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UNITED STATES DISTRICT COURT

FOR THE NORTHERN DISTRICT OF CALIFORNIA

SAN JOSE DIVISION

REGENTS OF THE UNIVERSITY OF MINNESOTA, Plaintiff, v. LSI CORPORATION AND AVAGO TECHNOLOGIES U.S. INC., Defendants.	Civil Action No. 18-cv-00821-EJD-NMC **DECLARATION OF PROFESSOR EMINA SOLJANIN**

I, Professor Emina Soljanin, declare as follows:

I. INTRODUCTION AND QUALIFICATIONS

A. Introduction.

1. I have been engaged as an expert on behalf of LSI Corporation and Avago Technologies U.S. Inc. (collectively, Defendants or "LSI") in the above-referenced case and in the *Inter Partes* Review ("IPR") proceeding involving the patent-in-suit (U.S. Patent and

Trademark Office Trial and Appeal Board, IPR2017-01068). The patent at issue in both proceedings is U.S. Patent No. 5,859,601 ("the '601 Patent").

2. I understand that ownership of the '601 Patent is claimed by the Regents of the University of Minnesota ("the University"). I understand that the University sued LSI in the U.S. District Court for the District of Minnesota on August 25, 2016, and that the '601 Patent expired on October 15, 2016. I understand that the District of Minnesota subsequently transferred this case to the U.S. District Court for the Northern District of California, San Jose Division.

3. In this Declaration, I offer my opinions regarding, among other things, certain terms in claims 13, 14, and 17 ("the Asserted Claims") of the '601 Patent. It is my opinion that the Asserted Claims are indefinite under 35 U.S.C. § 112(b) because the claims, read in light of the patent's specification and its prosecution history, fail to inform, with reasonable certainty, a person having ordinary skill in the art at the time of the invention the scope of the alleged inventions. The reasons for this opinion are set forth more fully below.

4. I also disclose below my understanding of certain legal principles regarding claim construction and 35 U.S.C. § 112(b) provided to me by counsel, as well as my view of the level of ordinary skill in the art at the time of the alleged inventions of the Asserted Claims.

5. I am being compensated at a rate of $420 per hour for my consulting services, including the preparation of this Declaration. I have no stake in the outcome of this civil action or the related IPR proceedings concerning the '601 Patent.

B. Expert Qualifications.

6. I am currently a professor of electrical and computer engineering at Rutgers University. My research interests are broad, but mainly concern theoretical understanding and practical solutions that enable efficient, reliable, and secure operation of communications networks. I also have expertise and interest in power systems and quantum computation.

7. My research has been funded by the National Science Foundation, the Center for Discrete Mathematics and Theoretical Computer Science (DIMACS), DARPA, and other

funding agencies.

8. All of my degrees are in electrical engineering. I earned a European Diploma degree from the University of Sarajevo, Bosnia, in 1986, and M.S. and Ph.D. degrees from Texas A & M University in 1989 and 1994, respectively.

9. Between my studies at the University of Sarajevo and my graduate studies, from 1986 to 1989, I worked in industry developing optimization algorithms and software for power system control.

10. Upon earning my Ph.D., I joined Bell Laboratories in Murray Hill, NJ, where I was a Member of the Technical Staff in the Mathematics of Networks and Communications research department. Over a dozen alumni of Bell Labs have won the Nobel prize in physics, with several more having been awarded the Turing Award, the highest distinction in computer science. In 2004 I was elevated to Distinguished Member of the Technical Staff.

11. During my time at Bell Labs, I was also an adjunct professor, guest lecturer, or visiting professor at various academic institutions around the world including, Columbia University, ENSE in Cergy-Pontoise, France, the University College Dublin, and others. I also mentored many students, interns, and postdoctoral researchers during that time.

12. In the course of my twenty year employment with Bell Labs, I participated in a wide range of research and business projects. These projects include designing the first distance enhancing codes to be implemented in commercial magnetic storage devices. Other projects that I worked on at Bell Labs included the first forward error correction for Lucent's optical transmission devices, color space quantization and color image processing, quantum computation, link error prediction methods for the third generation wireless network standards, and anomaly and intrusion detection. Some of my most recent activities are in the area of network and application layer coding.

13. According to the University's allegations in the First Amended Complaint in this case, the alleged invention of the '601 Patent is a "maximum transition run" ("MTR") code featuring a "j constraint" which "imposes a limit on the maximum number of consecutive transitions" in a binary system. I was conducting research in this area before the

application that matured into the ’601 Patent was filed.

14. The named inventors of the ’601 Patent, Professor Jaekyun Moon and his then-graduate student Dr. Barrett Brickner, published a paper in 1996 entitled “Maximum Transition Run Codes for Data Storage Systems,” which paper is attached to the First Amended Complaint as Exhibit 3, and referred to therein by the University as “the Moon 1996 IEEE Paper.” (*See* First Amended Complaint, Dkt. No. 40, at ¶¶ 49-52; attached hereto as Appendix A.)

15. The University alleges that this Moon 1996 IEEE Paper is “substantially similar to the ’601 Patent.” (*See id.*) This is noteworthy because Dr. Moon and Dr. Brickner confirmed in their 1996 IEEE Paper that I, in my “independent study,” had disclosed that “removing long runs of consecutive transitions” can improve the performance of data storage systems. (*See* Moon 1996 IEEE Paper, Appendix A, right column of first page, citing reference [6].) Reference [6], cited by Dr. Moon and Dr. Brickner in their 1996 IEEE paper, relates to my conference presentation in October 1995. (*See* Appendix A, Reference [6] listed as “E. Soljanin, ‘On-track and off-track distance properties of class4 partial response channels,’ SPIE Conference, Philadelphia, PA, Oct. 1995.”).

16. Additionally, my work was published in a 1995 paper entitled “On-track and off-track distance properties of class4 partial response channels,” which paper is attached as Appendix B. This paper discloses that digital storage systems can be improved “by limiting the length of subsequences of alternating symbols to four,” and that in the NRZI recording format, “this can be achieved by a code that limits the runs of consecutive ones to three” and discloses a “simple and inexpensive implementation” for such a code. (*See* Appendix A, at Section 4.2.) The first-named inventor on the ’601 Patent, Prof. Moon, attended my presentation given at the above-referenced conference, as described in LSI’s counterclaim for inequitable conduct. (Dkt. No. 62 at p. 23 *et seq*., ¶¶ 18-49.)

17. Further, one of my own patents, U.S. Patent No. 5,608,397, is cited on the face of the ’601 Patent. During prosecution, the examiner found that my U.S. Patent No. 5,608,397 (among others) “is considered pertinent to applicant’s disclosure.” (*See* File

History, Office Action dated Sept. 16, 1997.)

18. In addition to U.S. Patent No. 5,608,397, cited by the patent examiner and listed on the face of the ’601 Patent, I am the inventor of additional patents and pending patent applications. I have authored numerous peer-reviewed journal and conference publications, as well as books and book chapters. Among other professional recognitions, I was elected an IEEE Fellow for my “contributions to coding theory and coding schemes for transmission and storage systems.” My curriculum vitae includes additional details about my experience and professional background. It is attached as Appendix C.

II. MATERIALS REVIEWED

19. My opinions are based on years of education, research and experience, as well as investigation and study of relevant materials. In forming my opinions, I have considered the materials identified in this declaration, including the ’601 Patent’s claims (both the Asserted Claims and the non-asserted claims), its specification (including the figures and all of the written disclosure), and the prosecution history of the application that matured into the ’601 Patent. I have also reviewed the documents discussed in Section I.B above.[1]

III. THE HYPOTHETICAL PERSON OF ORDINARY SKILL IN THE ART

20. I have been informed that patent claims are to be interpreted the way a hypothetical person having ordinary skill in the art would have interpreted the claims at the time of the invention. For shorthand, I may refer to such a person herein as a “POSITA.”

21. The application resulting in the ’601 Patent was filed on October 15, 1996. The face of the patent claims priority to “Provisional application No. 60/014,954” filed April 5, 1996. Merely for argument’s sake, therefore, I will assume that the Asserted Claims are entitled to a priority date of April 5, 1996. As mentioned above, I was conducting research

[1] I may rely upon these materials and/or additional materials to respond to arguments raised by the University or its expert(s). I may also consider additional documents and information in forming any necessary opinions—including documents that may not yet have been provided to me. My analysis of the materials produced in this investigation is ongoing and I will continue to review any new material as it is provided. This report represents only those opinions I have formed to date. I reserve the right to revise, supplement, and/or amend my opinions stated herein based on new information and on my continuing analysis of the materials already provided.

and publishing my work in the relevant technological field prior to April 5, 1996.

22. In determining the characteristics of a person of ordinary skill in the art at the time of the claimed invention, I considered several things, including the factors discussed below, as well as (1) the levels of education and experience of the inventor and other persons actively working in the relevant field; (2) the types of problems encountered in the field; (3) prior art solutions to these problems; (4) the rapidity in which innovations are made; and (5) the sophistication of the relevant technology. I also placed myself back in the relevant time period and considered the individuals that I had worked with in the field.

23. It is my opinion that a person having ordinary skill in the relevant art at the time of the invention would have been someone with at least an undergraduate degree in electrical engineering or similar field, and three years of industry experience in the field of read channel technology.

24. I am prepared to testify as an expert in this field and also as someone who had at least the knowledge of a POSITA, and someone who worked with other POSITAs at the time of the alleged invention.

25. Unless otherwise stated, my statements below refer to the knowledge, beliefs, and abilities of a POSITA at the time of the claimed invention of the '601 patent.

IV. CLAIM CONSTRUCTION STANDARD

26. I understand that the Asserted Claims are construed as understood by a POSITA. Counsel informs me that sometimes the meaning of claim terms are readily apparent even to lay judges, and that, in such scenarios, claim construction involves little more than the application of widely accepted meaning of commonly understood words.

27. Otherwise, especially in highly-technical patents, courts look to the "intrinsic evidence" (*i.e.*, the words of the claims themselves, the specification and figures, and the prosecution history), and in some circumstances resort to consideration of extrinsic evidence concerning relevant scientific principles, the meaning of technical terms, and the state of the art to interpret a patent.

28. Regarding the intrinsic evidence, I understand that the claims themselves

provide substantial guidance as to the meaning of particular claim terms. For example, the context in which a term is used in the asserted claim can be highly instructive. Other claims of the patent in question, both asserted and un-asserted, can also be valuable sources of enlightenment as to the meaning of a claim term.

29. The claims do not stand alone, as they must be read in view of the specification, of which they are a part. I understand that the specification is always highly relevant to the claim construction analysis and is usually the single best guide to the meaning of a disputed term. I understand that the importance of the specification in claim construction derives from its statutory role, as the close kinship between the written description and the claims is enforced by the statutory requirement that the specification describe the claimed invention in "full, clear, concise, and exact terms." 35 U.S.C. § 112(a).

30. I understand further that the specification may reveal a "special definition" given to a claim term by the patentee that differs from the meaning it would otherwise possess. In such cases, the inventor's "lexicography" governs. In other cases, the specification may reveal an "intentional disclaimer, or disavowal, of claim scope by the inventor." In that instance as well, the inventor's intention governs.

31. In addition to consulting the claims and the specification, I understand that a court should also consider the patent's prosecution history. The prosecution history is a part of the intrinsic evidence and consists of the complete record of the proceedings before the Patent Office and includes the prior art cited during the examination of the patent. Like the specification, the prosecution provides evidence of how the Patent Office and the inventor understood the patent. Furthermore, like the specification, the prosecution history was created by the patentee in attempting to explain and obtain the patent. Yet because the prosecution history represents an ongoing negotiation between the Patent Office and the applicant, rather than the final product of that negotiation, it often lacks the clarity of the specification and thus is less useful for claim construction purposes.

32. I further understand that while extrinsic evidence (*e.g.*, expert testimony, dictionaries, learned treatises) can shed useful light on the relevant art, it is less significant

than the intrinsic record in determining the legally operative meaning of claim language. I understand further that the United States Court of Appeals for the Federal Circuit has viewed extrinsic evidence in general as less reliable than the patent and its prosecution history in determining how to read claims.

V. INDEFINITENESS STANDARD

33. A provision in the Patent Act states that "[t]he specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the inventor or joint inventor regards as the invention." 35 U.S.C. ¶ 112(b). I understand that a claim that does not comply with this provision is said to be "indefinite," and is invalid for that reason.

34. I understand that until recently, the legal standard for definiteness was determining whether a claim is "amenable to construction," and the claim, as construed, is not "insolubly ambiguous." If a claim could be construed and was not "insolubly ambiguous," then it was definite under 35 U.S.C. ¶ 112(b).

35. I understand that the United States Supreme Court relaxed this test in 2014. Counsel informs me that the Court, in a case called *Nautilus, Inc. v. Biosig Instruments, Inc.*, ("*Nautilus*") stated as follows:

> "We conclude that the Federal Circuit's formulation, which tolerates some ambiguous claims but not others, does not satisfy the statute's definiteness requirement. In place of the 'insolubly ambiguous' standard, we hold that a patent is invalid for indefiniteness if its claims, read in light of the specification delineating the patent, and the prosecution history, fail to inform, with reasonable certainty, those skilled in the art about the scope of the invention."

VI. THE ASSERTED CLAIMS

36. The text of the Asserted Claims is listed below:

<u>Claim 13</u>

[Preamble:] A method for encoding m-bit binary datawords into n-bit binary codewords in a recorded waveform, where m and n are preselected positive integers such that n is greater than m, comprising the steps of:

[Step 1:] receiving binary datawords; and

[Step 2:] producing sequences of n-bit codewords;

[Step 3:] imposing a pair of constraints (j;k) on the encoded waveform;

[Step 4:] generating no more than j consecutive transitions of said sequence in the recorded waveform such that $j \geq 2$; and

[Step 5:] generating no more than k consecutive sample periods of said sequences without a transition in the recorded waveform.

<u>Claim 14</u>

The method as in claim **13** wherein the consecutive transition limited is defined by the equation $2 \leq j < 10$.

<u>Claim 17</u>

The method as in claim **14** wherein the binary sequences produced by combining codewords have no more than one of j consecutive transitions from 0 to 1 and from 1 to 0 and no more than k+1 consecutive 0's and k+1 consecutive 1's when used in conjunction with the NRZ recording format.

VII. THE ASSERTED CLAIMS ARE INDEFINITE

37. It is my opinion that the claim terms below are indefinite: (1) "the encoded waveform" (claim 13); (2) "generating no more than j consecutive transitions of said sequence in the recorded waveform such that j≥2" (claim 13); (3) "generating no more than k consecutive sample periods of said sequences without a transition in the recorded waveform" (claim 13); (4) "wherein the binary sequences produced by combining codewords have no more than one of j consecutive transitions from 0 to 1 and from 1 to 0" (claim 17); and (5) "wherein the binary sequences produced by combining codewords have … no more than one of k+1 consecutive 0's and k+1 consecutive 1's" (claim 17).

38. My opinions are explained further below.

1. "The Encoded Waveform" (Claim 13)

39. Step 3 of claim 13 recites "imposing a pair of constraints (j;k) on the encoded waveform." The phrase "encoded waveform" renders claim 13 indefinite (as well as all

claims depending from it) because the claim, read in light of the specification of the ’601 Patent and the prosecution history, fails to inform, with reasonable certainty, those skilled in the art about the scope of the purported invention.

40. First, there is no antecedent basis for the phrase “the encoded waveform” in the claim. The phrase begins with the word “the,” which, according to counsel, is understood to be used in patent claims (and as I understand in normal English usage) to refer back to an element that was recited earlier in the same claim or in an independent claim from which the claim at issue depends. However, there is no earlier reference to “encoded waveform” in claim 13. The term is indefinite for at least this reason.

41. I am informed that the University’s expert, Prof. McLaughlin, agrees that the word “the” signals that the following phrase “encoded waveform” must have an antecedent basis in the claim. (*See* McLaughlin Declaration at ¶ 46.) Professor McLaughlin confirms that no such antecedent basis exists in the claim, stating that “[t]he ***only*** waveform previously referred to in the claim is the ‘***recorded*** waveform’ referred to in the claim preamble, which recorded waveform has encoded data as described above.” (*Id*. at ¶ 46) (emphasis added). Unable to find antecedent basis for “the encoded waveform,” Professor McLaughlin simply concludes that “the encoded waveform” is exactly the same as the “recorded” waveform. I do not agree; the claim uses different words to mean different things. If “the encoded waveform” was the same as the “recorded waveform,” then the claim would use the phrase “the recorded waveform” in step 3. Instead, it uses a different phrase—“the encoded waveform.”

