COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 00-2	FOR NSF USE ONLY
NSF 00-89 07/25/00	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) **CCR - COMMUNICATIONS RESEARCH**	**0093215**

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				059007500	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYMS(S)
516000297	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
University of Delaware	University of Delaware 210 Hullihen Hall Newark, DE. 19716
AWARDEE ORGANIZATION CODE (IF KNOWN) 0014316000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply)
(See GPG II.D.1 For Definitions) ☐ FOR-PROFIT ORGANIZATION ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS

TITLE OF PROPOSED PROJECT **CAREER: Iterative Decoding Schemes For Channels With Memory: Application To Fading Channels**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ 366,214	60 months	09/01/00	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG 1.A.3)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.D.1)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG II.D.10)
- ☐ NATIONAL ENVIRONMENTAL POLICY ACT (GPG II.D.10)
- ☐ HISTORIC PLACES (GPG II.D.10)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.12)
- ☐ VERTEBRATE ANIMALS (GPG II.D.12) IACUC App. Date ____
- ☐ HUMAN SUBJECTS (GPG II.D.12) Exemption Subsection ____ or IRB App. Date ____
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES ____
- ☐ FACILITATION FOR SCIENTISTS/ENGINEERS WITH DISABILITIES (GPG V.G.)
- ☐ RESEARCH OPPORTUNITY AWARD (GPG V.H)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
Electrical and Computer Engineering	Dept. of Electrical and Computer Eng. University of Delaware Newark, DE 19716 United States
PI/PD FAX NUMBER 302-831-4316	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Javier Garcia-Frias	Ph.D	1999	302-831-0751	jgarcia@eecis.udel.edu
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

 Electronic Signature

Received :07/25/2000

Iterative Decoding Schemes for Channels with Memory: Application to Fading Channels

Project Summary

Turbo codes and the rediscovery of low-density parity check (LDPC) codes represent two of the most significant advances in channel coding in recent years. Iterative decoding of these codes makes it possible to achieve performance close to the theoretical limits for memoryless channels.

The proposed research focuses on the study of iterative decoding for more realistic channels, such as wireless communications channels, characterized by having memory. The objective of this project is to achieve reliable communications, close to theoretical limits, for these types of channels. In order to achieve this goal, the memory of the channel will be exploited in the decoding process. This will be accomplished in a two-fold process, which will extend previous results obtained by the PI:

- Development of statistical models, such as hidden Markov models and stochastic grammars, capable of conveying the characteristics of general channels with memory
- Modification of the iterative decoding schemes to incorporate the statistical models in the decoding of turbo codes, LDPC codes, and concatenated space-time codes

It is important to remark that both steps are completely interwined. The idea is to jointly design the statistical models and the decoding modifications, taking the decoding performance for the real channel as the optimization criterion. Moreover, this process should work adaptively, with no *a priori* knowledge of the channel required: when the communications system is used in an unknown channel, a convenient statistical model of the channel should be obtained jointly with decoding (in either a completely blind fashion if possible or by using pilots). In every iteration such a model should be used for the decoding and be conveniently refined.

Incorporation of statistical channel models in iterative decoding is almost unexplored in the literature. This project will involve a detailed study of this approach for different types of environments and practical situations in wireless communications systems, leading to improved performance with respect to standard systems. The intermediate steps necessary to reach this main goal will also have an impact by themselves, producing new results. Among them, we can cite:

- Development of LDPC codes for PSK and QAM constellations
- Combination of iterative decoding and space-time codes
- Combination of blind equalization and iterative decoding for turbo codes and LDPC codes
- Evaluation of stochastic grammars as models for fading channels
- Development of new hidden Markov models for modeling soft decision environments in different constellations and fading conditions
- Incorporation of hidden Markov models and stochastic grammars in iterative decoding of turbo codes, LDPC codes, and space-time codes
- Performance analysis of iterative decoding for simplified channels with memory (e.g., Gilbert-Elliot channel)

My educational plan will be strongly influenced by the proposed research. New graduate courses in the areas of wireless communications and iterative decoding will be introduced at the Department of Electrical and Computer Engineering of the University of Delaware, and state of the art results from this proposal will be presented in class. This will greatly benefit graduate students, helping to motivate them to pursue research in these areas.

TABLE OF CONTENTS

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

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.

1 Introduction

1.1 Motivation

During the last years, the introduction of turbo codes [11, 12] and the rediscovery of low-density parity check (LDPC) codes [31, 32, 69, 70] have allowed communications at rates very close to the theoretical limits for memoryless channels. However, most wireless communications channels do indeed have memory, thus motivating the research described in this proposal on exploiting this memory in the context of iterative decoding methods. The traditional approach to cope with channels with memory is to use a channel interleaver to distribute the errors introduced by the channel, so that codes designed for a memoryless channel can be used. Ignoring the memory in the channel, however, leads to capacity loss[1]. Therefore, in order to achieve the best possible performance, the statistical properties of the channel must be considered in the receiver.

Traditional models for fading channels assume a time variant impulse response $c(\tau;t)$, where $c(\tau;t)$ represents the response of the equivalent lowpass channel at time t to an impulse applied at time $t-\tau$ [78]. The equivalent lowpass received signal, $r(t)$, can then be expressed as:

$$r(t) = \int_{-\infty}^{\infty} c(\tau;t)x(t-\tau)d\tau + n(t), \tag{1}$$

where $x(t)$ is the equivalent lowpass signal transmitted over the channel and $n(t)$ is assumed to be an additive white Gaussian noise (AWGN). Depending on the characteristics of $c(\tau;t)$, all different standard fading cases can be obtained (fast/slow fading, frequency non-selective/selective channels.)

