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TITLE OF PROPOSED PROJECT **Design and Analysis of Iteratively Decodable Codes for Wireless Communications and Digital Magnetic Recording**

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Design and Analysis of Iteratively Decodable Codes for Wireless Communications and Digital Magnetic Recording

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A. PROJECT SUMMARY

This proposal describes an integrated research and education plan in the area of concatenated coding and iterative decoding with applications to wireless communications and digital magnetic recording. Iterative decoding of concatenated codes has emerged as a practical solution to communicate at rates close to the capacity limits. The discovery of turbo codes and the recent rediscovery of low density parity check (LDPC) codes or Gallager codes are two of the landmark developments in this area. Until recently, most of the design and analysis of concatenated codes was based on the assumption that a maximum-likelihood (ML) decoder is available, although it was well-known that the iterative decoder used is not an ML decoder in general. Within the last two years, Luby *et al* and Richardson *et al* have developed a powerful technique known as density evolution that permits design and analysis of codes based on the convergence of the iterative decoding algorithm. Using this technique and by careful introduction of irregularity in to the code structure, Richardson *et al* were able to design LDPC codes that achieve performance as good as only 0.1dB away from the capacity limits for long block lengths.

Based on these recent developments and by taking advantage of the PI's previous work in this area, the research plan proposes several new research ideas and directions. The proposed work differs from the existing work in two main respects - (i) the focus is on the design of concatenated codes based on the convergence of the iterative decoding algorithm, rather than on the assumption of maximum likelihood decoding (ii) novel coding structures and new design criteria are proposed. Although the proposed research is applicable to a wide variety of systems, we concentrate on the design of codes for use with continuous phase modulation and digital magnetic recording. Specific areas covered in this proposal include

- Design and analysis of *irregular* turbo codes matched to the iterative decoding algorithm
- A comprehensive study of concatenated coding techniques for use with continuous phase modulation
- Design of concatenated codes and novel receiver structures for digital magnetic recording

The education plan of the proposal is focussed on building a strong undergraduate and graduate program in digital communications with emphasis on coding theory and applications at Texas A&M University. The plan takes advantage of the existing programs in the university, the proximity to the telecommunications corridor in the Dallas/Fort Worth area, and on some educational grants the PI has procured recently. Specific plans to achieve this goal include

- Curriculum development and upgrade
- Ways to integrate research and education by involving students in various research projects
- Development of an electronic (web-based) hand book on digital communications
- Several outreach activities and developing strong ties with the industry

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

Section		Total No. of Pages in Section	Page No.* (Optional)*
Cover Sheet (NSF Form 1207) (Submit Page 2 with original proposal only)			
A	Project Summary (not to exceed 1 page)	1	
B	Table of Contents (NSF Form 1359)	1	
C	Project Description (plus Results from Prior NSF Support) (not to exceed 15 pages) **(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**	15	
D	References Cited	5	
E	Biographical Sketches (Not to exceed 2 pages each)	2	
F	Budget (NSF Form 1030, plus up to 3 pages of budget justification)	7	
G	Current and Pending Support (NSF Form 1239)	1	
H	Facilities, Equipment and Other Resources (NSF Form 1363)	1	
I	Special Information/Supplementary Documentation	4	
J	Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

C. PROJECT DESCRIPTION

1 Introduction

What follows is a career development plan in the area of communication theory with emphasis on the design and analysis of concatenated codes that can be decoded using an iterative (turbo) decoding algorithm.

Objectives and Significance Since the introduction of turbo codes in 1993 [14], two concepts have gained popularity in coding theory. They are (i) the construction of good, long random codes by concatenating two or more simple component codes and (ii) iterative decoding of such codes. These concepts have been used to construct and decode a variety of codes including parallel, serial, and hybrid concatenated codes, turbo product codes and turbo-like codes which admit low decoding complexity. A recent important development in this category is the rediscovery of low density parity check (LDPC) codes or Gallager codes. The fact that these codes (turbo codes and LDPC codes) can be shown to perform a few tenths of a dB away from the capacity limits with a practical iterative decoding algorithm is testimony to the efficacy of these concepts. Although invented in 1962 by Gallager [44], LDPC codes were largely forgotten until recently, when they were rediscovered by Mackay [59, 61]. Since this rediscovery, two notable modifications to Gallager's original construction of LDPC codes have been studied. They are the introduction of irregularity into the code structure [57, 58, 62, 93] and the study of non-binary LDPC codes [23, 24].

Since turbo codes were proposed, there have been several attempts to understand the structure of concatenated codes and the iterative decoding algorithm. The first successful approach was that of Benedetto and Montorsi, who provided some tools to analyze concatenated codes based on the assumption that a maximum-likelihood (ML) decoder is available [13]. Based on the union bound that was developed in [13], they proposed criteria to design good component codes for use in concatenated codes in [12]. This has been the most popular approach to analyze and design turbo codes, although the iterative decoding algorithm used to decode these codes is not an ML decoder in general. Due to this difference, analysis and design of concatenated codes based on ML decoding provides good bounds and design criteria for large E_b/N_o; however, at low E_b/N_o, the analysis is not very useful. Similarly, for the case of LDPC codes, the original construction of Gallager in [44] provides excellent performance with a ML decoder and is not optimal when an iterative belief propagation decoder is used.

While it makes obvious sense to design codes matched to the decoding algorithm, the problem is rather complicated due to the fact that the iterative decoding algorithm cannot be analyzed very easily. Understanding the performance of the iterative algorithm especially on graphs with loops has been a topic of high research interest. Recently, Richardson and Urbanke have developed a technique known as density evolution that analyzes the convergence of the iterative decoding algorithm for infinite length code words [94]. Using this technique they have successfully designed LDPC codes that can achieve a bit error rate (BER) of 10^{-5} at an E_b/N_o of only 0.13 dB away from capacity in [93]. The introduction of irregularity into the code structure and the design based on the convergence are the main reasons for the phenomenal performance of these codes. Results in [93] along with several other studies clearly show that concatenated codes designed to optimize the convergence of the iterative decoding algorithm can significantly outperform the designs that optimize the distance spectrum (or, equivalently optimize the performance with ML decoding) in several cases. However, in other cases (for example, very short block lengths or very high rate codes) both the distance spectrum and the convergence properties are important.

The main objectives of the *research plan* are to further the understanding of the design and analysis of concatenated codes including LDPC codes based on the convergence properties, and to design novel concatenated coding schemes that are well-matched to iterative decoding. While this study is applicable to several systems, we concentrate on the design and analysis of codes for continuous phase modulation (CPM) and digital magnetic recording. The following topics will be studied in detail.

- Design and analysis of *irregular* and *non-binary* turbo codes - We propose to design irregular parallel and serial concatenated codes, turbo trellis coded modulation, non-binary parallel and serial concatenated convolutional codes using density evolution, and to analyze their performance.
- A comprehensive study of concatenated coding and decoding strategies for CPM, their performance analysis for AWGN, flat Rayleigh fading and ISI channels.
- Design and analysis of codes for digital magnetic recording - Particular emphasis is given to design of concatenated codes in the presence of an outer Reed-Solomon code, evaluating novel high rate codes and on low complexity receiver structures.

The *education plan* is to develop engineers and researchers at the undergraduate and graduate levels who can make long-term contributions to communication theory. Having started working as an assistant professor only 19 months ago, my career objective is to build a strong program at Texas A&M university in the area of communication theory in general and wireless communications in particular. The educational activities in this proposal include:

- Curriculum development - New graduate courses that teach the fundamentals and the state-of-the art developments in the areas of wireless communications and advanced coding techniques will be developed. An undergraduate laboratory course on digital communications is also currently being developed.
- Integrating research and education - The plan to integrate research and education is by (i) building a strong research program involving undergraduate and graduate students in various capacities in research projects. (ii) to actively participate and take advantage of several programs for undergraduates and minority students at Texas A&M university in order to attract them to communication theory. (iii) introducing a research component in to some undergraduate and graduate courses.

  Of particular importance within this category is a proposed project to develop an electronic handbook of digital communications. The idea is to create several web based resources that can graphically and interactively teach the principles and several algorithms in digital communications. This will be a novel and effective approach that goes beyond conventional text books to help students. Funding is requested to support undergraduate students to participate in this project. This will be an avenue for undergraduates to get involved in communication theory and hopefully motivate them to pursue graduate studies in this area.
- Developing industrial interaction - The plan is to take advantage of the proximity to the telecommunications industry in the Dallas/Forth Worth area to develop a tradition of interaction with the industry. The idea is to develop direct interaction between students and the industry through co-ops and seminars.

2 Technical Background

This proposal is mainly in the areas of iterative decoding of concatenated codes and low density parity check codes. Iterative decoding of parallel concatenated convolutional codes (PCCC) and serial concatenated convolutional codes (SCCC) has been a topic of high research interest in the past few years and, hence, we will not present the background material in detail. However, we will summarize some of the key properties of PCCC and SCCC in Section 2.4.1 that will be used in this proposal. We now present the encoder and decoder structure for low density parity check codes in some detail.

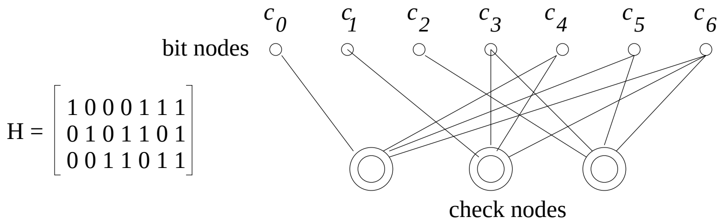
2.1 LDPC Codes - Encoder and Decoder Structure

As the name suggests, a low density parity check (LDPC) code is a linear block code specified by a very sparse parity check matrix. The parity check matrix $\boldsymbol{H}$ of a regular (N, K, t, j) LDPC code of rate $R = K/N$ is a $(N-K) \times N$ matrix, which has t ones in each column and $j > t$ ones in each row where $t << N$. Apart from these constraints, the ones are placed at random in the parity check matrix. When the number of ones in every column and is not the same, the code is known as an *irregular* LDPC code. It should be noted that the parity check matrix is not constructed in systematic form. Consequently, to obtain the generator matrix $\boldsymbol{G}$, we first apply Gaussian elimination to reduce the parity check matrix to a form $\boldsymbol{H} = [\boldsymbol{I}_{N-K}|\boldsymbol{P}^T]$, where $\boldsymbol{I}_{N-K}$ is the $(N-K) \times (N-K)$ identity matrix. Then, the generator matrix is given by $\boldsymbol{G} = [\boldsymbol{P}|\boldsymbol{I}_K]$. Since the parity check matrix H is sparse, the matrices $\boldsymbol{P}$ and $\boldsymbol{G}$ are dense. Consequently, the number of bit operations required to encode is $O(N^2)$ which is significantly larger than that for other codes. Analyzing LDPC codes by associating a bipartite graph or a factor graph [111, 115] with the parity check matrix yields additional insight in to the design of the parity check matrix. To explain this, let $(c_0, c_1, c_2, \ldots, c_{N-1})$ denote the coded bits and, let R_j and C_i be sets defined as

$$\begin{aligned} R_j &= \{i|H_{j,i} = 1\}, \quad j = 0, 1, 2, \ldots, N-K-1 \\ C_i &= \{j|H_{j,i} = 1\}, \quad i = 0, 1, 2, \ldots, N-1 \end{aligned}$$