42. Second, the structure of claim 13 supports the conclusion that “the encoded waveform” (recited in step 3) is not the same thing as the “recorded waveform” (recited in the preamble and in “generating” steps 4 and 5.) In particular, each of the five method steps recited in claim 13 begin with a verb ending in “ing”: receiving, producing, imposing, generating, and generating, and logically they proceed in sequential order. A “recorded waveform” does not exist until steps 4 and 5 are completed. In a digital storage device, the “generating” steps would happen on the recording medium, not in the “encoder.” In contrast,

the "imposing" step, *i.e.,* step 3 of claim 13, would happen in an encoder, which is typically a discrete electrical component separate from the recording medium, such as a system on a chip. The j and k constraints are "imposed" by the encoder on the sequence of n-bit codewords, which are not "the recorded waveform."

43. Third, consideration of claims other than claim 13 bolster my opinion. For example, see claim 18, which depends from claim 14, which in turn depends from claim 13. Claim 18 states that "the encoder" (as opposed to a recording medium or a component that can record on a medium) is the thing that "produces a codeword in response to each dataword sequentially," and the encoder imposes the j and k constraints by selecting the n-bit codewords according to certain specified steps. This is consistent with my conclusion about the distinction between the "recorded waveform" and "the encoded waveform" in claim 13.

44. Fourth, because the term "encoded waveform" does not appear earlier in claim 1, or in any other claim of the '601 Patent, one naturally would look to the specification for guidance. But the phrase does not appear in the specification. In addition, the phrase "encoded waveform" has no standard or industry-specific definition. In fact, the phrase "encoded waveform" was inserted during prosecution via a claim amendment and was introduced into amended claim 1 (which is not asserted here) and amended claim 13. However, neither the inventors nor the patent examiner provided a definition of this new phrase, even though the inventors stated that Claims 1 and 13 had been amended "to better define the invention." (*See* Response to Office Action at 3.) The patent examiner did not explain the meaning of "the encoded waveform" in the Notice of Allowability or elsewhere. (*See* File History (Dkt. No. 165-2).) This prosecution history underscores the fact that this term – "the encoded waveform" -- not only lacks an antecedent basis in claim 13, but lacks a foundation in the patent itself.

45. Fifth, it is not clear what is meant by a "waveform" in Step 3 of claim 13. In particular, Step 3 is listed prior to Steps 4 and 5. A waveform (in particular, a "recorded waveform") is said to be "generated" in Steps 4 and 5. The phrase "the encoded waveform" is used in Step 3, which is where the pair of constraints are "impos[ed]." According to the

specification, the step of "imposing" occurs in the production of binary codewords. *See*, *e.g.*, '601 Patent at Fig. 6 and 5:12-47 (providing "equations for the encoder"). Binary codewords are not a "waveform." (*See*, *e.g.*, Response to Office Action, Appendix A ("[C]ode bits are indicated above the appropriate waveform")); *see also* Claims 16, 17, 18 (showing that the j and k constraints are "imposed" at the binary level, *i.e.*, on sequences of 1's and 0's, and not on the recorded waveform). This lack of clarity further would leave a POSITA uncertain as to the meaning of the phrase "encoded waveform" in claim 13 of the '601 Patent.

46. For each of these reasons, taken alone or viewed together, claim 13 is indefinite under Section 112.

2. "Generating No More Than j Consecutive Transitions of Said Sequence in the Recorded Waveform Such That j≥2." (Claim 13)

47. Step 4 of claim 13 recites "generating no more than j consecutive transitions of said sequence in the recorded waveform such that j≥2." This phrase renders claim 13 indefinite (as well as all claims depending from it) because the claim, read in light of the specification of the '601 Patent and the prosecution history, fails to inform, with reasonable certainty, those skilled in the art about the scope of the purported invention.

48. First, take the case of j = 2. If only 1 (one) consecutive transition is generated, does this satisfy the limitation of Step 4? The claim disallows "*more than*" 2 consecutive transitions. Because 1 is less than 2, 1 consecutive transition meets the claim language "no more than j consecutive transitions." Yet the claim states that j≥2, which suggests that 1 consecutive transition would not satisfy the claim. In prosecution, its response to the patent examiner's rejection of the claims in view of prior art, the applicant attempted to explain what was being claimed and how it was different than the prior art (*see* File History), but note that claim 13 is written in terms of what is ***disallowed*** (*i.e.*, "***no more than***") instead of what is allowed. *Compare* independent method claim 13 ("generating ***no more than*** j consecutive transitions") *with* independent apparatus claim 1 ("wherein the j constraint is ***defined*** as the maximum number of consecutive transitions ***allowed*** on consecutive clock periods") (emphasis added). The "definition" in claim 1 is not recited in claim 13, even though claims 1

and 13 were amended at the same time, in response to the same Office Action. Moreover, the specification teaches that "the minimum distance pairs shown in FIG. 1 must be eliminated" and that "[i]n accordance with *the present invention*, this can be accomplished using the existing RLL (1,k) code, *which does not allow* consecutive transitions." '601 Patent at 4:8-12 (emphasis added). This adds up to lack of reasonable certainty as to the meaning of this claim limitation.

49. Second, Step 4 recites the phrase "transitions of said sequence." The "said sequence" appears to refer to n-bit codewords, but it does not make sense to speak of a transitions "of codewords." It does however make sense to think of transitions in terms of transitions between binary bits – 1 to 0 or 0 to 1. (*See e.g.*, claims 16 and 17.) This language is unclear. Moreover, a waveform does not have binary bits, making the claim ambiguous on multiple levels.

50. Third, Step 2 recites "sequences" (plural) while Step 4 recites "said sequence" (singular) and Step 5 recites "said sequences" (plural). There is no antecedent basis for the phrase "said sequence."

51. For each of these additional reasons, taken alone or viewed together, claim 13 is indefinite under Section 112.

3. "Generating No More Than k Consecutive Sample Periods of Said Sequences Without a Transition in the Recorded Waveform." (Claim 13)

52. Step 5 of claim 13 recites "generating no more than k consecutive sample periods of said sequences without a transition in the recorded waveform." This phrase renders claim 13 indefinite (as well as all claims depending from it) because the claim, read in light of the specification of the '601 Patent and the prosecution history, fail to inform, with reasonable certainty, those skilled in the art about the scope of the purported invention.

53. What is meant by the phrase "k consecutive sample periods" of "said sequences"? The phrase "said sequences" may refer to n-bit codewords because it does not make sense to speak of a transitions of sequences. Transitions refers to transitions between

binary bits – 1 to 0 or 0 to 1. Moreover, a waveform does not have binary bits, making the claim ambiguous on multiple levels.

54. Also, what "sample periods" are being referred to? Sampling is done, for example, when recorded data is read, not when data is being written. The '’601 patent at 2:10-37 discloses sampling the context of "sequence detectors" for "data recovery devices," i.e., reading previously-recorded data from a storage medium. But claim 13 addresses only a "writing" function, and is not directing to "reading" or recovery of stored data.

55. Further, as noted above, Step 2 recites "sequences" (plural) while Step 4 recites "said sequence" (singular) and Step 5 recites "said sequences" (plural). This adds to the ambiguity of the claim.

56. For each of these additional reasons, taken alone or viewed together, claim 13 is indefinite under Section 112.

4. "Wherein the Binary Sequences Produced by Combining Codewords Have No More Than One of j Consecutive Transitions from 0 to 1 and from 1 to 0." (Claim 17)

57. Claim 17 depends from claim 14, which depends from claim 13. Claim 17 recites "wherein the binary sequences produced by combining codewords have no more than one of j consecutive transitions from 0 to 1 and from 1 to 0." This phrase renders claim 17 indefinite because the claim read in light of the specification of the '601 Patent and the prosecution history, fails to inform, with reasonable certainty, those skilled in the art about the scope of the purported invention.

58. The meaning of "j consecutive transitions" in this claim is unclear. Consider the simple bit string 01. There is one (1) transition "from 0 to 1" but zero (0) transitions "from 1 to 0." So what is the value of j in this simple example? The claim does not specify that one would take the *maximum* of the two choices, or the *sum of both choices*, but it instead says that j is evaluated as "no more than ***one of***" two options that are not necessarily the same.

Which one? Claim 17 is indefinite under Section 112 for at least these additional reasons.

5. "Wherein the Binary Sequences Produced by Combining Codewords Have … No More Than One of k+1 Consecutive 0's and k+1 Consecutive 1's." (Claim 17)

59. Claim 17 is indefinite because the phrase "no more than one of k+1 consecutive 0's and k+1 consecutive 1's" is indefinite. Consider the simple bit string 00111. There are two (2) consecutive 0's and three (3) consecutive 1's. How does one evaluate the claimed "k+1" parameter? The claim does not specify that one would take the *maximum* of the two choices, but it instead says that k+1 is evaluated as "no more than one of" two options. Claim 17 is indefinite under Section 112 for at least these additional reasons.

VIII. CONCLUSION

60. I declare under 28 U.S.C. § 1746 and under penalty of perjury that the foregoing is true and correct.

Dated: April 13, 2018

By ______________________________
Emina Soljanin, Ph.D.

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APPENDIX A

Maximum Transition Run Codes for Data Storage Systems

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Abstract **– A new code is presented which improves the minimum distance properties of sequence detectors operating at high linear densities. This code, which is called the maximum transition run code, eliminates data patterns producing three or more consecutive transitions while imposing the usual k-constraint necessary for timing recovery. The code possesses the similar distance-gaining property of the (1,k) code, but can be implemented with considerably higher rates. Bit error rate simulations on fixed delay tree search with decision feedback and high order partial response maximum likelihood detectors confirm large coding gains over the conventional (0,k) code.**

I. INTRODUCTION

In this paper, we present a new code designed to improve the distance properties of sequence detectors operating at relatively high linear densities. The basic idea is to eliminate certain input bit patterns that would cause most errors in sequence detectors. More specifically, the code eliminates input patterns that contain three or more consecutive transitions in the corresponding current waveform, and, as a result, the performance of any near-optimal sequence detector improves substantially at high linear densities [1][2]. This code constraint, designated the maximum transition-run (MTR) constraint, can be realized with simple fixed-length block codes with rates only slightly lower than the conventional (0,k) code. Bit error rate (BER) simulation results with fixed delay tree search with decision feedback (FDTS/DF) detection and high order partial response maximum likelihood (PRML) detection confirm a large coding gain of the MTR codes over the conventional (0,k) code.

II. CODING METHODS

Investigation of high density error patterns in FDTS/DF detection reveals that errors arise mostly due to the detector's inability to distinguish the minimum distance transition patterns, four pairs of which are shown in Fig. 1. These pairs of magnetization waveforms give rise to an NRZ input error pattern of $e_k=\pm\{2\ -2\ 2\}$, assuming input data take on +1's and -1's. The proposed approach is to remove data patterns allowing this type of error pattern through coding. The potential improvement in the FDTS detection performance using this approach can be estimated by computing the increase in the minimum distance between two diverging lookahead tree paths after removing the paths that allow the $\pm\{2\ -2\ 2\}$ error events [3]. A simple minimum distance analysis for PRML systems reveals that this is also a critical error pattern in high order PRML systems such as E^2PR4ML. Note that a traditional (1,k) runlength limited (RLL) code eliminates all eight transition patterns shown in Fig. 1 [4][5], but the rate penalty is typically too large to see any coding gain unless the linear density is very high. The idea of MTR coding is to eliminate three or more consecutive transitions, but allow the dibit pattern in the written magnetization waveform. Thus, with MTR coding, the error events of the form $\pm\{2\ -2\ 2\}$ will still be prevented as with (1,k) coding, but the rate penalty is significantly smaller than that of the typical (1,k) RLL code. Notice that with the MTR constraint, the write precompensation efforts can be directed mainly on dibit transitions, unlike in conventional (0,k) coded systems. An independent study also suggests that removing long runs of consecutive transitions improves the offtrack performance in some PRML systems [6]. There exist other types of code constraints that can offer similar distance-enhancing properties for high order PRML systems [7].

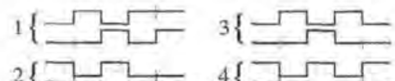

Fig. 1: Pairs of write patterns causing most errors in sequence detection at high linear densities.

Fig. 2 shows the state diagram of the MTR code based on the NRZI convention, where 1 and 0 represent the presence and absence, respectively, of a magnetic transition. Also included is the usual k-constraint for timing recovery. The capacity of the code can be obtained by finding the largest eigenvalue of the adjacency matrix for the given state diagram [8]. The capacities for different k values are given in Table 1.

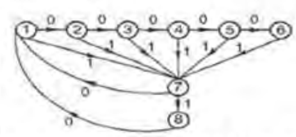

Fig. 2: State transition diagram for the MTR code with k=6.

k	capacity	k	capacity
4	.8376	8	.8760
5	.8579	9	.8774
6	.8680	10	.8782
7	.8732	∞	.8791

Table 1: Capacities for MTR codes.

While state-dependent encoders and sliding-block decoders can be designed for the MTR constraint (which can be easily generalized to limit any runs of consecutive transitions), we observe that simple fixed-length block codes can be realized with

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good rates and reasonable k values. A computer search is utilized to first find all n-bit codewords that are free of an NRZI 111 string or k+1 consecutive NRZI 0's. Then, in order to meet the MTR constraint at the codeword boundaries, words that start or end with an NRZI 11 string are removed. Also, the k constraint is satisfied at the boundary by removing the words with k_1+1 leading 0's or k_2+1 trailing 0's, where $k_1+k_2=k$. Finally, if the number of the remaining codewords is greater than or equal to 2^m, then those codewords can be used to implement a rate m/n block code. Table 2 shows important code parameters for representative block codes obtained through computer search. The efficiency was found by dividing the code rate m/n by the capacity computed for the given value of k and the MTR constraint. As an example of an MTR block code, 16 codewords required to implement the rate 4/5 code with k=8 are given in Table 3.

m	n	k	eff.	No. avail. codewords	No. needed codewords
4	5	8	.91	16	16
8	10	6	.92	282	256
9	11	6	.94	514	512
10	12	8	.95	1,066	1,024
14	17	6	.95	18,996	16,384
16	19	7	.96	69,534	65,536
24	28	8	.98	17,650,478	16,777,216

Table 2: Parameters for MTR block codes.

00001	00110	01100	10010
00010	01000	01101	10100
00100	01001	10000	10101
00101	01010	10001	10110

Table 3: A rate 4/5 MTR block code with k=8.

III. MODIFIED DETECTION AND DISTANCE INCREASE

To realize the coding gain at the detector output, the detector has to be modified. In the case of PRML systems, this amounts to removing those states and state transitions that correspond to the illegal data patterns from the trellis diagram. For the FDTS/DF detector, the code-violating lookahead paths must be prevented from being chosen as the most-likely path, a technique similar to the one used in the (1,7) coded FDTS/DF channel [9]. To illustrate the idea, consider Fig. 3 that shows a τ=2 lookahead tree utilized in FDTS/DF detection. By utilizing the past decision, an illegal path, which contains three consecutive transitions, can be identified as indicated by either the solid (when the past decision is -1) path or the shaded (when the past decision is 1) path. The complexity of the FDTS/DF detector can also be reduced considerably with the MTR code, as elaborated in a companion paper [10].

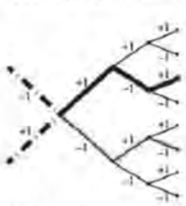

Fig. 3: Modified FDTS detection with MTR coding

With this modification in FDTS/DF detection, the squared minimum Euclidean distance between any two diverging paths, denoted by β^2_{min}, is given by $4\cdot(1+f_1^{\,2}+f_2^{\,2}+\cdots+f_\tau^{\,2})$ for τ greater than or equal to 2, where f_k represents the equalized dibit response (at the output of the forward equalizer). For example, the effective SNR gain of the τ=2 FDTS/DF over the decision feedback equalization (DFE) channel, assuming the same MTR code, is given by $10\cdot\log_{10}(1+f_1^{\,2}+f_2^{\,2})$ dB.

The distance gain with MTR coding is also significant for high order PRML systems such as E^2PR4. When the critical NRZ error pattern is $\pm\{2\ -2\ 2\}$, the minimum distance for the E^2PR4 response $\{1\ 2\ 0\ -2\ -1\}$ is $6\sqrt{2}$. With MTR coding, the worst case error pattern becomes a single bit error pattern of $\pm\{2\}$, and the corresponding channel output distance is simply the square root of the energy in the equalized dibit response, or $10\sqrt{2}$. This increase in the minimum distance is equivalent to an SNR gain of 2.218 dB. When the code rate penalty is small, the overall coding gain is significant.

IV. BER SIMULATION RESULTS

To verify the coding gain, FDTS/DF detection was simulated with the rate 4/5 and rate 16/19 MTR codes as well as with a rate 8/9 (0,k) code. The BERs were first obtained as a function of readback SNR for different tree depths. The BER of the PR4ML detector was also simulated for comparison. The Lorentzian transition response was assumed, and the user density, defined as PW50 over the user bit interval, is fixed at 2.5 for all codes. The SNR value required to achieve an error rate of 10^{-5} was then recorded for each depth/code combination.