For the case of frequency selective fading channels, the equivalent discrete-time model when the channel is known is obtained by using the so called "whitened matched filter", and is expressed as:

$$r_k = \sum_{n=0}^{L} a_{n,k}x_{k-n} + n_k, \tag{2}$$

where x_k is the transmitted constellation point, $\{n_k\}$ is an i.i.d complex white Gaussian noise sequence, and $a_{n,k}$ is the attenuation for the nth multipath component at time k. If the channel is unknown, the whitened matched filter cannot be identified, and therefore $\{r_k\}$ in (2) is no longer a sufficient statistic set. However, as shown in [19], under reasonable approximations it is possible to obtain a sufficient set of statistics by using multiple samples per symbol and a filter matched to the input waveform. Obviously, the case of flat fading is included in (2) by setting $L=0$.

To optimize communications systems over the fading models described above, diversity and coding techniques are used. In this proposal we will mainly focus on coding techniques, which can be seen as a form of time diversity. Obviously, the best performance is obtained when the receiver makes use of all possible information embedded in the channel. Although the fading models described above are quite realistic, in many occasions they are difficult to exploit in practical decoding schemes. In order to make use in the decoding of most of the information available from the channel, other ways of modeling the communication link, such as hidden Markov models, are therefore needed in these situations.

1.2 Objectives and impact

The main goal of this research is to achieve reliable communications, close to theoretical limits, for a wide range of channels with memory. In order to achieve this objective, two aspects will be

[1]Unless otherwise specified, in this description we will assume ergodic conditions in the channel [15], although non-ergodic concepts such as capacity versus outage will also be studied.

considered. First, statistical models capable of conveying the characteristics of general channels with memory (of the type encountered in wireless communications) will be developed. We will begin our study considering hidden Markov models, and then we will expand our research to the more general case of stochastic context-free grammars. Second, the memory in the channel will be exploited by incorporating these statistical models in iterative decoding (including turbo codes, turbo trellis-coded modulation schemes, low-density parity check codes, and "iterative" space-time codes.) Both aspects are completely interwined: The idea is not to develop very accurate statistical models with no application to decoding, or to study decoding modifications for very simple models, but to take the decoding performance for the real channel as the optimization criterion and then to jointly design the statistical models and the decoding modifications to achieve the best possible performance. When possible, this process should work adaptively, with no *a priori* knowledge of the channel required: when the communications system is used in an unknown channel, a convenient statistical model of the channel should be obtained jointly with decoding (in either a completely blind fashion if possible or by using pilots.) In every iteration such a model should be used for the decoding and be conveniently refined.

Incorporation of statistical channel models in iterative decoding is almost unexplored in the literature. This project will involve a detailed study of this approach for different types of environments and practical situations in wireless communications systems, leading to improved performance with respect to standard systems.

2 Technical background

2.1 Characterization of fading channels using hidden Markov models

The use of Markov and hidden Markov models in order to characterize fading channels has a long history [57]. The first proposed models focused on the case of binary signaling with hard decisions. Specifically, they modeled the binary error pattern resulting in the end-to-end communications channel using binary hidden Markov models. Binary hidden Markov models are characterized by a set of states $S_j, 0 \leq j \leq S-1$, the matrix of transition probabilities among states (A=(a_{ij}), with a_{ij} the probability of transition from state S_i to state S_j, i.e., $a_{ij} = P_t(S_j|S_i), 0 \leq i, j \leq S-1$), and the list giving the bit error probability to associate with each state (B=$(b_j(v))$, with $b_j(v)$ the probability of getting the output v in state S_j, i.e., $b_j(v) = P_o(v|S_j), 0 \leq j \leq S-1,\ v \in \{0,1\}$). The stationary probability of error is denoted by ρ.

In order to model a fading channel with a hidden Markov model, it is necessary to choose the parameters of the model which produce the best fit (according to a measure of approximation quality) between the hidden Markov model and the fading channel [96]. If another statistical model is available for the fading channel, one possibility is to use that knowledge to create the hidden Markov model. However, in general, the hidden Markov model will be obtained using the data (error profile) available from the channel. Gilbert [49] originally proposed a model based on a two state binary hidden Markov model. The first state (good state) is an error-free binary symmetric channel (BSC) while the second state (burst state) represents a BSC having non-zero crossover probabilities. Elliot [26] suggested a modification to the Gilbert's model by replacing the error free state by another state now representing a BSC with a nonzero crossover probability. In this way the resulting error process can also provide for a small background error probability when the channel is in the good state. Fritchman [29, 30] proposed a class of Markov models having a finite number, N, of states. These N states are partitioned in two groups. The first group is formed by k error free states while the second group consists of $N-k$ error states. Several researchers have investigated the behavior of a simplified version of the Fritchman's model (SFM) by choosing a single error state (i.e., $N-k=1$) and imposing constraints in the corresponding $N \times N$ transition probability matrix. In all these approaches, the parameters of the hidden Markov model are determined by theoretically calculating a set of statistics as a function of the model parameters and fitting them to the statistics obtained from the observed error profile of the channel.