The set R_j contains all column positions which have a 1 in the jth row of $\boldsymbol{H}$. Similarly, the set C_i contains all row positions which have a 1 in the ith column. In a regular LDPC code, the cardinality of C_i, denoted by $|C_i|$ is the same for all i. Note that each row of $\boldsymbol{H}$ places a constraint on the check nodes namely that

$$\sum_{l \in R_j} \oplus c_l = 0 \tag{1}$$



$$H = \begin{bmatrix} 1\,0\,0\,0\,1\,1\,1 \\ 0\,1\,0\,1\,1\,0\,1 \\ 0\,0\,1\,1\,0\,1\,1 \end{bmatrix}$$

Figure 1: An Irregular graph representing parity check nodes and bit nodes

The code with parity check matrix $\boldsymbol{H}$ can be represented by a bipartite graph which consists of two types of nodes - variable nodes and check codes. Each coded bit is a variable node while each parity check or each row of the parity check matrix represents a check node. An edge in the graph is placed between variable node i and check node j if $H_{j,i} = 1$. That is, each check node is connected to coded bits whose sum modulo-2 should be zero. The parity check matrix for an irregular $(7, 4)$ code and its associated bipartite graph is shown in Fig. 1 as an example.

Decoding of LDPC codes can be efficiently accomplished using a belief propagation algorithm [38, 44, 60, 85, 94]. The belief propagation algorithm has been shown to be a general approach to decoding codes on graphs and includes the turbo decoding algorithm as a special case [60, 51, 115]. The essential idea is to pass messages (extrinsic information) between the check nodes and variable nodes in an iterative fashion. An alternate way to look at this is to think of each row of $\boldsymbol{H}$ as a parity check code and the entire code to be a concatenation of several of these codes. Then, if we can accomplish soft output decoding of each of the parity check codes or, equivalently, if we can generate extrinsic information from each of the parity check codes, then we can iteratively decode the entire code. Consider each parity check node connected to, say, three variable nodes i.e., let us say $c_i \oplus c_j \oplus c_k = 0$. Further, let $L(x)$ denote the log likelihood ratio (LLR) of x defined as $L(x) = \log \frac{P(x=1)}{P(x=0)}$. In order to evaluate $L(c_i)$ given $L(c_j)$ and $L(c_k)$, we can rewrite the parity check equation as $c_i = c_j \oplus c_k$. Then, it can be seen that

$$L(c_i) = \log \frac{1 + e^{L(c_j)+L(c_k)}}{e^{L(c_j)} + e^{L(c_k)}} \tag{2}$$

Let us denote the above operation by a function $\odot$. That is $L(c_i) = L(c_j) \odot L(c_k)$. The LLR $L(c_i)$ calculated from (2) is the extrinsic information provided by the parity check node to the variable node c_i. The entire decoding for LDPC codes can be accomplished by the following algorithm operating in the log domain.

Initialization Initialize the LLRs. Set $L_j^{(0)} = L_c y_i$ for $i = 0, 1, 2, \ldots, N-1$, where L_c is the channel reliability function. For AWGN channels, $L_c = 4/N_o$, where N_o is the one-sided power spectral density of the noise.

At each iteration: For iteration $m = 1, 2, \ldots$

$$\begin{aligned} Le_j^{(m)}(x_i) &= \sum_{l \in R_j, l \neq i} \odot L_j^{(m-1)}(x_l) \quad \text{For } j = 0, 1, 2, \ldots, N-K-1, \forall i \in R_j && (3) \\ L_j^{(m)}(x_i) &= L_c y_i + \sum_{l \in C_i, l \notin j} Le_l^{(m)}(x_i) \quad \text{For } i = 0, 1, \ldots, N, \forall j \in C_i && (4) \end{aligned}$$

The soft output is given by $L^{(m)}(x_i) = L_c y_i + \sum_{j \in C_i} Le_j^{(m)}(x_i)$

2.2 Irregular Codes

In [62, 93] irregular LDPC codes, where the number of ones in the columns of the parity check matrix $\boldsymbol{H}$ is non uniform have been constructed and shown to perform better than regular LDPC codes. This means that in the associated bi-partite graph, some coded bits participate in more checks than others and, hence, can be considered as 'elite' bits. It has been conjectured in [23] that the reason for the improved performance of irregular codes is that the elite bits converge very early during the iterative process and, help the other bits in the future iterations. Irregularity can be defined using column and row degree profiles given by the polynomials $\lambda(x) = \sum_{i=1}^{t_{max}} \lambda_i x^i$ and $\rho(x) = \sum_{i=1}^{j_{max}} \rho_i x^i$. The coefficients λ_i and ρ_i denote the fractions of the columns (rows) that have weight i. By optimizing the degree profiles, Richardson *et al* produced codes that perform only 0.13 dB away from capacity. Mackay *et al* [62] have constructed irregular binary and non-binary LDPC codes and shown that irregular codes consistently outperform regular codes. Interestingly, Frey and MacKay used an ad-hoc construction to form irregular parallel concatenated codes that match the performance of the Richardson *et al*'s irregular LDPC code [42]. *In short, careful introduction of irregularity significantly improves the performance of graph based codes and, hence, irregular codes will be discussed throughout this proposal.*

2.3 Non-Binary LDPC codes

Regular LDPC codes over GF(2^q), $q \neq 1$ have been designed in [24] and shown to outperform binary LDPC codes. Irregular non-binary LDPC codes have been constructed using some empirical techniques and shown to significantly outperform regular codes [23]. In fact, irregular codes over GF(8) seem to be the best known codes of rate-1/4 for the AWGN channel [23]. It is clear from [24, 23] that non-binary LDPC codes can improve the performance over binary LDPC codes. It should be noted that although codes over GF(2^q) have equivalent binary representations, the decoding algorithm is not equivalent.

It should be emphasized that most of the studies on LDPC codes have been for binary modulation and for binary symmetric channels (BSC) or for the AWGN channel. There has been very little work on designing LDPC codes or evaluating the performance of LDPCs for fading channels or for modulation with memory.

2.4 Design and Performance Analysis of concatenated codes

2.4.1 Distance Spectrum Based Analysis

The most popular approach to analyze the performance of concatenated codes has been based on Benedetto and Montorsi's approach [13]. The idea is to derive the weight enumerating function (or, distance spectrum) of the overall concatenated code as a function of the component codes under the assumption of a hypothetical interleaver known as the 'uniform interleaver'. This provides the distance spectrum averaged over the ensemble of all possible interleavers. Once the distance spectrum of the concatenated code is evaluated, an upper bound on the probability of bit error can be computed using the union bound. The design of codes to optimize the performance based on the union bound has been considered in [8, 12, 27, 29, 45]. A summary of results based on the above approach from [9, 11, 13, 30, 87] is as follows:

- The main reason for the excellent performance of concatenated schemes is the effect of the interleaver which drastically reduces the number of codewords at small Hamming and Euclidean distances from a given code word. This is known as 'interleaving gain'. For parallel concatenated convolutional codes (PCCC), an interleaving gain is possible only if the component encoders are recursive. The important parameter to maximize for the component codes is not the free distance rather, the *effective free distance*, which is the minimum distance corresponding to weight-2 input sequences.

- For serial concatenated convolutional codes (SCCC), an interleaving gain is possible if and only if the inner code is recursive and the free distance of the outer code is at least 3. The interleaving gain for SCCC is typically much higher than that of PCCC. Consequently, the error floor appears only at extremely small BERs. Therefore, the performance of SCCC is often superior to PCCC at low BERs. Further, the interleaving gain is independent of the inner code parameters provided the inner code is recursive. The *effective* free distance of the inner code should be maximized whereas, for the outer code the free distance should be maximized.

While the above approach provides insight in to the structure of concatenated codes, the use of the union bound and the assumption of maximum-likelihood decoding restricts the usefulness of the approach. The union bound is useful only at high E_b/N_o. Since concatenated codes usually achieve low bit error rates at fairly low E_b/N_o, the usefulness of the union bound is very limited. One approach to alleviate this problem is to use a bound that is tighter than the union bound at low E_b/N_o [25, 35, 89, 104, 103, 113]. The problem still remains in that the iterative decoding algorithm used is not a maximum likelihood decoding algorithm. Consequently, design rules derived based on the distance spectrum are not optimal. An example of this can be seen in the design of serial concatenation schemes. Performance bounds derived based on ML decoding indicate that long constraint length outer codes would perform well; however, the performance of long constraint length with iterative decoding is significantly worse than short constraint length codes [67]. It is interesting to note that the above phenomenon is not an artifact of using the union bound - sometimes even the use of tighter bounds predicts that higher constraint length codes improve the performance, whereas simulation results show the opposite. So, it is clear that codes designed to improve the convergence of decoding algorithms can outperform those that perform well with ML decoding.

The same argument applies to LDPC codes also. Gallager's original construction shows that increasing the column weight of regular LDPC codes results in better performance with ML decoding [44]. However, based on the convergence properties it can be seen that codes where several columns have low weight significantly outperform regular LDPC codes with high column weight [93, 94].