The results are summarized in Fig. 4, where the effective SNR improvement of each system over PR4ML is shown. The performance advantage of MTR codes is clear. With the rate 16/19 MTR code, for example, the depth 1 FDTS/DF performs as well as the depth 5 FDTS/DF used with the conventional (0,k) code, yielding a 2.5 dB gain over the PR4ML. When the 4/5 MTR code is used, FDTS/DF with a tree depth of 2 outperforms the depth 5 FDTS/DF with the 8/9 (0,k) code. For a given tree depth, the rate 16/19 MTR code yields a 1.5 - 2 dB coding gain over the conventional 8/9 (0,k) code.

Also shown are the SNR performances of PRML systems with and without MTR coding. The coding gain is obvious with E^2PRML and E^3PRML, in which the minimum distance is improved with the MTR code. However, with EPR4ML the performance advantage of the MTR code is small since the MTR code does not improve the minimum distance in the EPR4 system. This is because the minimum distance error pattern in an EPR4 system is of the form $\pm\{2\}$, which is not affected by the MTR constraint. The MTR code does, however, eliminate non-minimum distance error patterns of the form $\pm\{...2\ -2\ 2...\}$, resulting in a small performance improvement over the (0,k) coded EPR4 system when the code rate is sufficiently high as with the 16/19 code.

Comparisons also can be made between the PRML systems and FDTS/DF systems. For example, the depth 2 FDTS/DF with the rate 4/5 MTR code improves more than 1 dB over EPR4ML with the rate 8/9 (0,k) code. At this density and with a Lorentzian transition response, EPR4ML has a 1.5 dB advantage over PR4ML. Of the PR targets, the EPR4 appears to provide a best fit to the natural channel as indicated by the superior performance of EPR4ML over even higher order PRML systems. Large enough FIR filters are used for equalization for both PRML and FDTS/DF systems so that the performances are not degraded by imperfect equalization.

In Fig. 5, similar plots are presented for a modeled MR head response. The trends are similar to the Lorentzian case, except that within the PRML family the performance improves as the order of the PR polynomial increases. Also, the MTR coding gain is larger than in the case of the Lorentzian response for all detectors. The depth 2 FDTS/DF channel with the rate 4/5 MTR code provides a 2.5 dB SNR gain over the EPR4ML channel with the rate 8/9 $(0,k)$ code. With the particular MR head response used here, EPR4ML already has a 4 dB advantage over PR4ML at this linear density.

Since the MTR code eliminates data patterns with crowded transitions, the overall transition noise, as measured per unit length of track, is expected to be reduced. Fig. 6 shows the simulation results similar to those presented in Fig. 5, except random transition position jitter and transition width variations are included in the read waveform construction process [11]. The rms values of both transition noise parameters are set at 4.4 % of the user bit interval. The SNR reflects only the additive noise component. As is evident from the figure, the coding gain of the MTR code over the $(0,k)$ code is much larger in the presence of transition noise. For example, with τ=2 FDTS/DF detection, the SNR difference is 6 dB between the rate 4/5 MTR code and the rate 8/9 $(0,k)$ code which allows long runs of consecutive transitions.

Although the results are not shown here, we have also observed that the MTR code tends to reduce the relative frequencies of long error events in DFE and FDTS/DF systems.

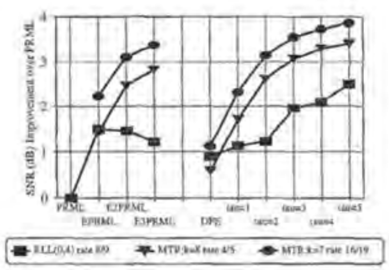

Fig. 4: Summary of PRML and FDTS/DF performances with and without MTR codes (Lorentzian response and additive noise).

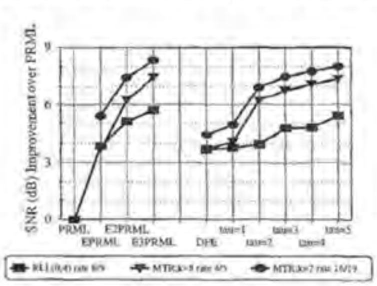

Fig. 5: Summary of PRML and FDTS/DF performances with and without MTR codes (MR head response and additive noise).

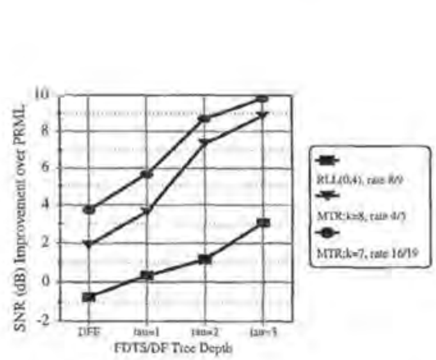

Fig. 6: Summary of FDTS/DF performances with and without MTR codes (MR head response and mixed noise).

V. CONCLUSION

A simple coding scheme is presented which improves the performance of FDTS/DF and high order PRML systems operating at relatively high linear densities. The code eliminates three or more consecutive transitions while allowing the k-constraint for timing purposes. The code can be implemented as simple block codes with reasonable rates such as 4/5, 8/10 and 16/19. BER simulations on FDTS/DF and PRML systems confirm large coding gains over the conventional $(0,k)$ code.

REFERENCES

[1] B. Brickner and J. Moon, "Coding for increased distance with a d=0 FDTS/DF detector," Seagate Internal Report, May 1995; Also see, J. Moon and B. Brickner, "Coded FDTS/DF," presented at the Annual Meeting of the National Storage Industry Consortium, Monterey, CA, June 1995.

[2] J. Moon and B. Brickner, "MTR codes for Data Storage Systems," Invention Disclosure No. 96025, University of Minnesota, September 1995.

[3] B. Brickner and J. Moon, "A signal space representation of FDTS for use with a d=0 code," Globecom'95, Singapore, November 1995.

[4] K. A. S. Immink, "Coding techniques for the noisy magnetic recording channel," *IEEE Trans. Commun.*, vol. 37, no. 6, May 1989.

[5] J. Moon and J.-G. Zhu, "Nonlinearities in thin-film media and their impact on data recovery," *IEEE Transactions on Magnetics*, vol. 29, No. 1, Jan. 1993.

[6] E. Soljanin, "On-track and off-track distance properties of class4 partial response channels," SPIE Conference, Philadelphia, PA, Oct. 1995.

[7] R. Karabed and P. H. Siegel, "Coding for high order partial response channels," SPIE Conference, Philadelphia, PA, Oct. 1995.

[8] P. H. Siegel, "Recording codes for digital magnetic storage," *IEEE Transactions on Magnetics*, vol. MAG-21, no. 5, pp. 1344 - 1349, Sept. 1985.

[9] J. Moon and L. R. Carley, "Performance Comparison of Detection Methods in Magnetic Recording," *IEEE Transactions on Magnetics*, vol. 26, no. 6, Nov. 1990.

[10] B. Brickner and J. Moon, "A high dimensional signal space implementation of FDTS/DF," presented at Intermag '96, Seattle, Washington, April 1996.

[11] J. Moon, "Discrete-time modeling of transition-noise-dominant channels and study of detection performance," *IEEE Transactions on Magnetics*, vol. 27, no. 6, Nov. 1991.

APPENDIX B

On–track and off–track distance properties of Class 4 partial response channels

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ABSTRACT

We consider Class 4 partial response (PR) channels, and examine off-track performance of maximum likelihood sequence estimators for these channels that ignore inter-track interference (ITI). We assume that the pulse response to the head from an adjacent track is the same Class 4 channel, and only its amplitude varies with the track-to-head distance, in a way not known to the receiver. For each of these channels, we find analytical expressions for off-track performance, as well as sets of sequences most susceptible to errors in the ITI environment. We also discuss how the problem of off-track error rate can be alleviated through coding.

Keywords: magnetic recording, class 4, partial response, off–track performance, coding.

1 INTRODUCTION

The transfer function of a digital magnetic recording channel for a given linear density can be closely approximated by a partial response (PR) polynomial of the form $(1-D)(1+D)^N$, for some integer $N \geq 1$. In general, higher linear densities require higher order polynomials. Equalization of a recording channel to the PR channel with the transfer function that best approximates the channel transfer function at a given density will incur the least equalization loss.

A significant noise source in magnetic recording channels is inter-track interference (ITI). When the read head is not centered over the data track, it is partially positioned over an adjacent track and picks up the magnetization from it. When tracks become narrow, the side *fringing* causes the head to pick up signals from an adjacent track, even if it is not physically over that track. An important issue that should affect the choice of N is, therefore, the performance of the corresponding channel in the presence of ITI, often referred to as off-track performance.

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Magnetic recording channels at current linear densities resemble channels with transfer functions of the above form for $N = 1, 2, 3$, referred to as *Class 4* partial response. These channels are also known as $1 - D^2$ or PR4, $(1 - D)(1 + D)^2$ or EPR4, and $(1 - D)(1 + D)^3$ or EEPR4. Most of the commercially available detectors employ PR equalization to the PR4 channel. Using the same detection system at higher linear densities would result in a performance loss. Thus the system should be either augmented by a coding scheme, which would recover the loss through the coding gain, or replaced by a detection system employing PR equalization to the EPR4 or EEPR4 channel. In any case the new system should have good off-track properties.

Several studies analyzed off-track performance of Class 4 channels by simulation (see for example Sayiner[9] and references therein). We find analytical expressions for off-track performance of these channels, as well as sets of sequences most susceptible to errors in the ITI environment. We discuss how the problem of off-track error rate can be alleviated through coding.

In Section II we derive a bound on the error-probability performance for a general discrete-time recording channel with additive white Gaussian noise and a general model of ITI. In Section III we consider Class 4 channels under the assumption that the pulse response to the head from an adjacent track is the same Class 4 channel and only its amplitude varies with the track to head distance. In Section IV we discuss possibilities of coding for these systems. In Section V we provide an extensive summary of the obtained results, for the benefit of a reader not very interested in mathematical details.

2 DISCRETE TIME MAGNETIC RECORDING CHANNEL

2.1 Channel model

We consider a discrete-time model for the magnetic recording channel with input $\boldsymbol{a} = \{a_n\} \in \mathcal{C} \subseteq \{-1, 1\}^\infty$, impulse response $\{h_n\}$, and output $\boldsymbol{y} = \{y_n\}$ given by

$$y_n = \sqrt{E} \sum_m a_m h_{n-m} + \eta_n, \tag{1}$$

where h_n are integer, η_n are independent Gaussian random variables with zero mean and variance σ^2, and E is a constant related to the output voltage amplitude. We refer to E/σ^2 as the signal-to-noise ratio (SNR) per track. In the case of ITI, when the read head picks up magnetization from an adjacent track, the channel model becomes

$$y_n = \sqrt{E} \sum_m a_m h_{n-m} + \sqrt{E} \sum_m x_m g_{n-m} + \eta_n, \tag{2}$$

where $\{g_n\}$ is the discrete-time impulse response of the head to the adjacent track and $\boldsymbol{x} = \{x_n\} \in \mathcal{C}$ is the sequence recorded on that track.

We analyze the performance of the receiver that ignores the ITI assuming the received signal to be as given by (1). It performs maximum likelihood sequence estimation (MLSE) for that model, *i.e.*, it determines an $\widehat{\boldsymbol{a}}$ satisfying

$$\min_{\boldsymbol{a}\in C}\Omega(\boldsymbol{a}) = \Omega(\widehat{\boldsymbol{a}}),$$

where $\Omega(\boldsymbol{a})$ is the well known log-likelihood function for channels with inter-symbol interference,[4]

$$\Omega(\boldsymbol{a}) = \sum_n \big(y_n - \sqrt{E}\sum_m a_m h_{n-m}\big)^2. \tag{3}$$

2.2 Error–probability performance

Let $\boldsymbol{a} = \{a_n\}$ and $\boldsymbol{b} = \{b_n\}$ be two allowable recorded sequences which differ in a finite number of places, and $\boldsymbol{\epsilon} = \{\epsilon_n = (a_n - b_n)/2\}$ be the normalized error sequence corresponding to $\boldsymbol{a}$ and $\boldsymbol{b}$. In the case of no ITI, probability of detecting $\boldsymbol{b}$ given that $\boldsymbol{a}$ was recorded equals to $Q(d(\boldsymbol{\epsilon})\sqrt{\mathrm{SNR}})$, where $d(\boldsymbol{\epsilon})$ is the distance between $\boldsymbol{a}$ and $\boldsymbol{b}$ given by

$$d^2(\boldsymbol{\epsilon}) = \sum_n \big(\sum_m \epsilon_m h_{n-m}\big)^2. \tag{4}$$

Thus a lower bound to the minimum probability of an error event in the system is proportional to $Q\big(d_{\min}\sqrt{\mathrm{SNR}}\big)$, where $d_{\min} = \min_{\boldsymbol{\epsilon}\neq 0} d(\boldsymbol{\epsilon})$.

In the case of ITI we examine the probability of detecting sequence $\boldsymbol{b}$ given that sequence $\boldsymbol{a}$ was recorded on the track being read and sequence $\boldsymbol{x}$ was recorded on an adjacent track. This probability is given by

$$P[\Omega(\boldsymbol{b}) < \Omega(\boldsymbol{a})|\boldsymbol{a},\boldsymbol{x}] = P[\Omega(\boldsymbol{b}) - \Omega(\boldsymbol{a}) < 0|\boldsymbol{a},\boldsymbol{x}].$$

Expressing $\Omega(\boldsymbol{a})$ and $\Omega(\boldsymbol{b})$ as in (3), we obtain

$$\begin{aligned}&P[\Omega(\boldsymbol{b}) - \Omega(\boldsymbol{a}) < 0|\boldsymbol{a},\boldsymbol{x}] =\\ &\qquad P\Big[\sum_n \big(y_n - \sqrt{E}\sum_m a_m h_{n-m}\big)^2 - \sum_n \big(y_n - \sqrt{E}\sum_m b_m h_{n-m}\big)^2 < 0|\boldsymbol{a},\boldsymbol{x}\Big]\end{aligned}$$

Substituting (2) for y_n in the above equation gives

$$\begin{aligned}P[\Omega(\boldsymbol{b}) - \Omega(\boldsymbol{a}) < 0|\boldsymbol{a},\boldsymbol{x}] \;=\; & P\Big[\sum_n \eta_n \sum_m \epsilon_m h_{n-m} + \sqrt{E}\sum_n\big(\sum_m \epsilon_m h_{n-m}\big)^2 +\\ & \sqrt{E}\sum_n\big(\sum_m x_m g_{n-m}\big)\big(\sum_m \epsilon_m h_{n-m}\big) < 0\Big],\end{aligned}$$

where and $\epsilon_n = (a_n - b_n)/2$. Since

$$\frac{1}{\sigma\Big[\sum_n\big(\sum_m \epsilon_m h_{n-m}\big)^2\Big]^{1/2}}\sum_n \eta_n \sum_m \epsilon_m h_{n-m}$$

is a zero-mean, unit-variance Gaussian random variable, we have

$$P[\Omega(\boldsymbol{b}) - \Omega(\boldsymbol{a}) < 0|\boldsymbol{a},\boldsymbol{x}] = Q\big(\delta(\boldsymbol{\epsilon},\boldsymbol{x})\sqrt{\mathrm{SNR}}\big),$$

where $\delta(\boldsymbol{\epsilon}, \boldsymbol{x})$ is the distance between $\boldsymbol{a}$ and $\boldsymbol{b}$ in the *presence* of $\boldsymbol{x}$ given by

$$\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) = \frac{\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2 + \sum_n \left(\sum_m x_m g_{n-m}\right)\left(\sum_m \epsilon_m h_{n-m}\right)}{\left[\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2\right]^{1/2}}.$$

Thus a lower bound to the minimum probability of an error event in the system is proportional to $Q\left(\delta_{\min}\sqrt{\mathrm{SNR}}\right)$, where $\delta_{\min} = \min_{\boldsymbol{\epsilon}\neq 0, \boldsymbol{x}\in\mathcal{C}} \delta(\boldsymbol{\epsilon}, \boldsymbol{x})$.

We derive a simple lower bound on $\delta(\boldsymbol{\epsilon}, \boldsymbol{x})$ as follows:

$$\begin{aligned}
\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) &\geq \frac{\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2 - \left|\sum_n \left(\sum_m x_m g_{n-m}\right)\left(\sum_m \epsilon_m h_{n-m}\right)\right|}{\left[\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2\right]^{1/2}} \\
&\geq \frac{\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2 - \sum_n M\left|\sum_m \epsilon_m h_{n-m}\right|}{\left[\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2\right]^{1/2}},
\end{aligned}$$

where $M = \max_{n,\boldsymbol{x}\in\mathcal{C}} \sum_m x_m g_{n-m}$, *i.e.*, M is the maximum absolute value of the interference. Note that $M = \sum_n |g_n|$. We'll assume that $M < 1$. Since the h_n are integers and $\epsilon_n \in \{-1, 0, 1\}$, we can further bound $\delta(\boldsymbol{\epsilon}, \boldsymbol{x})$ as follows:

$$\begin{aligned}
\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) &\geq \frac{\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2 - M\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2}{\left[\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2\right]^{1/2}} \\
&= (1-M)\left[\sum_n \left(\sum_m \epsilon_m h_{n-m}\right)^2\right]^{1/2},
\end{aligned}$$

and thus

$$\delta_{\min} = \min_{\boldsymbol{\epsilon},\boldsymbol{x}} \delta(\boldsymbol{\epsilon}, \boldsymbol{x}) \geq (1-M) d_{\min}.$$

The bound is achieved if and only if there exists an $\boldsymbol{\epsilon} \in \arg\min_{\boldsymbol{\epsilon}\neq 0} d(\boldsymbol{\epsilon})$ for which $\sum_m \epsilon_m h_{n-m} \in \{-1, 0, 1\}$ for all n, and there exists an $\boldsymbol{x} \in \mathcal{C}$ such that $\sum_m x_m g_{n-m} = \mp M$ whenever $\sum_m \epsilon_m h_{n-m} = \pm 1$. We show below that this bound can be achieved for the PR4 and the EPR4 channels but not for the EEPR4 channel.

