been noticed rather recently [45].

Generalizations of the I-MMSE relation as in (2.20) have been reported. In [168] such a relation is demonstrated via Malliavin calculus in abstract Wiener spaces. The notion of general causality is examined in [80], and information-estimation relations in a fractional Brownian motion have been discussed in [34]. An interesting observation, showing that the basic relation between causal/uncausal filtering (3.1) holds also in the realm of mismatched estimation (filtering/smoothing) is reported in [152]. Mismatch stands for the fact that though the input process $\{X_t\}$ is governed by the measure $\mathbb{P}$, the optimal conditional mean estimation is done assuming a mismatched measure $\mathbb{Q}$. The basic relation (3.1) holds with $\text{cmmse}(snr)$ and $\text{mmse}(\text{snr})$ are replaced respectively by their mismatched version:

$$\text{cmse}_{\mathbb{P},\mathbb{Q}}(\text{snr}) = \frac{1}{T}\int_0^T E_{\mathbb{P}}(X_t - E_{\mathbb{Q}}[X_t|Y_0^t])^2 dt, \tag{3.6}$$

$$\text{mse}_{\mathbb{P},\mathbb{Q}}(\text{snr}) = \frac{1}{T}\int_0^T E_{\mathbb{P}}(X_t - E_{\mathbb{Q}}[X_t|Y_0^T])^2 dt. \tag{3.7}$$

Related results and various applications in continuous time, such as in feedback channels [58], [59], asymptotics in optimal filtering and information rates [103], and divergence-mmse expressions [13], are reported in literature. Another interesting extension [139] addresses pointwide relations between the random quantities associated with information and estimation, the expected values of which provide the various I-MMSE type of relations. Namely, the basic I-MMSE relation is interpreted as the null expectation of the difference of two random variables, the information density and the square error of the optimal conditional mean estimator. This random variable is presented in terms of an Itō integral, and its properties (like the variance) are investigated.

A challenging question is whether one can find relations between the average mutual information and fixed lag smoothing. More specifically, consider the observed signal as in (2.16) and assume stationarity of X_t. Let $\mathsf{L\,mmse}(\text{snr}:\Delta)$ designate the MMSE of the Δ lag smoother, namely

$$\mathsf{L\,mmse}(\text{snr}:\Delta) = \mathsf{E}(X_t - \mathsf{E}\{X_t|Y_{-\infty}^{t+\Delta}\})^2. \tag{3.8}$$

A curious question is whether there exists a density function: $f_\Delta(\tau)$, $0 \le \tau \le \text{snr}$, $\int_0^{\text{snr}} f_\Delta(\tau)d\tau = 1$, which depends on Δ and on basic features of the input process X_t (including, but not solely, the power spectral density $S_x(f)$), such that:

$$\frac{2I(\text{snr})}{\text{snr}} = \int_0^{\text{snr}} f_\Delta(\tau)\,\mathsf{L\,mmse}(\tau:\Delta)d\tau. \tag{3.9}$$

Note that for the special cases $\Delta = 0$ (filtering) and $\Delta = \infty$ (smoothing) the answer is in the affirmative and the corresponding densities are $f_0(\tau) = \delta(\tau - \text{snr})$, $f_\infty(\tau) = (1/\text{snr})$, $0 \le \tau \le \text{snr}$ as can be concluded by (3.1). Recent indications show that unlike the cases of $\Delta = 0$ and $\Delta = \infty$, the mutual information does not characterize $\mathsf{L\,mmse}(\text{snr}:\Delta)$ as a function of SNR [138].

4. Constrained Signaling in Gaussian Channels

Since the advent of information theory, many studies were focused on constrained signaling on additive Gaussian channels, in an effort to capture the impact of practical constraints. While the classical results of Shannon [122] provide the capacity of the filtered Gaussian channels with an average power constraint, subsequent work focuses on a variety of other constraints of practical relevance, like peak power, time variation (slope), different spectral constraints and the like [8], [110], and references therein. In this short section, we demonstrate one of such results [111] taking a retrospective I-MMSE view.

Consider the communication system described in Fig. 4.1, where a peak-limited snr scaled signal, $\sqrt{\text{snr}}\,x(t)$ perturbs a linear channel input filter with impulse/frequency response, $h(t)$, $H(f)$ respectively. The output of this filter is designated by $\sqrt{\text{snr}}\,z(t)$ to which $n(t)$ – an AWGN normalized component is added to produce the received signal $y(t)$,

$$\begin{aligned} y(t) &= \sqrt{\text{snr}}\,z(t) + n(t) \\ z(t) &= \int_{-\infty}^{\infty} x(\tau)h(t-\tau)\,d\tau. \end{aligned} \tag{4.1}$$

Had the peak power constrained been removed and only an average power constraint is imposed on the input, the channel capacity is given by the water-pouring argument [122]. This for a flat bandlimited filter, $H(f) = 1, |f| \le B$, yields the classical [120] result $B\log(1+\text{snr})$. The basic question posed in [96] and appears also as an open problem in [28] is whether this additional constraint necessarily degrades performance. Note that the output $z(t)$ is not required to be peak-power limited and neither spectral or variational constraints are imposed on $x(t)$, making the problem not at all trivial. (See [110] where additional spectral constraints are imposed). An interesting observation made in [96] proves the equivalence in this setting of a peak $x(t) = \pm 1$ and peak limited $x(t) \le 1$ constrained signaling. An answer in the positive along with a quantitative bound was given in [111] summarized here, reinterpreting the result by the I-MMSE relation.

The mmse of $z(t)$ based on $y(t)$ is upper bounded by the Wiener-expression

$$\text{mmse}_z(\text{snr}) \le \int_{-\infty}^{\infty} \frac{S_x(f)\,|H(f)|^2}{1+\text{snr}\,S_x(f)\,|H(f)|^2}df \tag{4.2}$$

upon integration of which yields the expression for the average mutual information (2.22). This is to be optimized over the power spectral density $S_x(f)$ of a peak-limited process, called also a unit process, namely,

$$I(\text{snr}) \le \sup_{S_x(f)} \int_0^{\text{snr}} \text{mmse}_z(u)\,du, \tag{4.3}$$

where $S_x(f)$, satisfies [81], [125]

$$\begin{aligned} &S_x(f) = S_x(-f),\ f \ \ge\ 0,\ \int_{-\infty}^{\infty} S_x(f)df = 1 \\ &\int_{-\infty}^{\infty} S_x(f)K(f)df \ge 0, \\ &\forall\ K(f) = \sum_{n=1}^{N}\sum_{m=1}^{N} a_{nm}e^{2\pi i f(t_n - t_m)} \\ &\forall \text{ integer } N, \forall\ \{t_1, t_2, \ldots, t_N\} \text{ and } \forall\ \boldsymbol{A} = \{a_{nm}\} \end{aligned} \tag{4.4}$$

where A is a corner positive matrix.

A specific selection of A a 3×3 matrix in [109] yields.

$$K(f) = 4\cos(2\pi f\tau)(\cos(2\pi f\tau) - 1), \tag{4.5}$$

which upon optimization over $B\tau$, yields for high snr,

$$I(\text{snr}) \le B\log(0.9337\text{snr}),\ \ \text{snr} \gg 1 \tag{4.6}$$

This settles to the negative the possible achievability of the average power constrained capacity [28]. As for lower bounds on $I(\text{snr})$ for this setting [96] presents a result based on a unit pulse amplitude modulated signal, which reads: $I(\text{snr}) \ge B\log(1 + (2e/\pi^3)\text{snr})$.

Another simpler thought less tight bound can be devised based on recent results on pulse width modulation representation of band and peak limited signals [53], and this bound reads: $I(\text{snr}) \ge B\log(1 + (8/\pi^3 e)\text{snr})$.

An interesting challenge is to devise tighter lower bounds and one option is to use as an input $x(t)$ a random telegraph process with average rate λ. This corresponds to the Lorenzian power spectral density $S_{\text{RTW}}(f) = \lambda/(\pi^2 f^2 + \lambda^2)$. For $B \to \infty$, our former relations (3.4), (3.5), (2.22) yield $I(\text{snr}) \sim \lambda\log\text{snr}, \text{snr} \gg 1$, while the Wiener filter upper bound for finite B, gives $I_{\text{RTW}}(\text{snr}) \le B\log(0.63\,\text{snr}),\ \text{snr} \gg 1$. In [111] it is claimed that this upper bounding expression should be reasonably tight. Yet a rigorous analytical expression for a lower bound on $\text{mmse}(\text{snr})$ for the filtered random telegraph process will enable via the I-MMSE relation to estimate how good, if at all, is the upper bound (4.6).

5. Network Information Theory

In this section we address numerous multiterminal information theoretic models adhering to the I-MMSE perspective. Specifically, we study the scalar and parallel broadcast channels, scalar and vector wiretap channels and interference channels. The section is concluded by highlighting the timely topic of interference alignment.

5.1. The Gaussian Broadcast Channel—Converse via I-MMSE

Consider the classical scalar Gaussian broadcast channel described by

$$Y = \sqrt{\text{snr}_y}\,X + N_y,\quad Z = \sqrt{\text{snr}_z}\,X + N_z, \tag{5.1}$$

where Y, Z designate the outputs of the two receivers, and X is the input signal. It is assumed that $E(X^2) \le 1$ and N_y, N_z are standard Gaussian noises. The respective SNRs are designated by $\text{snr}_y \ge \text{snr}_z \ge 0$. The classical capacity region is given by

$$\begin{aligned} &R_y \le \frac{1}{2}\log(1 + \alpha\text{snr}_y) \\ &R_c + R_z \le \frac{1}{2}\log\left(1 + \frac{(1-\alpha)\text{snr}_z}{\alpha\text{snr}_z + 1}\right) \\ &0 \le \alpha \le 1. \end{aligned} \tag{5.2}$$

Here, R_y, R_z designate the private rates transmitted to users y and z respectively, while R_c stands for the common rate. The direct part is established by superposition coding [27] and the converse is proved via the EPI [12].

Here we outline the elegant converse proof via the I-MMSE relation [51]. The proof relies on the single crossing property of MMSE expression when compared to a Gaussian input X, with an arbitrary variance. In Fig. 5.1 we show the MMSE and the corresponding I (mutual information) for $y = \sqrt{\text{snr}}\,X + N$, where subscripts b,g are used to designate a symmetric ± 1 binary/Gaussian inputs (X_b), (X_g) and where ρ (0.8 in the figure) is the variance of the Gaussian input X_g. The basic idea of the I-MMSE proof [51] uses the conditioned single crossing property in the standard

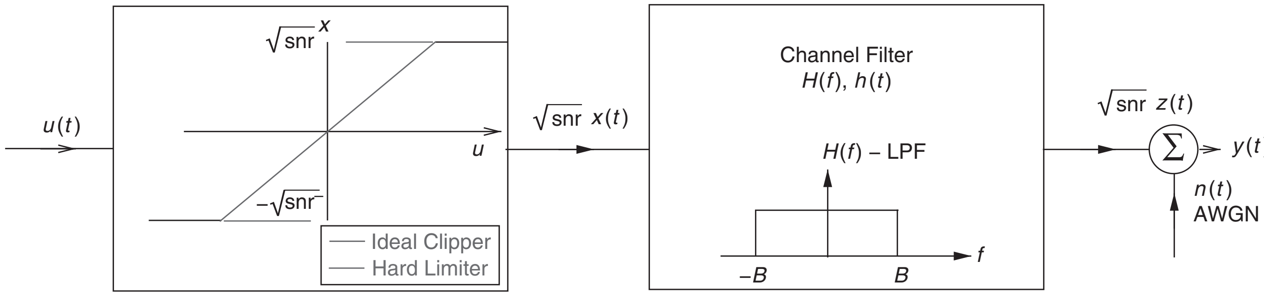

Fig. 4.1. Peak-Limited Constrained Filtered Gaussian Channel.

expressions for the capacity region of the degraded broadcast channel [39], [11], [2], where U is an auxiliary random variable.

$$\begin{aligned} R_c + R_z &\le I(U; Z) = I(X; Z) - I(X; Z|U) \\ R_y &\le I(X; Y|U),\ U - X - Y. \end{aligned} \tag{5.3}$$

It follows that once $0 \le \alpha \le 1$ is determined such that

$$I(X:Z|U) = \frac{1}{2}\log(1+\alpha \text{snr}_z) = \frac{1}{2}\int_0^{\text{snr}_z} \frac{\alpha}{1+\alpha\nu} d\nu \tag{5.4}$$

and thus since snr_0 the crossing point satisfies $\text{snr}_0 < \text{snr}_z < \text{snr}_y$, we find

$$I(X:Y|U) \le \frac{1}{2}\log(1+\alpha \text{snr}_y) \tag{5.5}$$

Since Gaussian inputs are optimal for a Gaussian channel:

$$I(X\,;Z) \le \frac{1}{2}\log(1+\text{snr}_z), \tag{5.6}$$

and therefore

$$\begin{aligned} I(U:Z) &\le \frac{1}{2}\log(1+\text{snr}_z) - \frac{1}{2}\log(1+\alpha\text{snr}_z) \\ &= \frac{1}{2}\log\left(1+\frac{(1-\alpha)\text{snr}_z}{\alpha\text{snr}_z+1}\right). \end{aligned} \tag{5.7}$$

Equations (5.5) and (5.7) yield the capacity region in (5.2). In [20] the technique has been extended to address parallel degraded MIMO Gaussian broadcast channels, under an input covariance constraint.