2.4.2 Convergence Based Analysis - Density Evolution

Density evolution is a technique to analyze the performance of an ensemble of codes under message passing decoding (iterative decoding). This technique has been studied in different forms in [44, 57, 94]. Let us first consider the use of this technique for LDPC codes. The basic idea here is to derive a relationship for the probability density function (pdf) of the extrinsic information that is being passed to and from the check and variable nodes as a function of iteration. To explain this further, consider decoding an LDPC code using the algorithm in Section 2.1. Equations (3) and (4) define the iterations or give a relationship between $Le_j^{(m)}(x_i)$ and $L_j^{(m)}(x_i)$. With reference to equation (4), we can see if the pdf of $Le_j^{(m)}(x_i)$ is known, then we can compute the pdf of $L_j^{(m)}(x_i)$ assuming that $Le_j^{(m)}(x_i)$ are independent for all j. This essentially means that there are no loops in the graph or the length of the codeword is infinite. With this assumption, the pdf of $L_j^{(m)}(x_i)$ is given by

$$P(L_j^{(m)}(x_i)) = P(Lcy_i) \otimes P(Le_1^{(m)}(x_i)) \otimes \ldots \otimes P(Le_t^{(m)}(x_i)) \tag{5}$$

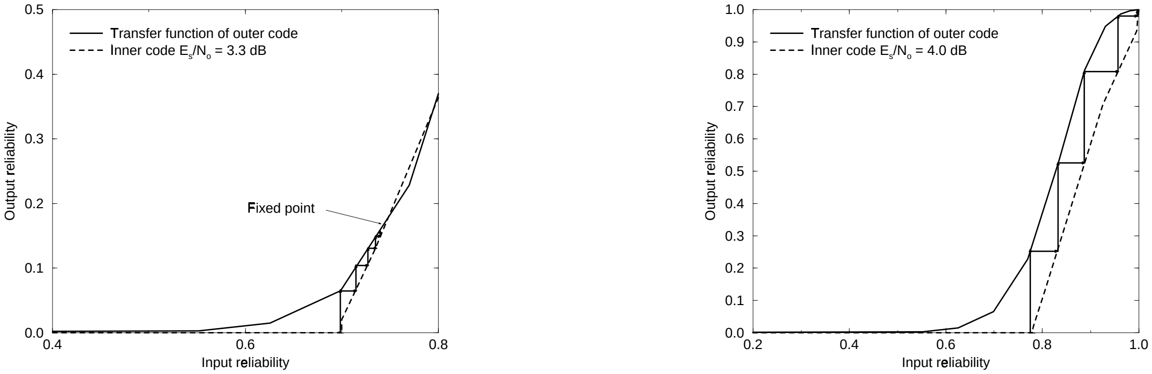
where $\otimes$ denotes convolution. The above pdf can can be very efficiently computed in the Fourier domain. Similarly, the pdf of $Le_j^{(m)}(x_i)$ can be computed using (3) assuming independence of $L_j^{(m)}(x_i)$. With this two step process, the pdf of the extrinsic information can be derived as a function of iteration. Once the pdf is derived, the fraction of the messages (extrinsic information) that corresponds to erroneous decisions can be found. The fraction of messages with erroneous sign (if the all zeros code word is transmitted, this is equivalent to the extrinsic information being negative) is given by $P_w = \int_{-\infty}^{0} P(L_j^{(m)}(x_i))$.

Richardson and Urbanke proved that there exists an E_b/N_o threshold above which the fraction of erroneous messages converges to zero with iterations and, hence, zero error probability can be achieved [94]. They also proved a concentration theorem for linear codes which states that for all codes in the ensemble and for all input sequences the performance of the iterative decoder is concentrated around that of the average behavior [94]. Therefore, the density evolution can be used to compute the threshold for the LDPC codes which corresponds to the capacity of these codes.

For parallel concatenated codes, the decoder iterates on the extrinsic information on the information bits. Therefore, one should derive the pdf of the extrinsic information at the output of each soft output decoder as a function of the pdf of the input extrinsic information and the channel output. For serial concatenated codes, the pdf of the extrinsic information of the coded bits of the outer code should be derived.

Gaussian Approximation: In most situations, computing the probability densities analytically is very complex. For example in the PCCC and SCCC case, it is quite difficult to analytically evaluate the pdf of the extrinsic information output from soft output decoders. Recently, some authors have simplified this problem by assuming that the messages being passed (extrinsic info) are Gaussian distributed (even though strictly they may not be). This simplifies the analysis of these codes because, instead of having to evaluate a pdf as a function of iterations, only the mean of the Gaussian distribution has to be evaluated (it can be shown that due to a consistency condition the variance and the mean of the distributed are related and, hence, the LLRs are completely characterized by the mean of the distribution [21, 95]). Using this assumption, the capacity of LDPC codes was analyzed in [21]. El Gamal and Hammons [36] have also used the same assumption to analyze the turbo decoding algorithm. Since this reduces the problem to a one-parameter description of the process, the evolution of the mean (or, equivalently a measure of reliability of the extrinsic information) can be shown graphically as suggested by Ten Brink [19]. Such a diagram shows the fixed points of the turbo decoding algorithm nicely [36]. Independent of [36], we considered the fixed points of the turbo equalization algorithm in [67, 68] by defining a different measure of reliability.

To explain this further, let us consider a serial concatenated convolutional code and let $F_o(x)$ and $F_i(x)$ denote transfer function of the outer and inner codes, respectively. The transfer function refers to the reliability of the output extrinsic information as a function of the reliability of the input extrinsic information, under the assumption that the input extrinsic information is independent from one time instant to another. Although several measures of reliability (such as the mean of the extrinsic information) can be used, here the reliability is defined as the mean of the hyperbolic tangent of the extrinsic information. Therefore, a reliability of 1 indicates perfectly reliable estimates and correct decoding. Then, the evolution of the reliability can be shown as in Fig. 2 where the functions $F_i(x)$ and $F_o(x)$ are shown. The function $F_o(x)$ is plotted with the X and Y axes reversed. The increase in reliability with iterations can be shown through horizontal and vertical projections between the curves $F_o(x)$ and $F_i(x)$, since the output of one decoder is the input to the other. When the two curves intersect, the reliability does not increase beyond the intersection point and, hence, represent a fixed point. When they do not intersect, the reliability increases steadily which signifies correct decoding. The minimum E_b/N_o for which the



(a) (b)

Figure 2: Evolution of reliability with iterations for (a) $E_s/N_o = 3.3\ dB$ and (b) $E_s/N_o = 4.0\ dB$

two curves do not intersect can be thought of as the *threshold* beyond which zero error probability is achievable. From Figures 2(a) and (b) it can be seen that when $E_b/N_o = 3.3$, the curves intersect and the reliability does not increase beyond a small value; however, when $E_b/N_o = 4.0$, the reliability increases to 1 (perfect decoding). The functions $F_o(x)$ and $F_i(x)$ have to be usually evaluated using Monte-Carlo simulations. Richardson and Urbanke have proved some consistency conditions for the pdf of the extrinsic information in [94, 95] which makes these computations relatively easy for both turbo codes and LDPC codes.

Code Design Based on Density Evolution: The design of irregular LDPC codes based on density evolution has been considered by Luby *et al* in [57] and Richardson *et al* [93]. The approach is to optimize the degree sequences $\lambda(x)$ and $\rho(x)$ such that the least E_b/N_o threshold is obtained. An optimization technique known as differential evolution [90] has been shown to be quite useful for this purpose [93, 57, 58]. The design of LDPC codes using linear programming and the Gaussian approximation has been considered by Chung *et al* [21]. These codes clearly show that designed based on density evolution can significantly improve the performance over designs that optimize distance spectrum. However, to the best of our knowledge, design of concatenated convolutional codes based on density evolution has not been studied in detail.

2.5 Turbo Codes Vs. LDPC Codes

Based on the above discussion and from several results available in the literature, we can say that both turbo codes (PCCC and SCCC) and LDPC codes have advantages and disadvantages. While carefully designed LDPC codes have been shown to outperform turbo codes for very long lengths, for short lengths, the structure in turbo codes still seems to give them an edge [94]. The decoding complexity for LDPC codes may be less than that for PCCC and SCCC. Further, the decoding algorithm for LDPC is highly parallelizable. However, the encoding complexity is significantly higher and, importantly requires storing the generator matrix (the non-systematic part of it) which could consume significant amount of memory in hardware. The minimum distance of LDPC codes increases linearly with N with a probability close to one, if $t \geq 3$, for large N. Consequently, the decoding errors for LDPC codes are usually only detected errors. Therefore, it is useful to study both turbo codes (parallel and serial concatenated codes) and LDPC codes as one may be better suited than the other for the particular application at hand.

3 Proposed Research

A Note: Before we proceed to discuss the proposed research, we make some general comments that are applicable to the following sections. It should be noted that the design based on convergence (using density evolution) assumes an infinite length interleaver and, hence, due to the interleaving gain, assumes that there are no finite weight codewords. In this proposal, we consider practical block lengths and, hence, such an assumption is not valid. Although convergence based design is reasonably accurate for long (still practical) block lengths, for short block lengths the existence of finite weight codewords will have an impact on the error performance. Similarly, the behavior of the decoding algorithm may deviate from the average behavior significantly for finite block lengths. Whenever we design codes based on convergence, we will compare these codes with others based on optimizing the distance spectrum in order to study the finite length effects also. Further, it should be emphasized here that when density evolution is used, we will try to evaluate the pdf of the extrinsic information (or the reliability) analytically and if it is not possible we will use Monte-Carlo simulations to evaluate it. Whenever the Gaussian approximation is used for the pdf of the extrinsic information, we will be careful to verify the accuracy through simulations and we do not take the validity of the assumption for granted.

Rather than restricting ourselves to codes and decoders with low complexity or good power efficiency, we study several coding and decoding strategies that span a wide range in the complexity-performance plane. Wherever appropriate, we will consider the design and analysis of codes for both AWGN and flat Rayleigh fading channels although we do not explicitly mention it.

3.1 Design and Analysis of Irregular Turbo Codes

In the first part of the proposed work, we consider the design and analysis of irregular turbo codes and the use of density evolution to analyze turbo trellis coded modulation. While these topics are of interest in their own right, they will also form the ground work for the following sections of this proposal.

3.1.1 Irregular Binary Parallel and Serial Concatenated Codes

When viewed as a code based on a graph, it becomes clear that in a conventional parallel concatenated convolutional code (PCCC), each bit participates in exactly two checks (if there are two component encoders) and, hence, is a regular code. As seen in Sec. 2.2, improved performace is possible by introducing irregularity into the code structure. This was the motivation for Frey and MacKay when they considered irregular PCCC in [42, 43]. They showed that if each data bit is repeated a number of times i according to a degree profile $\lambda(x) = \sum_{i=1}^{t} \lambda_i x^i$, where λ_i is the fraction of information bits that are repeated i times, and then encoded by the PCCC, then some bits can be made to participate in more number of number of checks than others. By an ad-hoc construction, they were able to produce irregular parallel concatenated codes that perform similar to the best irregular LDPC codes and was significantly better than regular turbo codes for long block lengths. This being a new development, irregular turbo codes have not been studied in detail. No formal technique was given in [42] to optimize the degree sequences. Similarly no analysis has been performed. We first propose to optimize the degree profile $\lambda(x)$ for irregular PCCC. The idea will be to use density evolution to compute the pdf of the extrinsic information as a function of the component encoders and the degree profiles and, then, to use differential evolution to optimize the degree profile. It was observed in [43] that while irregular PCCC perform better at low E_b/N_o (the cliff region of the BER curve), they have a higher error floor than regular PCCC. We propose to analyze the distance spectrum of these irregular codes based on [13]. Since distance spectrum based approaches work well in the error floor region, this will throw some light in to techniques to reduce the floor such as interleaver design [5, 6, 33, 110] or selective error protection [83, 70]. Finally, we will also study techniques to introduce irregularity by varying the puncturing pattern. In this case, some bits may be made to participate in 'stronger' checks than others.