3 DISTANCE PROPERTIES OF BINARY CLASS 4 CHANNELS

We now consider Class 4 channels, *i.e.*, channels with transfer functions given by $H(D) = \sum_n h_n D^n = (1-D)(1+D)^N$ for $N = 1, 2, 3$. We assume that the pulse response to the head from an adjacent track is the same Class 4 channel, and only its amplitude varies with the track to head distance with a parameter α, *i.e.* $g_n = \alpha h_n$. This assumption is only approximate since the transition response from a track to a head gets wider as the distance between them increases, as discussed by Vea and Moura[2] and Lindholm.[3] With $g_n = \alpha h_n$, the above lower bound becomes

$$\delta_{\min} = \min_{\boldsymbol{\epsilon},\boldsymbol{x}} \delta(\boldsymbol{\epsilon}, \boldsymbol{x}) \geq (1-\alpha A) d_{\min}, \tag{5}$$

where A is the maximum value of the noiseless Class 4 channel output; $A = 2, 4, 6$ and $d^2_{\min} = 2, 4, 6$ for $N = 1, 2, 3$, respectively.

For the three Class 4 channels, we examine if the bound can be achieved by working in the transform domain where each sequence $\{s_n\}$ has a corresponding function $S(D) = \sum_n s_n D^n$. For that purpose, we note that the minimum distance of the uncoded channel with transfer function $H(D)$ with no ITI, defined by (4), can be expressed as

$$d^2_{\min} = \min_{\epsilon(D)\neq 0} \|H(D)\epsilon(D)\|^2,$$

where $\epsilon(D) = \sum_{i=0}^{l-1} \epsilon_i D^i$, $\epsilon_i \in \{-1,0,1\}$, $\epsilon_0 \neq 0$, $\epsilon_{l-1} \neq 0$, is the polynomial corresponding to a normalized error sequence $\boldsymbol{\epsilon} = \{\epsilon_i\}_{i=1}^{l-1}$ of length l, and the squared norm of a polynomial refers to the sum of its squared coefficients. The bound (5) is achieved if and only if there exists an $\epsilon(D)$ for which $\|H(D)\epsilon(D)\|^2 = d^2_{\min}$ and all coefficients y_n of $y(D) = H(D)\epsilon(D)$ are in the set $\{-1,0,1\}$, and there exists an $\boldsymbol{x} \in \mathcal{C}$ such that in $H(D)\cdot\sum_n x_n D^n = \sum_n z_n D^n$, $z_n = \mp A$ whenever $y_n = \pm 1$.

3.1 The PR4 channel

For $N = 1$ the channel transfer function is equal to $1 - D^2$. This channel is usually treated as two interleaved $1 - D$ channels. For the $1 - D$ channel $d^2_{\min} = 2$ is attained for $\epsilon(D) = \sum_{k=0}^{l-1} D^k$. In this case $\delta(\boldsymbol{\epsilon}, \boldsymbol{x})$ achieves lower bound (5) for $\boldsymbol{x} = \{\cdots, x_{-2}, 1, -1, x_1, \cdots, x_{l-2}, -1, 1, x_{l+1}, \cdots\}$, since the only non-zero coefficients of $y(D) = 1 - D^l$ are $y_0 = 1$, $y_l = -1$, and in $(1 - D)\cdot\sum_n x_n D^n = \sum_k z_k D^k$, we have $z_0 = -2$ and $z_l = 2$. Therefore, for the PR4 channel, $\delta_{\min} = \sqrt{2}(1 - 2\alpha)$.

EXAMPLE 1. Consider a noiseless $1 - D$ channel. Let sequences $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{\epsilon} = (\boldsymbol{a} - \boldsymbol{b})/2$, and $\boldsymbol{x}$ be as follows:

$$\begin{aligned}
\boldsymbol{a} &= \cdots, a_{-1}, -1, +1, +1, +1, a_4, \cdots \\
\boldsymbol{b} &= \cdots, a_{-1}, -1, -1, -1, +1, a_4, \cdots \\
\boldsymbol{\epsilon} &= \cdots, \ 0, \ 0, +1, +1, \ 0, \ 0, \cdots \\
\boldsymbol{x} &= \cdots, x_{-1}, +1, -1, -1, +1, x_4, \cdots
\end{aligned}$$

Let $\boldsymbol{a}$ be recorded on the track being read and $\boldsymbol{x}$ recorded on an adjacent track. Then $\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) = \sqrt{2}$ for $\alpha = 0$, $\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) = 1/\sqrt{2}$ for $\alpha = 0.25$, and $\delta(\boldsymbol{\epsilon}, \boldsymbol{x}) = 0$ for $\alpha = 0.5$.

3.2 The EPR4 channel

For $N = 2$ the channel transfer function is equal to $(1-D)(1+D)^2$. It is well known that $d^2_{\min} = 4$ is attained for $\epsilon(D) = 1$, which gives $y(D) = 1 + D - D^2 - D^3$. However, for the corresponding error sequence, $\delta(\boldsymbol{\epsilon}, \boldsymbol{x})$ cannot achieve lower bound (5) because that would require a sequence $\boldsymbol{x}$ for which two successive outputs of the EPR4 channel equal to 4. In order to see if the lower bound can be achieved, we find all error polynomials $\epsilon(D)$ for which $\|(1-D)(1+D)^2\epsilon(D)\|^2 = 4$.

Polynomial $y(D) = (1-D)(1+D)^2\epsilon(D)$ with $\|y(D)\|^2 = 4$ is of the form $1 + c_1 D^{p_1} + c_2 D^{p_2} + c_3 D^{p_3}$ where, for $i \in \{1,2,3\}$, $c_i \in \{-1,1\}$ and p_i are three different positive integers. From the definition of $y(D)$, we know that $y(1) = 0$, $y(-1) = 0$, $y'\epsilon(1) = 0$ must be satisfied. It can be shown that these conditions require that $y(D)$ be either of the form $\left(1 - D^{2k} + D^{2n+1} - D^{2(k+n)+1}\right)$, $k \geq 1$, $n \geq 0$, or of the form $\left(1 - D^{2k} - D^{2n} + D^{2(k+n)}\right)$, $k, n \geq 1$, $k \neq n$. To further specify $y(D)$ and find the corresponding $\epsilon(D)$, we consider these two cases separately.

1. Polynomial $(1-D)(1+D)^2\epsilon(D) = 1 - D^{2k} + D^{2n+1} - D^{2(k+n)+1}$ factors as
$$(1-D)(1+D)^2 \cdot \Big(\sum_{j=0}^{k-1} D^{2j}\Big)\Big(\sum_{i=0}^{2n}(-1)^i D^i\Big).$$
Therefore $\epsilon(D) = \left(\sum_{i=0}^{2n}(-1)^i D^i\right)\left(\sum_{j=0}^{k-1} D^{2j}\right)$. Since the coefficient of $\epsilon(D)$ are in $\{-1, 0, 1\}$, we conclude that an arbitrary $k > 1$ requires $n = 0$ and an arbitrary $n > 0$ requires $k = 1$. In the first case $\epsilon(D) = \sum_{j=0}^{k-1} D^{2j}$ and $y(D) = 1 + D - D^{2k} - D^{2k+1}$. In the second case $\epsilon(D) = \sum_{i=0}^{2n}(-1)^i D^i$ and $y(D) = \left(1 - D^2 + D^{2n+1} - D^{2n+3}\right)$.

2. Polynomial $(1-D)(1+D)^2\epsilon(D) = 1 - D^{2n} - D^{2k} - D^{2(k+n)}$ factors as
$$(1-D)(1+D)^2 \cdot \Big(\sum_{j=0}^{k-1} D^{2j}\Big)\Big(\sum_{i=0}^{2n-1}(-1)^i D^i\Big).$$
Therefore $\epsilon(D) = \left(\sum_{i=0}^{2n-1}(-1)^i D^i\right)\left(\sum_{j=0}^{k-1} D^{2j}\right)$. Since the coefficient of $\epsilon(D)$ are in $\{-1, 0, 1\}$, we conclude that an arbitrary $k > 1$ requires $n = 1$ and an arbitrary $n > 1$ requires $k = 1$. In the first case $\epsilon(D) = \sum_{j=0}^{2k-1}(-1)^j D^j$ and $y(D) = 1 - D^2 - D^{2k} + D^{2k+2}$. In the second case $\epsilon(D) = \sum_{i=0}^{2n-1}(-1)^i D^i$ and $y(D) = 1 - D^2 - D^{2n} + D^{2n+2}$. These two cases are equivalent as was expected from the symmetry of the original $y(D)$ with respect to n and k.

From 1. and 2. we conclude that the error polynomials $\epsilon(D)$ for which $\|(1-D)(1+D)^2\epsilon(D)\|^2 = 4$ are either of the form $\epsilon(D) = \sum_{j=0}^{k-1} D^{2j}$, $k \geq 1$, in which case $y(D) = \left(1 + D - D^{2k} - D^{2k+1}\right)$, or of the form $\epsilon(D) = \sum_{i=0}^{l-1}(-1)^i D^i$, $l \geq 3$, in which case $y(D) = \left(1 - D^2 - (-1)^l D^l + (-1)^l D^{l+2}\right)$. In the former case $\delta(\epsilon, \boldsymbol{x})$ cannot achieve lower bound (5) because, as above, it would require a sequence $\boldsymbol{x}$ for which two successive outputs of the EPR4 channel equal to 4. It can be shown that in this case $\min_{\boldsymbol{x}\in\mathcal{C}} \delta(\epsilon, \boldsymbol{x}) = \sqrt{4}(1 - 3\alpha)$. In the latter case $\delta(\epsilon, \boldsymbol{x})$ achieves the lower bound for

$$\boldsymbol{x} = \{\cdots, x_{-4}, -1, -1, 1, 1, -1, -1, x_3, \cdots, x_{l-4}, -1, -1, 1, 1, -1, -1, x_{l+3}, \cdots\}$$

for odd $l \geq 5$, or

$$\boldsymbol{x} = \{\cdots, x_4, -1, -1, 1, 1, -1, -1, x_3, \cdots, x_{l-4}, 1, 1, -1, -1, 1, 1, x_{l+3}, \cdots\}$$

for even $l \geq 6$. It can be shown that $\min_{\boldsymbol{x}\in\mathcal{C}} \delta(\epsilon, \boldsymbol{x}) = \sqrt{4}(1 - 3\alpha)$ for $l = 3, 4$. Therefore, for the EPR4 channel, $\delta_{\min} = \sqrt{4}(1 - 4\alpha)$.

EXAMPLE 2. Consider a noiseless EPR4 channel. Let sequences $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{\epsilon} = (\boldsymbol{a} - \boldsymbol{b})/2$, and $\boldsymbol{x}$ be as follows:

$$\begin{aligned}
\boldsymbol{a} &= \cdots, a_{-3}, a_{-2}, a_{-1}, -1, +1, -1, +1, -1, +1, a_6, a_7, a_8, \cdots \\
\boldsymbol{b} &= \cdots, a_{-3}, a_{-2}, a_{-1}, +1, -1, +1, -1, +1, -1, a_6, a_7, a_8, \cdots \\
\boldsymbol{\epsilon} &= \cdots, 0, 0, 0, -1, +1, -1, +1, -1, +1, 0, 0, 0, \cdots \\
\boldsymbol{x} &= \cdots, -1, -1, +1, +1, -1, -1, +1, +1, -1, -1, +1, +1, \cdots
\end{aligned}$$

Let a be recorded on the track being read and x recorded on an adjacent track. Then $\delta(\epsilon, x) = \sqrt{4}$ for $\alpha = 0$, and $\delta(\epsilon, x) = 0$ for $\alpha = 0.25$.

3.3 The EEPR4 channel

For $N = 3$ the channel transfer function is equal to $(1-D)(1+D)^3$. Again, it is well known that $d^2_{\min} = 6$ is attained for $\epsilon(D) = 1 - D + D^2$, which gives $y(D) = 1 + D - D^2 + D^4 - D^5 - D^6$. However, similarly as above, for the corresponding error sequence, $\delta(\epsilon, x)$ cannot achieve lower bound (5) because that would require a sequence x for which a string of three successive outputs of the EEPR4 channel equals to $6, 6, -6$. In order to see if the bound can be achieved, we find all error polynomials $\epsilon(D)$ for which $\|(1-D)(1+D)^3\epsilon(D)\|^2 = 6$. We consider polynomial $y(D) = (1-D)(1+D)^3\epsilon(D) = (1+2D-2D^3-D^4)\cdot(1+\epsilon_1 D+\epsilon_2 D^2+\cdots+\epsilon_{l-3}D^{l-3}+\epsilon_{l-2}D^{l-2}+\epsilon_{l-1}D^{l-1})$. It is easy to check that for all error sequences of length $l \leq 2$, $\|y(D)\|^2 \geq 10$. For error sequences of length $l \geq 3$, polynomial $y(D)$ is of the form $1+(\epsilon_1+2)D+(\epsilon_2+2\epsilon_1)D^2+D^3 z(D)+(-2\epsilon_{l-2}-\epsilon_{l-3})D^{l+1}+(-2\epsilon_{l-1}-\epsilon_{l-2})D^{l+2}+(-\epsilon_{l-1})D^{l+3}$, where $z(D)$ is a polynomial with degree of at most $l-3$. Since $\epsilon_{l-1} \neq 0$, we have $\|y(D)\|^2 \geq 3 + \|z(D)\|^2 + 3$, and therefore $\|y(D)\|^2 = 6$ only if $z(D) = 0$. Therefore $y(D) = 1 + D - D^2 + (-2\epsilon_{l-2} - \epsilon_{l-3})D^{l+1} + (-2\epsilon_{l-1} - \epsilon_{l-2})D^{l+2} + (-\epsilon_{l-1})D^{l+3})$. For $y(1) = 0$, we need $y(D) = 1 + D - D^2 + D^{l+1} - D^{l+2} - D^{l+3}$. For $y(-1) = 0$, we need $y(D) = 1 + D - D^2 + D^{2k} - D^{2k+1} - D^{2k+2}$. For $y'(-1) = 0$, we need $y(D) = 1 + D - D^2 + D^4 - D^5 - D^6$. Note that $y(D) = 1 + D - D^2 + D^4 - D^5 - D^6 = (1-D)(1+D)^3 \cdot (1 - D + D^2)$, and therefore $\epsilon(D) = 1 - D + D^2$ is the only error polynomial for which $\|(1-D)(1+D)^3\epsilon(D)\|^2 = 6$. It can be shown that for the corresponding error sequence ϵ, $\min_{x \in C} \delta(\epsilon, x) = \sqrt{6}(1 - 4\alpha)$. Note that this does not determine $\delta_{\min}$ for the EEPR4 channel.

4 CODING FOR IMPROVING OFF–TRACK PERFORMANCE

It was shown above that a lower bound to the minimum probability of an error-event in the system with ITI is proportional to $Q(\delta_{\min}\sqrt{\text{SNR}})$, where

$$\delta_{\min} = \min_{\epsilon, x} \delta(\epsilon, x) \geq (1 - M) d_{\min}.$$

This bound was derived for an arbitrary set of recorded sequences, $\mathcal{C} \subseteq \{-1, 1\}^\infty$, and therefore holds in coded as well as uncoded systems. Whether it can be achieved depends on the code. The value of $d^2_{\min}$ is also determined by the code. To improve the error-probability performance of the system, we need codes that increase $d^2_{\min}$ or ensure that the above bound is never achieved or, preferably, perform both tasks.