The single crossing point property proved in [20] which is central to this extension refers to the individual eigenvalues of $\mathbb{E}_G(\text{snr}) - \mathbb{E}(\text{snr})$, where $\mathbb{E}, \mathbb{E}_G$ designate the MMSE matrix of the actual input process and the reference Gaussian process. As demonstrated for the scalar case $\mathbb{E}(\text{snr})$ may account for conditioning on some auxiliary variable.

Challenges: The central challenge of the I-MMSE approach in this context, is first to reconstruct the converse proof of the MIMO Gaussian broadcast channel, without relying on the enhancement principle [149] or extremal inequalities [77]. The solution of the parallel broadcast channels [20] is a step towards this yet unresolved challenge.

Another challenge is to see whether the I-MMSE relation is capable of reproducing the capacity region of the MIMO broadcast channel with a common rate, which is intended for both users, solved recently in [41]. It has been shown that the natural (Marton) region suggested in [56] is indeed optimal. A partial answer was given in [148], where the optimality of the region has been established for a common rate that exceeds some critical value ($R_c \ge R_c^{\text{th}}$). Further insight into this challenging problem was reported in [73] where the derivation relies on the enhancement principle [149] combined with extremal inequality version [151]. The complete capacity region of a 2 user MIMO broadcast channel with common rate has been established in [41] based on an elegant method to show the optimality of Gaussian distributions, in Gaussian channels.

5.2. The Gaussian Wiretap Channel

The classical wiretap channel has been introduced by Wyner [162] and the special Gaussian version has been treated in [66]. The model is described as in (5.1) where Y designates the received signal at the desired user, while Z is the signal available to the eavesdropper. This is a degraded setting for which the secrecy capacity C_s is given by [162]

$$C_s = \max_{\mathbb{P}(X)}\{I(X;Y) - I(X;Z)\} \tag{5.8}$$

where the max is taken over all unit power input measures. Using the I-MMSE relation (2.3), we find

$$\begin{aligned} C_s &= \max_{\mathbb{P}(X)} \int_{\text{snr}_z}^{\text{snr}_y} \text{mmse}(X:\gamma)\,d\gamma \\ &\le \frac{1}{2}\int_{\text{snr}_z}^{\text{snr}_y} \frac{1}{1+\gamma}d\gamma = \frac{1}{2}\log\left(\frac{1+\text{snr}_y}{1+\text{snr}_z}\right). \end{aligned} \tag{5.9}$$

The inequality in (5.9) results due to the Gaussian (linear estimation) upper bound on $\text{mmse}(X:\gamma)$, and is satisfied with equality for Gaussian inputs. This single line proof appearing in [51] is the alternative to the original proof in [66], which relies on the EPI.

The MIMO Gaussian wiretap model is a non-trivial extension of the scalar Gaussian wiretap channel discussed here. This is since

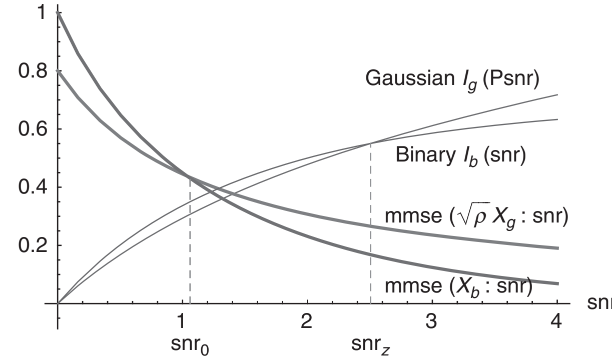

Fig. 5.1. *I* and MMSE for Gaussian X_g (variance ρ = 0.8) and symmetric binary X_b (variance 1) inputs.

in the MIMO setting the classical degradation relation is in general lost. We consider the aligned model where

$$Y_x = X + N_x, \quad Y_e = X + N_e. \tag{5.10}$$

The observed component vectors at the legitimate user and the eavesdropper are denoted by (Y_x, Y_e) respectively. The n-length input vector X is assumed to be subjected to a covariance constraint $(1/n)E(X^T X) \preceq S$ and the respective Gaussian noise vectors (N_x, N_e) covariances are designated by K_x, K_e. The general secrecy capacity formula should be used, namely: the Csiszar-Kröner [29] expression

$$C_s = \sup_{\mathbb{P}(U,X): U-X-(Y_x,Y_e)} \{I(U:Y_x) - I(U:Y_e)\}. \tag{5.11}$$

Yet by different approaches [60], [95] (using Sato-like arguments) and [75] (applying the enhancement approach [149]) it is shown that under various constraints, such as the total power or covariance $0 \preceq E(X^* X^T) \preceq S$, the optimal choice is still $U = X$ as in the degraded case [162]. This results in the nonconvex optimization problem for the secrecy capacity with a covariance constraint:

$$C_s = \max_{0 \preceq K_x \preceq S} \left\{\frac{1}{2}\log\det(I + K_x K_r^{-1}) - \frac{1}{2}\log\det(I + K_x K_e^{-1})\right\}. \tag{5.12}$$

In [15] the extension of the I-MMSE relation by [97] is applied. The result in [97] reads:

$$\nabla_K I(X; X + N) = -K^{-1}\mathbb{E}K^{-1}, \tag{5.13}$$

where, $\mathbb{E} = \mathsf{E}\{(X - \mathsf{E}\{X|Y\})(X - \mathsf{E}\{X|Y\})^T\}$ and K is the covariance matrix the additive Gaussian noise N. An enhancement-degradation principle for the MIMO Secrecy Channel and an extension of the I-MMSE methodology, as used for the scalar Gaussian wiretap problem [51] and discussed above yields [15] a closed form solution of (5.1). Further, a closed form result for the covariance of the noise prefix is provided also for the equivalent MIMO secrecy expression [74]. There, the input employs the full allowed 'potential' that is covariance S, but an additional independent ('prefix') noise is first added as to create a prefix channel, yielding the same optimal secrecy capacity. Other secrecy problems such as conveying separate secret messages over the broadcast channel can also benefit from this approach [74].

It should be noted that the closed form results are given for the matrix covariance constraints, while for an average power constraint another optimization is yet required over all covariances S'satisfying that power constraint. In [60] a closed form expression for high SNR is provided, in the case of an average input power constraint.

5.3 Interference Channels

Consider first the Gaussian Z interference channel

$$\begin{aligned} Y_1 &= \sqrt{\mathrm{snr}_1}\ X_1 + \sqrt{a}\ \sqrt{\mathrm{snr}_2}\, X_2 + N_1 \\ Y_2 &= \sqrt{\mathrm{snr}_2}\ X_2 + N_2, \end{aligned} \tag{5.14}$$

where X_1, X_2 designate the respectively unit power constrained inputs and snr_1 snr_2 the corresponding normalized powers of the two users. Here, N_1, N_2 stand for the unit variance Gaussian noises, and $0 \le a \le 1$ specifies the 'weak-interference' regime.

In [20], the vector extension of the single-crossing property is developed, stating that:

$$q(\gamma) = \mathrm{mmse}(X_G | \sqrt{\gamma}X_G + N) - \mathrm{mmse}(X | \sqrt{\gamma}X + N) \tag{5.15}$$

has at most a single zero crossing $\gamma \in [0, \infty)$, for any random vector X. Here, X_G stands for a Gaussian iid vector and mmse expressions in (5.15) designates the trace of the associated error covariance matrix.

The recent work [16] combines this crossing feature into the non single letter characterization of the interference channel capacity region [1]

$$\lim_{n\to\infty}\left(\bigcup_{\mathbb{P}_{X_1^n X_2^n}}\left\{(R_1, R_2): \begin{array}{l} R_1 \le \frac{1}{n}I(X_1^n; Y_1^n) \\ R_2 \le \frac{1}{n}I(X_2^n; Y_2^n) \end{array}\right\}\right) \tag{5.16}$$

to rederive via the I-MMSE principle the classical Sato bound on the Z interference channel. The Sato bound reads:

$$\begin{aligned} R_1 &\le \frac{1}{2}\log(1 + \mathrm{snr}_1 + a\mathrm{snr}_2) - \frac{1}{2}\log(1 + \alpha a\mathrm{snr}_2) \\ R_2 &\le \frac{1}{2}\log(1 + \alpha\mathrm{snr}_2) \end{aligned} \tag{5.17}$$

and it is sum-rate tight [109]. The Sato bound has also been rederived in another way from the multiletter expression (5.16) in [89].

The central challenge in this domain is to invoke I-MMSE properties into the non-single letter characterization of the capacity region of the interference and other multiterminal channels, giving rise to interesting optimization problems. The challenge is to use such an approach in an effort to derive novel outer bounds in different settings of the interference, broadcast and X channels.

It seems that the I-MMSE procedure may be useful in case additional constraints are imposed. For example, consider a legacy cognitive setting where the primary terminal uses standard Gaussian codes at a given rate. An interesting question relates to the optimum strategy of a secondary user, even in the simple case where interference is inflicted only on the primary receiving terminal (Z-interference channel).

In [17] it has been established via the I-MMSE methodology, that rate splitting of the secondary user (Han-Kobayashi approach) is in fact optimum when interference is measured by MMSE. The challenging question (as stated above) is whether this observation implies the following rate-splitting based strategy to yield the capacity region for this cognitive Gaussian interference channel.

$$\begin{aligned} R_1 &\le \frac{1}{2}\log(1 + \mathrm{snr}_1/(1 + \alpha\mathrm{snr}_2)) \\ R_2 &\le \frac{1}{2}\log\left(1 + \frac{(1-\alpha)a\mathrm{snr}_2}{1 + \mathrm{snr}_1 + \alpha a\mathrm{snr}_2}\right) + \frac{1}{2}\log(1 + \alpha\mathrm{snr}_2) \end{aligned} \tag{5.18}$$

for $0 \le \alpha \le 1$. Here $\alpha = 0$ corresponds to the Costa conjectured capacity point, see [109] for comments.

5.4. Interference Alignment

Interference alignment plays a central role in identifying the potential and limitation of multiterminal channels. It reflects the performance expected for high rate communication systems, operating evidently in the high SNR regime. See [55] for a recent tutorial on the subject. Our goal here is to highlight some novel views, using MMSE related measures [160]. To that end, we shall shortly introduce some known and relatively novel concepts.

Information dimension, [105]: Let X be a real valued random variable. For $m \in \mathcal{N}$ let $\langle X \rangle_m \triangleq \lfloor mX \rfloor / m$, where $\lfloor X \rfloor$ designates the lower bounding highest integer for X. The information dimension of X is defined as

$$d(X) = \lim_{m \to \infty} \frac{H(\langle X \rangle_m)}{\log m}.$$

where $H(\cdot)$ designates the entropy function. If the limit does not exist, $\liminf$ and $\limsup$ are used and designated by $\underline{d}(X), \bar{d}(X)$ respectively. The definition can be readily extended to random vectors and has been recently used in various information theoretic settings [157]. The MMSE dimension $\mathcal{D}(X)$[158] yields the asymtotic $\mathrm{mmse}(X : \mathrm{snr}) = \mathrm{mmse}(X|\sqrt{\mathrm{snr}}\, X + N)$ in snr behavior, that is

$$\mathcal{D}(X) = \lim_{\mathrm{snr} \to \infty} \mathrm{snr}\ \mathrm{mmse}(X|\sqrt{\mathrm{snr}}\, X + N). \tag{5.19}$$

It is shown [158] that

$$\underline{D}(X) \le \underline{d}(x) \le \bar{d}(x) \le \bar{D}(X), \tag{5.20}$$

with equality for discrete, continuous and mixture random variables. Here $\underline{D}(X), \bar{D}(X)$ designate the liminf, limsup expressions, if different of $D(X)$. Further, it is known, that for $H(\lfloor X \rceil) < \infty$,

$$\lim_{\mathrm{snr} \to \infty} \frac{I(X; \sqrt{\mathrm{snr}}\, X + N)}{\frac{1}{2} \log \mathrm{snr}} = d(X), \tag{5.21}$$

Consider the K-user real valued interference channel, with channel inputs and outputs $\{X_i\}, \{Y_i\}$ respectively

$$Y_i = \sum_{j=1}^{K} \sqrt{\mathrm{snr}}\, h_{ij} X_j + N_i, \tag{5.22}$$

where $\{X_i, N_i\}_{i=1}^{K}$ are independent $N_i \in \mathcal{N}(0,1)$, $E(X_i^2) \le 1$, and $\{h_{ij}\} = H$, are the corresponding channel coefficients. Let $\mathbb{C}(H, \mathrm{snr})$ designate the capacity region and $C(H, \mathrm{snr})$ the sum-rate capacity. The degrees of freedom DoF, sumrate prelog or sumrate multiplexing gain is defined by

$$\mathsf{DoF}(H) = \lim_{\mathrm{snr} \to \infty} \frac{C(H, \mathrm{snr})}{\frac{1}{2} \log \mathrm{snr}}. \tag{5.23}$$

Central results for $\mathsf{DoF}(H)$ can be found in [55], [52], [21], [22], [90], [37] and references therein. Unlike previously believed the $\mathsf{DoF}(H)$, almost surely for all real H, is $K/2$, where the central tool establishing this is the number-theoretic Diophantine Approximation, [55, and references therein].