The presence of the high error floor motivates us to study *irregular serial concatenated convolutional codes* which to the best of our knowledge has not been studied yet. Irregular serial concatenated codes will be an efficient class of codes, because irregularity will improve the performance at low E_b/N_o and, since the error floor of serial concatenated codes usually occurs at very low BERs that are not of practical interest, even if the irregularity results in a higher error floor, the effect of it will not be pronounced for most practical purposes. Irregularity can be introduced in to serial concatenation schemes either by repeating the information bits according to a degree profile or by repeating the coded bits of the outer code word. A preliminary study reveals that the decoder complexity is not increased significantly if the coded bits of the outer codeword are repeated, rather than the information symbols. We will then consider the optimization of degree profiles through density evolution. The case of serial concatenated codes with rate-1 inner codes [31, 64, 47, 86] will be given particular attention since results for these codes can be extended to iterative demodulation, iterative equalization, iterative multiuser detection, etc.

3.1.2 Irregular Non-Binary Codes

Motivated by Davey and MacKay's result that non-binary LDPC codes can outperform binary LDPC codes [24, 23], we propose to study irregular non-binary parallel and serial concatenated codes. Recently Berrou and Jezequel have shown that (regular) non-binary PCCC codes over GF(4) outperform binary PCCC both in terms of error performance and hardware complexity of the decoder [15]. Here, we propose to improve the performance still further by considering the design of *irregular* linear non-binary LDPC codes, PCCC and SCCC based on density evolution.

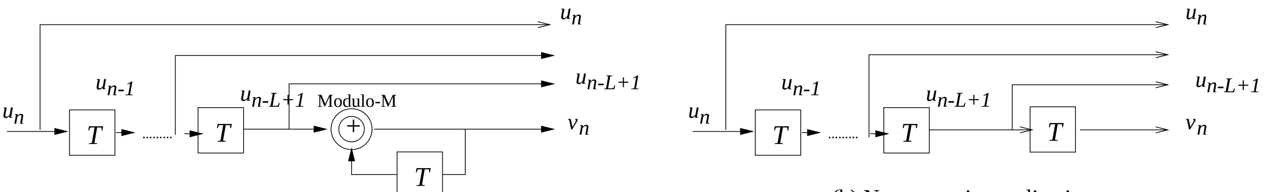
In the case of binary codes, density evolution studies the pdf of the extrinsic part of the log-likelihood ratio as function of iterations. However, in the case of codes over GF(2^q), what is passed between the decoders is a 2^q-ary vector of likelihoods and, hence, one needs to study the evolution of the joint pdf of the vector of likelihoods and, hence, it is difficult to parameterize the iterative process with one parameter. When bit interleaving is used, the problem can be simplified by studying the evolution of the pdf of LLR of the bits, rather the vector of symbol likelihoods; but when symbol interleaving is used, this cannot be used. It is quite complicated to derive the joint pdf and, even if it is possible, the joint pdf may obscure insight in to the convergence process. We first propose to find a good single parameter characterization of the process. One possible parameter is the entropy of the pdf vector. Another approach is to consider the pdf of the largest among all the elements of the likelihood vector and to assume that the other likelihoods are all equal. In this way, we only need to derive the pdf (or evaluate through simulations) of a single parameter. It is easy to see that both these parameters provide a useful description of the process and makes intuitive sense.

Then, we propose to analyze the performance of different forms of turbo trellis coded modulation at low E_b/N_o based on this technique. This is especially useful because several techniques have been proposed for bandwidth efficient turbo coding including turbo trellis coded modulation by Robertson and Wörz [97, 98, 99], parallel concatenated bandwidth efficient coding with bit interleaving by Benedetto *et al* [7, 10] which has been used with symbol interleaving by Fragouli and Wessel [39], pragmatic approach by Le Goff *et al* [53], Multilevel coding by Wachsmann and Huber [114]. A comprehensive comparison of these techniques based on their performance at low SNRs is yet unavailable. The proposed analysis will determine which construction of turbo trellis coded modulation performs closest to capacity. Extension of the density evolution technique to the turbo trellis coded modulation case is a bit involved. Since the modulation is non linear, first of all the all-zeroes sequence cannot be used as the reference sequence and, hence, the concentration theorem proved for the binary case in [94] is not directly applicable. We conjecture that a similar concentration theorem can be proved by assuming that the inputs are all from a typical set and the performance of the iterative decoder will be concentrated around the average performance for all inputs from the typical set. We will first attempt to see if the conjecture is true or not. If not, we have to carefully interpret the use of density evolution. Another difficulty in analyzing the particular scheme of Robertson and Wörz [97] is that two types of extrinsic information are updated in every iteration - the extrinsic information for the data and also the extrinsic information about the punctured parity bits. Consequently, in evaluating the thresholds, we have to compute the transfer function of the component codes as functions of two types of extrinsic information. We propose to first evaluate the transfer function as a function of both parameters and, then to find a correlation between the two types of extrinsic information to see if the problem can be simplified to a one parameter problem.

3.2 Concatenated Coding for Continuous Phase Modulation

Continuous phase modulation (CPM) is an attractive modulation format for wireless systems due to its constant envelope property and compact power spectral density. When trellis coding is combined with CPM, excellent power and bandwidth efficiency can be achieved, making it an ideal choice for use in power and bandwidth limited applications. Several systems including satellite communication systems and the European cellular standard, GSM have successfully employed CPM schemes. The basic difference between CPM and PSK or PAM is that the modulator inherently possesses memory. While there has been intense activity in the past several years in designing turbo codes with PSK or PAM, the design of concatenated codes for use with CPM has received much lesser attention. Here, we propose a comprehensive study of several possible coding and decoding structures.

Prior work on coding for CPM: The design and performance of convolutional codes with CPM for AWGN channels has been considered by many researchers [3, 17, 55, 88]. The basic idea in the design of codes with CPM has been to exploit the inherent memory in the CPM modulator. By carefully matching the trellis code to the memory in the modulator, the overall distance spectrum can be improved. Rimoldi [96] showed that every $M-$ary CPM scheme (including partial response CPM) can be expressed as a convolutional code, known as the continuous phase encoder (CPE) followed by a memoryless mapper. If the partial response pulse shape spans L symbols (full response is the special case with $L = 1$, then the CPE is a $L/L + 1$ convolutional code defined over the ring of integers modulo-M as shown in Fig. 3. Rimoldi also showed that the CPE can be a recursive or a non-recursive code as shown in Figs. 3(a) and (b) and, in general there are many realization of the CPM scheme. *While these two modulators in Figs. 3(a) and (b) generate the same set of CPM signals, we will see that particular properties of these encoders can be exploited when designing coding schemes for CPM signals.* By using Rimoldi's decomposition, Yang and Taylor proposed non-binary ring convolutional codes which when combined with the CPE result in increased free distance [116]. The design and performance of trellis coded CPM for fading channels was considered in [50, 117]. However, none of the aforementioned work exploits the recursive nature of the CPM modulator. Similarly, they have not considered the use of an iterative decoder. Multilevel coding for CPM with convolutional codes has been considered by Bossert *et al* [46, 18] and Altunbas and Aygolu in [2].



(a) Recursive realization (b) Non-recursive realization

Figure 3: Recursive and Non-recursive realizations of CPM

PI's previous work in this area - Iterative demodulation and decoding: In [64], we studied the concept of iterative demodulation and decoding from a serial concatenation perspective. In [80], we analyzed interleaved trellis coded CPM schemes by treating the CPM modulator as the inner code in a serial concatenated scheme. When the recursive realization of the CPM modulator is used, the resulting concatenation scheme has a recursive inner code and, hence, results in excellent bit error performance. In [80], we derived union bounds on the performance of such schemes for AWGN and correlated flat Rayleigh fading channels by considering the combination of the trellis code, interleaver and CPM as a serial concatenated code. In this proposal, we refer to this system as bit interleaved coded CPM (BICCPM). In [71, 80] we considered iterative non-coherent detection of BICCPM also.

It should be noted that in the last year several authors have independently used the BICCPM approach [20, 112, 109]. Receiver structures for iterative demodulation and decoding of CPM has also been considered in [47, 56, 71, 80]. Except for the BICCPM discussed above, there has not been much work on combining concatenated codes with CPM. Here, we propose a comprehensive study of the analysis and design of concatenated codes (parallel and serial) for CPM both based on the distance spectrum and on convergence. We consider the fairly general case of *partial response CPM with multi-levels (non-binary)*, since this includes full response and binary schemes as special cases. Further, we refer to any system where redundancy is added to reduce the data rate as convolutionally encoded CPM, while we refer to system without data rate reduction as trellis coded CPM.

Proposed Work

3.2.1 Parallel and Serial Concatenated Codes

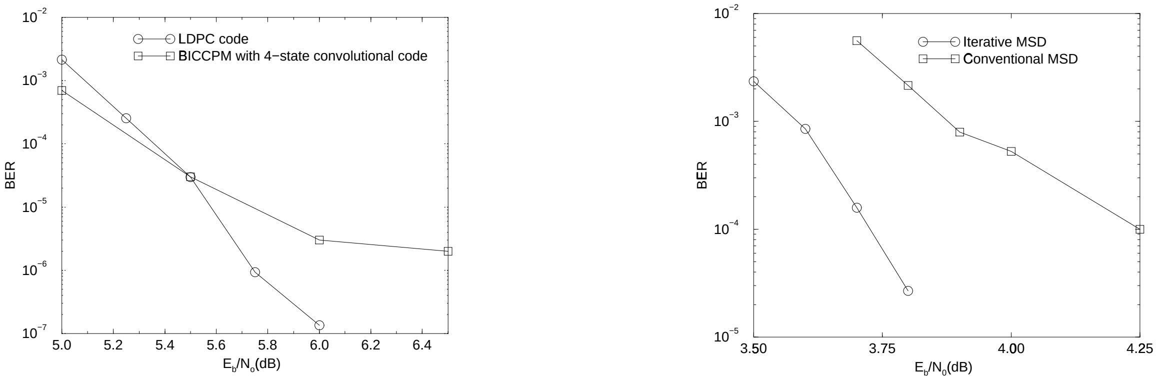
Consider the design of a code for p b/s/Hz using a $M = 2^q$-ary CPM. The basic idea is to use convolutional codes over the ring $R(2^q)$ in a parallel concatenated scheme. Since the code and the modulator are both defined over the same ring, the receiver operates on the combined trellis of the component code and the CPE, and produces soft output or extrinsic information which is used in an iterative scheme. Since the continuous phase encoder is recursive, the combination of the code and the modulator can be made recursive. In this work, we will derive bounds on the effective free distance as a function of p, q, and ν, where ν is the constraint length. The approach will be similar to that in [12, 28, 39]. Then, we will undertake a code search to find the codes that optimize the effective free distance (rather the free distance as in [116]) Since these codes are inherently recursive, it may turn out that some of the codes in [116] may already be optimum in terms of effective free distance. However, in some cases, Yang and Taylor's code have parallel transitions. When used with symbol interleaved concatenation, parallel transitions will result in poor performance. Hence, we propose to find good codes that do not admit parallel transitions. To simplify the code search, we will first consider a canonical structure for these codes such as in [37, 39] and we will search over the canonical encoders. Finally, we propose to study the distance spectrum of these codes for both symbol and bit interleaving. While this proposal was being written, we came to know of an yet unpublished manuscript by Shane and Wesel [106], who report encouraging results for PCCC for minimum shift keying (MSK) and Gaussian MSK (GMSK) using the above approach.