It was not until very recently that the use of continuous hidden Markov models (and non-binary discrete hidden Markov models resulting from careful discretization) has been considered, therefore addressing soft decisions and non-binary constellations [89, 90]. Continuous hidden Markov models have the same structure as discrete ones: the only difference is that instead of specifying the bit error probability in each state, they define the distribution of the fade level or of the signal to noise ratio (SNR). In [66] a method for fitting a continuous first order Markov model to flat Rayleigh fading channels is proposed based on the rules described in [100]. The basic idea is to partition the range of the received SNR into a finite number of intervals (as many as states in the model.) In each state the fade level is fixed (therefore defining a non-hidden Markov model.) Extension of these approaches can be found in [2], where higher order Markov models for relatively fast fading channels are built. Markov modeling of the phase variation for PSK in relatively fast flat Rayleigh fading was proposed in [60, 61]. The phase is quantized and each value in the resulting finite set is associated to a state in the Markov model. Transition probabilities are obtained from the joint pdf of two successive sample phases. More powerful fitting methods for hidden Markov models based on the use of the Baum-Welch (Expectation-Maximization) algorithm are considered in [96], where it is also shown that hidden Markov models with enough number of states can approach very general autocorrelation functions. Expectation-Maximization techniques obtain the parameters of the hidden Markov model that best fit the received error profile, in the sense of locally maximizing the probability that the error profile has been generated by the model.

Hidden and non-hidden Markov models for fading channels have been traditionally considered as powerful modeling tools: By training a hidden Markov model with realizations of a fading channel (soft or hard error profile,) the model was capable of generating new realizations with statistical distributions similar to the original ones. This allowed to use the hidden Markov model to analytically derive relevant parameters characterizing the channel, and therefore studies of the channel could be undertaken without the need of having the channel available. However, in general, these models were not exploited in the decoding process. As detailed in sections 2.2 and 3.1, if the channel is defined by a hidden Markov model, it is indeed possible to consider the channel structure in the decoder and to improve the system performance. In our research we will follow a two-fold approach. Certainly, we are interested in obtaining good statistical models for realistic fading channels, but even more importantly, our objective is to exploit these statistics in the decoding process to achieve the best possible performance for a given fading channel.

2.2 Combining hidden Markov models with channel decoding

If a fading channel were perfectly represented by a hidden Markov model[2], the theoretical limit for reliable communications would be given by the capacity of the hidden Markov channel. The capacity of hidden Markov channels was treated for the special case of Gilbert-Elliot channels by Mushkin and Bar-David in [75] and more generally by Goldsmith and Varaiya in [52]. In terms of the notation introduced in [75], the "capacities" that can be associated with a hidden Markov channel include the true capacity C^{μ}, the capacity when side information about the instantaneous state is available to the receiver C^{SI}, and the capacity C^{NM} ("no memory") of a memoryless channel with the same stationary bit error probability as the hidden Markov channel. Clearly, $C^{NM} \leq C^{\mu} \leq C^{SI}$.

[2]We will denote these channels as hidden Markov channels or finite-state Markov channels as they are usually known in the literature, which sometimes does not distinguish between hidden and non-hidden Markov channels.

In practice, many communications systems make use of a channel interleaver to distribute the errors so that codes designed for a memoryless channel can be used. While the application of interleaving does not change the capacity of the channel, the achievable performance of a decoder which assumes that the channel is memoryless is limited by C^{NM}. Exploiting the higher capacity of hidden Markov channels in practice has proven to be challenging. Both [52] and [75] utilize decision feedback decoders which perform recursive state estimations that are used in the decoding process. However, the recursions are vulnerable to error propagation, and the decision feedback decoder can not be reliably used when the quality of the channel degrades. We will show in section 3 that it is possible to exploit the structure of hidden Markov channels in the context of iterative decoding, and allow communication at rates greater than C^{NM} and close to C^{μ}. The decoder will exploit only the *a priori* structure of the channel as opposed to performing recursive state estimation, which allows good performance for poor channels. Notice that in theory it is always possible to perform maximum likelihood decoding for hidden Markov channels (if the channel parameters are known.) However, the decoding complexity grows exponentially as a function of the block length [64, 66], and therefore this approach is unfeasible in practice.

2.3 Stochastic grammars

Hidden Markov models are a special case of stochastic grammars. Transformational grammars were first proposed by Chomsky [16, 17] in the context of natural languages. Later on, they have been applied in many areas of computer science and signal processing (e.g., specification of computer languages [47, 55], bioinformatics [25], speech recognition [22], and lossless data compression [20, 59].) A transformational grammar [25] consists of symbols and production rules. Two types of symbols can be distinguished: terminal (represented by lower-case letters) and nonterminal (represented by upper-case letters). The production rules specify how strings of symbols can be generated in the language. For example, if the grammar is specified by the rules $S \to aS$, $S \to bbS$, $S \to e$ (where a and b are terminal symbols, e is a terminal symbol ending the generation process, and S is a nonterminal symbol,) the string abbabb can be generated by the grammar by successively applying the corresponding rules: $S \to aS \to abbS \to abbaS \to abbabbS \to aabbabbe$. Depending on which type of production rules are allowed in the grammar, we can distinguish four classes of transformational grammars (Chomsky's hierarchy.)

- Regular grammars: The only valid production rules are of the form $S \to aS$ or $S \to a$, where S and a can represent any nonterminal and terminal symbols, respectively.
- Context-free grammars: Any rule of the form $S \to \alpha$ is allowed, where S can represent any nonterminal symbol and α represents a string of terminal and nonterminal symbols.
- Context-sensitive grammars: The rules allowed are of the form $\beta_1 S \beta_2 \to \beta_1 \alpha \beta_2$, where S can represent any nonterminal symbol and α, β_1, and β_2 represent strings consisting of terminal and nonterminal symbols. Notice how the production rules depend on the context β_1, β_2.
- Unrestricted grammars.