In a recent contribution [160], the information/MMSE-dimension is used to gain further insight into the DoF problem. First, the non single letter K-users interference channel capacity region [1]

$$\mathbb{C}(\mathbf{H}, \mathrm{snr}) = \lim_{n \to \infty} \sup_{\mathbb{P}(X_1^n)\mathbb{P}(X_2^n), \cdots \mathbb{P}(X_K^n)} \{R_i \le I(X_i^n; Y_i^n), \quad i = 1, 2 \cdots K\} \tag{5.24}$$

is exploited, along with the standard chain-rule decomposition:

$$I(X_i^n; Y_i^n) = I(X_1^n, X_2^n \cdots X_K^n; Y_i^n) - I(X_1^n, \cdots, X_K^n; Y_i^n | X_i^n) \tag{5.25}$$

to find the single letter expression

$$\mathsf{dof}(X^{(K)} : \mathbf{H}) \triangleq \sum_{i=1}^{K} \left\{ d\left(\sum_{j=1}^{K} h_{ij} X_j \right) - d\left(\sum_{j \ne 1}^{K} h_{ij} X_j \right) \right\}. \tag{5.26}$$

Then,

$$\mathsf{DoF}(\mathbf{H}) = \sup_{\mathbb{P}(X_1)\mathbb{P}(X_2) \cdots \mathbb{P}(X_k)} \mathsf{dof}(X^{(K)} : \mathbf{H}). \tag{5.27}$$

The Information/MMSE Dimension Approach yields the following conclusions:

- To achieve $\mathsf{DoF}(\mathbf{H}) > 1$, it is necessary to employ **singular** components, meaning that the MMSE dimension oscillates in SNR(dB) around the information dimension.
- $\mathsf{DoF}(\mathbf{H})$ is invariant under raw or column scaling.
- Removal of cross-links does not decrease $\mathsf{DoF}(\mathbf{H})$.
- If off-diagonal entries of $\mathbf{H}$ are rational and diagonal entries irrational, then $\mathsf{DoF}(\mathbf{H}) = K/2$. There is no need for irrational algebraic numbers [37].
- Some improvement is observed with this novel approach.

  For $K = 3$ with $\mathbf{H} = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 2 & 0 \\ 1 & 1 & 1 \end{pmatrix}$,

  $\mathsf{DoF}(\mathbf{H}) \ge 1 + \log_6((1 + \sqrt{5})/2) > ((2 + \log_6 3)/6))$, where the RHS is the [37] result and the improved result is shown in [160].

Challenges: While shown useful for the interference alignment of the interference channel, it is yet only plausible whether the Information/MMSE dimension approach is useful for general multiterminal interference-alignment problems. For example, the MIMO broadcast channel with imperfect CSI [65], and the compound MIMO broadcast channel introduced in [150] and studied in full in [43], [79]. A clue to a positive answer is provided in [X1], extending the analysis of [160] to vector interference channels.

While Degrees-of-Freedom characterize the infinite $\mathrm{snr} \to \infty$, prelog behavior, it is of great theoretical and practical importance to assess the impact of finite large SNR behavior as well as the impact of imperfect CSI expressed in terms of capacity gaps. Recent efforts along these lines appear in [94] and relevant references therein. A central challenge is to see whether the approach discussed here [160] based on information dimension can be extended to deal with second order approximation. Specifically, the generalized d-dimension [105] seems to offer a promising direction. Different conclusions are expected for different channel models, for example X-channels versus interference channels [55]. Further, as indicated in [X1], the required singularity needed to achieve the optimal DoF, could be realized in different vector settings via signaling in lower dimensional spaces. This observation supports the application of information/MMSE dimension based approaches to study DoF issues in non infinite SNR regimes.

6. Good/Bad Codes and Impact of Interference

In this section, we adopt the I-MMSE viewpoint as to examine desirable features of efficient coded communication over Gaussian single and multiple-terminal channels.

6.1. 'Good' Codes on Gaussian Channels

Consider first the standard AWGN channel as in (2.12) with $H = I$, where now X stands for the length m codeword. It is evident that

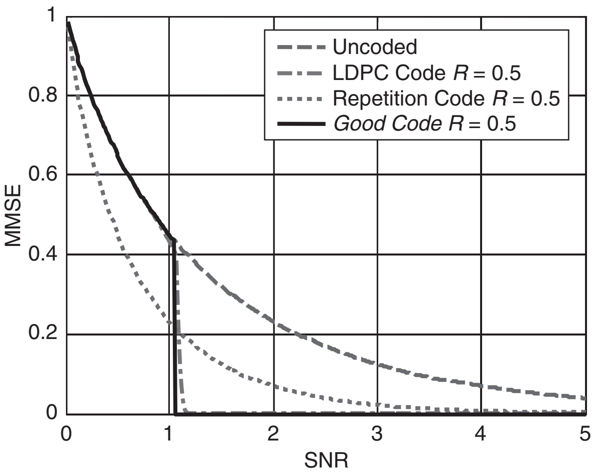

Fig. 6.1. MMSE behavior of a binary input AWGN channel as a function of snr, for uncoded and repetition, LDPC and good codes of rate = 0.5.

if the code is good that is operates at rate $R = (1/2)\ \log(1+\mathrm{snr}_0)$ and achieves capacity (for $m \to \infty$) at $\mathrm{snr} = \mathrm{snr}_0$, then the mutual information $1/m(X:Y) = (1/2)\log(1+\mathrm{snr})$, $\mathrm{snr} \le \mathrm{snr}_0$ and $(1/m)(X:Y) = R = (1/2)\log(1+\mathrm{snr}_0)$, for $\mathrm{snr} \ge \mathrm{snr}_0$. The MMSE behaves correspondingly, exhibiting a threshold (for $m \to \infty$) at $\mathrm{snr} = \mathrm{snr}_0$, where the MMSE falls to zero. This is demonstrated for binary (± 1) channel inputs in Fig. 6.1, where performance of good codes is rather closely mimicked by a rate $1/2$ LDPC code [101]. Note that the area under the MMSE curve, which undergoes a phase transition (to be further addressed), equals exactly to R the code rate. The study [101] examines also extrinsic-information (EXIT) chart behavior of good codes. This gives insight why component codes, say at a classical turbo-encoder, should not be selected as 'good' codes, as their operation via the iterative message passing procedure starts at SNR which corresponds to rates above the Shannon capacity. Relevant observations are reported in [3], [82].

6.2. 'Bad' Codes on Interference/Relay Channels

An extension of this view, addressing multiterminal channels is discussed in [10]. The basic idea addressing the classical Gaussian interference channel, is to use a non optimal ('bad') code for each user, where this degradation on one hand is compensated by the lower interference induced by that code on the other receiver. As we have noticed, 'good' codes imply 'full' interference (where their structure is of no use to alleviate the interference effect for lower snr values which do not permit reliable decoding of such a code). In the Gaussian relay channel the focus in [10] is directed to the cases where no decoding is possible at the relay. As opposed to procedures of quantize and forward where no use of the coding structure is made, here a soft decode and forward procedure, reducing the associated noise is advocated.

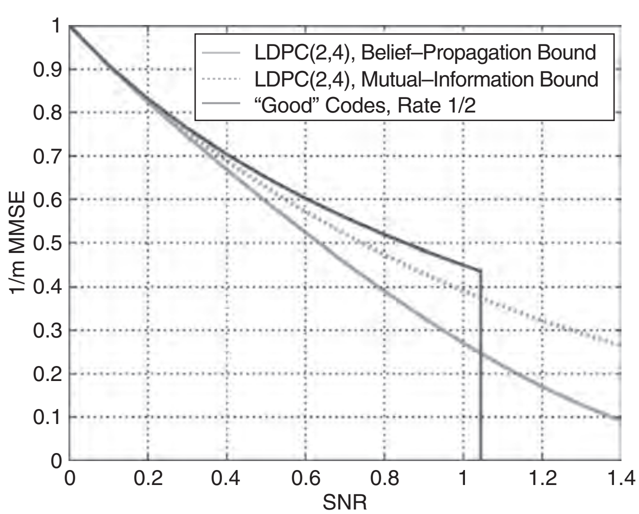

Fig. 6.2. The MMSE behavior for binary optimal codes and the LDPC (2,4) code.

In Fig. 6.2 the MMSE of a simple LDPC (2,4) code is contrasted with the corresponding behavior of a good code, all of rate 1/2. The MMSE bounds are evaluated either based on the information bounds developed in [154] or on belief-propagation analysis reported in [106].

It is to be emphasized that for the sake of reduced decoding complexity, we impose in this discussion [10] a single coding system, ignoring appealing operation modes (to be addressed in the following) based on superposition coding (rate-splitting), where either at the interfered receiver or at the relay reliable decoding of some rate is attempted eliminating that part of the interference channel and decoding-forwarding this in the relay setting. Indeed, such an approach using 'bad' point-to-point codes demonstrates advantages over the case where 'good' codes are employed [6].

6.3. A Rate-MMSE Optimization Problem

Related to our discussion in section 6.2. about the interference inflicted by codes, we examine here the following optimization problem.

Consider a standard vector Gaussian channel $Y = \sqrt{\mathrm{snr}}\,X + N$, with m component vectors, where $(1/m)E\|X\|^2 \le 1$ and $N \sim \mathcal{N}(0, I)$. As usual,

$$\mathrm{mmse}(\mathrm{snr}) = \frac{1}{m} E\|X - E(X|Y)\|^2$$

and

$$I(\mathrm{snr}) = \frac{1}{m} I(X;Y) = \frac{1}{2}\int_0^{\mathrm{snr}} \mathrm{mmse}(\delta)d\delta.$$

Let $\mathrm{snr}_1 \ge \mathrm{snr}_0 \ge 0$. The optimization problem over the measure $\mathbb{P}(X)$ reads

$$\inf_{\mathbb{P}(X):\frac{1}{m}E\|X\|^2 \le 1} \mathrm{mmse}(\mathrm{snr}_0) \tag{6.1}$$

under the constraint $(1/m)\ E\|X\|^2 \le 1$, and subject to:

$$I(\mathrm{snr}_1) \ge \frac{1}{2}\log(1+\alpha\mathrm{snr}_1) \tag{6.2}$$

with $0 \le \alpha \le 1$ designating a fixed constant. This optimization can also be interpreted in a dual way. Namely, for a given interference constraint at snr_0, where interference is gauged by MMSE, we seek rate maximization at $\mathrm{snr}_1 > \mathrm{snr}_0$, where the rate is measured by the corresponding mutual information.

For $m \to \infty$, the solution is given in [17] and in fact the minimal mmse for a prescribed mutual information at snr_1 is achieved for all $\mathrm{snr} \le \mathrm{snr}_1$ values under the optimization conditions, by the rate splitting (superposition coding, Han-Kobayashi approach) technique. The result then reads

$$\min \operatorname{mmse}(\mathrm{snr}_0) = \frac{b}{1+\mathrm{snr}_0}, \tag{6.3}$$

where $0 \le b \le \alpha$ is the minimum value satisfying

$$\frac{1+\mathrm{snr}_0}{1+b\,\mathrm{snr}_0} \ge \frac{1+\alpha\,\mathrm{snr}_1}{1+b\,\mathrm{snr}_1}. \tag{6.4}$$

It is obvious that for $\alpha\mathrm{snr}_1 \le \mathrm{snr}_0 \Rightarrow b = 0$. This result motivates the application of Han-Kobayashi rate splitting to the interference and relay channels considered in 6.2 and indeed the single code based schemes in [10] are in this sense, suboptimal.