Codes that increase $d^2_{\min}$ are existing codes designed to improve the on-track performance, *i.e.*, performance of channels with no ITI, as for example matched spectral null codes.[7] In general, these codes may improve the off-track performance as well, since they are likely to reduce the fraction of sequences x for which the bound on $\delta(\epsilon, x)$ can be achieved for a given ϵ. To argue that, we recall that the bound is achieved if and only if there exists an $\epsilon \in \arg\min_{\epsilon \neq 0} d(\epsilon)$ for which $\sum_m \epsilon_m h_{n-m} \in \{-1, 0, 1\}$ for all n and there exists an $x \in \mathcal{C}$ such that $\sum_m x_m g_{n-m} = \mp M$ whenever $\sum_m \epsilon_m h_{n-m} = \pm 1$. Codes for improving noise immunity reduce the set of sequences $\epsilon \in \arg\min_{\epsilon \neq 0} d(\epsilon)$ for which $\sum_m \epsilon_m h_{n-m} \in \{-1, 0, 1\}$ for all n. For the sequences that remain, the number of n such that $\sum_m \epsilon_m h_{n-m} = \pm 1$ is higher, and therefore sequence $\boldsymbol{x}$ has to satisfy more conditions. A good example of this case is a dc-free coded PR4 channel.

Design of high rate codes which improve both on- and off-track error probability performance of Class 4 channels may be a complex problem, and we do not attempt to solve it at this point. Instead, we discuss off-track performance of a dc-free coded PR4 channel and present some coding ideas for the EPR4 and EEPR4 channels which transpired from the above distance properties analysis.

4.1 The PR4 channel

It has been observed in laboratory experiments that a dc-free coded PR4 channel has better off-track performance than its uncoded counterpart.[5] For a dc-free coded $1-D$ channel $d^2_{\min} = 4$ is obtained for $e(D) = 1 - D^{l-1}$, and the corresponding $y(D)$ is equal to $1 - D - D^{l-1} + D^l$. It is easy to see that in this case $\delta(\epsilon, \boldsymbol{x})$ achieves lower bound (5) for $\boldsymbol{x} = \{\cdots, x_2, 1, -1, 1, x_2, \cdots, x_{l-3}, -1, 1, -1, x_{l+1}, \cdots\}$ where $l \geq 4$. Therefore, for the dc-free coded PR4 channel, $\delta_{\min} = \sqrt{4}(1 - 2\alpha)$ degrades with α at the same rate as it does for the uncoded system. However, the sequence $\boldsymbol{x}$ for which the bound is achieved has 6 symbols specified as opposed to at most 4 in the uncoded case. In addition, the bound cannot be achieved for all error sequences for which $\|e(D)H(D)\|^2 = d^2_{\min}$, as in uncoded case, but only for those of length $l \geq 4$.

4.2 The EPR4 channel

Based on the distance properties described above, we know that $\min_{\boldsymbol{x} \in C} \delta(\epsilon, \boldsymbol{x}) = \sqrt{4}(1 - 4\alpha)$ if and only if $\epsilon(D) = \sum_{i=0}^{l-1}(-1)^i D^i$, $l \geq 5$. It can be shown that for all other error sequences for which $\|H(D)e(D)\|^2 = 4$, we have $\min_{\boldsymbol{x} \in C} \delta(\epsilon, \boldsymbol{x}) = \sqrt{4}(1 - 3\alpha)$. Therefore, an improvement in the off-track performance of this channel can be accomplished by limiting the length of subsequences of alternating symbols to four. For the NRZI type of recording, this can be achieved by a code that limits the runs of successive ones to three, as the binary complement of the industry standard $8/9\,(0, 3)$ block code, introduced for IBM 3480 tape drive. This code has a simple and inexpensive implementation proposed by A. M. Patel.[6] In general, using a code that removes long sequences of alternating symbols at the input of the EPR4 channel is advantageous since these sequences result in long sequences of zeros at the channel output, which is undesirable for timing and gain control.

4.3 The EEPR4 channel

It was shown above that the only error polynomial for which $\|(1-D)(1+D)^3\epsilon(D)\|^2 = 6$ is $\epsilon(D) = 1 - D + D^2$. This error event can be removed by a code that does not allow successive transitions. For the NRZI type of recording, this can be achieved by a code that does not allow successive ones, as $2/3\,(1, 7)$ code. Using this code for high linear density recording systems has already been proposed as a means of reducing the problems associated with closely recorded neighboring transitions. It can be shown that the code also removes all error sequences for which this polynomial has all its coefficients in the set $\{-1, 0, 1\}$. Therefore $2/3\,(1,7)$ code gives a performance improvement of for EEPR4 channel with no ITI, and ensures that the lower bound on the performance of the channel with ITI is never achieved. An additional benefit of the code is that it reduces the number of states in the EEPR4 Viterbi detector from 16 to 10 since successive transitions are illegal. The main drawback of the code is its low rate.

5 SUMMARY AND CONCLUSIONS

Magnetic storage detectors employing PR4 equalization exhibit loss in performance at high recording densities and need to be replaced. Two systems are being considered for next generation products: the dc-free coded PR4 channel and the EPR4 channel. Various error probability performance and implementation issues of these two systems should be examined in order to decide which one is a better choice. The analytical results of this paper together with the simulation results obtained by Sayiner[8,9] allow as to compare the systems on the basis of their off-track performance. In addition, the analytical results give an understanding of the systems necessary if coding is to be used for performance improvement.

We analyzed on- and off-track distance properties of PR4, EPR4, and EEPR4 channels, known as Class 4. We also looked at off-track performance of the dc-free coded PR4 channel, and showed some possibilities of improving performance of the EPR4 and EEPR4 channels through coding. Design of high rate codes which improve both on- and off-track error probability performance of Class 4 channels is, however, an interesting open problem. Most of the obtained results are summarized below.

Magnetic recording channels operate at high SNR where the probability of an error event in the system with no ITI is well approximated by $Q(d_{\min}\sqrt{\text{SNR}})$. We found that under the same conditions probability of an error event in the system with ITI is well approximated by $Q(\delta_{\min}\sqrt{\text{SNR}})$, where $\delta_{\min} \geq d_{\min}(1-M)$ and M is the maximum value that the output of the noiseless channel between the reading head and an adjacent track can take. With the assumption that the pulse response to the reading head from an adjacent track is the same Class 4 channel, and only its amplitude varies with the track to head distance with a parameter α, we have $\delta_{\min} \geq d_{\min}(1-\alpha A)$ where A is the maximum value the noiseless Class 4 channel output can take ($A = 2, 4$, and 6 for PR4, EPR4, and EPR4 respectively).

We found that the uncoded as well as coded PR4 channel have much better off-track performance than the EPR4 channel, *i.e.*, $\delta_{\min}/d_{\min} = 1 - 2\alpha$ for the PR4 channel and $\delta_{\min}/d_{\min} = 1 - 4\alpha$ for the EPR4 channel, as shown in Fig. 1. The results are in agreement with the ones reported earlier by Sayiner.[8,9] It was found[8] that at a given user density of 2.2, the EPR4 is about 1.2 dB better than the PR4 at 0 % off-track, but only about 0.2 dB at 5 % off-track. In Fig. 1 we see that at 5 % off-track the loss in performance of the PR4 is about 1 dB smaller than the loss of the EPR4.

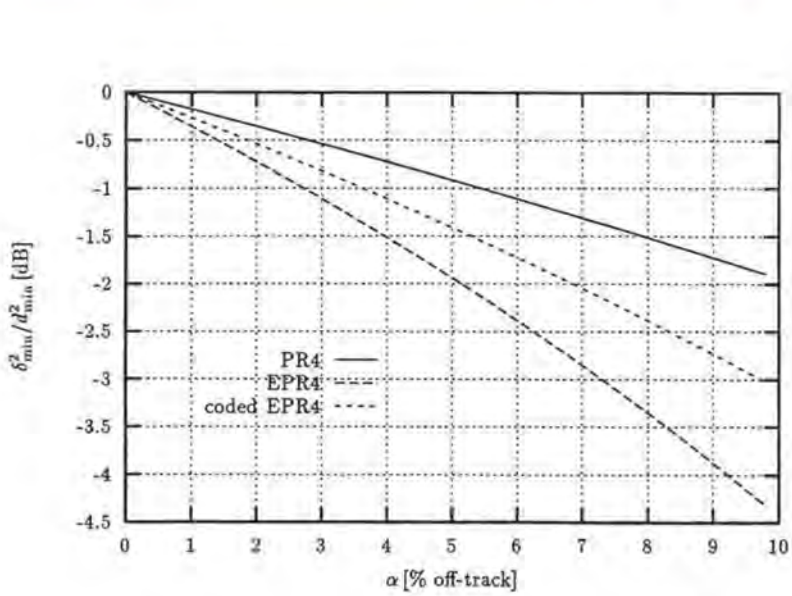

Figure 1: Off-track performance of PR4 and EPR4 channels.

From the EPR4 channel distance properties analysis, we concluded that the channel off-track performance can be improved by a code that limits the runs of successive ones to three. For this purpose we can use the binary complement of the industry standard 8/9 (0, 3) block code.

As mentioned above, we also analyzed the distance properties of the EEPR4 channel and showed that its off-track performance for small α is the same as the off-track performance of the EPR4 channel. We also found that the 2/3 (1, 7) code gives a performance improvement for the EEPR4 channel with no ITI, and ensures that the lower bound on the performance of the channel with ITI is not achieved.

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6 REFERENCES

[1] W. L. Abbot, J. M. Cioffi, and H. K. Thapar, "Performance of digital magnetic recording with equalization and off-track interference," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 705–716, Jan. 1991.

[2] M. P. Vea and J. M. F. Moura, "Magnetic recording channel model with inter-track interference," *IEEE Trans. Magn.*, vol. 27, no. 6, pp. 4834–4836, Nov. 1991.

[3] D. A. Lindholm, "Spacing losses in finite track width reproducing systems," *IEEE Trans. Magn.*, vol. 14, no. 2, pp. 55–59, Mar. 1978.

[4] J. G. Proakis, *Digital Communications*, New York, NY: McGraw-Hill, 1983.

[5] P. H. Siegel, *Personal communications.*

[6] C. D. Mee and E. D. Daniel, *Magnetic Recording, Volume II: Computer Data Storage*, New York, NY: McGraw-Hill, 1987.

[7] R. Karabed and P. H. Siegel, "Matched spectral-null codes for partial response channels," *IEEE Trans. Inform. Theory*, vol. 37, no. 3, pt. II, pp. 818–855, May 1991.

[8] N. Sayiner, "Use of extended partial response for magnetic recording - pt. 1: Performance simulation with SHIVA architecture," *538510000-950116-01 TM*

[9] N. Sayiner, "The impact of the track density vs. linear density trade-off on the read channel: TCPR4 vs. EPR4," *this conference.*

APPENDIX C

EMINA SOLJANIN

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RESEARCH EXPERTISE AND INTERESTS

Theoretical understanding and practical solutions that enable efficient, reliable, and secure operation of communications networks. Power systems. Quantum computation.

EDUCATION

Ph.D. Electrical Engineering, Texas A&M University, *1994.*

Dissertation: *Coding for Improving Noise Immunity in Multi-Track, Multi-Head Recording Systems*

Research areas: constrained coding, symbolic dynamics, multi-input, multi-output communications, and data storage.

M.S. Electrical Engineering, Texas A&M University, *1989.*

Thesis: *New Approach to the Design of Digital Algorithms for Electric Power Measurements*

Research areas: power systems and digital signal processing.

B.S. European Diploma Degree (M.S. equivalent), Electrical Engineering, University of Sarajevo, Bosnia and Herzegovina (former Yugoslavia), *1986.*

Thesis: *Long-Term Hydro-Plants Scheduling for Electric Power Networks*

Research areas: power systems, stochastic and combinatorial optimization, and graph theory.

EMPLOYMENT HISTORY

Professor, Rutgers University, *Jan. 2016 –*

Member of Technical Staff, Mathematics of Networks and Systems Research Department, Bell Labs, **Postdoctoral** *Sept. 1994 – Dec. 2015 Jan. 1996,* **Regular** *Feb. 1996 – Mar. 2004,* **Distinguished** *Apr. 2004 –.*
Working on a wide range of mathematical problems arising in communications and storage networks; in particular coding, information theoretic, and (more recently) queueing problems concerning efficient, reliable, and secure networking for big data.

Research Engineer, Energoinvest, IRIS Institute, Department for Mathematical Modelling, Sarajevo, Bosnia, *June 1986 – May 1988.*
Developing optimization algorithms and software for power system planning and operation.

TEACHING, MENTORING, AND UNIVERSITY RESEARCH VISITS

Visiting Scientist The Simons Institute for the Theory of Computing, UC Berkeley, *Spring 2015.*

Lecturer for the *2011 Information Theory Summer School.*

Guest Professor at ENSEA/Univ. Cergy-Pontoise/CNRS, ETIS group, France, *Sept. 2010.*

Guest Lecturer at the University College Dublin, Claude Shannon Institute, *Jan. 2009,* teaching an intensive course on *Network Coding.*

Visiting Professor at Ecole Polytechnique Fédérale de Lausanne (EPFL), *Jan.–Dec. 2008*

Adjunct Professor at Columbia University, *Spring 2004–Fall 2005,* teaching *Communication Theory I & II.*

Adjunct Professor at Brooklyn Polytechnic University, *Fall 2004,* teaching *Inform. Theory*

Lecturer at Texas A&M University, *academic year 1993/1994,* teaching *Elec. Circuit Theory.*

Lecturer at University of Sarajevo, Bosnia, *academic years 1986/1987 and 1987/1988,* teaching *Signal Processing I & II.*

Mentor for an NSF postdoctoral researcher at Bell Labs, *July 2010 – July 2012*

Mentor for two Bell Labs postdoctoral researchers, *May 1998 – May 2000* and *Jan. 2000 – Jan. 2001,* organizing and supervising their research projects.

Mentor for summer interns at Bell Labs and DIMACS, organizing and supervising research projects for up to three interns almost every summer since 1997.

Ph.D Thesis Committee Member, students at Rutgers (4), Columbia (1), EPFL (3), Aalborg (1), MIT (2), Toronto (1). – *various degrees of supervision/involvement*

Host Scientist for Bell Labs Global Science Scholars program for final-year high-school (2003–2005). Project design, lecturing, and a week-long supervision for visiting students.

PROFESSIONAL ACTIVITIES AND SERVICE

IEEE Information Theory Society Fellows Committee Member, 2016 – .

IEEE Koji Kobayashi Award Committee Member, 2014 –

IEEE Richard W. Hamming Medal Committee Member, 2013 –2016.

External Advisory Committee and **Industrial Board Member** for the NSF Science & Technology Center for Science of Information (NSF-STC-CSoI), 2013 –.

Best Paper Award Committee Member (3 times) for *IEEE Inform. Theory Society*

Board of Governors Member for the *IEEE Inform. Theory Soc.*, 2009 – 2011 and 2013 –.

DIMACS Council Member, 2003 –.

DIMACS Postdoctoral Committee Member, 2001 – 2011.

Co-Chair for DIMACS Special Focus on Cybersecurity, 2011 – 2015.

Co-Chair for DIMACS Special Focus on Comput. Inform. Th. and Coding, 2000 – 2005.

Guest Editor for the *Elsevier-PhyCom, Special Issue on Network Coding and its Applications to Wireless Communications,* March 2013.

Editorial Board Member *Springer Journal on Applicable Algebra in Engineering, Communication and Computing,* 2008 –.

Associate Editor for Coding Techniques, *IEEE Trans. on Inform. Theory,* 1997 – 2000.

Technical Program Co-Chair for the *2008 IEEE Inform. Theory Workshop* and *2012 International Symposium on Network Coding*

Workshop Co-Organizer

(upcoming, organization and funding granted based on a proposal):

Codes for Data Storage with Queues for Data Access, July, 2017 within the ICERM Women in Data Science and Mathematics Research Collaboration Workshop.

(past selected, organization and funding granted based on a proposal):

Dagstuhl Seminar on *Coding Theory in the Time of Big Data,* Schloss Dagstuhl, Aug. 2016, DIMACS Workshop on *Network Coding: the Next 15 Years,* Dec. 2015, BIRS Workshop on *Mathematical Coding Theory in Multimedia Streaming,* Banff, Oct. 2015. DIMACS Workshop on *Coding Theoretic Methods for Network Security,* April 2015, INFOCOM Workshop on *Communications and Networking Techniques for Contemporary Video*, April 2014, DIMACS Workshop and Working Group on Algorithms for Green Data Strage, Dec. 2013, Dagstuhl Seminar on Coding Theory, Schloss Dagstuhl, Aug. 2013, BIRS Workshop on *Applications of Matroid Theory and Combinatorial Optimization to Information and Coding Theory,* Banff, Aug. 2009, DIMACS Working Group and Workshop on *Coding, Streaming and Compressive Sensing* (March 2009), DIMACS Working Group on *Network Coding* Jan. 2005 and DIMACS Working Group and Workshop on *Theoretical Advances In Information Recording* (March 2004).

Special-Session Organizer *(selected, invited to organize):* Tutorials at *2015 IEEE Internat. Symp. on Inform. Theory (ISIT'15),* "Information Theory & Coding for Contemporary Video," *2013 IEEE Inform. Theory Workshop (ITW'13)* in Seville, "Network Coding" at *2006 IEEE Comm. Theory Workshop* (CTW'06) in Puerto Rico, "Network Coding" at *2006 IEEE Inform. Theory Workshop (ITW'06)* in Chengdu, "Emerging Applications of Information Theory" at *2004 IEEE Inform. Theory Workshop (ITW'04)* in San Antonio.