It is easy to see that regular grammars are a subset of context-free grammars, which are a subset of context-sensitive grammars, which again are a subset of unrestricted grammars. Any of these grammars can be used in stochastic form. The only modification is that a probability is assigned to each one of the production rules, in such a way that the sum of probabilities of all production rules with the same left hand side is equal to one. It also easy to show that hidden Markov models are equivalent to stochastic regular grammars. The number of nonterminal symbols in the equivalent stochastic regular grammar is equal to the number of states in the hidden Markov model.

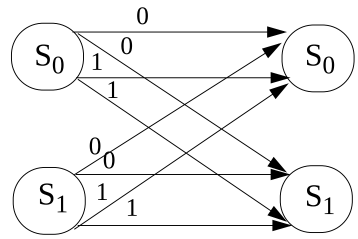

Figure 1: Trellis representing a binary hidden Markov channel with two states. The figures represent the error pattern associated with each branch.

3 Preliminary results

This section presents recent results obtained by the PI showing how to exploit hidden Markov channels in iterative decoding. Our proposed research will be based on the ideas introduced here.

3.1 Combining hidden Markov channels with serial/parallel concatenated codes

A turbo code [11, 12] consists of two or more constituent convolutional encoders, with interleavers used to randomize the input bits prior to the convolutional encoders. The decoder for a turbo code consists of one constituent decoder corresponding to each convolutional coder. The constituent decoders perform iterative processing and exchange information (called "extrinsic" information in the turbo code literature) about the reliability of the input bits as the decoding progresses.

Work about incorporating hidden Markov channels in turbo decoding has been performed by the PI. Basically, there are two ways of exploiting the statistics of a hidden Markov channel in turbo decoding. The first approach [40, 41, 43] is based on building supertrellises describing the combination of the hidden Markov model and each one of the constituent encoders. In order to build the supertrellises, channel interleaver is not used. The disadvantage of this approach is that the turbo encoder structure has to be customized to the channel. Complexity is also considerably greater than in standard turbo decoding. The second method, which has also been recently proposed by the PI for simple hidden Markov models [35], extends the turbo decoding principle by considering the hidden Markov channel as another constituent decoder. Extrinsic information is calculated in each decoder (including the channel block) and passed to the other blocks in an appropriate way. For the case of binary hidden Markov channels (generalization to continuous hidden Markov channels is straightforward as described in [36]), the channel block uses as extrinsic information the estimation of the probability of the error pattern that is provided by the constituent decoder blocks. On the other hand, it produces a new estimation of such a probability which will be used as extrinsic information by the constituent turbo decoders. The complexity of this approach is similar to that of standard turbo decoding. Another advantage with respect to the method based on building supertrellises is that the encoder does not have to be customized to the particular channel under consideration. In order to obtain good performance, it is necessary to use channel interleaving.

Figure 1 shows the trellis for a binary hidden Markov channel with two states. The error pattern bit corresponding to branch e is denoted by $\epsilon(e)$. Notice that the trellis has two parallel branches between states (one associated with the error pattern $\epsilon(e) = 0$ and the other with the error pattern $\epsilon(e) = 1$). Each one of the branches in the trellis will have an associated *a priori* probability, which is obtained from the hidden Markov model as $a_e = P(e|s^S(e)) = P_o(\epsilon(e)|s^S(e)) \times P_t(s^E(e)|s^S(e))$, where the starting and ending state associated with a particular edge e are represented by $s^S(e)$ and $s^E(e)$ respectively. ϵ_k and v_k denote the error pattern and the received bit associated with time

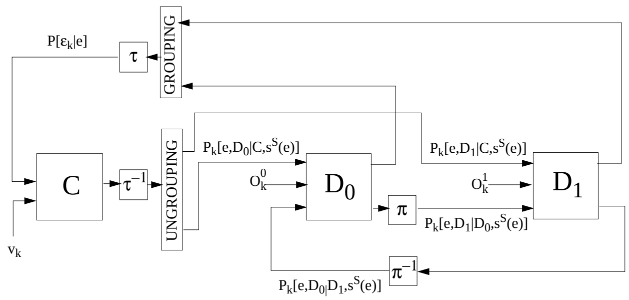

Figure 2: Decoder structure for the method proposed in section 3.1. The figure outlines the information flow as defined in the text. Notice the iterative exchange of extrinsic information among the block representing the hidden Markov channel (C) and the constituent decoders D_0 and D_1.

k ($\epsilon_k, v_k \in \{0,1\}$). The constituent decoder blocks produce an estimation, that we will denote by $\tilde{x}_k$, for each of the coded bits. Therefore, this results in an estimation, $\tilde{\epsilon}_k = v_k \oplus \tilde{x}_k$, of the error pattern. Looking at the trellis of the binary hidden Markov channel, it is clear that $P(\tilde{\epsilon}_k|e) = 0$ if $\tilde{\epsilon}_k \neq \epsilon(e)$ and $P(\tilde{\epsilon}_k|e) = 1$ if $\tilde{\epsilon}_k = \epsilon(e)$. We can then estimate the value of $P[\epsilon_k|e]$ by using:

$$P[\epsilon_k|e] = E[P(\tilde{\epsilon}_k|e)] = P(\tilde{\epsilon}_k = \epsilon(e)) = P(\tilde{x}_k = v_k \oplus \epsilon(e)) = P(c'^{j,i}_{k'} = v_k \oplus \epsilon(e)|D_i), \tag{3}$$

where $P(c'^{j,i}_{k'} = v_k \oplus \epsilon(e)|D_i)$ is the extrinsic information proceeding from the decoder block i and represents an estimation of the transmitted coded bit associated with time instant k in the hidden Markov block. Notice that due to the channel interleaver and grouping process, bit x_k will correspond to one of the coded bits (for example the one in position j) associated with trellis transition k' of one of the constituent encoders (for example, encoder i) and therefore it will be denoted by $c'^{j,i}_{k'}$. The resulting equations for the hidden Markov channel block are then given by:

$$\alpha_k(s) = \sum_{e:s^E(e)=s} \alpha_{k-1}\left[s^S(e)\right] a_e \, P[\epsilon_k|e] \tag{4}$$

$$\beta_k(s) = \sum_{e:s^S(e)=s} \beta_{k+1}\left[s^E(e)\right] a_e \, P[\epsilon_{k+1}|e] \tag{5}$$

$$P(\epsilon_k = i|C) \propto \sum_{e:\epsilon(e)=i} \alpha_{k-1}\left[s^S(e)\right] a_e \, \beta_k\left[s^E(e)\right], \tag{6}$$

where as indicated before $P[\epsilon_k|e]$ is obtained from (3) and represents the extrinsic information passed from the constituent decoders to the channel block. Notice that in order to avoid positive feedback with the constituent decoders blocks, the value of $P[\epsilon_k|e]$ is not used in (6). Figure 2 shows the decoder structure. $\{O^i_k\}$ represents the observation sequence associated to decoder i. $P_k[e, D_i|C, s^S(e)]$ represents the extrinsic information passed from the channel to the decoder block i. Its value is calculated from (6) by using the fact that $\tilde{x}_k = v_k \oplus \tilde{\epsilon}_k$.

Figure 3 presents the results for a simulation using a rate 1/3 turbo code that includes a systematic bit and two identical recursive 8-state convolutional encoders with generator matrix $G(D) = \frac{1+D+D^2+D^3}{1+D^2+D^3}$. The interleaver length for the turbo code is 16384. We consider a binary hidden Markov channel with two states. The transition probability from the good to the bad state is .0486, and .0914 is the value of the transition probability from the bad to the good state. The bit error probability in the bad state is fixed to .5, and the performance of the system is studied as a function of the value of the bit error probability in the good state (notice that, since all the other parameters are fixed, there is a one to one correspondence between the bit error probability in the good state and the stationary bit error probability, ρ, which is the parameter used in Figure 3.) For rate 1/3 codes, the bit error probability corresponding to the capacity of a BSC is .174. Therefore, by using channel interleaving and ignoring the memory of the channel (the usual approach to cope with bursty channels,) it is impossible to send reliable information through this channel when the stationary bit error probability is higher than .174. Figure 3 shows the decoded bit error rate (BER) as a function of the stationary bit error probability, ρ. Convergence is achieved at $\rho = .18 - .185$, which is higher than the memoryless limit and close to the theoretical limit for this specific channel (which corresponds to a value $\rho = .2083$.) Notice that no pilots are used in this approach.

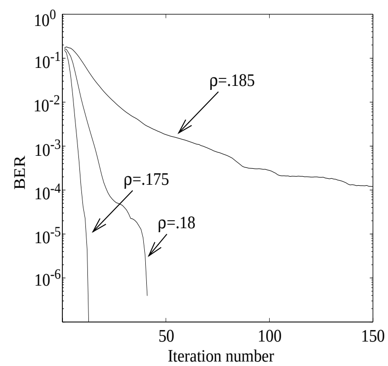

Figure 3: Convergence behavior for the rate 1/3 turbo code and the hidden Markov channel described in section 3.1. For a BSC, capacity occurs for $\rho = .174$. Notice that we can decode above this limit and close to the real capacity of the channel, which corresponds to a value $\rho = .2083$.

Although only discrete channels have been considered in this section, it has been shown by the PI that it is also possible (and simpler) to deal with continuous hidden Markov models [36]. Related work for continuous channels can be found in [58, 60, 61]. In [60, 61] turbo decoding over relatively fast flat Rayleigh fading with PSK modulation was studied. A Markov model representing the phase evolution was obtained and incorporated into turbo decoding following the ideas previously described in this section. The Markov model is not estimated jointly with decoding, but fixed *a priori* for a given channel (by assuming knowledge of some channel characteristics.) The resulting performance when pilots are used is quite good for relatively slow fading channels ($f_D T = .05$), beating systems based on either coherent detection with channel estimation (without using Markov models [97, 98]) or differential detection [72]. However, the performance degrades substantially for faster fading. Another scheme which does not utilize pilots (based on building supertrellises) is also presented by the authors, but it achieves worse performance.