Then, we propose to consider the design of codes over the ring modulo-M based on density evolution. The idea will be to optimize the component codes to result in the least E_b/N_o threshold. There is still no clear understanding of what type of component codes optimize the threshold, even for memoryless modulation. This study will try to provide insight into the structure of convolutional codes in general (binary and non-binary) that perform well at low E_b/N_o in an iterative setup. Finally, we will consider irregular codes as discussed in Sect. 3.1.

For the trellis coded CPM case (p b/s/Hz using 2^{p+1}-ary CPM), we will consider extending the turbo TCM, parallel concatenated TCM techniques discussed in Section 3.1.2.

3.2.2 Bit Interleaved Coded CPM with LDPC codes

The proposed research builds on our previous work in [64, 80, 71]. Instead of regular convolutional codes considered there, we consider the design of irregular codes as in Section 3.1. Again, using the technique of density evolution, we will determine optimum degree profiles for use with CPM. We also propose to derive union bounds for the case of irregular codes.



(a) (b)

Figure 4: (a) Performance of regular LDPC codes with 8-ary CPFSK; $h = 1/8$ (b) Performance of MLC with iterative MSD for 8-PSK

Then, we consider the use of LDPC codes as outer codes. The motivation for considering LDPC codes in this setup is the possibility to obtain improved performance at reduced decoding complexity. To understand this, let us consider the design of a BICCPM scheme for use with 8-ary continuous phase frequency shift keying (CPFSK) with modulation index $h = 1/8$. In this case, the modulator has 8 states and 8 branches from each state. Therefore, the soft-output demodulator has to operate on a trellis with 64 transitions in each stage. Since for BICCPM, a soft output demodulator is required in every iteration, the decoding complexity is quite high. The main bottleneck is that both the memory and the recursiveness can be exploited only through the soft output demodulator. When LDPC codes are used as outer codes, it is not essential that the inner code be recursive. Since iterative demodulation is required only to take advantage of the memory in the modulator, much fewer iterations using the soft output demodulator are required. Consequently, the complexity is significantly lower. In Figure 4(a), we compare the performance of an LDPC code for 8-ary CPFSK with modulation index $h = 1/8$, with that of a BICCPM system with a convolutional outer code from [112]. A regular LDPC code with average column weight of 3 (without any optimization) was chosen. It can be seen that LDPC codes outperform the BICCPM codes with convolutional outer codes even when the complexity of the LDPC scheme was approximately 1/4th that of the BICCPM scheme.

For BICCPM, the choice of the realization of the modulator (recursive or non-recursive), and choice of mapping bits to symbols are crucial and can significantly affect the performance. Density evolution is a powerful tool to analyze the effects of these. We propose to think of the LDPC code and the CPM modulator together as one code defined on a graph. The overall graph will be an extended graph of the LDPC code, where the CPE in the modulator specifies an $M-$ary constraint instead of a binary constraint. Then, the effect of modulator realization, bits to symbol mapping etc, will be studied on the threshold for this graph. Recently, we have been able to prove that the non-recursive realization significantly outperforms the recursive realization during the first iteration. That is $I(u_n, \boldsymbol{r})_{rec} \leq I(u_n, \boldsymbol{r})_{nonrec}$ (please see Fig. 3) where $\boldsymbol{r}$ is the received signal). This essentially means that the initial conditions for the iterations are better for the non-recursive realization than the recursive realization. We propose to study the effect of this difference in the initial conditions on the threshold. This will clearly indicate which of the two realizations should be used. Further, the recursive realization of the CPM modulator itself is not unique. Some realizations will have a lower threshold than others. Therefore, we propose to find some design criteria to find good recursive realizations. This problem is similar to the problem of designing rate-1 precoder for ISI channels that we have treated in [67, 74]. Finally, we will also consider the mapping from bits to symbols for non-binary CPM since it will also have an effect on the threshold.

3.2.3 Multilevel Coding

While the use of parallel and serial concatenated trellis coded modulation will result in good power efficiency with CPM, the computational complexity can be fairly high. Bit interleaved coded CPM may have lower complexity than TTCM, however, the bit error performance of BICCPM is generally worse. Multilevel coding is a potential solution to achieve excellent error performance at low decoding complexity. In this section, we concentrate on the design of multilevel coded CPM with irregular LDPC and turbo codes as component codes. Further, we propose an iterative receiver structure that naturally combines the iterations within the LDPC code and the CPM modulator.

This section builds on our recent result on extending LDPC codes to non-binary modulation (8-PSK) through MLC [72]. We investigated the performance of iterative multi-stage decoding (MSD), where instead of passing hard decisions from lower levels to the upper level, soft-output is passed to and from all the levels by considering a graph that represents the combination of the code and the modulation [72]. A sample result is shown 8PSK in Fig. 4(b) for a block length of $N = 3000$ symbols and an AWGN channel. It can be seen that iterative MSD, significantly improves the performance over conventional MSD and the performance is only 0.8 dB away from the constrained capacity for a BER of 10^{-5}, even though the LDPC codes are not fully optimized. Motivated by these results, we consider the design of codes for CPM.

Design of Irregular LDPC codes for Multilevel coded CPM In multilevel coding, the signal set is partitioned progressively in to smaller subsets and at each stage a binary code of appropriate rate is used to protect the address bits for that level of partition [48]. Wachsmann and Huber [114] have shown that if the rates in each of the levels are chosen to match the capacity of the equivalent channels as seen at each of the levels, then the overall MLC can achieve capacity with multi stage decoding if the codes in each of the levels achieves capacity. We propose to first derive optimal code rates for the different levels for CPM signals as a function of the modulation index, phase response, and the mapping (Gray, natural or mixed [114]). Unlike in the case of memoryless modulation, the capacity for CPM signals may not be well-defined because of the inherent Markov structure. However, the cut-off rate for CPM is well-defined [1, 3] and, hence, we propose to derive the code rates for each level based on the cut-off rate of the equivalent channels. For short length blocks we will use the coding exponent rule [114].

We then consider two kinds of decoders and design LDPC codes matched to each of the two decoders. We first consider conventional multi-stage decoding, that is, a decoder where the hard decisions from levels $1, 2, \ldots, i-1$ are fed in to the decoder at level i. In this case, the optimal code design would be to design irregular LDPC codes based on density evolution at level i of rate R_i, where R_i is the cutoff rate at level i. Then, we consider an iterative multi-stage receiver, where soft-outputs (extrinsic information) is exchanged across all the levels in a multi-stage decoder. We can think of this as a generic decoder which employs message passing in a graph which represents the code and the modulator in one graph. The code design in this case is different from the case of conventional multi-stage decoding since messages are passed across all the levels. Finally, we will consider the use of codes over GF(2^q) in each of the levels. Since the decoding complexity for codes over GF(2^q) is higher than that of binary codes, we will also consider the use of GF(2^q) codes only at the lowest level. It should be noted that usually the required rates at the lowest level is very low and the highest level is very high. It was noted in [43] that irregular turbo codes would provide good improvement in performance for low rate codes and, hence, our results from Sec. 3.1 will be useful here. Similarly, the design of good high rate LDPC codes is difficult and the turbo product codes that we consider in Sec. 3.3.2 will be a good choice.

3.3 Concatenated Coding for Digital Magnetic Recording

In the past few years, there has been much interest in applying the concept of concatenated coding and iterative (turbo) decoding to digital magnetic recording. In order to understand the significance of this proposal and how the proposed techniques are different from the existing techniques, let us consider the system model as shown in Fig. 5

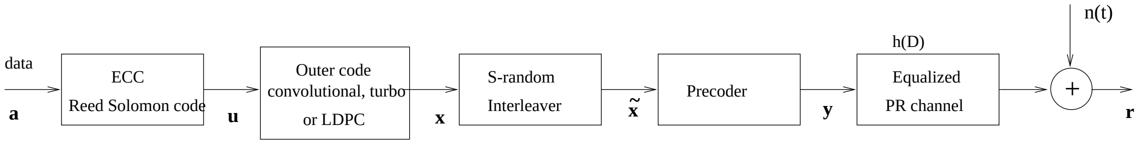


Figure 5: System Model

The data is first encoded using an error correcting code (ECC), which is typically a Reed-Solomon (RS) code and then encoded by a convolutional code, turbo code or an LDPC code. This is referred to as the outer code in this proposal. The codewords of the outer code are interleaved and encoded using an optional precoder, which is a rate-1 recursive convolutional code and then recorded on the magnetic disk. Assuming that the read back is equalized to some partial response (PR) target, the net effect is having passed the inner codewords through an inter-symbol interference channel. At the receiver a soft output equalizer (for the precoded channel) and a soft output decoder for the outer code are usually employed in an iterative fashion. The use of parallel concatenated outer codes has been considered in [100, 108, 34]. The use of simple convolutional codes as outer codes with a precoded partial response channel has been considered and shown to provide good performance in [108, 84, 101, 63, 34, 4]. The reason for the good performance even with a simple convolutional outer code is that the precoded partial response channel acts as a recursive inner code and, hence, the concatenation of the outer code and the precoded channel provides good error performance. Recently, LDPC codes have also been shown to provide good error performance in [49, 107].

The peculiarity of the magnetic recording application compared to other convolutional encoded systems with turbo equalization is that the end target BERs are extremely low (of the order of 10^{-15}) and the outer code is a very high rate code (rate 8/9, 16/17 or, higher). In order to achieve such a small bit error rate, the Reed-Solomon error correcting code (ECC) is essential. Almost all the papers referenced above have ignored the presence of the ECC and analyzed or designed outer codes and precoders with the assumption that the *average* target BER at the output of the outer decoder is around 10^{-5} or 10^{-6}. The ECC would then bring the error rate down to 10^{-15}. Since a target BER of around 10^{-6} for the outer code and the ISI channel implies operating at the beginning of the error floor region of the BER curve, the design of codes was based on reducing the BER floor to as low BERs as possible [101]. However, in the presence of an RS code, this design approach is sub-optimal because, *it ignores the error distribution at the output of the decoder.* Because of the fact that the turbo decoder is not an ML decoder, the output can be bursty at times causing the RS decoder to fail, even though the average BER is very small.