The results in Eqs. (6.2)–(6.4) are demonstrated in Fig. 6.3, where $\mathrm{snr}_0 = 2$ and $\mathrm{snr}_1 = 2.5$. The reference curve is $\max I(\mathrm{snr}_1)$, $\alpha = 1$, which inflicts maximum MMSE interference at snr_0. The second curve allows for some information degradation at snr_1, and that gives rise to reduced MMSE interference at snr_0, which is minimized by rate splitting as evident in the figure.

Challenges: A related challenge is to consider the optimization problem in section 6.3., Eqs. (6.1) and (6.2) in the other extreme, that is the scalar case of $m = 1$. It is conjectured here that for $\alpha < 1$ and $0 < \mathrm{snr}_0 < \mathrm{snr}_1$, the optimizing distribution $\mathbb{P}(x)$ is associated with a discrete random variable. A more demanding challenge considers this optimization for a finite m, addressing thus non-asymptotic coding problems.

Here and in section 6.3. the minimized factor $\operatorname{mmse}(\mathrm{snr}_0)$ can be viewed as a measure of disturbance (interference). If instead we use mutual information as a disturbance measure, as advocated in [7], that is

$$I(\mathrm{snr}_0) = \frac{1}{2}\int_0^{\mathrm{snr}_0} \operatorname{mmse}(\delta)\, d\delta$$

replaces $\operatorname{mmse}(\mathrm{snr}_0)$, then the optimization problem is solved easily for all $m \ge 1$. The I-MMSE solution is insightful and requires a single line. As $I(\mathrm{snr}_0) \le (1/2)\log(1+\alpha\mathrm{snr}_0)$, we can choose $\alpha \le 1$ such that $I(\mathrm{snr}_0) = (1/2)\log(1+\alpha\mathrm{snr}_0)$. Now the crossing point discussed in section 2 occurs at $\mathrm{snr} \le \mathrm{snr}_0$ and hence

$$I(\mathrm{snr}_1) \le \frac{1}{2}\log(1+\alpha\mathrm{snr}_0) + \frac{1}{2}\int_{\mathrm{snr}_0}^{\mathrm{snr}_1} \frac{\alpha}{1+\alpha\gamma}\, d\gamma = \frac{1}{2}\log(1+\alpha\mathrm{snr}_1). \tag{6.5}$$

Equality results by selecting the input $X \sim \mathcal{N}(0, \alpha I)$ for all m.

In [7] the EPI was originally used to solve this problem.

An extension of the problem in its dual formulation, that is maximization of $I(\mathrm{snr}_k)$ under given K constraints of MMSE (snr_k), $k = 0,1,\ldots K-1$, with $\mathrm{snr}_{k-1} \le \mathrm{snr}_k \le \mathrm{snr}_K$, is addressed in [17], [18], [19]. It is shown that a K level superposition coding is optimal. The K constrained problem with disturbance measured by mutual information is also discussed in [17], [18], [19]. The results here enhance the engineering insight into the relative efficiency of the Han-Kobayashi technique. An interesting challenge is to study the implications of structured codes as means of controling interference [92] based on an information-estimation inspired view. I-MMSE insights could be used also to address alternative approaches coping with interference, as those discussed in [X2].

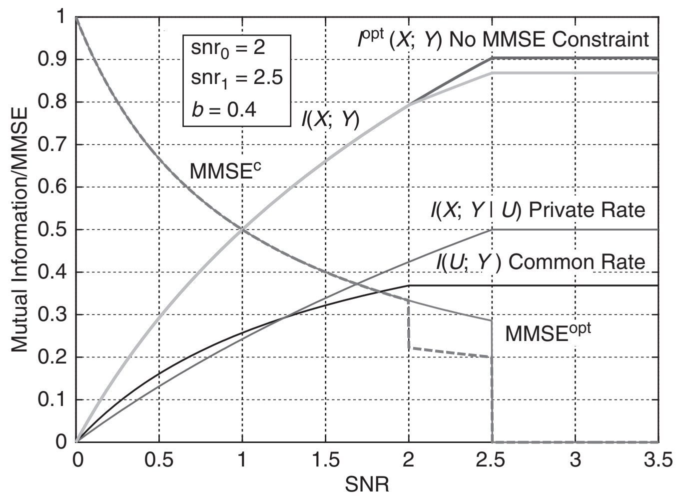

Fig. 6.3. Information $I(\mathrm{snr}_1)$ and interference $\operatorname{mmse}(\mathrm{snr}_0)$.

7. Applications, Implications, Connections and Generalizations

7.1. The Incremental Channel and Its Dual

The central proof of the I-MMSE relation in [45] is based on the incremental channel approach. This is depicted in Fig. 7.1, where the incremental channel outputs are designated by $Y_{j+1} = Y_j + \Delta N_j$, $j = 1, 2 \ldots n$, with $Y_1 = X + N$. Here X is the input, N is the additive Gaussian noise and $\{\Delta N_j\}$ $j = 1, 2\ldots$ are incremental independent Gaussian noises. The chain rule and Markov relation yield

$$I(X;Y_1) = I(X;Y_1,Y_2\cdots Y_n) = \sum_{i=n}^{1} I(X;Y_i|Y_{i+1}) \tag{7.1}$$

The proof in [45], of the basic I-MMSE relation (2.3) follows the observation that for incremental $\mathrm{snr}(n\to\infty)$ (as is the case of y_i conditioned on y_{i+1}) the mutual information is proportional to the conditioned input covariance [142], [64].

The natural dual expression, considers an incremental input rather than output namely, $Y = \sqrt{\mathrm{snr}}\,\sum_{i=1}^{K} U_i + N$, where the cumulative input is given by $X_j = \sum_{\ell=K}^{j} U_\ell$ and where $\{U_i\}$ take the interpretation of independent information layers. The chain rule and Markov relation yield here

$$I(U_1,U_2,\ldots,U_K;Y) = I(X_1;Y) = \sum_{j=K}^{1} I(Y;X_j|X_{j+1}) \tag{7.2}$$

This 'dual' approach constitutes basically the central ingredient in the MAC interpretation of the I-MMSE (2.3) relation [45]. Again, by letting $K \to \infty$ and $E(U_i^2) \to 0$ such that the total power $E(X_1^2)$ is fixed, yields the standard setting of incremental multilayer communications with successive interference cancellation.

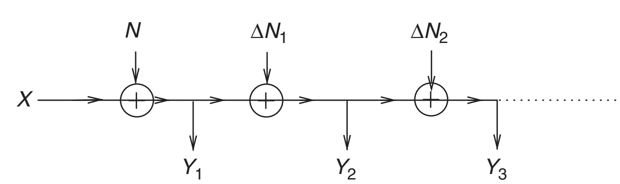

Fig. 7.1. The incremental Gaussian channel.

7.2. Applications and Implications

This setting is adapted to address the broadcast approach in scalar [115] and vector (MIMO) [118] fading Gaussian channels. In fact, multilayering over fixed Gaussian channels [161], [146] can be considered as a special case.

Challenges: While simple settings of the Broadcast approach are easily treated as described here, other problems pose challenges, some of which are detailed in the following:

- Parallel fading channels, which are motivated by delay constrained problems where the delay allows for several blocks. Some preliminary results appear in [153]. See also [25] for additional results mixing delay constrained and ergodic approaches.

- MIMO block fading channels: While the scalar fading case exhibits a clear degradation order, with respect to the fading power realization. This is not the case in the MIMO setting, leaving the full characterization of the broadcast approach open. Partial results appear in [118], where sub-optimal ordering by imposing majorization is studied. The MISO/SIMO cases assume closed form solutions [130].

- Multiple access fading channels. While the problem and preliminary results have been addressed in the past [116], the full solution has not yet been presented. Additional results appear in [87], [88].

- Source-channel coding in network separated approaches in fading channels has been addressed in [131], [93]. An interesting question is when such a separation is optimal. Partial answers [131] account for common knowledge principles [129].

- The whole setting of the broadcast approach has been conceptually generalized in terms of variable-to-fixed channel coding [144]. An interesting question is to see whether the information-estimation framework can be naturally adopted in such a setting.

The dual concept applies immediately to the Gaussian vector channel where $Y = (y_1, y_2 \cdots y_N)$, $X = (x_1, x_2 \cdots x_K)$, $N = (n_1, n_2 \cdots n_N)$ stand respectively for the output, input and noise vectors, and where H is the $N \times K$ channel matrix. This interpretation gives rise to many models and results which are connected to the I-MMSE relations. Sometimes such interpretations follow by a retrospective view, and in other cases the I-MMSE paradigm was employed to derive different results for the associated models. We mainly mention and reference such cases which address large systems, and relate directly to the I-MMSE paradigm, without any detailing. Specifically:

- Code division multiple access (CDMA) with random spreading codes [132], [140]. Closed form results for Gaussian iid inputs are given in [141]. With fading and Gaussian inputs the relevant results are found in [119], for binary iid inputs in [91] and for arbitrary iid inputs in [46].

- The classical relation for CDMA systems [132], [140], [46] $C_{\text{joint}}(\beta) = \int_0^\beta C_{\text{sep}}(\beta')\, d\beta'$, directly related to the dual decomposition discussed before. Here, $C_{\text{joint}}(\beta) = (1/N)\, I(X;Y)$ stands for the sumrate (per channel use) of the joint multiuser detector and $C_{\text{sep}}(\beta) = \beta I(x;Y)$ for the sumrate (per channel use) of the separate single-user detector, where $\beta = K/N$ is the system load assuming the limit of large systems $K, N \to \infty$.

- Frequency-Time selective fading models are examined in [136] for Gaussian inputs. For general iid inputs X not necessarily Gaussian, and a Haar channel response matrix F, the replica method used in [137].

- Compressive sensing models are studied in [50] and [137] and related results appear in [104], [X3] and references therein. A recent study [X4] reports some applications to compressive sensing models, and partial extensions of I-MMSE gradient relations as in [97], to the Renyi entropy.

- A classical problem is the intersymbol interference (ISI) channel which is characterized by a Topelitz H matrix. The standard dual I-MMSE decomposition gives rise to the minimum-mean-square-error decision feedback equalizer (MMSE-DFE) [24], [38], which leads to the classical mutual information results of time invariant frequency dependent channels [122]. Such relations also motivate the study of practically appealing MMSE based receivers and coding strategies in vector channels, see [X5] and references therein.

- A lower bound on the capacity (mutual information) based on the sampled whitened matched filter for general inputs was reported in [112] while estimates based on the MMSE-DFE interpretation appears in [114]. The challenge is to provide tight rigorous bounds on the ISI channel via the I-MMSE paradigm. Another challenge refers to frequency selective, ISI channels with erased measurements. Here, the challenge is to find results which resemble the analytic result proved for the frequency-time selective model studied in [136].

- Cellular models: The intersymbol interference channel is at the center of cellular models of the Wyner type [163] with central uplink processing. Here, the intersymbol interferences takes effect in the spatial rather than the time domain.

This Wyner type cellular model has been extensively studied. In [128] the uplink-downlink duality [166] is used to characterize the downlink Wyner model performance. The involved impact of fading has been addressed in [127], [69], [70], [71]. The impact of mobile user activity and cell connectivity are studied in [68], [108]. Planar Wyner-like cellular models introduced already in [163], are also examined in [124], [67].

Challenges: Also here we detail some challenges, on which the I-MMSE relation may shed light.

- Non Gaussian symbols $\{x_i\}$. Exact solutions will probably require new tools on top of the standard replica procedure as the matrix H is finite diagonal Toeplitz. Bounds however could be useful and relate directly to bounds on achievable rates in ISI channels.

- An appealing model to consider which is motivated by practical arguments is random span spatial ISI channel, that is the span of the interfering signals (mobiles) at each cell is itself an independent random variable.

- The impact of user and cell activity in general Wyner type models connects to the filtered Gaussian channel problem in the presence of erasures as discussed above.

We close this paragraph by mentioning recent wide scope tutorials [42], [126].

Communications through fading channels [36]: The non-coherent regime is addressed where no channel state information is available at either receiver or transmitter. The I-MMSE relation is a key ingredient in the derivation of several bounds on the corresponding mutual-information expressions. These bounds being tight in the infinite bandwidth limit, provide quantitative insight into the efficiency of peak limited (in the time domain) communications through this practically appealing channel model.

Distributed processing in cellular systems: In [108] the Wyner-type cellular model, uplink communications is considered. However, unlike previous work shortly mention before, [163], [128], [42] and relevant references therein, here the cell sites can cooperate in decoding the mobiles only via finite capacity backhaul links connecting them to a central processing unit. Achievable symmetric communication rates are developed by combining compress-and-forward processing with local decoding. The I-MMSE relation is fundamental in identifying the minimizing rate equation, within a set of log det expressions, specifying thus the most restrictive equation within the set and also providing insight to such a selection. This facilitates expressing in closed form the achievable rates in both the standard and soft-handoff Wyner cellular models [126].