Technical Program Committee Member for *(selected) IEEE Internat. Symp. on Inform. Theory (ISIT),* 2000 – 2002, 2004, and 2008 – , *IEEE Inform. Theory Workshop (ITW),* 2004 – 2009, *IEEE 2005 Int. Conf. Wireless Networks, Commun., and Mobile Comput., Int. Workshop on Wireless Networks: Communication, Cooperation and Competition,* 2007, *Commun. Theory Symp. at IEEE Global Telecommun. Conf. (GLOBECOM) 2007–2008*, *Internat. Conf. on Comm. (ICC)* 2009.

Technical proof-reader for the *IEEE Transac. Inform. Theory,* 1990 – 1992.

Research Proposal Reviewer for NSF, BSF (United States-Israel Binational Science Foundation), Danish Research Council for Technology and Production Sciences, Research Grants Council of Hong Kong, SFI (Science Foundation of Ireland), UC MICRO Program (University of California Microelectronics Innovation and Computer Research Opportunities).

Affiliations with IEEE Inform. Theory Society, American Mathematical Society (AMS), NSF Center for Discrete Mathematics and Computer Science (DIMACS).

SELECTED BELL LABS SERVICE

Graduate Research Program for Women (GRPW) and **Cooperative Research Fellowship Program (CRFP) for Minorities and Women** committee member, 2002 – 2009.

Global Science Scholars committee member and host to student visitors, 2003–2005.

Afirmative Action Committee Member, 1996 – 1999.

Library Liaison, provided periodic recommendations for book ordering, collected and provided feedback on journal usage, 1996 – .

Seminars Sponsor, recruited and hosted speakers for several internal seminars and reading groups, 1996 – .

Committee Service, served on numerous hiring and various ad-hoc committees, 1995 – .

RECOGNITIONS

- *Distinguished Lecturer* for IEEE Information Theory Society, 2015 – 2016.
- *IEEE Fellow*, for contributions to coding theory and coding schemes for transmission and storage systems, *class of 2014*.
- *IEEE IT Society 2013 Padovani Lecturer,* a person whose research is considered to be of particular interest to students and postdocs is selected to give a special lecture at the yearly North American School of Information Theory. Lecture Ttile: "Secret Lives of Codes: From Theory to Practice and Back"
- *Best Paper Award* for the paper "Trade-off between cost and goodput in wireless: replacing transmitters with coding," (with M. Kim, M. Medard, MIT, J. Barros, Univ. of Porto, and T. Klien, Bell Labs) at *MONAMI'13*.
- *Honorable mention of the paper* "Asymptotic spectra of trapping sets in irregular LDPC code ensembles," (with O. Milenkovic, and P. Whiting, Bell Labs) at the *ICC 2006;* citation: "It provided an important contribution towards the statistical characterization and understanding of trapping sets, which are crucial to the assessment of error-floor effects in LDPC codes."
- *Distinguished Member of Technical Staff*, Bell Labs, March 2004.
- *IEEE Senior Member*, July 2003.
- Recognized as an *exceptional Bell Labs intern mentor* for the Summer 2003.
- IEEE *Referee Recognition* Award, 1998.
- Recognized in the 25th anniversary issue of *EE Times* as one of the 20 young engineers who are likely to make "significant contributions in the new millennium", Oct. 1997.
- Recognized for *teamwork at Bell Labs*, Dec. 1994.
- *Fouraker Fellowship* by EE Department, Texas A&M University, Sep. 1992 – Aug. 1993.
- *Electrical Powe Institute Fellowship* for the masters at EE Department, Texas A&M University, Jun. 1988 – Dec. 1989.

FUNDING

DIMACS Funds – awarded by the NSF and other funding agencies for *DIMACS Special Focus on Cybersecurity,* for workshops, seminar series, visitors, and postdocs from 2011 through 2015. *(Focus Co-Chair)*

NSF NeTS Medium Grant for *Collaborative Research: Secure Networking Using Network Coding* at the level of $882,357 (with Caltech, Purdue, and UT Austin), Sept. 2009 – Aug. 2013. *(Co-PI)*

DARPA IAMANET Contract for *PIANO: Principles for Intrinsically Assurable Network Operation,* with a multidisciplinary team from several universities (Caltech, MIT, Stanford, UMass, UT Austin), led by BAE, 2008. *(personal share $241,000 over 18 months)*

NSF NeTS-NBD Small Grant for *Coding and Transmission Schemes for Content Download* at the level of $569,000 (with UIUC and Rutgers), Sept. 2007 – Aug. 2010. *(Co-PI)*

NSF ITR Medium Grant for *Network Coding From Theory to Practice* at the level of $1.85 million (with Caltech, MIT, and UIUC), Sept. 2003 – Aug. 2008. *(Co-PI)*

DIMACS Funds – $205,000 budget awarded by the NSF and other funding agencies for *DIMACS Special Focus on Computational Information Theory and Coding* for workshops, seminar series, visitors, and postdocs from 2001 through 2004. *(Focus Co-Chair)*

NAE Research Grant – American recipient of the 1999 $10,000 Research Grant by the German-American Networking Program of the *National Academy of Engineering* and its German counterpart. (Elke Offer, TU Munich, was the German recipient.)

JOURNAL PUBLICATIONS

1. L. Tan, Y. Li, A. Khisti, E. Soljanin, "Successive segmentation-based coding for broadcasting over erasure channels," *IEEE Trans. Inform. Theory,* pp. 3026–3038, Jun. 2016.

2. C. Fragouli and E. Soljanin, "(Secure) Linear network coding multicast - A theoretical minimum and some open problems," *Journal on Des. Codes and Cryptography, The 25th Anniversary Issue,* pp. 269–310, Jan. 2016.

3. G. Joshi, E. Soljanin, and G. Wornell, "On the delay-storage trade-off in content download from coded distributed storage systems," *ACM Transactions on Modeling and Performance Evaluation of Computing Systems,* submitted Oct. 2015, revised Nov. 2016.

4. K. Guan, A. Tulino, P. Winzer, and E. Soljanin, "Secrecy capacities in space-division multiplexed fiber-optic communication systems," *IEEE Trans. Inform. Forensics & Security,* pp. 1325–1335, July 2015.

5. M. Kim, T. Klein, E. Soljanin, J. Barros, M. Médard, "Modeling network coded TCP: analysis of throughput and energy cost," *ACM Springer Mobile Networks and Applications (MONET) Journal,* pp. 790–803, Dec. 2014.

6. G. Joshi, Y. Liu, and E. Soljanin, "On the delay-storage trade-off in content download from coded distributed storage systems," *IEEE J-SAC Special Issue on Communication Methodologies for the Next-Generation Storage Systems,* pp. 989–997, May 2014.

7. E. Song, E. Soljanin, P. Cuff, and V. H. Poor, "Rate-distortion-based physical layer secrecy with applications to multimode fiber," *IEEE Trans. Commun.,* pp. 1080–1090, March 2014.

8. S. Kokalj, E. Soljanin, and P. Spasojevic, "Low complexity differentiating adaptive erasure codes in multimedia wireless broadcast," *IEEE Trans. Commun.,* pp. 3462-3471, Aug. 2013.

9. Y. Li, E. Soljanin, and P. Spasojević, "Three schemes for wireless coded broadcast to heterogeneous users," *Elsevier-PhyCom, Special Issue on Network Coding and its Applications to Wireless Communications,* pp. 114–123, March 2013.

10. Z. Kong, E. Yeh, and E. Soljanin, "Coding improves the throughput-delay trade-off in mobile wireless networks," *IEEE Trans. Inform. Theory,* pp. 6894–6906, Nov. 2012.

11. I. Andriyanova and E. Soljanin, "Optimized IR-HARQ schemes based on punctured LDPC codes over the BEC," *IEEE Trans. Inform. Theory,* pp. 6433-6445, Oct. 2012.

12. S. Kokalj and E. Soljanin, "Suppressing the cliff effect in video reproduction quality," *Bell Labs Technical Journal, Video Issue,* March 2012.

13. S. El Rouayheb, E. Soljanin, and A. Sprintson, "Secure network coding for wiretap networks of type II," *IEEE Trans. Inform. Theory,* pp. 1361–1371, March 2012.

14. Y. Li, E. Soljanin, and P. Spasojević, "Effects of generation size and overlap on throughput and complexity in randomized linear network coding," *IEEE Trans. Inform. Theory,* pp. 1111–1123, Feb. 2011.

15. Z. Kong, S. Aly, and E. Soljanin, "Decentralized coding algorithms for distributed storage in wireless sensor networks," invited for *IEEE J-SAC Special Issue on Data Communication Techniques for Storage Channels and Networks,* pp. 261–267, Feb. 2010.

16. S. Kokalj, P. Spasojevic, and E. Soljanin, "Doped Fountain coding for minimum delay data collection in circular networks," *IEEE J-SAC Special Issue on Network Coding for Wireless Communication Networks,* pp. 673–684, June 2009.

17. E. Soljanin, P. Gupta, G. Kramer, "Network coding for efficient network multicast," *Bell Labs Technical Journal, Enabling Science and Technology Issue,* pp. 157-166, March 2009.

18. Z. Kong, S. Aly, E. Soljanin, E. Yeh, and A. Klappenecker, "Network coding capacity of random wireless networks under a signal-to-noise-and-interference ratio model," *IEEE Trans. Inform. Theory,* submitted 2008.

19. E. Soljanin, "Network Multicast with Network Coding," *IEEE Signal Processing Magazine*, pp. 109–112, Sept. 2008.

20. R. Liu, P. Spasojevic, and E. Soljanin, "Incremental redundancy cooperative coding for wireless networks: cooperative diversity, coding, and transmission energy gain," *IEEE Trans. Inform. Theory,* pp. 1207–1224, March 2008.

21. O. Milenkovic, E. Soljanin, and P. Whiting, "Asymptotic spectra of trapping sets in regular and irregular LDPC code ensembles," *IEEE Trans. Inform. Theory,* pp. 39–55, Jan. 2007.

22. C. Chekuri, C. Fragouli, and E. Soljanin, "On average throughput benefits and alphabet size in network coding," *IEEE Trans. Inform. Theory,* pp. 2410–2424, June 2006.

23. R. Liu, P. Spasojevic, and E. Soljanin, "Reliable channel regions for good binary codes transmitted over parallel channels," *IEEE Trans. Inform. Theory,* pp. 1405–1424, April 2006.

24. C. Fragouli and E. Soljanin, "Information flow decomposition for network coding," *IEEE Trans. Inform. Theory,* pp. 829–848, March 2006.

25. R. Liu, P. Spasojevic, and E. Soljanin, "On the weight spectrum of good linear binary codes," *IEEE Trans. Inform. Theory,* pp. 4369–4373, Dec. 2005.

26. E. Soljanin, N. Varnica, and P. Whiting, "Incremental redundancy hybrid ARQ with LDPC and Raptor codes," submitted to *IEEE Trans. Inform. Theory,* Sept. 2005.

27. E. Soljanin and E. Offer, "Bit-optimal decoding of codes whose Tanner graphs are trees," J. Discrete Applied Mathematics, Elsevier Science, vol. 128/1, pp. 293–303, 2003.

28. E. Soljanin, "Compressing quantum mixed-state sources by sending classical information," *IEEE Trans. Inform. Theory,* pp. 2263–2275, Aug. 2002.

29. E. Soljanin, "Writing sequences on the plane," *IEEE Trans. Inform. Theory,* pp. 2263–2275, June 2002.

30. A. Mojsilović, J. Hu, and E. Soljanin, "Extraction of perceptually important colors and similarity measurement for image matching, Retrieval, and Analysis," *IEEE Trans. Image. Proc.,* pp. 1238–1248, Nov. 2002.

31. A. Mojsilovic and E. Soljanin, "Color quantization and processing by Fibonacci lattices," *IEEE Trans. Image Proc.,* pp. 1712–1725, Nov. 2001.

32. E. Soljanin and A. J. Van Wijngaarden, "Application of distance enhancing codes," *IEEE Trans. Magn.,* pp. 762–767, Mar. 2001.

33. R. Karabed, P. H. Siegel and E. Soljanin, "Constrained coding for binary channels with high intersymbol interference," *IEEE Trans. Inform. Theory,* pp. 1777–1797, Sept. 1999.

34. B. E. Moision, P. H. Siegel, and E. Soljanin, "Distance-enhancing codes for digital recording," *IEEE Trans. Magn.,* pp. 69-74, Jan. 1998.

35. E. Soljanin and C. N. Georghiades, "Multihead detection for multitrack recording channels," *IEEE Trans. Inform. Theory,* pp. 2988–2997, Nov 1998.

36. E. Soljanin "A coding scheme for generating bipolar dc-free sequences," *IEEE Trans. Magn.,* pp. 2755–2757, Sept. 1997.

37. E. Soljanin and C. N. Georghiades, "Coding for two-head recording systems," *IEEE Trans. Inform. Theory,* pp. 747–755, May 1995.

38. M. Kezunovic, E. Soljanin, B. Perunicic, and S. Levi, "New approach to the design of digital algorithms for electric power measurements," *IEEE Trans. Power Delivery,* Vol. 6, pp. 516–523, Apr. 1991.

39. B. Perunicic, M. Kezunovic, and E. Soljanin, and S. Levi, "Digital signal processing algorithms for power and line parameter measurements with low sensitivity to frequency change," *IEEE Trans. Power Delivery,* Vol. 5, pp. 1209–1215, Apr. 1990.

REFEREED CONFERENCE PUBLICATIONS

1. M. Noori, E. Soljanin, M. Ardakani, "On storage allocation for maximum service rate in distributed storage systems," *2016 IEEE Int. Symp. Inform. Theory (ISIT'16),* Barcelona, July 2016.

2. K. Guan, P. Winzer, A. Tulino, and E. Soljanin, "Physical layer security of space-division multiplexed fiber-optic communication system in the presence of multiple eavesdroppers," *2015 IEEE Global Telecommunications Conf. (GLOBECOM'15),* San Diego, Dec. 2015.

3. G. Joshi, E. Soljanin, and G. Wornell, "Using efficient redundancy to reduce latency in cloud systems," *52nd Annual Allerton Conference,* Monticello, IL, Oct. 2015.

4. S. Kadhe, E. Soljanin, and A. Sprintson, "When do the availability codes make the stored data more available?" invited for *53nd Annual Allerton Conference,* Monticello, IL, Oct. 2015.

5. Y. Li, K. Guo, X. Wang, E. Soljanin, and T. Woo, "SEARS: Space efficient and reliable storage system in the cloud," *40th IEEE Conference on Local Computer Networks (LCN),* Clearwater Beach, FL, USA, Oct. 2015.
6. U. J. Ferner, M. Médard, E. Soljanin, "Why reading patterns matter in storage coding and scheduling design," *8'th IEEE International Conference on Cloud Computing (IEEE CLOUD 2015)*, New York, July, 2015.
7. G. Joshi, E. Soljanin, and G. Wornell, "Queues with Redundancy: Latency-Cost Analysis," *Mathematical Performance Modeling and Analysis (MAMA) Workshop in conjunction with ACM SIGMETRICS,* Prtland, OR, June 2015.
8. S. Kadhe, E. Soljanin, and A. Sprintson, "Analyzing the download time of availability codes," *2015 IEEE Int. Symp. Inform. Theory (ISIT'15),* Hong Kong, June 2015.
9. L. Tan, M. Kaveh, A. Khisti, and E. Soljanin, "Coding for source-broadcasting over erasure channels with feedback," *2015 IEEE Int. Symp. Inform. Theory (ISIT'15),* Hong Kong, June 2015.
10. M. Heindelmaier and E. Soljanin, "Isn't hybrid ARQ enough?" invited for *52nd Annual Allerton Conference,* Monticello, IL, Oct. 2014.
11. A. Singh Rawat and E. Soljanin, "Dynamic control of video quality for AVS," *2014 IEEE Int. Symp. Inform. Theory (ISIT'14),* Honolulu, July 2014.
12. Y. Li, L. Tan, A. Khisti, and E. Soljanin, "Successive segmentation-based coding for broadcasting over erasure channels," *2014 IEEE Int. Symp. Inform. Theory (ISIT'14),* Honolulu, July 2014.
13. I. Andriyanova, A. Julé, and E. Soljanin, "The code rebalancing problem for a storage-flexible data center network," *2013 IEEE International Conference on Big Data (IEEE BigData 2013)*, Santa Clara, CA, Oct. 2013.
14. K. Guan, P. Winzer, E. Soljanin, and A. Tulino, "On the secrecy capacity of the space-division multiplexed fiber optical communication systems," *2013 First IEEE Conference on Communications and Network Security (CNS'13),* Washington, DC, Oct. 2013.
15. M. Kim, T. Klien, E. Soljann, M. Médard, and J. Barros,"Trade-off between cost and goodput in wireless: replacing transmitters with coding," *5th Int. Conf. on Mobile Networks and Management (MONAMI'13)*, Cork, Ireland, Sept. 2013. *(best paper award)*
16. E. Soljanin, "Some coding and information theoretic problems in contemporary (video) content delivery," *2013 IEEE Inform. Theory Workshop (ITW'13),* Seville, Spain, Sept. 2013. *(invited)*
17. L. Tan, Y. Li, A. Khisti, and E. Soljanin, "Source broadcasting over erasure channels: distortion bounds and code design," *2013 IEEE Inform. Theory Workshop (ITW'13),* Seville, Spain, Sept. 2013.
18. G. Joshi and E. Soljanin, "Round-robin overlapping generations coding for fast content download," *2013 IEEE Int. Symp. Inform. Theory (ISIT'13),* Istanbul, Turkey, July 2013.
19. L. Tan, A. Khisti, E. Soljanin, "Distortion bounds for broadcasting a binary source over binary erasure channels," *13'th Canadian Workshop on Information Theory (CWIT'13),* Toronto, Canada, June 2013.
20. K. Guan, E. Song, E. Soljanin, and P. Winzer, "Physical layer security in space-division multiplexed fiber optic communications," *46th Asilomar Conference on Signals, Systems, and Computers,* Monterey, California, Amsterdam, The Netherlands Nov. 2012.
21. K. Guan, P. Winzer, and E. Soljanin, "Information-Theoretic Security in Space-Division Multiplexed Fiber Optic Networks," *2012 European Conference and Exhibition on Optical Communication (ECEOC'2012),* Amsterdam, The Netherlands, June 2012.