In this proposal, we consider the design of outer codes, precoders and modulation codes based on the convergence of the iterative decoding process and on the distance spectrum such that the performance is optimized in the presence of an outer code.

PI's previous work in this area: The effective of the precoded ISI channel on the distance spectrum of the overall concatenated code was studied by us in [63]. In [67, 75], we analyzed the effect of the precoded ISI channel on the convergence of the turbo equalization process by treating turbo equalization as one parameter dynamical system similar to the ideas in [36, 19]. We showed that the precoder has a significant impact on the convergence process and analyzed the effect of the precoder both during the first iteration and asymptotically as $E_b/N_o \rightarrow \infty$. Using this we provided some counterexamples to show situations where the design based purely on the distance spectrum of the outer code and the precoder fails in the presence of an ECC. Related work on the design of codes for ISI channels matched to the turbo equalization can be found in [67, 74].

Proposed Work:

3.3.1 Design in the Presence of an ECC

When a t-error correcting RS code is present, the probability of error is the probability that there are more than t errors at the output of the outer decoder. This event can occur due to two reasons - (i) due to low weight code words (these error events occur even in the presence of an ML decoder) (ii) due to the poor convergence of the turbo equalization algorithm. Further, in practice, one has to use a small fixed number (say around 5 or 6) iterations. Therefore, we propose a new design criteria which identifies codes that converge rapidly, not necessarily to the right code word but to a sequence at very small Hamming distance (less than t) from the correct code word. The RS code can correct the residual errors.

The key idea is to characterize the turbo equalization process as a dynamical system which updates the reliability of the extrinsic information and to study the effect of the outer code, precoder and modulation codes on the rate of increase of the extrinsic information. We will first determine a target reliability that should be reached in order to assume that the turbo decoding algorithm has achieved performance close to that of the maximum likelihood decoder. The objective will then be to find a combination of the outer code and the precoder that can achieve this threshold for the least SNR. Rather than studying how the average reliability evolves with iterations we propose to study the *worst case* reliability, since for finite lengths the deviation of the behavior from the average can be significant. In [67], we showed an example with two different precoders in which the average reliability for precoder 1 increased at a faster rate than that of precoder 2, whereas the worst case reliability was better for precoder 2. We further showed that precoder 2 outperforms precoder 1 when an RS code is used, even when precoder 1 has a lower BER floor. The problem still remains in that the worst case reliability is not easy to compute analytically. Since it is impractical to run simulations to get reliability estimates of worst case reliability, we propose to investigate techniques to model the pdf of the reliability as function of iterations (for example, Gaussianity is one special case). Then, we can bound the worst case reliability and with a certain confidence, predict the burstiness of the iterative decoder. One of the main objectives of the proposed research is to build an understanding of the relationship between the burstiness at the output of the iterative decoder and the structure of the outer code and precoder. Some of the research on the pseudo-codewords may be relevant to this understanding [41].

3.3.2 Analysis of Turbo Product Codes

Recently, we have shown that turbo product codes (TPC) based on single parity check (SPC) codes can provide performance similar to LDPC codes for equalized PR channels [54]. Turbo product codes based on SPC codes are attractive for digital magnetic recording because they are easy to encode ($O(N)$), easy to decode, have better burst statistics than LDPC codes [54] and have a minimum distance of 2^n where n is the dimensionality. It should be noted that when high rate convolutional codes or turbo codes are used as outer codes, the minimum distance is usually very low (less than three). In spite of these advantages, there have not been many studies that have considered these codes for digital magnetic recording applications. While TPC codes themselves have been studied extensively [92, 91], and TPC codes based on SPC codes have been shown to be inferior to LDPC codes [52], the concatenation of TPC codes with a *recursive* inner code (such as a precoded PR channel) has good performance. Since the $d_{free} > 3$ and the precoded channel is recursive, a significant interleaving gain results [9].

Motivated by our results in [54], we propose to analyze these codes in detail. We propose to first compute thresholds for the concatenation of the TPC code and the channel. In this case, one has to be careful since the TPC itself has short loops (even for infinite length codewords) and, hence, we cannot use infinite iterations in the density evolution process for the TPC alone. However, the exchange of extrinsic information between the TPC decoder and the PR4 equalizer can be done several times. Then, we propose to study some tools to analyze the the burstiness at the output of the decoder in order to explain our experimental results.

Since the distance spectrum of the outer TPC code based on SPC codes can be computed exactly, a coding theorem can be proven (at least for the AWGN channel) for the concatenation of the TPC code and the precoder. That is, the existence of a threshold E_b/N_o above which, the probability of error decreases exponentially in length with ML decoding. We propose to use an approach similar to [84] to compute the distance spectrum and then to bound the terms in the union bound as in [26]. It should be noted that for high rate convolutional outer codes and PCCC) such a theorem cannot be proved because $d_{free} < 3$ and the distance spectrum cannot be computed exactly.

3.3.3 Novel Receiver Structures

Two novel approaches are proposed. The first is to use a list decoder to generate a list of paths L at the output of the iterative decoder so that the RS code can pick one of these paths. Since the outer code is a very high rate code, there may be low weight codewords for the overall concatenated code and, hence achieving a BER of 10^{-15} may be quite difficult even with an ML decoder. The probability of a frame error can be decreased significantly in the error floor region of the BER curve using list decoding. We propose to study the use of list decoding algorithms such as in [105, 102, 66, 82] to generate the list. We also propose to analyze the asymptotic performance ($E_b/N_o \to \infty$) of the list decoders under the assumption that a list of L globally best paths can be generated.

Second is the use of novel low complexity soft output M-algorithms such as the M-BCJR algorithm in [40]. In our recent work, we have shown that the M-BCJR algorithm in [40] is inherently too 'optimistic' and we proposed an alternate algorithm using the soft output Viterbi algorithm (SOVA) which provides better performance at reduced complexity [78, 22]. We propose to study and design such algorithms for iterative equalization of PR channels. Finally, we will also consider parallel implementations of the decoding algorithm such as in [22] in order to reduce the worst case decoding delay. This will be useful because a VLSI implementation of the decoders can take advantage of the parallelism.

4 Education Plan

My desire to be a teacher has been the major influence in several choices I have made throughout my graduate studies, including pursuing graduate studies. After having first hand experience for 19 months now, I couldn't be more enthusiastic about the opportunities to teach and interact with students. I hope to convey at least some of this enthusiasm through the following education plan.

4.1 Career Objectives

My main objectives in establishing myself as a teacher at Texas A&M University are (i) To build a strong research program that emphasizes fundamental concepts and practical applications in the areas of communication theory generally, and in the areas of coding and wireless communications specifically, (ii) To be a teacher who not only teaches well, but motivates students and kindles their interest, (iii) To develop new courses and upgrade existing ones and introduce novel teaching aids especially through the use of the Internet, (iv) To develop students who are well-rounded and who can contribute to the field of communications on a long-term basis in various capacities,

(v) To develop a tradition of interacting with the industry, (vi) To reach out to students and attract high quality undergraduate and graduate students.

4.2 General Plan

My general plan to achieve these ambitious goals include

4.2.1 Curriculum Development

The area of communications is undergoing rapid development and changes. The last few years have been very exciting for coding theory especially due to the invention of turbo codes, space-time codes etc and the re-discovery of low density parity check codes. What this means at the educational level is that students need to be trained and taught several new concepts. This requires introducing new courses and upgrading existing courses.

In the first semester of my teaching here at Texas A&M university, I developed and taught a graduate level course called **Advanced topics in channel coding**. This course is designed to be a second level course in channel coding and mainly covered the concepts of concatenated coding, iterative decoding and trellis coded modulation. Since I taught this course last year, there have been recent developments in this area. I propose to constantly upgrade this course so that the fundamental concepts and the state-of-the art techniques in this area are covered in this course. Similarly, the **Wireless communications** course here at Texas A&M will also be upgraded with several of the recent developments in this area.

We are in the process of developing a new undergraduate laboratory course on digital communications. What is envisioned is a laboratory where signal generators, A-to-D converters, digital signal processors and some PCs are interfaced such that students will be able to load different algorithms, study them, and see the operation of the algorithms on real-time signals.

4.2.2 Integrating Research and Education

The advantage of being in a university with a sizeable undergraduate/graduate program is the ability to integrate research and education. I feel that the symbiosis between the two is of utmost importance and I plan to develop this in the following ways

Electronic Handbook on Digital Communications In order to get students motivated and to convey ideas to students in the most efficient way, one has to go beyond pedagogic exercises and develop novel approaches to teaching. The Internet is an amazing tool, which provides at least two great advantages over conventional books - (i) interacting capability (ii) easy upgradability.

The proposed project to develop a comprehensive electronic library of resources to teach communication theory exploits both the advantages. The PI along with a graduate student and a couple of undergraduate students, proposes to develop several web-based resources that *interactively* teach the concepts of communication theory. For example, the step by step operation of several basic algorithms (e.g. Viterbi algorithm, BCJR algorithm, SOVA etc) will be graphically shown. The student will be able to interactively change the parameters and step through the algorithm at his/her pace. Similarly several games in understanding the concepts of probability will be simulated. Funding is requested for undergraduate students who are expected to learn the operation of algorithms and to be able to develop the applets. This will provide an avenue to involve undergraduate students in research and to get interested in communications so that they hopefully continue graduate studies at A&M.

I have already received an educational grant from Rockwell Collins to support a graduate student to participate in this project for two semesters to develop material for use in the advanced topics in channel coding course. We wish to emphasize that what is proposed here is not just a few algorithms rather a comprehensive library with extensive references and links to other resources that will be beneficial to several of the communications related classes being taught throughout the world. Although this is a big task, I am confident this can be accomplished with the help of the students involved in the project. A preliminary, yet non-interactive step by step tutorial to teach LDPC decoding can be found on my homepage at http://ee.tamu.edu/krishna/.

Outreach Activities I propose to develop strong ties with the existing outreach activities at Texas A&M to attract undergraduate students to digital communications. There are two important activities at Texas A&M that will be tied to the proposed research activities here - the “GE Find a Faculty Program” and the “Texas Engineering Experimental Station Undergraduate Research Program”. Both these programs are aimed at identifying/ recruiting undergraduate students, especially minority students from all over the US and shape them to becoming future faculty members and engineers. In the past few years 30% of the students in this program were women and 25% were ethnic minority. These programs are organized such that a professor funds a student and supervises the research, while the program provides guidance and assistance with presentation skills, communication skills and organizes student conferences to showcase the students' research to local companies. The students also participate in a one-day program where they talk to several local high school students.