Entropy power inequalities: Entropy power inequalities (EPI) are central in information theory since its very advent by Shannon. An elegant proof of the classical EPI via the I-MMSE principle is reported in [143]. In [47] the I-MMSE relation was used to provide a simple proof to the Zamir-Feder [169] entropy inequality. Further, also the classical Costa EPI [26] was proved [47] via the I-MMSE relation. In [73] an extended Costa EPI has been established via the I-MMSE principles [45], [97]. This extension is used as a tool in [73] to characterize the rates over different setting of the broadcast vector channels with eavesdropping receivers. A special case of the scalar EPI where one of the variables is Gaussian is shown in [51] via the single-crossing property of the I-MMSE. Further observations and relations can be found in [99], [107].

Many other relevant applications which are not mentioned exist, for example mercury/water filling in parallel [78] and MIMO [102] channels, fading broadcast channels [134] and relative entropy-score function [49]. Another important usage of the I-MMSE relation provides an elegant perspective on monotonicity results in non-Gaussianness in central limit theorems [135].

7.3. Connections: Statistical-Physics of the I-MMSE

Here we summarize some results and observations made in [84]. The standard I-MMSE relation is expressed by

$$\mathrm{mmse}(\boldsymbol{X}|\boldsymbol{Y}) = 2\cdot\frac{\mathrm{d}I(\boldsymbol{X};\boldsymbol{Y})}{\mathrm{d}\beta} = -2\frac{\partial}{\partial\beta}\boldsymbol{E}_\beta\{\log Z(\beta|\boldsymbol{Y})\}. \qquad (7.3)$$

Here $\beta=(1/kT)$, k – Boltzmann's constant, T – temperature, $Z(\beta)=\sum_x e^{-\beta\mathcal{E}(x)}$ designates the classical partition function which is the normalization factor of the Boltzmann-Gibbs distribution

$$\mathbb{P}(x)=\exp(-\beta\mathcal{E}(x))/Z(\beta) \qquad (7.4)$$

of the n component vector. The 'micro state' at thermal equilibrium are designated by x and the energy $\mathcal{E}(x)$ is the associated Hamiltonian. The mutual information

$$I(\boldsymbol{X};\boldsymbol{Y})=\boldsymbol{E}_\beta\left\{\log\frac{P(\boldsymbol{X}|\boldsymbol{Y})}{P(\boldsymbol{X})}\right\}=-\frac{n}{2}-\boldsymbol{E}_\beta\{\log Z(\beta|\boldsymbol{Y})\} \qquad (7.5)$$

can also be expressed as an operation over a partition function given here by

$$Z(\beta\,|\,\boldsymbol{Y})=\sum_x P(x)\exp\{-\beta\|\boldsymbol{Y}-x\|^2/2\}. \qquad (7.6)$$

Here, $\boldsymbol{Y}$ designates the output vector of the AWGN channel $Y=X+N$.

Interesting examples that are worked out in [84] include a random codebook of length n and rate R lying on a sphere surface (independent and uniformly distributed codewords). It is shown that the mutual information averaged over random codebooks drawn independently and uniform over the surface of radius $\sqrt{m\sigma^2}$ satisfy

$$\lim_{n\to\infty}\frac{\boldsymbol{E}\{I(\boldsymbol{X};\boldsymbol{Y})\}}{n}=\begin{cases}\frac{1}{2}\log(1+\beta\sigma^2), & \beta<\beta_R\\ R & \beta\ge\beta_R\end{cases} \qquad (7.7)$$

where β_R is the solution of:

$$R=\frac{1}{2}\log(1+\beta_R\sigma^2). \qquad (7.8)$$

The corresponding MMSE is given then by

$$\lim_{n\to\infty}\frac{\mathrm{mmse}(\boldsymbol{X}\,|\,\boldsymbol{Y})}{n}=\begin{cases}\dfrac{\sigma^2}{1+\beta\sigma^2}, & \beta<\beta_R\\ 0 & \beta\ge\beta_R.\end{cases} \qquad (7.9)$$

This exhibits a first order phase transition in MMSE. In high temperatures it behaves as if $\boldsymbol{X}$ was Gaussian and at $\beta=\beta_R$ it jumps to zero. Also, the superposition optimal codes for the scalar Gaussian broadcast channel are looked at in [84], where two phase transitions are demonstrated. These coding strategies reflect the I-MMSE behavior of good codes [101] as well as superposition coding shown optimal in [17], [18], [19] in terms of achieving the best rate/MMSE interference tradeoff (see section 6.3. for details). For further results, generalization connections and observations, the reader is directed to the tutorial [85] and references [123], [86].

7.4. Generalization—The Poisson Law

The Poisson channel model serves as a standard model for optical photon based communications and it received considerable information theoretic attention, see [72], [32], [57], [113], [62] (and references therein).

In [48] a Poisson process Y_t is considered with a rate function specified by $\alpha X_t+\lambda$, where α is a scaling factor, λ- the dark current, and X_t the input process. Thus, $\mathbb{P}\{Y_s-Y_t=k\,|\,\{\alpha X_t+\lambda\}\}$

$= \Lambda^k e^{-\Lambda}/k!$, where $\Lambda = \int_t^s (\alpha X_\xi + \lambda) d\xi$. This Poisson law is denoted by $\mathcal{P}_t(\alpha X_t + \lambda)$ and $\langle X \rangle = \mathsf{E}(X|\mathcal{P}_t(\alpha X_t + \lambda))$ designates the conditional mean operation. For processes the filtering (causal) and smoothing (non-causal) estimators are designated by $\langle\,\rangle_t$ and $\langle\,\rangle_T$ respectively.

The following results are derived via the incremental channel mechanism in [48] similar to the classical Gaussian setting [45], discussed before.

$$I(X_0^T; \mathcal{P}_0^T(X_t)) = \int_0^T \mathsf{E}\{X_t \log X_t - \langle X_t \rangle_t \log \langle X_t \rangle_t\} \mathrm{d}t. \quad (7.10)$$

recovering the classical result by Liptser-Shiryaev [72]. The information-estimation results based on non-causal estimation read [48]

$$\frac{\partial}{\partial\lambda} I(X_0^T; \mathcal{P}_0^T(X_t + \lambda)) = \int_0^T \mathsf{E}\{\log(X_t + \lambda) - \log\langle X_t + \lambda \rangle_T\} dt. \quad (7.11)$$

$$\frac{\partial}{\partial\alpha} I(X_0^T; \mathcal{P}_0^T(\alpha X_t)) = \int_0^T \mathsf{E}\left\{X_t \log(\alpha X_t) - \frac{1}{\alpha}\langle \alpha X_t \rangle_T \log\langle \alpha X \rangle_T\right\} dt, \quad (7.12)$$

where in (7.11), (7.12) the derivative are taken respectively with respect to the 'dark current' λ and scaling parameter α. The results for the scalar Poisson channel follow by taking $X_t = X$.

An elegant view was recently given in [4] where a loss function has been derived such that

$$\mathcal{D}(\mathbb{P}(\lambda_1) \,\|\, \mathbb{P}(\lambda_2)) = \ell(\lambda_1 \lambda_2), \quad (7.13)$$

where in the Gaussian domain we have

$$\mathcal{D}(\mathcal{N}(\mu_1, 1) \,\|\, \mathcal{N}(\mu_2, 1)) = \frac{1}{2}(\mu_1 - \mu_2)^2. \quad (7.14)$$

Thus the identified loss function

$$\ell(x, \hat{x}) = x \log(x/\hat{x}) - x + \hat{x} \quad (7.15)$$

serves under the Poisson law the role of the mean square error in the Gaussian regime. Indeed, then all relations between filtering-smoothing as well as matched and mismatched estimators extend to the Poisson regime verbatim [4].

There is an intimate connection between the formulation of the loss function and the usage of the incremental channel technique. Both require infinite divisibility and independent increments and hence can be extended to Lévy processes, conditioned on the input. See [34], [35] and as mentioned other extensions to abstract Wiener spaces [168], [80].

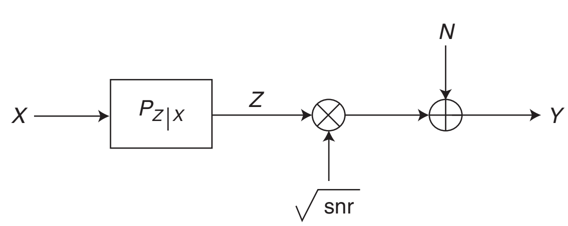

Fig. 8.1. The general additive Gaussian channel.

8. Concluding Outlook

So far, we have focused on the Gaussian and Poisson channels, whether scalar vector, discrete or continuous in time. I-MMSE relations have been generalized to other channel models, for example recent work addresses binomial type channels [X6], [X7]. In [45] a more general setting is also discussed as depicted in Fig. 8.1 Here X is a random object jointly distributed with say a real valued random variable Z. The channel output is $Y = \sqrt{\text{snr}}\, Z + N$, where $N \sim \mathcal{N}(0,1)$ is a Gaussian noise variable independent of X and Z. Due to the Markov relation $X - Z - Y$ we have

$$\begin{aligned} I(X;Y) &= I(Z;Y) - I(Z;Y|X) \\ &= \frac{1}{2}\int_0^\infty \{\mathrm{mmse}(Z|\sqrt{\text{snr}}\,Z + N\,) \\ &\quad - \mathrm{mmse}(Z\,|\sqrt{\text{snr}}\,Z + N, X)\} d\text{snr} \end{aligned} \quad (8.1)$$

Note that this follows also similarly from the relation in (5.3) by properly choosing the auxiliary variable U.

In [145] a general expression for the divergence (relative-entropy) is given in terms of estimation-theoretic representation. Namely

$$\begin{aligned} \mathbf{D}(\mathbb{P}\,\|\,\mathbb{Q}) &\triangleq \int d\mathbb{P} \log\frac{d\mathbb{P}}{d\mathbb{Q}} \\ &= \frac{1}{2}\int_0^\infty \{\mathsf{E}_{\mathbb{P}}\|U - \mathsf{E}_{\mathbb{Q}}(U|\sqrt{\text{snr}}\,U + N)\|^2 \\ &\quad - \mathsf{E}_{\mathbb{P}}\|U - \mathsf{E}_{\mathbb{P}}(U|\sqrt{\text{snr}}\,U + N)\|^2\} d\text{snr}. \end{aligned} \quad (8.2)$$

We assume that the random variable $U \sim \mathbb{P}$, $\mathsf{E}_\mu(U|\sqrt{\text{snr}}\,U + N)$ designates the conditional mean of U based on the measurement $\sqrt{\text{snr}}\,U + N$, assuming that $U \sim \mu$. If $\mu \neq \mathbb{P}$ it is referred to as mismatched estimation. The mutual information of a general channel can be expressed in terms of a divergence

$$I(X;Z) = \mathsf{E}_X \mathbf{D}(\mathbb{P}_{Y|X} \,\|\, \mathbb{P}_Y |\, X) = \mathbf{D}(\mathbb{P}_{X,Y} | \mathbb{P}_X \mathbb{P}_Y)$$

Looking at $\mathsf{E}_X \mathbf{D}(\mathbb{P}_{Y|X} \,\|\, \mathbb{P}_Y | X)$ and comparing that to (8.1) with the interpretation that $\mathbb{P}_{Y|X}$ is the matched metric while $\mathbb{P}_Y$ is the mismatched one, it is seen that the average of a mismatched MMSE equals the matched MMSE of a degraded channel.

As has been discussed in section 3, the mismatched causal filtering and smoothing exhibit the very same connections as the matched case (3.1). Also, statistical physics techniques are capable of handling a mismatch between the actual prior $\mathbb{P}$ and an assumed prior $\mathbb{Q}$ of an input signal [84]. A natural question emerges here, seeking for an operational meaning of the mismatch operation in terms of reliable communications associated with actual codes.

Mismatch-decoding based on a mismatched metrics is no new face in information theory and is associated with classical problems of compound/arbitrary varying channels as well as robust approaches [63]. A timely problem which receives massive attention due to its practical relevance is the impact of inaccuracies in channel state information at the receiver on performance, in an information theoretic sense and the associated impact of robust decoding metrics, see for example [14], [64], [147].

Mismatched decoding, that is decoding with a prescribed not-necessarily channel adapted metric has been widely studied [30], [54], [83], [31], [5], [40], [117] but the mismatched capacity still forms a difficult open problem in general. The best general lower bound (achievable rate) on the mismatched capacity, with the mismatch metric $d(x,y)$ known as the Csiszár-Körner-Hui achievable rate. This rate [30], [54], [40] $I_{\mathrm{CKH}}(\mathbb{P}_X)$ for a given input distribution $\mathbb{P}_X$, reads:

$$I_{\mathrm{CKH}}(\mathbb{P}_X) = \min_{\nu_{X,Y}} \mathbf{D}(\nu_{X,Y} \| \mathbb{P}_X\mathbb{P}_Y) \tag{8.3}$$

such that:

$$\sum_X \nu_{X,Y} = \mathbb{P}_Y, \quad \sum_Y \nu_{X,Y} = \mathbb{P}_X \tag{8.4}$$

$$\sum_{X,Y} \nu_{X,Y} d(x,y) \le \sum_{X,Y} \mathbb{P}_{X,Y} d(x,y). \tag{8.5}$$

This rate takes on the interpretation of the matched capacity of a degraded channel $\nu^*_{Y|X}$ the minimizing conditional measure solving the min operation in (8.3) and possessing the same input/output $\mathbb{P}_X$, $\mathbb{P}_Y$ distributions (8.4).