3.2 Combining hidden Markov channels with low-density parity check codes

Low-density parity check codes where first proposed by Gallager [31, 32], and rediscovered by McKay [69, 70]. They are linear codes with a very sparse parity check matrix. The ones in the matrix are allocated randomly after fixing the column and/or row weight. In order to understand the iterative decoding of these codes, it is convenient to represent them as a bipartite graph (see Figure 4), where the check nodes $\{c_k\}$ are connected to the corresponding bits nodes (or error pattern nodes $\{e_k\}$.) Since the transmitted codeword must satisfy all the check constraints, it is possible to estimate the error pattern introduced by the channel in the following way:

1 Fix the probability of the error pattern to its *a priori* value (e.g., for BSC $P(e_k = 1) = ber$ for any e_k. This probability can also be easily calculated for AWGN channels.) This value will

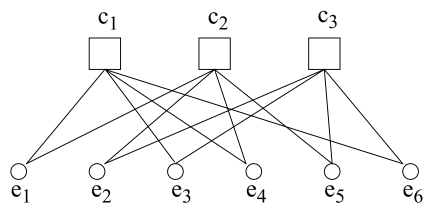

Figure 4: Bipartite graph representing a low-density parity check code. $\{c_k\}$ and $\{e_k\}$ represent the check and the error pattern nodes, respectively.

be used in step 2 for the first iteration.

2 For any of the error pattern nodes (e_k) connected to a given check node (c_i), estimate the probability of e_k using the values of the probabilities of the other errors nodes participating in check c_i (as obtained in step 3) and the observed value of the check. Notice that we will obtain as many estimations of e_k as the number of checks in which e_k participates.

3 For any check node c_i, estimate the probability of each of the error pattern nodes e_k participating in the check by combining the *a priori* value of e_k with all the estimations of e_k obtained in step 2, except the one produced by check c_i. Proceed to step 2 until all checks are satisfied or a number of iterations is reached.

The decoding of LDPC codes (and also of turbo codes) can be understood in the context of Bayesian networks [77] (or factor graph decoding [63],) where messages are passed through the graph representing the code until convergence is achieved. Although the traditional message passing algorithm (belief propagation) is only exact for networks without cycles (and the networks representing all these codes present cycles,) nonetheless, the performance of LDPC codes for i.i.d. sources and memoryless channels is extraordinarily close to the theoretical limits. Provided that the parameters of the code are properly chosen (i.e., asymmetric codes are used [81, 82],) performance is even better than that of turbo codes.

The possibility of incorporating hidden Markov models representing fading channels in this kind of decoding schemes is suggested, although without further elaboration, in [101] for codes defined over general graphs. To the best of our knowledge, there are no results about incorporating hidden Markov channels in LDPC codes. The basic idea is to "link" the error pattern nodes with the hidden Markov model. Then we can consider the whole structure as a Bayesian network and proceed with the message passing algorithm.

Figure 5 presents preliminary results for a binary hidden Markov channel with two states. The transition probability from the good to the bad state is .02, and .12 is the value of the transition probability from the bad to the good state. The bit error probability in the bad state is fixed to .5, and the performance of the system is studied as a function of the stationary bit error probability, ρ, which is the parameter used in Figure 5. The code is a rate 1/2 (3,6) low-density parity check code, with 3 indicating the column weight in each column of the parity matrix (i.e., the number of checks in which a coded bit participates), and 6 indicating the number of coded bits participating in each check (row weight). The number of coded bits is 35000. Incorporation of the hidden Markov channel is performed by applying a modified version of (4-6) over the estimations for $\{e_k\}$ obtained from step 3 of the iterative decoding. The new estimations of $\{e_k\}$ resulting from (4-6) are used again in step 2 for the next iteration. Notice the improvement shown in Figure 5 when the decoding scheme is modified to incorporate the hidden Markov channel. Convergence is achieved for a value of the stationary probability of error $\rho = .85$, which is higher than the theoretical limit (independently of the length) for the same LDPC code over a BSC. Although only discrete channels have been

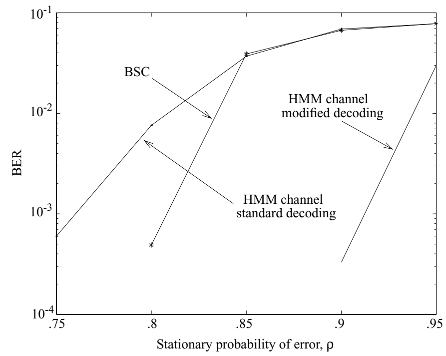

Figure 5: Performance for the LDPC code and hidden Markov channel described in section 3.2. Notice the improvement when the decoding scheme is modified to incorporate the hidden Markov channel. For comparison purposes, the performance of the same code over a BSC with parameter ρ is also shown in the figure.

discussed, it is also possible to deal with continuous hidden Markov channels.

4 Proposed research

The objective of this research is to achieve reliable communications, close to theoretical limits, for a wide range of channels with memory. Two complementary aspects that are necessary to achieve this goal will be integrated. On the one hand, statistical models capable of conveying the statistical characteristics of these channels will be developed. On the other hand, these models will be successfully incorporated into the iterative decoding process. This jointly design of the statistical models and the decoding modifications will imply a continuous iteration among the following subsections.

4.1 Study of hidden Markov models for the modeling of fading channels

As indicated in section 2.1, Markov and hidden Markov models have been profusely studied for the modeling of fading channels. However, (except for the recent work in [2, 13, 91] which focuses on particular classes of models or channels,) we are not aware of a systematic study on the application, and possible limitations, of different families of models (with their corresponding fitting methods) for the modeling of different types of fading channels.

In this proposal we will develop such a study, investigating the usefulness of different families of Markov and hidden Markov models for the modeling of different types of fading channels. Although most of the previous research has focused on binary hidden Markov models, in order to consider the advantages of soft decoding, it is extremely important to develop either continuous (hidden) Markov models or non-binary discrete (hidden) Markov models resulting from a careful discretization [60, 61]. Suitability of different training methods in each situation will be assessed, including comparison between approaches which assume some *a priori* knowledge about the channel and methods based only on the (soft) error profile. In the latter case, fitting degradation due to unsufficient number of observations will also be studied.