I also propose to start a program to have one day or two day seminars or open-houses in the wireless communications labs, where undergraduates can visit the labs and talk to graduate students about the research topics in wireless communications. I think this will be a good way to get undergraduates interested in communications. As part of one of the research grants that I have from the Texas higher education coordination board, additional funding is available to mentor high-school mathematics teachers. I will be eligible to apply for this grant next summer and I will actively pursue this.

Research projects in courses: In addition to home works and mid-terms, I propose to introduce projects for students to work in a team on a research topic relevant to the course. I have experimented with this when I taught graduate classes both in the Spring and Fall semester of 1999. The testimony to the success of this was the eagerness shown by the students in working on the project. Most of the students went on to do excellent projects and voluntarily did more than what was expected of them. I propose to continue to introduce such projects in to undergraduate classes as well.

Student supervision: The proposed project will lead to several theses and research projects for graduate and undergraduate students. For M.S. and Ph.D. thesis, students will work on one or more of the items in the research plan and will be expected to make significant theoretical and experimental contributions. I cannot stress enough my inclination to foster and encourage students engaging in this research. After an year and a half of being here, I am currently advising 2 Ph.D. students and 3 M.S. degree students, and one student who I co-advised has recently graduated.

4.2.3 Industrial Interaction

My plan to develop a tradition of interaction with the industry takes advantage of the proximity to the telecommunications corridor in the Dallas/Fort Worth area and Texas A&M's membership in Texas Telecommunications consortium (TxTEC). These provide an excellent opportunity for me and the students to make research visible to the industry and to get feedback. The plan to develop interactions is through (i) arranging visits to industry - I plan to visit the companies to keep them abreast of the development in research and curriculum developments. (ii) arrange for industry visits on campus. (iii) aggressively pursuing co-op opportunities for students (iv) attract input from the industry about course projects.

In the last 19 months, I have obtained four grants from the industry (3 individual and 1 joint) from Texas Instruments (TI) Inc, Motorola Inc, Rockwell Inc and Tadiran Microwave Networks. Through the research contacts that I have developed, one of my students is currently a co-op student at Seagate Research working the area of magnetic recording and another student is at TI working on turbo decoder implementation.

5 Prior Research and Educational Accomplishments

The PI's research interests are broadly in the areas of communication theory and on coding theory and its applications in particular. He has been working in the area of concatenated coding and iterative processing for the past five years. Results from his research include - novel retransmission strategies for use with turbo coded ARQ schemes [69, 79], bandwidth efficient concatenated schemes with turbo codes by exploiting the unequal error protection property of turbo codes [70], design and analysis of list decoders for turbo codes [79, 66], analysis of concatenated schemes that use differential modulation or CPM schemes as inner codes over AWGN and Rayleigh fading channels [64, 80, 71, 65]. Recently, his researched has focussed on turbo equalization for wireless communications and magnetic recording [63, 67, 74, 68, 32, 54], low complexity iterative decoding [67, 22], space-time coding [73] and DSP implementation of iterative decoders [16]. Apart from these areas, he has worked on interference rejection in direct sequence spread spectrum systems [81], equalization for high speed indoor wireless communications [76, 77]. He currently serves as an associate editor for IEEE Communications Letters and served as a session chair for ICC 2000 and VTC'99 (Spring).

He has been the PI on 5 extramural grants that were awarded in the last year and co-PI on one grant, totalling about $350,000. Sponsors include NSF [*], The Texas Higher Education Coordination Board, Texas Instruments Inc., Motorola Inc., Rockwell Collins Inc.(educational grant), and Tadiran Microwave Networks Inc.

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[*] Although the program director has recommended the proposal for funding, official notification of the award has not been received yet. Therefore this grant is not listed as current support

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E. BIOGRAPHICAL SKETCHES

Biographical Sketch of Prof. Narayanan

Vita

Krishna Narayanan received the Ph.D. degree in Electrical Engineering from Georgia Institute of Technology in December 1998 and immediately joined the Department of Electrical Engineering, Texas A&M University as an Assistant Professor.

His research interests are in the areas of communication theory and signal processing for communications. Specifically, in the areas of modulation and coding, equalization and interference rejection. His current research focuses on concatenated coding (turbo codes, low density parity check codes), space-time coding and iterative processing for wireless communications and magnetic recording. He has also worked in the areas of interference rejection for direct sequence spread spectrum systems and equalization for high speed indoor wireless communications. During the summer of 1995, he was an intern at AT&T Labs – Research working on equalizer design for high speed wireless communications. He is currently an associate editor for IEEE communications letters and served as the session chair in ICC 2000 and VTC'99 (spring).

He has been the PI on five extramural grants and co-PI on one grant that were awarded in the last year. Sponsors include National Science Foundation [1], The Texas Higher Education Coordination Board, Texas Instruments Inc, Motorola Inc., Rockwell Collins Inc., and Tadiran Microwave Networks Inc.

He has developed and taught a course on advanced topics in coding theory which covers concatenated coding, iterative decoding and trellis coded modulation in detail. He currently advises 2 Ph.D. students and 3 M.S. degree students and was the co-advisor of a Ph.D. student who graduated recently.

Five Related Publications

- K. R. Narayanan and G. L. Stüber, "A Serial Concatenation Approach to Iterative Demodulation and Decoding", *IEEE Trans. Communications* , pp. 956–961, July 1999
- K. R. Narayanan and G. L. Stüber, "Performance of Trellis coded CPM with Iterative Demodulation and Decoding",*to appear in IEEE Trans. Comm, also in IEEE Comm. Theory Mini. Conf., Globecom 1999*
- K.R. Narayanan and G. L. Stüber, "List Decoding of Turbo Codes", *IEEE Transactions on Communications*, pp. 754-762, June 1998,
- L. McPheters, S. W. McLaughlin and K.R. Narayanan, "Precoded PRML, Serial Concatenation, and Iterative (Turbo) Decoding for Digital Magnetic Recording", IEEE Tran. Magnetics, pp. 2325–2327, Sept, 1999.
- K. R. Narayanan, "The Effect of Precoding on the Convergence of Turbo Equalization for Partial Response Channels", *under review for IEEE Journal Selected Areas in Communications, Feb 2000, also to appear in IEEE Globecom, Nov. 2000*

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[1] Although the program director has recommended the proposal for funding, official notification of the award has not been received yet

Five Additional Publications

- K.R.Narayanan and U.Dasgupta, “Design of Codes and Low Complexity Receivers for ISI channels with Turbo Equalization”,*submitted to IEEE Journal Selected Areas in Communications, May 2000.*
- K. R. Narayanan and G. L. Stüber, “Selective Serial Concatenation of Turbo Codes”, *IEEE Communications Letters*, pp. 136-139, Sept 1997
- K. R. Narayanan and G. L. Stüber, “A Novel ARQ Technique Using the Turbo Coding Principle”, *IEEE Communications Letters*, pp. 47-50, March 1997
- K.R. Narayanan and J.Li, “Bandwidth Efficient Low Density Parity Check Codes Using Multilevel Coding and Iterative Multistage Decoding”,*to appear in Proc. of Intl. Symp. on Turbo codes and Related Topics, Sept. 2000*
- K. R. Narayanan and J. F. Doherty, “A Convex Projections Method for Improved Narrowband Interference Rejection in Direct Sequence Spread Spectrum Systems”, *IEEE Trans. Communications*, 722-724, July 1997

Collaborators - Past 48 Months

Prof. G. L. Stüber (Dept. of Electrical Engineering, Georgia Institute of Technology, GA);
Prof. S. W. McLaughlin (Dept. of Electrical Engineering, Georgia Institute of Technology, GA);
Dr. L. J. Cimini (AT&T Labs-Research, Red Bank, NJ);
Dr. S. Ariyavisitakul (Home Wireless Networks, Atlanta, GA);
Prof. C. N. Georghiades (Dept. of Elect. Engineering, Texas A&M University, College Station, TX);
Prof. S. L. Miller(Dept. of Elect. Engineering, Texas A&M University, College Station, TX);
Prof. X. Wang (Dept. of Elect. Engineering, Texas A&M University, College Station, TX);
Dr. E. Kurtas (Seagate Research Labs, Pittsburgh, PA)
Dr. D. H. Kim (Lucent Technologies, Atlanta, GA);

Advisors

Doctoral Thesis Advisor : Prof. Gordon L. Stüber, Georgia Institute of Technology.

Master’s Thesis Advisor: Prof. John F. Doherty, Pennsylvania State University.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **Texas Engineering Experiment Station**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Krishna Narayanan - Asst. Professor**	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (2) GRADUATE STUDENTS				29,088	
4. (2) UNDERGRADUATE STUDENTS				6,326	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				35,414	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				6,380	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				41,794	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				1,000	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				43,794	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 22.0000, Base: 43794)**					
TOTAL INDIRECT COSTS (F&A)				9,634	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				53,428	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 53,428	$

M. COST SHARING PROPOSED LEVEL $ 15,670	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

NSF Form 1030 (10/99) Supersedes all previous editions

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **Texas Engineering Experiment Station**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed	 Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Krishna Narayanan - Asst. Professor**	**0.00**	**0.00**	**0.00**	$ **0**	$
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	**0.00**	**0.00**	**0.00**	**0**	
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	**0.00**	**0.00**	**0.00**	**0**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL ASSOCIATES	**0.00**	**0.00**	**0.00**	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	**0.00**	**0.00**	**0.00**	**0**	
3. (**2**) GRADUATE STUDENTS				**29,961**	
4. (**2**) UNDERGRADUATE STUDENTS				**6,516**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**36,477**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**6,387**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**42,864**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**1,000**	
2. FOREIGN				**0**	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ **0**					
2. TRAVEL **0**					
3. SUBSISTENCE **0**					
4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**1,000**	
TOTAL OTHER DIRECT COSTS				**1,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**44,864**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 22.0000, Base: 44864)**					
TOTAL INDIRECT COSTS (F&A)				**9,870**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**54,734**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **54,734**	$

M. COST SHARING PROPOSED LEVEL $ **5,670**	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION **Texas Engineering Experiment Station**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Krishna Narayanan - Asst. Professor	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (2) GRADUATE STUDENTS				30,859	
4. (2) UNDERGRADUATE STUDENTS				6,711	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				37,570	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				6,393	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				43,963	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				1,000	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				45,963	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 22.0000, Base: 45963)					
TOTAL INDIRECT COSTS (F&A)				10,111	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				56,074	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 56,074	$

M. COST SHARING PROPOSED LEVEL $ 5,670	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

YEAR 4

ORGANIZATION **Texas Engineering Experiment Station**	**FOR NSF USE ONLY**		
	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Krishna Narayanan - Asst. Professor**	0.00	0.00	2.00	$ 15,032	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	15,032	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (2) GRADUATE STUDENTS				31,786	
4. (2) UNDERGRADUATE STUDENTS				6,912	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				53,730	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,354	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				63,084	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				1,000	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				65,084	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 22.0000, Base: 65084)**					
TOTAL INDIRECT COSTS (F&A)				14,318	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				79,402	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 79,402	$

M. COST SHARING PROPOSED LEVEL $ 5,670	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

SUMMARY PROPOSAL BUDGET

YEAR 5

ORGANIZATION **Texas Engineering Experiment Station**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Krishna Narayanan - Asst. Professor	0.00	0.00	2.00	$ 15,483	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	15,483	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (2) GRADUATE STUDENTS				32,739	
4. (2) UNDERGRADUATE STUDENTS				7,121	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				55,343	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,431	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				64,774	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				1,000	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				66,774	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 22.0000, Base: 66774)					
TOTAL INDIRECT COSTS (F&A)				14,690	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				81,464	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 81,464	$

M. COST SHARING PROPOSED LEVEL $ 5,670	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

Cumulative

	FOR NSF USE ONLY		
ORGANIZATION **Texas Engineering Experiment Station**	PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Krishna Narayanan**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Krishna Narayanan - Asst. Professor	0.00	0.00	4.00	$ 30,515	$
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	4.00	30,515	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (10) GRADUATE STUDENTS				154,433	
4. (10) UNDERGRADUATE STUDENTS				33,586	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				218,534	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				37,945	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				256,479	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				5,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				5,000	
TOTAL OTHER DIRECT COSTS				5,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				266,479	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				58,625	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				325,104	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 325,104	$

M. COST SHARING PROPOSED LEVEL $ 38,350	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Krishna Narayanan**	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

C***SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)**

6 Budget Justification

The following is a justification of the budget in the next page.