22. G. Joshi, Y. Liu, and E. Soljanin, "Coding for fast content download," invited for *50th Annual Allerton Conference,* Monticello, IL, Oct. 2012.

23. U. J. Ferner, M. Médard, E. Soljanin, "Toward sustainable networking: storage area networks with network coding," *50th Annual Allerton Conference,* Monticello, IL, Oct. 2012.

24. L. Tan, A. Khisti, E. Soljanin, "Quadratic gaussian source broadcast with individual bandwidth mismatches," *2012 IEEE Int. Symp. Inform. Theory (ISIT'12),* Cambridge, MA, June 2012.

25. Y. Li, P. Vingelmann, M. V. Pedersen, and Emina Soljanin, "Round robin streaming with generations," *2012 Int. Symp. on Network Coding, (NetCod'12),* Cambridge, MA, June 2012.

26. S. Kokalj, E. Soljanin, and P. Spasojevic,"Is rateless paradigm fitted for lossless compression of erasure–impaired sources?" invited for *49th Annual Allerton Conference,* Monticello, IL, Sept. 2011.

27. A. Bhowmick, A. Rawat, E. Soljanin, and S. Vishwanath, "Update efficient codes for distributed storage," *2011 IEEE Int. Symp. Inform. Theory (ISIT'11),* St. Petersburg, July 2011.

28. S. Kokalj-Filipovic, E. Soljanin, and Y. Gao, "Cliff effect suppression through multiple-descriptions with split personality," *2011 IEEE Int. Symp. Inform. Theory (ISIT'11),* St. Petersburg, July 2011.

29. N. P. Anthapadmanabhan, E. Soljanin, and S. Vishwanath, "Update-Efficient Codes for Erasure Correction," invited for *48th Annual Allerton Conference,* Monticello, IL, Sept. 2010.

30. E. Soljanin, "Reducing Delay in Mobile Muti-Agent Information Relaying," invited for *48th Annual Allerton Conference,* Monticello, IL, Sept. 2010.

31. Y. Li, E. Soljanin, and P. Spasojević, "Collecting coded coupons over generations," *2010 IEEE Int. Symp. Inform. Theory (ISIT'10),* Austin, USA, June 2010.

32. M. Sardari, R. Restrepo, F. Fekri, and E. Soljanin, "Memory allocation in distributed storage networks," *2010 IEEE Int. Symp. Inform. Theory(ISIT'10),* Austin, USA, June 2010.

33. Y. Li, E. Soljanin, and P. Spasojević, "Collecting coded coupons over overlapping generations," *2010 Int. Symp. on Network Coding, (NetCod'10)*, Toronto, Canada, June 2010.

34. I. Andriyanova and E. Soljanin, "IR-HARQ schemes with finite-length punctured LDPC codes over the BEC," *Proc. 2009 IEEE Int. Inform. Theory Workshop (ITW'09),* Taormina, Italy, Oct. 2009.

35. Y. Li and E. Soljanin, "Rateless codes for single-server streaming to diverse users," in *Proc. 48th Annual Allerton Conference,* Monticello, IL, Sept. 2009.

36. Z. Kong, E. Yeh, and E. Soljanin, "Coding improves the throughput-delay trade-off in mobile wireless networks," *2009 IEEE Int. Symp. Inform. Theory (ISIT'09)*, Seul, Korea, July 2009.

37. S. Kokalj, P. Spasojevic, E. Soljanin, and R. Yates, "ARQ with doped Fountain decoding," *Proc. 2008 IEEE Int. Symp. on Spread Spectrum Techniques and Applications (ISSSTA'08),* Bologna, Italy, Aug. 2008.

38. S. Aly, Z. Kong, and E. Soljanin, "Raptor codes based distributed storage algorithms for large-scale wireless sensor networks," *2008 IEEE Int. Symp. Inform. Theory (ISIT'08)*, Toronto, Canada, July 2008.

39. A. Mills, B. Smith, T. C. Clancy, E. Soljanin, and S. Vishwanath "On secure communications over wireless erasure networks," *2008 IEEE Int. Symp. Inform. Theory (ISIT'08)*, Toronto, Canada, July 2008.

40. S. Aly, Z. Kong, and E. Soljanin, "Fountain codes based distributed storage algorithms for large-scale wireless sensor networks," in *Proc. Int. Conf. Inform. Processing in Sensor Networks (IPSN'08),* St. Louis, MO, USA, April 2008.

41. S. Kokalj, P. Spasojevic, R. Yates, and E. Soljanin, "Decentralized Fountain codes for minimum-delay data collection," *Proc. 42nd Annual Conference on Information Sciences and Systems (CISS'08),* Princeton, NJ, March 2008.

42. Z. Kong, S. Aly, E. Soljanin, A. Klappenecker, and E. Yeh, "Network coding capacity of random wireless networks under a signal-to-interference-and-noise model," in *Proc. 45th Annual Allerton Conference,* Monticello, IL, Sept. 2007.

43. C Lott, O Milenkovic, and E. Soljanin, "Hybrid ARQ: theory, state of the art and future directions," in *Proc. 2007 IEEE Int. Workshop Inform. Theory (ITW'07),* Bergen, Norway, July 2007 (*Invited*)

44. S. El Rouayheb and E. Soljanin, "On wiretap networks II," *2007 IEEE Int. Symp. Inform. Theory (ISIT'07),* Nice, France, June 2007.

45. S. El Rouayheb, C. N. Georghiades, E. Soljanin, A. Sprintson, "Bounds on codes based on graph theory," *2007 IEEE Int. Symp. Inform. Theory (ISIT'07)*, Nice, France, June 2007.

46. E. Soljanin, N. Varnica, and P. Whiting, "Raptor codes for hybrid ARQ," in *Proc. 44th Annual Allerton Conference,* Monticello, IL, Oct. 2006.

47. O. Milenkovic and E. Soljanin, "Enumeration of RNA secondary structures: a constrained coding approach," *40th Asilomar Conference on Signals, Systems, and Computers,* Monterey, California, Oct. 2006.

48. C. Chekuri, C. Fragouli, and E. Soljanin, "Achievable information rates in single-source non-uniform demand networks," in *Proc. 2006 IEEE Int. Symp. Inform. Theory (ISIT'06)*, Seattle, WA, USA., July 2006.

49. O. Milenkovic, E. Soljanin, and P. Whiting, "Asymptotic spectra of trapping sets in irregular LDPC code ensembles," *2006 IEEE Int. Conf. Commun. (ICC '06),* Istanbul, Turkey, June 2006.

50. E. Soljanin, N. Varnica, and P. Whiting, "Punctured vs rateless codes for hybrid ARQ," in *Proc. 2006 IEEE Int. Inform. Theory Workshop (ITW'06),* Punta del Este, Uruguay, March 2006. (*invited*)

51. Y. Shi and E. Soljanin, "On multicast in quantum networks," in *Proc. 40th Annual Conference on Inform. Sciences and Systems (CISS'06),* Princeton, NJ, March 2006. *(invited)*

52. O. Milenkovic, E. Soljanin, and P. Whiting, "Stopping and trapping sets in generalized covering arrays," in *Proc. 40th Annual Conference on Information Sciences and Systems (CISS'06),* Princeton, NJ, March 2006.

53. O. Milenkovic, E. Soljanin, and P. Whiting, "Asymptotic spectra of trapping sets in regular LDPC code ensembles," in *Proc. 43st Annual Allerton Conference,* Monticello, IL, Oct. 2005.

54. C. Chekuri, C. Fragouli, and E. Soljanin, "On throughput benefits and alphabet size in network coding," *2005 IEEE Int. Symp. Inform. Theory (ISIT 2005),* Adelaide, Australia, Sept.,2005.

55. E. Soljanin, N. Varnica, and P. Whiting, "LDPC codes for hybrid ARQ," *2005 IEEE Int. Symp. Inform. Theory (ISIT 2005),* Adelaide, Australia, Sept. 2005.

56. R. Liu, P. Spasojevic, and E. Soljanin, "Cooperative diversity with incremental redundancy turbo coding for quasi-static wireless networks," in *Proc. the 6th IEEE Internat. Workshop on Signal Processing Advances for Wireless Commun. (SPAWC'05),* New York City, June 2005.

57. C. Fragouli and E. Soljanin, "Decentralized network coding," *Proc. 2005 IEEE Int. Inform. Theory Workshop (ITW'04),* San Antonio, TX, Oct. 2004.

58. C. Fragouli and E. Soljanin, "On average throughput benefits for network coding," *Proc. 42st Annual Allerton Conference,* Monticello, IL, Oct. 2004.

59. R. Liu, P. Spasojevic, and E. Soljanin, "Performance analysis of multilevel punctured turbo codes," *Proc. 42st Annual Allerton Conference,* Monticello, IL, Oct. 2004.

60. A. Ashikhmin, N. Gopalakrishnan, J. Kim, E. Soljanin, and A. Wijngaarden, "On efficient link error prediction based on convex metrics," in *Proc. IEEE Vehicular Technology Conference (VTC2004-Fall),* Los Angeles, CA, Sept. 2004.

61. C. Fragouli and E. Soljanin, "Subtree decomposition for network coding," *Proc. 2004 IEEE Int. Symp. Inform. Theory (ISIT 2004)*, Chicago, USA, June 27–July 2, 2004.

62. R. Liu, P. Spasojevic, and E. Soljanin, "Reliable channel regions for good codes transmitted over parallel channels," *Proc. 2004 IEEE Int. Symp. Inform. Theory (ISIT 2004)*, Chicago, USA, June 27–July 2, 2004.

63. C. Fragouli and E. Soljanin, "A connection between network coding and convolutional codes," *Proc. 2004 IEEE Int. Conf. Commun. (ICC'04),* Paris, France, June 2004.

64. R. Liu, P. Spasojevic, and E. Soljanin, "Incremental multi-hop based on good punctured codes and its reliable hop rate," in *Proc. IEEE Wireless Communications and Networking Conference 2004 (WCNC 2004),* Atlanta, Georgia, Mar. 21–25, 2004.

65. C. Fragouli and E. Soljanin, and A. Shokrollahi, "Network coding as a coloring problem," in *Proc. 38 Annual Conference on Information Sciences and Systems (CISS'04,)* Princeton, NJ, March 2004. *(invited)*

66. R. Liu, P. Spasojevic, and E. Soljanin, "A throughput analysis of incremental redundancy hybrid ARQ schemes with turbo codes," in *Proc. 38 Annual Conference on Information Sciences and Systems (CISS'04,)* Princeton, NJ, March 2004.

67. R. Liu, P. Spasojevic, and E. Soljanin, "User cooperation with punctured turbo codes," *Proc. 41st Annual Allerton Conference,* Monticello, IL, Oct. 1–3, 2003.

68. R. Liu, P. Spasojevic, and E. Soljanin, "On the role of puncturing in hybrid ARQ schemes," *2003 Int. Symp. Inform. Theory (ISIT'03),* Yokohama, Japan, June, 2003.

69. R. Liu, P. Spasojevic, and E. Soljanin, "Punctured turbo code ensembles," *2003 Inform. Theory Workshop (ITW'03),* Paris, France, Mar. 31-Apr. 4, 2003.

70. E. Soljanin, R. Liu, and P. Spasojevic, "Hybrid ARQ with random transmission assignments," *DIMACS Workshop on Network Information Theory,* March 2003.

71. E. Soljanin and E. Offer, "LDPC codes: a group algebra formulation," *2001 Workshop on Coding and Cryptography* (WCC'01), Paris, France, Jan. 2001.

72. A. Mojsilovic and E. Soljanin, "Quantization of color spaces by fibonacci lattices," *2001 IEEE Int. Symp. Inform. Theory (ISIT'01),* Washington, DC, June 2001.

73. E. Soljanin, "Simple soft-output detection for magnetic recording channels," *2000 IEEE Int. Symp. Inform. Theory (ISIT'00),* Sorrento, Italy, June 2000.

74. E. Offer and E. Soljanin, "On the efficiency of some suboptimal algorithms for bit decoding of binary codes," *2000 IEEE Int. Symp. Inform. Theory (ISIT'00),* Sorrento, Italy, June 2000.

75. A. Mojsilovic and E. Soljanin, "Quantization of color spaces and processing of color images by Fibonacci lattices," *2000 SPIE Int. Symp.* San Jose, CA, Jan. 2000.

76. E. Soljanin and A. van Wijngaarden, "On the capacity of distance enhancing constraints for high density magnetic recording channels," *Proc. 1999 Workshop on Coding and Cryptography (WCC'99)*, Paris, France, Jan. 1999.

77. E. Soljanin, "Coding for Magnetic Recording Channels with Colored Noise and Intertrack Interference," *Proc. 1998 Inform. Theory Workshop (ITW'98)* San Diego, CA, Feb. 9-13, 1998., pp. 24.

78. B. Moision, P. H. Siegel, and E. Soljanin, "Error event characterization and coding for the equalized Lorentzian channel," *1998 IEEE Int. Symp. Inform. Theory (ISIT'98),* Cambridge, MA, Aug. 1998.

79. E. Soljanin, "A Shannon Theoretic Study of Penrose Tilings," *1998 IEEE Int. Symp. Inform. Theory (ISIT'98),* Cambridge, MA, Aug. 1998.

80. E. Soljanin, "Extended role of constrained coding in high density magnetic recording channels," *Proc. 1997 IEEE Int. Workshop Inform. Theory (ITW'97),* Longyearbyen, Norway, July 1997, *(Invited)*

81. B. Moision, P. H. Siegel, and E. Soljain, "Distance-enhancing codes for digital recording," *Proc. 1997 IEEE Magnetic Rec. Conf. (TMRC'97)* Minneapolis, MN, Sept. 1997.

82. E. Soljainin, "A coding scheme for generating dc–free sequences," *International Magnetics Conference (INTERMAG'97)*, New Orleans, Louisiana, Apr. 1–4, 1997.

83. E. Soljanin, "Decoding techniques for some specially constructed dc–free codes," *1997 IEEE Int. Conf. Commun. (ICC '97),* Montreal, Canada, June 1997.

84. E. Soljain and R. Urbanke, "On the performance of recursive decoding schemes," *1997 IEEE Int. Symp. Inform. Theory (ISIT'97),* Ulm, Germany, July 1997.

85. E. Soljanin, "On coding for binary partial-response channels that don't achieve the matched-filter-bound," *Proc. 1996 Inform. Theory Workshop (ITW'96),* Haifa, Israel, June 9-13, 1996, pp. 24. (*Invited*)

86. E. Soljanin and O. Agazzi, "An interleaved coding scheme for $(1-D)(1+D)^2$ partial response with concatenated Decoding," *Proc. 1996 IEEE Global Telecommunications Conf. (GLOBECOM'96),* London, UK, Nov. 1996.

87. E. Soljanin, "On–track and off–track distance properties of class 4 partial response channels," *Proc. 1995 SPIE Int. Symp. on Voice, Video, and Data Communications,* Philadelphia, PA, Oct. 1995, vol. 2605, pp. 92–102.

88. E. Soljanin, C. N. Georghiades, "A five-head, three-track, magnetic recording channel," *Proc. 1995 IEEE Int. Symp. Inform. Theory (ISIT'95),* Whistler, Canada, Sept. 1995, pp. 244.

89. E. Soljanin, C. N. Georghiades, "Coding for two-head recording systems," *IEEE Trans. Inform. Theory,* pp. 747–755, May 1995.