Because of its capability of generating good approximations for fading channels with a limited number of states, we will carefully considered the utilization of hidden Markov models trained with the Baum-Welch (Expectation-Maximization) algorithm [6, 7, 79]. Expectation-Maximization techniques for the estimation of hidden Markov model parameters are of great interest for several reasons. First, by applying these techniques, the measure of approximation between the hidden Markov model and the fading channel is defined in a natural way: the resulting hidden Markov model locally maximizes the probability that the observation sequence has been generated by the model. Notice that for other fitting methods the quality measure is sometimes defined in a very ad-hoc manner (just to facilitate the fitting.) Second, the relation between the Baum-Welch algorithm and turbo decoding can be exploited in the decoding process. This allows to iteratively estimate the hidden Markov model based on the received sequence, without any prior assumptions about the channel (and in many occasions without the use of pilot symbols.)

4.2 Study of stochastic grammars for the modeling of fading channels

Hidden Markov models are equivalent to stochastic regular grammars, the lowest family in Chomky's hierarchy. This implies that more powerful families of stochastic grammars (e.g., stochastic context-free grammars) can be used to model stochastic processes even with more flexibility and generality than hidden Markov models.

We plan to study the application of stochastic context-free grammars for the modeling of fading channels. The advantage of stochastic context-free grammars over stochastic regular grammars (i.e., hidden Markov models) is that they are much more powerful in modeling palindromes. In one traditional method of modeling fading channels with (hidden) Markov models [66, 100], we can think of each state in the model as a fading level. Consider for example the case of indoors radio channels, in which the resulting error profiles are qualitatively described by long well defined error bursts interleaved with longer error free intervals [33]. For a large proportion of the error bursts, the error density inside a burst follows a bell-shaped curve. Therefore, any attempt to model its behavior with a hidden Markov model with a low number of states will lose the particular way in which the errors are clustered. However, this statistical structure can be easily modeled with a stochastic context-free grammar by taking advantage of its capability of generating palindromes. Although grammars are usually used with a discrete alphabet, in order to consider the case of soft decision decoding, we will also consider continuous alphabets.

As explained in the previous subsection, Expectation-Maximization techniques for the estimation of hidden Markov model parameters are of great interest. For general stochastic grammars, and even for the case of stochastic context-sensitive grammars, equivalent algorithms are not available. However, for the family of stochastic context-free grammars (which include the family of stochastic regular grammars as a particular case,) equivalent versions of these algorithms, that can be used for matching a stochastic context-free grammar to any stochastic process, have been developed [65]. The main problem with this approach is the complexity of the training algorithms, which is much higher than in the case of hidden Markov models. Our research will develop in two parallel paths. First, we will consider fitting methods that do not require the use of Expectation-Maximization techniques. We will study the generalization of the rules proposed in [100] for Markov models to the case of stochastic context-free grammars. Second, we will investigate the application of techniques based on the Expectation-Maximization algorithm. In order to reduce complexity, suboptimum methods based on simplification of the algorithm and segmentation of the observation sequence (error profile) will be considered.

4.3 Parallel and serial concatenated codes for fading channels

The research described here is based on section 3.1, where we show that for channels perfectly defined by hidden Markov models (i.e., hidden Markov channels,) it is possible to exploit the channel statistics in turbo decoding, and to obtain performances very close to the theoretical limits. We will extend this approach for the case in which the fading channel is not perfectly defined by a hidden Markov model, but instead the hidden Markov model is just an approximation of its statistical behavior.

It is important to remark that, since we are concerned about the performance over real fading channels, we will not usually assume that the parameters of the hidden Markov model are known *a priori*. Instead, when possible, a hidden Markov model of the channel should be obtained jointly with decoding (in either a completely blind fashion or by using pilots.) In every iteration such a model should be used for decoding and be conveniently refined. Notice however, that, depending on the situation, some information about the channel may be available (e.g., we may know the type of environment -indoors, rural area, slow fading, fast fading- in which the system is operating.) In this case, the information should be incorporated into the hidden Markov model.

The first step in our research will be to extend the approach proposed in section 3.1 to the case of unknown hidden Markov channels. Preliminary results in this direction have been obtained by the PI in [36, 40]. We will consider binary hidden Markov channels (representing hard decision decoding schemes,) but our main focus will be on continuous hidden Markov models (representing soft decision schemes.) Both, standard binary turbo codes as well as turbo TCM schemes over higher constellations (based on bit [9, 10, 51, 83, 84, 85] or symbol [27] interleaving) will be considered. Although during the initial steps of our research we will use data based on the models described in (1), at a later point it will be critical to have access to data from real wireless channels. The creation of a wireless laboratory at the Department of Electrical and Computer Engineering of the University of Delaware (described in section 5.3) will be a fundamental asset for this research. Some of the specific points that will be studied are the following:

- For the case of slow fading[3], we will extend techniques previously proposed by the PI to combine blind equalization and decoding [39]. Notice that if we consider an unknown dispersive continuous-time channel, the whitened matched filter cannot be identified, and therefore $\{v_k\}$ in (1) is no longer a sufficient statistic set. However, as shown in [19], under reasonable approximations it is possible to obtain a sufficient set of statistics by using multiple samples per symbol and a filter matched to the input waveform. We will extend our previous methods to take into account this situation.