In [5] it is shown that I_{CKH} is tight for binary input alphabets. In general I_{CKH} is not tight [31]. In [83] it is observed via the Lagrangian dual, which leads to a parametric solution to $\nu^*_{x,y}$(8.3), that for general DMCs the constraint (8.5) is satisfied with equality. Further, using the mismatched metric $\log \nu^*_{X,Y}$ for $d(x,y)$ yields the same expression for $I_{\mathrm{CKH}}(\mathbb{P}_X)$. This dictates:

$$\sum_{x,y} \nu^*_{X,Y} \log \nu^*_{X,Y} = \sum_{x,y} \mathbb{P}_{X,Y} \log \nu^*_{X,Y} \tag{8.6}$$

and therefore using (8.3) yields,

$$\mathbf{D}(\nu^*_{X,Y} \| \mathbb{P}_X\mathbb{P}_Y) = \mathbf{D}(\mathbb{P}_{X,Y} | \mathbb{P}_X\mathbb{P}_Y) - \mathbf{D}(\mathbb{P}_{X,Y} \| \nu^*_{X,Y}). \tag{8.7}$$

Thus, $\mathbf{D}(\mathbb{P}_{X,Y} \| \nu^*_{X,Y})$ takes on the natural interpretation of a mismatched decoding penalty and assumes the I-MMSE form of (8.2) [145].

The challenge here is to understand whether such and, hopefully other, connections and interpretations shed further insight on the fundamental and hard problem of mis-matched decoding? Could this direction lead to the identification of other settings, in addition to the one of binary inputs [5] where I_{CKH} or its evident multiletter extensions [31] are indeed tight? May such expressions shed further light on the ultimate performance of coded communications operating with a prescribed mismatched decoding metric?

So far in the previous sections we have highlighted the I-MMSE perspective in different network and multiterminal settings. We have addressed in short, broadcast channels; interference and cognitive interference channels, interference alignment; wire tap vector channels, relay channels, distributed network processing; and spatial networks, such as Wyner cellular models.

Yet it is of primary interest to realize whether more can be said on the power of the information-estimation perspective. Issues like source-channel joint and separated coding as well as general channels and networks still demand some fundamental understanding. Insights and new concepts and relations are sought for, beyond those already given by current results, such as [98], where general mutual information expressions are represented by input estimates and [145], discussed before, which applies to general divergence expressions. One of the possible challenges could address cardinality bounds as those recently reported for the broadcast channel [44].

One of the recent promising direction, which led to new results, insights, and understandings of the behavior of multiterminal and network information theoretical problems is the "Approximation Approach". See the recent overview [133]. This approach takes advantage of the fact that many multiterminal information theoretic problems can be fully solved when a deterministic approximation is used. Can an Information-Estimation perspective be beneficial for such an approach? Evidently, the interplay between detection and estimation is classical and very useful bounds on the MMSE are devised in a Gaussian channel via detection principles [170], [9]. More general information theoretic paradigms relying on generalized data-processing arguments that connect information and estimation aspects, appear in [159], [167]. Another simple example refers to binary input-output symmetric channels with input $X = \pm 1$ and output Y. It is shown in [23] that $2P_e(X|Y) \le \mathrm{mmse}(X|Y) \le 4P_e(X|Y)$. Here, $P_e(X|Y)$ designates respectively the optimal error probability and $\mathrm{mmse}(X|Y)$ the optimal MMSE of the binary input X based on a general measurement Y.

A better clue to the potential value of an information-estimation role in "approximation" approaches can be deduced by going back to the classical scalar Gaussian channel. $Y = \sqrt{\mathrm{snr}}\, X + N$, $\mathsf{E}(X^2) = \mathsf{E}(N^2) = 1$. This classical model has been considered by Shannon in the monumental work published on July/October 1948 that laid the foundations to Information Theory [120] and the famous Gaussian channel capacity expression $C_G(\mathrm{snr}) = (1/2)\log_2(1+\mathrm{snr})$ is stated therein. On March 29, 1948!, Shannon, in an unpublished note [121] used an "approximate" good signaling to approach the Gaussian capacity, in a high snr ($\mathrm{snr} \to \infty$) regime. The idea is just to use symbols that are standard K level Gray coded (Stibitz codes in Shannon's terminology of the time), pulse amplitude modulated signals following a normalized Gaussian $(1/\sqrt{2\pi})e^{(-x^2/2)}$ level distribution. Shannon has demonstrated that the average bit error probability can be made as small as desired (by increasing K), as long as the information rate $\log_2 K$ per channel use does not exceed $C_G(\mathrm{snr})$, but can approach the capacity as $K \to \infty$.

The arguments Shannon used can be repeated for an MMSE approximate detector $E(X|Y) \sim (\sqrt{\mathrm{snr}}\, Y)/(1+\mathrm{snr})$, with the corresponding $\mathrm{mmse}(\mathrm{snr}) = 1/(1+\mathrm{snr})$. An approximate bit-error rate calculation, following Shannon's methodology, yields,

$$P_e \tilde{\le} \frac{K}{\log_2 K} \int_0^\infty \frac{|z|}{\sqrt{2\pi \mathrm{mmse}(\mathrm{snr})}} e^{\frac{-z^2}{2\mathrm{mmse}(\mathrm{snr})}} dz \tag{8.8}$$

It follows that $P_e \to 0$ for $K \to \infty (\mathrm{snr} \to \infty)$ as long as the rate $R = \log_2 K < C_G(\mathrm{snr})$. This unmatched insight by Shannon, gives hope that an information-estimation perspective, might be useful also in modern "approximation" approaches along with many other frameworks and settings as has been shortly and only partly overviewed here.

In closing the interested reader is referred to an overview publication on I-MMSE relations and their applications, implications and impacts [X8].

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GOLOMB'S PUZZLE COLUMN™

Some Infinite Sequences

Solomon W. Golomb

An infinite increasing sequence of positive integers, $S = \{s_n\} = \{s_1, s_2, s_3, \ldots\}$ with $0 < s_1 < s_2 < \ldots$ is called an *infinite spanning ruler* if all differences $\{s_j - s_i\}$ with $0 < i < j$ of $\triangle S$ are distinct. Here we consider *pairs* of such sequences, $A = \{a_n\}$ and $B = \{b_n\}$, where A and B individually are infinite spanning rulers, and where moreover $\triangle A \cap \triangle B = \emptyset$, i.e. there are no overlaps between $\triangle A$ and $\triangle B$. We will call such a pair A and B of infinite increasing sequences of positive integers an *infinite spanning biruler*.

1) Show that the sequences $A = \{3^{n-1}\} = \{1,3,9,27,\ldots\}$ and $B = \{2 \cdot 3^{n-1}\} = \{2,6,18,54,\ldots\}$ form an infinite spanning biruler.

2) Define the sequence $F = \{f_n\}$ by $f_1 = 1$, $f_2 = 2$, $f_{n+1} = f_n + f_{n-1}$ for all $n > 1$ Let $A = \{f_{2n-1}\} = \{1, 3, 8, 21, \ldots\}$ and $B = \{f_{2n}\} = \{2, 5, 13, 34, \ldots\}$. Show that this pair of sequences A, B forms an infinite spanning biruler.

3) As a lemma for the foregoing, prove that every positive integer has at most one representation as a sum of terms of $F = \{f_n\}$ no two of which are consecutive. (More is true: every positive integer has *exactly* one such representation.)

4) Suppose $A = \{a_n\}$ and $B = \{b_n\}$ form an infinite spanning biruler, where a_n and b_n have the same asymptotic rate of growth. Show that this rate of growth must be at least $0(n^2)$.

5) Can you show that an infinite spanning biruler can be found where the two sequences A and B have "only" polynomial growth?

6) Returning to the Fibonacci Sequence $F = \{f_n\}$ of problem 2, can you find a non-zero polynomial $p(x, y)$ in two variables x and y, such that $p(x, y) = 0$ whenever $x = f_n$ and $y = f_{n+1}$ for all $n \geq 1$? If so, how low a degree polynomial $p(x, y)$ can you find?

GOLOMB'S PUZZLE COLUMN™

Knight's Tours Solutions

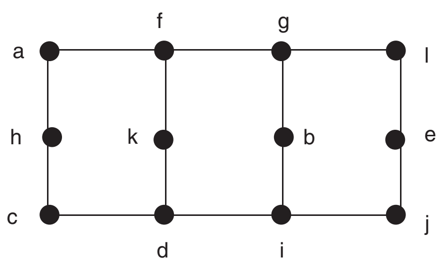
Solomon W. Golomb

1) On the board

a	b	c
d	e	f
g	h	i
j	k	l

, one "open" knight's tour is the sequence *ahcdkfgbijel*.

2) The connectivity of the twelve squares shown above, where two squares are "adjacent" if and only if they are connected by a knight's move, has the following surprisingly simple graph.



A knight's tour on the 3 × 4 board is the same as a "Hamiltonian path" on the corresponding graph, i.e. a sequence of edges that visits each node exactly once. There are eight Hamiltonian paths, each of which can be traversed in either of two directions: *ahcdkfgbijel* (from *a* to *l*, or from *l* to *a*), and *chafkdibglej* (from *c* to *j*, or from *j* to *c*), as well as *kdchafglejib* and *kfahcdijelgb* (each from *k* to *b* or from *b* to *k*). The other four are *kfahcdibglej* (from *k* to *j* or from *j* to *k*), *kdchafgbijel* (from *k* to *l* or from *l* to *k*), *bglejidkfahc* (from *b* to *c* or from *c* to *b*), and *bijelgfkdcha* (from *b* to *a* or from *a* to *b*). This corrects the problem statement that the only knight's tours on the 3 × 4 board go between opposite corners.

3) Here are four different knight's tours on a 4 × 5 board. (The end-points of each tour are circled.)

9	4	19	14
20	15	10	5
3	8	13	18
16	11	6	1
7	2	17	12

A

1	6	19	14
20	15	10	5
7	2	13	18
16	11	4	9
3	8	17	12

B

5	10	17	12
18	13	4	9
1	6	11	16
14	19	8	3
7	2	15	20

C

1	6	17	12
16	11	2	7
5	8	13	18
20	15	10	3
9	4	19	14

D

In example A, diametrically opposite squares have numbers that sum to 21. In all four cases, it would take *three* knight's moves to go from square 1 to square 20.

4) To show that a closed knight's tour on *any* 4 × *n* board is not possible, letter the squares of such a board as follows:

A	A	A	A	A	A	•	•	•
B	C	B	C	B	C	•	•	•
C	B	C	B	C	B	•	•	•
A	A	A	A	A	A	•	•	•

A knight on an A square must move to a B or a C square; and the number of A squares equals the combined numbers of B and C squares. If a closed knight's tour exists, A squares must *always* follow B *and* C squares. But one such sequence is … ABABABAB … and the other such sequence is … ACACACAC …, and these won't connect to each other.

5) Here is an open knight's tour on a 6 × 6 board:

3	20	11	36	9	26
12	29	2	27	18	35
21	4	19	10	25	8
30	13	28	1	34	17
5	22	15	32	7	24
14	31	6	23	16	33

Did you find a *closed* tour? (They exist.)

Here is a remarkable closed knight's tour on the 8 × 8 board.

46	55	44	19	58	9	22	7
43	18	47	56	21	6	59	10
54	45	20	41	12	57	8	23
17	42	53	48	5	24	11	60
52	3	32	13	40	61	34	25
31	16	49	4	33	28	37	62
2	51	14	29	64	39	26	35
15	30	1	50	27	36	63	38

It has the "magical" property that all rows and all columns have the same sum: 260. This example was found by C.F. Jaenisch in 1862, long after Euler. Modern computers have been used to show that it is not possible to improve this example to one in which the two long diagonals also have the same common sum.