90. E. Soljanin, C. N. Georghiades, "Two-track codes for magnetic recording channels," *Proc. 1994 IEEE Int. Symp. Inform. Theory (ISIT'94),* Trondheim, Norway, June 1994, pp. 150.

91. E. Soljanin, C. N. Georghiades, "Sliding-block codes for two-track magnetic recording channels," *28th Annual Conference on Inform. Sciences and Systems (CISS'94),* Princeton, NJ, March 1994.

92. E. Soljanin, C. N. Georghiades, "On coding in multi-track, multi-head, digital recording systems," *Proc. 1993 IEEE Global Telecommunications Conf. (GLOBECOM'93),* Houston, TX, Dec. 1993, pp. 18–22.

93. B. Perunicic, S. Levi, M. Kezunovic, E. Soljanin, "Digital metering of active and reactive power in non-sinusoidal conditions using bilinear forms of voltage and current samples," *Proc. IEEE Int. Symp. on Networks, Systems, and Signal Processing,* Zagreb, Yugoslavia, June 1989.

94. D. Dervisevic and E. Soljanin, "Automatic generation control in hydro–thermal electric power systems," *Lecture Notes in Control and Inform. Sciences Series vol. 113, Springer–Verlag, System Modeling and Optimization, IFIP'87,* pp. 549–557.

95. N. Bajraktarevic, N. Cerimovic, D. Pikula, E. Soljanin, "Software package for real-time modeling of electric power system operation," *YU CIGRE*, Cavtat, Yugoslavia, 1988. *(in Serbo–Croatian)*

96. E. Soljanin, D. Pikula, "Long-term hydro scheduling," *1987 Yug. Symp. on Operations Research (SIMOPIS '87)*, Brioni, Yugoslavia, 1987. *(in Serbo–Croatian)*

97. Z. Tica, N. Cerimovic, D. Hadziosmanovic, D. Pikula, E. Soljanin, "Software package for long-term planning of electric power systems," *YU CIGRE*, Cavtat, Yugoslavia, 1986. *(in Serbo–Croatian)*

BOOKS, BOOK CHAPTERS, EDITING

1. C. Fragouli and E. Soljanin, invited monograph, *Network Coding Fundamentals,* Foundations and Trends in Networking. Hanover, MA: now Publishers Inc., June 2007.

2. C. Fragouli and E. Soljanin, invited monograph, *Network Coding Applications,* Foundations and Trends in Networking. Hanover, MA: now Publishers Inc., Jan. 2008.

3. *Advances in Information Recording,* DIMACS Series in Discrete Mathematics and Theoretical Computer Science, v. 73, American Mathematical Society, 2008, Paul H. Siegel, Emina Soljanin, B. Vasič, and A. J. van Wijngaarden, eds.

4. E. Soljanin, R. Liu, P. Spasojević, "Hybrid ARQ with random transmission assignments," in *Advances in Network Information Theory,* DIMACS Series in Discrete Mathematics and Theoretical Computer Science, v. 66, American Mathematical Society, 2004. P. Gupta, G. Kramer, and A. Wijngarden, eds.

5. B. Marcus and E. Soljanin, "Modulation codes for storage systems," in *The Computer Engineering Handbook*, Boca Raton: CRC Press, 2002, V. G. Oklobdzija, ed.

6. E. Offer and E. Soljanin, "An algebraic description of iterative decoding schemes," IMA Volumes in Mathematics and its Applications v. 123, Springer-Verlag, 2001, B. Marcus and J. Rosenthal, eds.

SELECTED INVITED TUTORIAL/EXPOSITORY TALKS

1. "Network coding: a combinatorial framework and an open problem," *BIRS Workshop on Mathematics of Communications: Sequences, Codes and Designs*, Banff, January 2015.

2. "Basics of Network Coding," *BIRS Workshop on Applications of Matroid Theory and Combinatorial Optimization to Information and Coding Theory,* Banff, August 2009.

3. "Network Coding: Theory and Practice," *2007 IEEE Int. Symp. Inform. Theory (ISIT'07)*, Nice, France, June 2007.

4. "Hybrid ARQ: State of the Art," *2007 IEEE Int. Inform. Theory Workshop (ITW'07),* Bergen, Norway, July 2007.

SELECTED PLENARY AND INVITED RESEARCH TALKS

1. *Queues for Data Access from Coded Distributed Storage,* 18th INFORMS Applied Probability Society Conference, Istanbul, July. 2015.

2. *Cloud Storage Space vs. Download Time for Large Files,* NYIT REU Program, New York, June 2015.

3. *Storage Codes and Data Retrieval,* Workshop on Coding: From Practice to Theory, The Simons Institute for the Theory of Computing, UC Berkeley, Feb. 2015.

4. *Codes for Storage with Queues for Access,* Workshop on Inform. Theory and Applic. (ITA), UCSD, Feb. 2015.

5. *Codes For All Seasons,* plenary talk at 2014 IEEE Workshop on Inform. Theory, Nov. 2014.

6. *Urns & Balls and Communications,* Dept. of Statistics, Univ. of Auckland, Nov. 2014.

7. *How Does Applied Math Become Applicable?* MIT Graduate Women (GW6) student group coffee hour seminar, May 2014.

8. *A coding Tale of a Tail at Scale,* Stanford, Apr. 2014.

9. *How Should We Code in Multicast to Diverse Users and What For?* Stanford, Apr. 2014, and University of Hawaii, Nov. 2014.

10. *Secret Lives of Codes: From Theory to Practice and Back* 2013 Padovani Lecture at the 2013 North American School of Information Theory, Purdue University, June 2013.

11. *Is Coding Beyond the Physical Layer Helpful in Content Centric Networking?,* Workshop on Inform. Theory and Applic. (ITA), UCSD Feb. 2013.

12. *Rateless Codes for Efficient Content Download in Highly Heterogeneous Scenarios,* Aalborg University, Sept. 2012.

13. *Pushing Codes into Clouds,* NSF Workshop on Communication Theory and Signal Processing in the Cloud Era, Berkeley, June 2012.

14. *Urns & Balls and Communications,* MIT Math Seminar, Apr. 2012.

15. *What are Good Coding Schemes for Multicast in Heterogeneous Wireless Networks?* International Zurich Seminar on Communications, March 2012.

16. *How Does Applied Math Become Applicable?* plenary talk at Workshop on Inform. Theory and Applic. (ITA), UCSD Jan. 2012.

17. *Three Types of Redundancy Against Three Sources of Delay,* UIUC CSL Seminar, Apr. 2011.

18. *Double Dixie Cup Unicast,* UIUC CS Theory Seminar, Apr. 2011, Dagstuhl Seminar on Coding Theory, Nov. 2011.

19. *Content Preparation, Delivery, and Storage for Highly Heterogenous Networks,* EPFL, Oct. 2011, MIT EECS, Sept. 2011.

20. *Urns & Balls and Communications,* 2013 North American School of Information Theory, UT Austin, May 2011.

21. *On Storing and Retrieving (Coded) Data in Mobile P2P Networks,* Isaac Newton Institute for Mathematical Sciences, special programme on *Stochastic Processes in Communication Sciences,* Cambridge, UK, April 2010.

22. *Coded Streaming in Heterogenous Networks,* BL/HHI Joint Workshop, June 2011, ENST Sept. 2011.

23. *Coding for Delay in Networks,* Texas A&M, Mar. 2011, ETIS/CNRS, Sept. 2011.

24. *Quantum Network Multicast and Coding,* International Seminar on Quantum Networking (Towards Quantum Internet, Madrid, June 2009.

25. *Two (Non)standardized Applications of Fountain Codes,* ETH Zürich, December 2008.

26. *Coding Technologies: Trends, Challenges, Opportunities and Applications,* Alcatel–Lucent Technical Academy, Antwerp, Belgium, July 2008.

27. *On Wiretap Networks Implementing Network Coding,* EPFL, Feb. 2008, Universität Zürich, October 2008, Univ. Collage Cork Coding and Cryptography, May 2008.

28. *Coding Based P2P Storage and Distribution,* EPFL, Apr. 2008, Univ. Collage Cork Workshop Coding and Cryptography, May 2008, Supélec June 2008.

29. *Von Neumann Entropy in Quantum Data Compression,* EPFL & UMLV Workshop on Entropy, Sept. 2008.

30. *On the Throughput/Delay Tradeoff in Mobile Ad-Hoc Networks Implementing Network Coding,* Workshop on Inform. Theory and Applic. (ITA), UCSD Jan. 2008. Princeton, Supélec and Bell Labs Workshop on Wireless Networks, Princeton, Feb. 2008.

31. *Hybrid ARQ: Theory, State of the Art, and Future Directions,* EPFL, April 2008, ENST June 2008, and University of Arizona, EE, Nov. 2007.

32. *On Benefits of Network Coding in Content Distribution,* University of California Los Angeles (UCLA) and University of Arizona, Math, Nov. 2007.

33. *Punctured vs Rateless Codes For Hybrid ARQ,* Tsinghua University, Bejing, Oct. 2006, IEEE Int. Inform. Theory Workshop (ITW'06), Punta del Este, Uruguay, March 2006.

34. *On Throughput Benefits of Network Coding,* University of Southern California, Los Angeles, Aug. 2006, International Workshop on Wireless Ad Hoc & Sensor Networks (IWWAN 2006), New York, June 2006, CUBIN/ACoRN Inform. Theory Workshop, Melbourne, Australia, Sept. 2005.

35. *Some Computer Science Problems in Network Coding,* 2004 IEEE Inform. Theory Workshop, San Antonio, Texas, Oct. 2004.

36. *Network Coding: from Graph Theory to Algebraic Geometry,* EECS Distinguished Lecture Series, Univesrity of Michigan at Ann Arbor, Jan. 2003, and Columbia University, Feb. 2003.

37. *Frames in Quantum and Classical Information Theory,* EPFL, Lausanne, Switzerland, June 2004, Institute for Quantum Information Seminar, Caltech, Sept. 2003, Quantum Computing Seminar, Texas A&M University, April 2003, and DIMACS Workshop on Source Coding and Harmonic Analysis, May 2002

38. *Network Coding Based on Subtree Decomposition,* EE Seminar, Brooklyn Polytechnic University, Oct. 2003, and Information Science & Technology Seminar, Caltech, Sept. 2003.

39. *Hybrid ARQ in Wireless Networks,* Wireless Communications Lab Seminar, Texas A&M University, April 2003.

40. *Algebra of LDPC Codes*, AMS 2002 National Meeting, San Diego, CA, Jan. 2002, and Technical University, Ulm, Germany, Oct. 2000.

41. *Quantum Data Compression,* MSRI Information Theory Workshop, Berkeley, CA, Feb. 2002.

42. *LDPC Codes: A Group Algebra Formulation," DIMACS Workshop on Codes and Complexity*, Dec. 2001.

43. *Writing sequences on the plane,* DIMACS Mixer Seminar Series, Florham Park, NJ, Sept. 2001.

44. *On Quantum Source Coding Problems Beyond the Schumacher Compression,* AMS 2001 Spring Eastern Section Meeting, Hoboken, NJ, April 2001.

45. *Application of Distance Enhancing Modulation Codes to High Density Magnetic Recording Systems, TMRC 2000,* Santa Clara, CA, Aug. 2000.

46. *A Shannon Theoretic Study of Penrose Tilings,* Ecole Nationale Supérieure des Télécommunications (ENST), Paris, France, Jan. 1999.

47. *Writing Sequences on the Plane,* Lehrstuhl für Nachrichtentechnik, TU München, Munich, Germany, Oct. 1999.

48. *On the Role of Channel Distance Properties in Partial Response Signaling,* Lehrstuhl für Nachrichtentechnik, TU München, Munich, Germany, July 1999, and UC Berkeley, Berkeley, CA, Nov. 1997.

49. *Coding for Magnetic Recording Channels with Colored Noise and Intertrack Interference,* 1998 National Storage Industry Consortium (NSIC'98), Berkeley, CA, Jan. 1998.

50. *The Multi–User Problem in Magnetic Recording,* AT&T Labs – Research, Florham Park, NJ, March 1998.

51. *Coding in Recording and Transmission Systems,* Brown University, Department of Applied Mathematics, Providence, RI, April 1996.

52. *On Coding for Binary Partial-Response Channels that don't Achieve the Matched-Filter-Bound,* University of California at San Diego, Center for Magnetic Recording Research, San Diego, CA, May 1996.

SELECTED RESEARCH REPORTS

1. E. Soljanin, "Raptor codes: from a math idea to LTE eMBMS," *Bell Labs Internal Report,* 2013.

2. R. Alface, S. Kokalj, J-F. Macq, C. Nuzman, and E. Soljanin, "Video Coding for Customized Direct Access," *Bell Labs Internal Report,* Dec. 2011.

3. U. Niesen, E. Soljanin, and G. Tucci, "Structured matrices for compressed sensing applications," *Bell Labs Internal Report,* June 2011.

4. A. Ashikhmin, E. Soljanin, R. Liu, and P. Spasojevic, "Hybrid ARQ for wireless networks: analysis of the standard scheme and directions for improvements," *Bell Labs Internal Report,* Oct. 2002.

5. E. Soljanin, "Spectrum shaping codes for 10Gb/s ethernet," *Bell Labs Internal Report,* Sept. 1999.

6. E. Soljanin, "Penrose tiling and recording data on the plane," *Bell Labs Internal Report,* Oct. 1998.

7. A. Barg, E. Soljanin, and R. Urbanke, "Efficient forward error correction for Lucent Technologies SONET Terminals," *Bell Labs Internal Report,* Sept. 1998.

8. E. Soljanin and R. Urbanke, "An efficient architecture for implementation of a multiplier and inverter in GF(2^8), *Bell Labs Internal Report,* Mar. 1996.

9. C. N. Georghiades, E. Soljanin, K. Chang, R. Velidi, L. Cavalheiro, "Communications in intelligent vehicle highway systems,"*Research Report* 1245-3, Texas Transportation Institute, September 1990 – August 1991.

10. C. N. Georghiades, S. Patarasen, E. Soljanin, H. Jardak, W. Wills, "Communications in intelligent vehicle highway systems,"*Research Report* 1245-2, Texas Transportation Institute, Jan.– Aug. 1990.

PATENTS

1. A. Emad, C. Nuzman, and E. Soljanin, "Methods and systems for determining crosstalk for a line in a vectored system," *Patent Application,* filed June 2015.
2. C. Nuzman, E. Soljanin, and A. Tulino, "Methods and systems for determining crosstalk for a joining line in a vectored system," *Patent Application,* filed May 2014.
3. K. Guo, E. Soljanin, and T. Wu, "Secure file transfers within network-based storage," *Patent Application,* filed Aug. 2013.
4. K. Guan, E. Soljanin, and P. Winzer, "Secure Data Transmission via Spatially Multiplexed Optical Signals," *Patent Application,* filed Dec. 2012.
5. K. Guan, E. Soljanin, and P. Winzer, "Optical fibers with varied mode-dependent loss," *Patent Application,* filed Dec. 2012.
6. S. Kokalj-Filipovic, and E. Soljanin, "System and method for mitigating the cliff effect for content delivery over a heterogeneous network," *Patent Application,* filed Feb. 2011.
7. T. Marzetta and E. Soljanin, "Secure compressive sampling using codebook of sampling matrices," *Patent Application,* filed December 2009.
8. S. Aly, Z. Kong, and E. Soljanin, "Distributed storage in wireless sensor networks," *Patent Application,* filed June 2008.
9. E. Soljanin, N. Varnica, and P. Whiting, "Encoded Transmission," *U.S. Patent 7,669,103,* Feb. 2010.
10. A. Ashikhmin, N. Gopalakrishnan, J. Kim, E. Soljanin, and A. Wijngaarden "Method and apparatus for link error prediction in a communication system," *U.S. Patent 7331009,* Feb. 2008.
11. A. Mojsilovic and E. Soljanin, "Method of color quantization in color images," *U.S. Patent 6,898,308,* May 2005.
12. A. Mojsilovic and E. Soljanin, "Method of color quantization in color images," *U.S. Patent 6,678,406,* Jan. 2004.
13. E. Soljanin and A. van Wijngaarden, "Method and apparatus for implementing run-length limited and maximum-transition-run codes," *U.S. Patent 6,2417,78,* June 2001.
14. E. Soljanin, "A low disparity coding method for digital data," *U.S. Patent 6188337,* Feb. 2001; *Europ. Patent 00304355.1-2216,* July 2000.
15. A. Mojsilovic and E. Soljanin, "Method of color quantization in color images," *Europ. Patent 00306489.6-2202*, Oct. 2000.
16. N. Sayiner and E. Soljanin, "Method of detecting dc-free sequences," *U.S. Patent 5,910,969,* June 1999.
17. E. Soljanin, "Method and apparatus for generating dc-free sequences," *U.S. Patent 5,608,397,* Mar. 1997.
18. E. Soljanin, "Method and apparatus for generating dc-free sequences," *U.S. Patent 5,608,397,* Mar. 1997.