- Student support: The main item requested in the budget is support for graduate students. Support is requested for two Ph.D. students to work as a half-time research assistants on this project. The Ph.D. students will work throughout the course of the project.

  Support is also requested for two undergraduate students to work towards the proposed web based book project. Funding is requested for all five years.

- Summer support for PI: The PI plans to spend two summer months each year working on this project. The salary for PI is requested in the budget only for the fourth and fifth years.

- Permanent equipment cost: Funding is required to purchase two workstations and some software for this project. Since the PI's department will provide $10,000 toward this, no funding is requested for equipment cost.

- Fringe and insurance cost: The fringe benefits for the PI and health insurance for the students are covered in this budget as per Texas A&M university plans.

- Travel and publication costs: $1000 per year is requested to cover travel and publication costs. The PI's department will provide travel support for up to $4000 per year.

- Indirect costs: The indirect costs add 22% to the total direct costs.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Krishna Narayanan**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Low Density Parity Check Codes and Turbo Codes for Wireless Communication**

Source of Support: **National Science Foundation**

Total Award Amount: $ **179,925** Total Award Period Covered: **01/01/00 - 01/01/00**

Location of Project:

Person-Months Per Year Committed to the Project. Cal: **2.00** Acad: **0.00** Sumr: **2.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Design of Distributed Wireless Local Area Networks**

Source of Support: **National Science Foundation**

Total Award Amount: $ **2,268,465** Total Award Period Covered: **09/01/01 - 08/31/05**

Location of Project:

Person-Months Per Year Committed to the Project. Cal: **1.50** Acad: **0.00** Sumr: **1.50**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

7 Facilities Equipment and Other Resources

Much of the infrastructure for the proposed project will be from the Wireless Communication Laboratory in the department of Electrical Engineering at Texas A&M university. The Wireless communication laboratory is supported by government agencies including National Science Foundation, Texas Advanced Technology Program and the Academy of Advanced Telecommunications and Learning Technologies. Several companies including Texas Instruments, Alcatel, Nortel, Motorola, SK Telecom, Final Analysis Communications, Tadiran Microwave Networks also support the lab. It is anticipated that during the course of the project support from these agencies and companies will continue.

Another important source of support is the Texas Telecommunications Consortium (TxTEC), which is a consortium of several companies in Texas and five schools in Texas, including Texas A&M. Currently, there are ten companies in the consortium and it is expected this will grow to twenty soon. Each member company provides $200,000 per year for university support in the area of telecommunications. The consortium provides a great opportunity for students and professors to interact with the university, identify common research projects, focus on special areas that need more educational activities and strengthen fundamental courses in telecommunications. The member universities have the opportunity to use the industry support to leverage more funding the from the state of Texas through the Advanced research/technology programs.

The current facilities in the WCL include the following:

- *Computers* - Ten ULTRA 10 Sun workstations, five SPARC 20 workstations and several high-end PCs.
- *Digital signal processors* - TMS320C6x, TMS320C5x, TMS320C4x, TMS320C3x
- *General purpose hardware* - Oscilloscopes, spectrum analyzers, signal generators and RF power meters
- *Communication specific hardware* - Real-time RF channel simulator, RF modulator, waveform generators, vector signal generator and VHF/UHF transceivers
- *Software* - MATLAB, SPW, Lab View

TEXAS A&M UNIVERSITY
Department of Electrical Engineering
College Station, Texas 77843-3128
(409) 845-7441
FAX (409) 845-6259

July 24, 2000

MEMORANDUM

TO: NSF Career Awards Administrator

FROM: Chanan Singh
Professor and Head

SUBJECT: Endorsement for Dr. Krishna Narayanan's Career Development Plan

This memo is in support of Professor Krishna Narayanan's application for the NSF Career Award. Professor Narayanan joined our department on December 1, 1998, in his first tenure track appointment, immediately after obtaining a Ph.D. from Georgia Institute of Technology.

His appointment was the result of a one-year search for a faculty member with outstanding potential to become a leader in research and teaching in the area of communication theory. In the nineteen months he has been here, he has demonstrated his eagerness and potential to develop a strong program in the areas of coding theory and wireless communications at Texas A&M University. He has continued his excellent publication record, while developing and teaching a new graduate course on advanced channel coding and is currently advising five graduate students. He has actively pursued funding for his research and serves as the PI or Co-PI on five extramural grants. The department is strongly committed to telecommunication research and education. This is evidenced by our creation and commitment to the VLSI Telecommunication Research Center and hiring of three faculty members in this area. Also Teas A&M is a member of the Texas Telecommunications Engineering Consortium, a joint industry and academia venture whose objective is to encourage both research and education development in telecommunication. This integrated career development plan will dovetail very nicely with the goals of this consortium and any support provided by the CAREER award, if granted, will be significantly leveraged by consortium funds. The consortium will provide him with strong opportunities to interact with the industry members of the consortium and other engineering schools in Texas.

Our department has been active in hiring young faculty members and has a long-term interest in their career. WE are committed to providing the best environment and support to develop world-class researchers and teachers. As a support of Professor Narayanan's application, the department will provide the following cost sharing if his application is successful:

- $4,000/year for the five years for travel and publication costs
- $10,000 for one time equipment matching
- Reduced teaching load to 1 course/semester for the first two years

This support will be provided in addition to start-up package offered as a result of his hiring which included a reduced teaching load for two years. I strongly feel Professor Narayanan will significantly contribute towards reaching the department's goal of providing the highest quality education, conducting world-class research and in shaping the engineers of tomorrow. I have read and endorse his Career Development Plan. Thank you for positive consideration of Dr. Narayanan's proposal.

TEXAS A&M UNIVERSITY
1876

Institute for Telecommunications & Information Technologies
Texas Engineering Experiment Station

Richard E. Ewing, Director

July 24, 2000

CAREER Program Committee
National Science Foundation
4201 Wilson Blvd. Room P60
Arlington, VA 22230

Dear NSF CAREER Program Committee:

This letter is to confirm the commitment of the Texas Telecommunications Engineering Consortium (TxTEC) through the Institute for Telecommunications and Information Technology [(IT)^2] to collaborate with Professor Krishna Narayanan during the course of his proposed project entitled "*Design and Analysis of Iteratively Decodable Codes for Wireless Communications and Digital Magnetic Recording.*"

TxTEC is a joint effort between five universities and currently 10 industry members to work together to strengthen the education of our graduates and the research of our faculty and graduates to benefit both the universities and industry. TxTEC also offers a collaborative forum where faculty and corporate researchers can exchange ideas and information about research areas relevant to telecommunications and information technologies. We continue to attract industry to join us in this endeavor. One objective of TxTEC is to produce graduates more prepared and better informed when they enter industry. We feel Professor Narayanan can help us fulfill this objective.

As a part of our commitment, TxTEC, through (IT)^2, will pay one month of Dr. Narayanan's salary per year for the five years of the grant. We will also help support his course or laboratory development plans by providing access to personnel trained in the latest course development techniques (i.e. web-based technology delivery) and providing some matching for any equipment needed.

TxTEC, through (IT)^2, is committed to collaboration with Professor Narayanan in both research and education. We are eager to see and help Professor Narayanan build a successful career in the field of Telecommunications. His research in designing codes for use in next-generation wireless systems and in next-generation magnetic disk drives is of vital interest to TxTEC members.

Sincerely,

Richard E. Ewing

Richard E. Ewing
Texas Engineering Experiment Station (TEES) Distinguished Research Chair
Mobil Technology Company Chair in Scientific Computation
Director, Institute for Scientific Computation
Dean, College of Science
Distinguished Professor of Mathematics and Engineering

3404 TAMU, College Station, Texas 77843-3404 • Phone (979) 862-5674, FAX (979) 845-5827 • E-Mail: IT2@tamu.edu

TEXAS A&M UNIVERSITY
1876

Institute for Telecommunications & Information Technologies
Texas Engineering Experiment Station

Richard E. Ewing, Director

July 24, 2000

CAREER Program Committee
National Science Foundation
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Sincerely,

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Jerome J. (Jerry) Gaspar
Vice President
Engineering & Technology

400 Collins Road NE
Cedar Rapids, IA 52498-0001
319.295.4299 Fax 319.295.6080
jjgaspar@collins.rockwell.com

Rockwell Collins

June 19, 2000

Professor Krishna Narayanan
Engineering Department
Texas A & M University
College Station, TX 77640

Dear Professor Narayanan:

Your request for financial support for Texas A & M University has been reviewed for financial consideration. I am pleased to inform you that your request has been approved by the Rockwell Collins businesses located in Cedar Rapids and the Rockwell Corporate Trust Committee. Enclosed find a check from Rockwell International in the amount of $21,000 to provide financial assistance for Concatenated Coding and Iterative Decoding.

Rockwell makes contributions both from funds of Rockwell and the Rockwell Trust. Accordingly, we prefer to be identified simply as Rockwell in any reports/brochures listing your contributors.

If you have any questions regarding this contribution, please contact Cindy Dietz at (319) 295-7444 or Tom Tapp (319) 295-9687.

Warm regards,

JJ Gaspar

Jerome J. Gaspar
Vice President, Engineering & Technology

Enclosure

c: T. Tapp, 137-125
A. Pettifor, 106-193