IEEE Information Theory Society Board of Governors Meeting Minutes

Catamaran Resort, San Diego, 02.05.2012,
1–6 pm Natasha Devroye

Present: Giuseppe Caire, Muriel Medard, Bruce Hajek, Gerhard Kramer, Natasha Devroye, Frank Kschischang, Abbas El Gamal, Alex Vardy, Emanuele Viterbo, Prakash Narayan, Aylin Yener, Hans-Andrea Loeliger, Paul Siegel, Michelle Effros, Rolf Johannesson, Li Ping, Max Costa, Salman Avestimehr, Tara Javidi, Elza Erkip, Urbashi Mitra, Martin Bossert, Alon Orlitsky, David Tse

The meeting was called to order at 1:09 pm by the Information Theory Society (ITsoc) President, Muriel Medard, who welcomed the Board of Governors (BoG). Everyone introduced themselves.

1) The minutes of the BoG Meeting on 10/17/2011 at ITW Paraty, Brazil were approved.

2) The agenda was approved.

3) Muriel presented the President's report: the main topic was the IEEE society review process. New BoG members were mentioned: Abbas El Gamal, Elza Erkip, Ubli Mitra, Alon Orlitsky, Paul Siegel and Sergio Verdu. Outgoing members are Alex Grant and Emina Soljanin.

   Ad-hoc committees were mentioned: Ad-hoc committee on the future of the IT Transactions with members Helmut Bolcskei, Emmanuel Candes, Abbas El Gamal (chair), Bruce Hajek, David Forney, Frank Kschischang, Madhu Sudan and Alex Vardy. A full report will be given in fall 2012, the committee has been working very hard. Partial recommendations are expected at the ISIT 2012 BoG in Boston. Michelle Effros is leading another Ad-hoc committee to consider potential opportunities for our Society to advocate activities; she will report on this later.

   Finances are stable but less strong than in the past, the quality of the Transactions is still outstanding, conferences have strong participation, membership has a slight, slow but steady erosion which we need to think about. Interms of# of downloads our ranking (compared to other IEEE periodicals on Xplore) we are still quite strong (around 11) but there is a slight but steady erosion.

   Society review: Muriel Medard will be going to the TAB meeting for the IT Transactions review in February 2012 in Arizona. A review of the society (other than the Transactions) will take place in November. She attended the past IEEE review meeting in November and saw the review as quite useful, thorough and thoughtful. She believes it is an opportunity for us to consider what our vision is for the Society and to reflect on what our contribution is to our members. At the Officer's retreat on 02/24/12 this was discussed.

   Some interesting issues are coming up in the IEEE: 1) bundled membership: a committee is considering to offer free choice of membership to societies as part of the standard IEEE membership package; an informal poll showed very high interest in joining ITSOC if it were free. 2) issues in publications: there is a proliferation of new publications coming up. Helmut does not feel these will affect the Transactions. There is a proposal for a Rapid Process service for IEEE journals. There is a proposal for an IEEE Open Forum (an Open Access journal), but Muriel stated that it is still not very clear which type of online open access model will be considered.

4) ITSOC treasurer Aylin Yener reported on the ITSOC's financial health in 2011.

   The forecast for 2011 is a net operating loss of −15.4 K, in line with earlier projections; this loss is due to a significantly increased page budget in 2011 to clear our IT Transactions publication queue (approx. 2000 pages). The investment return for 2011 is still unknown; the final numbers are due in spring 2012. Quite a bit of our income comes from the downloads on IEEE Xplore (regular IT Transactions paper, ISIT and ITW papers. **TO DO**: Aylin Yener check if Conference Explore includes any technically co-sponsored conferences. Goal is to end up at $+\epsilon$ in the future.

   Society membership is fairly flat, so member due income is fairly stable. Print subscriptions number have been going down (this was the hope when prices were increased). Non-member subscriptions are not subsidized and provide significant revenue.

   In terms of 2012 outlook, Aylin highlighted that the IEEE per page charge is $63, and its value is not clear (versions often return with more mistakes than the originally submitted papers), something Helmut the EIC is looking at. IEEE sends the papers to multiple vendors to translate the papers handed in in latex to the final product. There is a general sense of dissatisfaction about the editing process and costs. Alex Vardy wants to get a feeling from the BoG as to whether this is an urgent issue. Muriel highlighted that hundreds of thousands of dollars are paid each year (half a million USD last year), and that this is one of our largest ticket items. Andreas believes there must be translators from latex to XML (format IEEE uses). Alex Vardy asks whether XML is necessary or not. Alex Vardy suggests forming a small committee to look at this. **TO DO:** Muriel Medard will query other society presidents to see what type of editing they are using. Frank Kschischang suggests Stefan Moser who is a latex expert and has written papers on how to best write papers so that IEEE would least distort them. **TO DO**: Muriel Medard contact Stefan Moser.

   Possible avenues to reduce cost is looking at the page editing costs, redirect to initiatives that benefit members (esp.

students, perhaps junior faculty?) IT Society Student Membership is $15, but there do not appear to be any benefits beyond what they obtain by becoming an IEEE Student member; should we re-visit (no charge, or give them something for it?)?

5) Membership and Chapters committee report was given by Abbas El Gamal and Gerhard Kramer.

   Job of this committee is: follow up on the IT summer schools, approve the Padovani lecturer (2012 will be Tom Richardsom), select the Distinguished Lecturers and encourage them to convert the title into action (only about 25% actually lecture). TO DO: Abbas will try to update the list of chapter and send an email to the Distinguished Lecturers to encourage participation. Abbas will propose a re-organization of the committees, as there is very little to do in the Membership and Chapters committee.

   Salman Avestimehr reported on the North American IT School to be held in Cornell in summer 2012, co-organized by Salman Avestimehr and Aaron Wagner. Will be June 19–June 22, 2012 (one week after ICC, 2 weeks before ISIT). Applications due March 30, 2012, decisions are made by April 16 and must register by May 1, 2012. Four lecturers are confirmed: Tom Richardson, Suhas Diggavi, Elza Erkip, Pramod Viswanath. The website is up. Lodging will be in the Cornell dorms, lecturer in the Statler hotel. Meals will be in all-you-can-eat cafeterias. Expecting about 125 students. Fundraising: IT School from ITSOC $20k, Cornell ECE department $20k, $2k from IBM, $2k from FoIE, will submit proposal to ARO (Bob Ulman) for $15k. Will there be registration? Thinking about $50 registration so can be sure how many people will come. Gerhard says it is important to have a credit card registration. Aylin suggests having students send cheques and return them if they come, keep otherwise.

   Gerhard Kramer reported on the European IT School to be held in Antalya, Turkey from April 16–20, 2012. Deniz Gunduz and Gerhard Kramer are the general organizers (Deniz is doing most of the work). Lecturers are Frans Willems, Sennur Ulukus, Meir Feder, Alex Dimakis, Michael Gastpar, Amos Lapidoth. There will be a charge of 450 euro/person (double), 590 euro/person (single) includes everything. So far 63 registrations representing 12 countries. ITSOC support is about $15k euros.

6) Elza Erkip spoke for Joerg Kliewer on the Outreach committee. Main idea of Mentoring program is to outreach to students, junior faculty and young professional, a tool for membership retention. An important event has been the Mentoring breakfast at ISIT; new initiatives are planned. First item is to recruit more mentors, perhaps in collaboration with student committee. Joerg was thinking about asking for travel grants to make sure mentors and mentees can meet. Committee headed by Joerg Kliewer, four additional members are Elza Erkip, Daniela Tuninetti and Bobak Nazer.

7) Muriel Medard reported on behalf of WITHITS at ISIT. An event is planned at ISIT, jointly co-ordinated with IEEE Society of Women in Engineering.

8) Frank Kschischang reported on the Nominations and Appointments Committee which consists of Giuseppe Caire Daniel J. Costello, Jr., G. David Forney, Jr., Frank Kschischang (chair), David L. Neuhof.

   The fellow committee is Frans M. J. Willems (chair), Michelle Effos, Rolf Johannesson, A. Robert Calder-bank, Alon Orlitsky, Thomas J. Richardson, Raymond W. Yeung.

   2012 Shannon Award Selection committee: Muriel Medard (Chair), Gerhard Kramer, Abbas El Gamal, Richard E. Blahut, Sergio Verdu, Raymond W. Yeung, Jacob Ziv.

   New committee was formed last year, the external nominations committee which consists of Prakash Narayan (Chair) Muriel Medard, Max H. M. Costa, Alon Orlitsky, A. J. Han Vinck. 2012 will be the first year of operation of this committee, created in a bylaws amendment by the BoG last year. This committee is responsible for the solicitation, processing and submission on behalf of the Society of nominations for appropriate IEEE awards (such as, for example, the IEEE W. R. G. Baker Award) and, as applicable, for awards outside of the IEEE." The bylaws stipulate that the committee shall consist of a Chair and three additional members appointed by the NAC, along with the society President.

   Motion: to approve the student committee chairs Elza Erkip and Sriram Vishwanath. Motion was passed.

   TO DO: 1) create a slate of candidates for election to the BoG, 2) appoint a new Conference Committee Chair (to start Jan. 2013), 3) start looking for a new IT Transactions EiC (to start Jul. 2013), 4) staff the 2013 Fellows Committee

9) Rolf Johanneson presented the 2011 Fellows Committee report on behalf of Frans Willems. Members 2011: Rob Calderbank (1st year), Michelle Effros (2nd year), Hideki Imai (3rd year), Rolf Johannesson (2nd year), Alon Orlitsky (1st year), Marcelo Weinberger (3rd year), Frans Willems (chair, 2nd year)/Members 2012: Rob Calderbank (2nd year), Michelle Effros (3rd year), Rolf Johannesson (3rd year), Alon Orlitsky (2nd year), Tom Richardson (1st year), Frans Willems (chair, 3rd (final) year), Raymond Yeung (1st year), Rolf Johannesson (reporter) and Frans M.J. Willems (chair).

   The committee evaluated 13 candidates in April - June 2011. In November the IEEE BoG approved the list of newly elevated Fellow Members. The list included 6 of our candidates: Erdal Arikan, for contributions to coding theory; Martin Bossert, for contributions to reliable data; transmission including code constructions and soft decision decoding; Adam Krzyzak, for contributions to nonparametric algorithms and classification systems for machine learning; Jong-Seon No, for contributions to sequences and cyclic difference sets for communications algorithms; Emre Telatar, for contributions to information theory and coding; Bane Vasic, for contributions to coding theory and its applications in data storage systems and optical communications.

   Interesting/surprising to note that the ITSOC Fellow Committee society does not see the letter of recommendation for the IEEE Fellows. A discussion was had about whether the letters have any impact—what the IEEE committee selects as fellows tends to align with the ITSOC recommendations. TO DO: ask Frans Willems on whether seeing letters would be important to the ITSOC fellows committee. It seems that many people in our society are elevated to Fellows by other societies; there seems to be a trend compared to other societies to elevate at later stages. There is a perception that ITSOC is a difficult one to go through; standard is higher. Ubli Mitra: should we encourage more nominations through our society? Michelle Effros thinks putting up more nominations would be beneficial to the society.

10) Nick Laneman (on Skype) reported on the Online Committee for Matthieu Bloch. Website is running well, quite a bit of traffic. Matthieu has had trouble getting contracts through IEEE for SixFeetOut (developers). Quality of Skype made a conversation impossible, just looked at report online. http://www.itsoc.org/people/bog/it-bog-meeting-ita-2012-ucsd/online-committee-report-ita-2012

11) Bruce Hajek reported on the Conference Committee. ISIT 2011 expects about a $80k surplus. ISIT 2012 in Cambridge, MA is on track. There were roughly 1000 submissions, similar to last year. Things are going well. ISIT 2013 in Istanbul seems on track. ISIT 2014 Hawaii and ISIT 2015 Hong Kong on track. Future ISITs – next one not decided is in 2016; usually approve this in BoG in summer (at ISIT). Barcelona, Stockholm, Aachen, Melbourne are proposals at the moment. Nothing is set in stone that ISIT alternates between North America, non-North America, but this is how it has been happening in the past. Whether there will be any proposal from North America for 2016 is still open. Ubli and Michelle (on behalf of a potential submission from Los Angeles area) suggest asking a location to do ISIT and working out the details after rather than having competing proposals; not to waste everyone's time if the decision is location based anyways. Giuseppe Caire states that putting together proposal is a good exercise; David Tse agrees. Frank says that given BoG and ISIT tradition he agrees with Bruce Hajek's guess of 95% successful North American proposal for ISIT 2016, if one were to be made (but there is none at the moment).

Motion to make broad geographic decision (North America versus non North America) for ISIT 2016 ahead of proposals being received. A long discussion was had. Motion was not passed.

ITW Paraty was a success, surplus of $24k. Lausanne ITW in 2012 is going to be unique: the format will be all session plenary, everyone speaks for 5 minutes and then everyone has a poster. Should be an interesting experiment. There are no proposals for ITW 2013 this far, hoping there will be a proposal. Max Costa says for ITW 2011 they tried a new format which was interesting: in a session 3 invited papers and then explicit time allocated to a panel-like discussion.

Frank states that ITW should not become "mini-ISITs". Bruce stated that officers agreed that there is not enough industry participation and welcomes any ideas on this (ITW focuses?).

12) Michelle Effros spoke on the Ad hoc Committee to look into potential opportunities for the IT Society to advocate activities. She is serving on a committee for the NSF CISE in an advisory role, which is insightful in how decisions are made at NSF. It has made her aware that there are other communities that are taking a more active role in putting forth their research, leading to more funding opportunities in these areas. This ad hoc committee was formed to ask whether the ITSOC could be doing more in this direction. The title of Michelle's presentation is to "Educate, Inspire and Empower". The more active communities are active on a wide variety of fronts—hence the title. Examples of things she has seen other societies do:

1) Educate: media, popular culture, K-12 (e.g. teach CS earlier, they are very active in talking to people in congress), AP exams (new one in CS and one in statistics, as people in communities go out an sell why this area is important), government (put together workshops with government officials, show impact of their investment, what are the next great things that we could help with, what needs to be done), many internal leadership roles (make more visible and understood).

2) Inspire: visioning workshops (pro-active workshops to think about the future), "wild-ideas" sessions (at conferences), enablement of white papers (to help program officers by giving them a menu of topics of interest to put together a program)

3) Empower: fellowship programs (group formed to ask NSF for postdoctoral fellowships which they got), jobs data bases (all sorts of positions), educational and inspirational materials (blog, videos to inspire people about what it would mead to study a certain area), active role in trying to define new initiatives for funding programs

Does the ITSOC want to get involved in these types of activities? Michelle encouraged everyone to think about these types of questions. Abbas noted that CS and statistics are much broader fields than us, so we should compare with smaller sub-branches. Michelle: do we consider ourselves in isolation or as a part of other communities (CS, statistics, math,...?). We could join forces with others, or do nothing. EE is not present at all in CISE (NSF), but computer science is almost synonymous with CISE (perception-wise). Very organized web-site http://www.cra.org/ccc/ Bruce believes that CS is such a large community, we must join them. Vardy stated that this effort of the CS community was a very very large effort. Giuseppe asked whether it would be possible/relevant to join forces with the Engineering side of NSF rather than the CISE side. Michelle feels we have been in a reactive rather than a pro-active role. Alon believes two sides: 1) trying to convince people what we do is relevant and 2) trying to do things that are more relevant. David believes terminology is important: computer scientists use the word "computational" which may be added to almost anything, interesting way to strategize. Gerhard believes the word "information" is a fantastic word and we do have a fundamental understanding so could be applied in many areas. Everyone is interested in "information"—like "computational". How to capitalize on it?

Muriel asked whether anyone has an active collaboration outside our traditional funding areas. Very few in the room did. Frank says Physics people are much better at conveying and extrapolating the importance of the research. We should write better letters, be better sales-people. Abbas: we need to find out what we want to sell, need to figure this out as a community, what is the big idea to sell? Elza: are we too modest and too self-critical to have great visionary ideas? David: his perception is that our field is very narrow, this may be hindering us. Prakash says people in other fields that have used information theory in their work have done so with great success. Andy applauded Alon for putting on this ITA workshop which is exactly a little broader than the usual IT venues.

Alon asked whether if we decide to take a proactive role, whether BoG will help organize this and in what fashion. Muriel said this would be appropriate. Abbas says visibility can be done; online, friendly courses, not to be confused funding and the larger vision or what to sell. One proposal would be to try and have an online course reaching tens of thousands of people. Tell people what is interesting about information theory. We could try to be more visible online; the transactions may need to change format to more magazine-like.

Muriel thanked the committee members for the excellent work in stimulating an excellent conversation and encouraged specific ideas and proposals on this matter. Muriel would love to hear back about progress in the Fall ITW BoG meeting.

13) Muriel wanted to share some highlights of the Officer's retreat on 02/04/12, which focused on preparing for the 5 year IEEE SRC review. One of the tasks was to go through the report we gave in the last review in 2006. One of things that came out of this was the Field of Interest (FOI) and Mission and Vision statements, which were re-visited.

Our FOI was last updated in 1987 and is currently as follows:

The processing, transmission, storage, and use of information, and the foundations of the communication process. It specifically encompasses theoretical and certain applied aspects of coding, communications and communications networks, complexity and cryptography, detection and estimation, learning, Shannon Theory, and stochastic processes.

Question: Do we as a board want to examine our FOI at the next ISIT? There was an interest. Frank mentioned that this might be a risky undertaking as new FOIs need approval at TAB meetings and can get contentious.

In looking at the review document, one of tasks is the vision and mission statement. The officers looked at these and came up with new mission and vision statements. The new statements that the officers came up with on 02/04/12 were presented to the board:

Vision: To be the pre-eminent community developing the mathematical underpinnings of information technology for the benefit of humanity.

The BoG was concerned about the words "mathematical" and "under-pinning" and "technology". Suggestion to change to "information science and technology", the vision was changed.

Mission: To support the open exchange of ideas in information theory, broadly construed, through publications, communications, meetings, outreach, education, mentoring, and recognition of excellence.

The BoG liked the mission statement.

14) Other business was brought to the table. Abbas El Gamal stated that we have 13 standing committees. He stated that the Membership and Chapter Committee does not do much. Abbas' brief recommendation is to have one committee called 'Membership' which would combine Membership, Student and Outreach committees, and have members in these committees deal with the specific subtasks. We have too many committees. A discussion was had about the different roles of the different committees. There is interest in exploring this. **TO DO**: Abbas to make specific recommendations, could present a motion at the next BoG.

The meeting was adjourned at 5:06 pm.

2013 IEEE International Symposium on Information Theory

Photo: Bertil Videt
http://commons.wikimedia.org/wiki/File:Bosphorus.jpg

July 7 – 12, 2013, Istanbul, Turkey

The 2013 IEEE International Symposium on Information Theory will be held in Istanbul, Turkey, from Sunday July 7th through Friday July 12th, 2013. Istanbul is the cultural, economic, and financial center of Turkey and a bridge between two continents as well as between cultures and traditions.

Interested authors are encouraged to submit previously unpublished contributions from a broad range of topics related to information theory, including (but not limited to) the following areas:

- Coding theory and practice
- Compression
- Detection and estimation
- Information theory in networks
- Pattern recognition and learning
- Sequences and complexity
- Signal processing
- Communication theory
- Cryptography and data security
- Information theory and statistics
- Multi-terminal information theory
- Quantum information theory
- Shannon theory
- Source coding

Researchers working on novel applications of information theory are especially encouraged to submit original findings. Submitted papers should be of sufficient detail for review by experts in the field. Both submitted and final papers will be limited to 5 pages in standard IEEE conference format. The submission deadline is **January 27, 2013,** at midnight, GMT. Authors should refrain from submitting multiple papers on the same topic. Detailed information on paper submission, technical program, tutorials, travel, and social programs will be announced on the ISIT 2013 web site: **http://www.isit2013.org**

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PLANNED TECHNICAL SYMPOSIA

Selected Areas in Communications Symposium

E-Health Area
Pradeep Ray, University of New South Wales, Australia

Power Line Communications Area
Andrea Tonello, University of Udine, Italy
Stephan Weiss, University of Strathclyde, UK

Smart Grids Area
Bahram Honary, Lancaster University, UK

Tactical Communications & Operations Area
Gabe Jakobson, Altusys, USA

Satellite & Space Communication Area
Hiromitsu Wakana, NICT, Japan

Data Storage Area
Tiffany Jing Li, Lehigh University, USA

Access Systems and Networks Area
Michael Peeters, Alcatel-Lucent, Belgium

Green Communication Systems and Networks
Athanassios Manikas, Imperial College London, UK

Wireless Communications Symposium
Zhaocheng Wang, Tsinghua University, China
Metha B. Neelesh, Indian Institute of Science, India
Hanna Bogucka, Poznan University of Technology, Poland
Fredrik Tufvesson, Lund University, Sweden

Wireless Networking Symposium
Azzedine Boukerche, University of Ottawa, Canada
Pan Li, Mississippi State University, USA
Min Chen, Seoul National Unversity, Korea

Communication Theory Symposium
David Gesbert, EURECOM, France
Angel Lozano, Universitat Pompeu Fabra, Spain
Velio Tralli, University of Ferrara, Italy
Sennur Ulukus, University of Maryland, USA

Signal Processing for Communications Symposium
Hai Lin, Osaka Prefecture University, Japan
Octavia Dobre, Memorial University, Canada
Saiid Boussakta, Newcastle University, UK
Hongyang Chen, Fujitsu Laboratories, Japan

Optical Networks and Systems Symposium
Xavier Masip-Bruin, Technical University of Catalonia, Spain
Franco Callegati, University of Bologna, Italy
Tibor Cinkler, Budapest University of Technology and Economics, Hungary

Next-Generation Networking Symposium
Malathi "MV" Veeraraghavan, University of Virginia, USA
Joel Rodrigues, University of Beira Interior, Portugal
Wojciech Kabacinski, Poznan University of Technology, Poland

Communication QoS, Reliability & Modeling Symposium
Tetsuya Yokotani, Mitsubishi Electric Corporation, Japan
Harry Skianis, University of the Aegean, Greece
Janos Tapolcai, Budapest University of Technology and Economics, Hungary

Ad-hoc and Sensor Networking Symposium
Guoliang Xue, Arizona State University, USA
Abdallah Shami, University of Western Ontario, Canada
Xinbing Wang, Shanghai Jiaotong University, China

Communication Software and Services Symposium
Jiangtao (Gene) Wen, Tsinghua University, China
Lynda Mokdad, University Paris-Est, France

Communication and Information Systems Security Symposium
Tansu Alpcan, TU Berlin, Germany
Mark Felegyhazi, Budapest University of Technology and Economics, Hungary
Kejie Lu, University of Puerto Rico at Mayagüez, PR

Cognitive Radio and Networks Symposium
Honggang Zhang, Zhejiang University, China
David Grace, University of York, UK
Andrea Giorgetti, University of Bologna, Italy

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IMPORTANT DATES

Paper Submission	Acceptance Notification	Camera-Ready	Tutorial Proposal	Workshop Proposal	Business Forum Proposal
16 September 2012	27 January 2013	24 February 2013	7 October 2012	25 June 2012	8 April 2012


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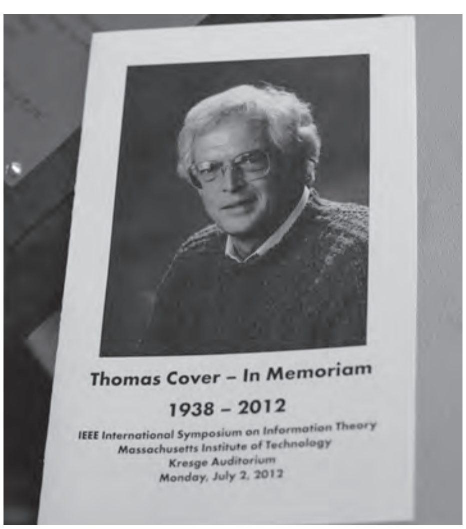
Thomas Cover – In Memoriam
1938 – 2012
IEEE International Symposium on Information Theory
Massachusetts Institute of Technology
Kresge Auditorium
Monday, July 2, 2012

Conference Calendar

DATE	CONFERENCE	LOCATION	WEB PAGE	DUE DATE
October 1–5, 2012	50th Annual Allerton Conference on Communication, Control, and Computing	Monticello, IL, USA	http://www.csl.uiuc.edu/allerton/	Passed
October 28–31, 2012	2012 International Symposium on Information Theory and its Applications (ISITA 2012)	Honolulu, HI, USA	http://www.isita.ieice.org/2012	Passed
November 4–7, 2012	Asilomar Conference on Signals, Systems, and Computers (ASILOMAR 2012)	Pacific Grove, CA, USA	http://www.asilomarssc.org/	Passed
November 19–20, 2012	5th International Workshop on Multiple Access Communications (MACOM 2012)	Dublin, Ireland	http://www.macom.ws/	Passed
December 3–7, 2012	2012 IEEE Global Communications Conference (GLOBECOM 2012)	Anaheim, California, USA	http://www.ieee-globecom.org/	Passed
April 14–19, 2013	32nd IEEE International Conference on Computer Communications (INFOCOM 2013)	Turin, Italy	http://infocom.di.unimi.it/	September 8, 2012
June 2–5, 2013	2013 77th Vehicular Technology Conference (VTC2013-Spring)	Dresden, Germany	http://www.ieeevtc.org/vtc2013spring/	September 30, 2012
June 9–13, 2013	IEEE International Conference on Communications (ICC 2013)	Budapest, Hungary	http://www.ieee-icc.org/	September 16, 2012
July 7–12, 2013	2013 IEEE International Symposium on Information Theory (ISIT 2013)	Istanbul, Turkey	http://www.isit2013.org/	January 27, 2013

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