- For the case of relative fast fading channels, we will make use of the (hidden) Markov models developed in section 4.1 to represent the fading channel. We will extend the work developed in [60, 61] for the specific case of PSK constellations to consider different constellations and more general fading scenarios. Different schemes with and without pilot symbols will be investigated. Important aspects to consider here include the conditions which allow good estimations of the channel (i.e., how fast the fading can be,) how the channel estimation degrades depending on the quality of the channel, and when it is possible to estimate the hidden Markov structure representing the channel jointly with the decoding process (with and without using pilot symbols.) The performance of our approaches will be compared with the bound obtained by using perfect side information at the receiver [53], and with noncoherent techniques using multiple differential detection of turbo codes [72].

- Extension of all the previous points to the case of stochastic context-free grammars. Although the combination of stochastic grammars with turbo decoding follows the same ideas as the introduction of hidden Markov models, new problems derived by the complexity of Expectation-Maximization training methods arise here.

[3] Obviously, since the only diversity scheme that we are considering is channel coding, very slow fading channels will not be studied in this proposal.

4.4 Low-density parity check codes for fading channels

Most of the work on LDPC codes has focused on binary signaling. However, it is possible to use these codes with any discrete alphabet [31]. The research proposed here is based on section 3.2, where we show that it is possible to combine binary hidden Markov models representing the fading channel with LDPC codes. We plan to investigate the use of LDPC codes with non-binary constellations (such as PSK and QAM,) with the aim at achieving a performance close to the theoretical limits for high rate codes over DMC and AWGN channels. After this first step is completed, we will combine binary and non-binary LDPC codes with hidden Markov models and stochastic grammars representing different fading environments. All points described in section 4.3 will be studied here, including joint LDPC decoding and estimation of the unknown model representing the channel (with and without using pilots). Moreover, there are some aspects that are specific to LDPC codes and will be carefully considered:

- As indicated in section 3.2, the introduction of a hidden Markov channel in LDPC decoding requires only the modification of the graph structure. The message passing decoding algorithm (belief propagation) is the same as for memoryless channels. The results obtained in section 3.2 involved the use of modified versions of (4-6) in each of the decoding iterations, which can be interpreted as a particular instantiation of the belief propagation algorithm. Several authors [28, 74] have shown that in the case of turbo codes the order in which message passing is performed is not critical. However, incorporating a hidden Markov model creates more loops in the network. We plan to study the performance of simpler instances of the belief propagation algorithm (e.g., message passing schemes that do not need to run through the whole hidden Markov model before returning the messages back to the check nodes.)

- Analytical studies on the convergence of LDPC codes over memoryless channels have been developed very recently. The matching between theoretical predictions and simulation results is almost perfect [81, 82]. Using similar techniques, we will study the theoretical performance of LDPC codes over hidden Markov channels. This will allow us to obtain coding design rules depending on the model parameters (and more generally, depending on the type of fading channel.) One interesting question is if the asymmetric codes designed for memoryless channels are also optimum for the case of hidden Markov channels. Extension of these approaches to turbo codes will also be studied.

4.5 Combination of iterative decoding and space-time codes

Space-time codes have been proposed very recently [93]. They are utilized in communications systems where more than one antenna is used to transmit the information. The basic idea is to distribute the output of the encoder between the different transmit antennas. The received signal in any given receive antenna is a weighted noisy superposition of all the signals originated from the transmit antennas. By building a maximum-likelihood decoder that takes into account all the received signals it is possible to achieve large gains over traditional coding schemes.

The complexity of the standard maximum-likelihood decoder for space-time codes increases exponentially with the product of the rate and the number of transmit antennas. In order to reduce the decoding complexity, and also to provide additional coding gain, we will study the use of serial and parallel concatenated space-time codes and iterative decoding algorithms. Some approaches in this direction can be found in [5, 67, 76]. The main novelty of our approach will be the extension of these techniques to include fading channels described by hidden Markov models, with the final objective of designing good space-time 'turbo-like' codes for realistic fading channels.

5 Educational Plan

One of the main objectives of this proposal is to make sure that the research developed in this project benefits the greatest possible number of graduate and undergraduate students. Obviously, the first beneficiary will be the graduate student directly involved in the project, but my educational plan will be greatly influenced by the proposed research. The main goals of my educational plan are the following:

- To attract both graduate and undergraduate students to our communications program in the Department of Electrical and Computer Engineering at the University of Delaware.
- To develop a series of new courses, with emphasis in wireless communications, based on the advanced techniques developed in this research.
- To build a wireless communications laboratory, which will be used both in research and for graduate and undergraduate teaching.
- Outreach to students of other disciplines, such as Mathematics, Statistics, and Computer Science.

5.1 Attracting students into communications

One of the problems faced by our society is the lack of specialized workers in the field of information technologies. Many highly competent high schools students prefer to pursue careers in other areas, such as economics, medicine, law, etc. The reasons for this trend are very complex, and not easy to revert. However, in my opinion, a main reason is that high school students do not perceive Electrical Engineering as a very attractive field. In many cases they do not have role models about Electrical Engineering, and there is a lack of information about the field. This situation is particularly acute among minority and female students. In order to bring our field closer to prospective students, I propose a two-phase plan:

- To visit high schools situated in the vicinity of the University of Delaware. The objective will be to explain students the different aspects of Electrical Engineering and the possibilities of our profession. I think that this first interaction will help to increase the number of high school students who may consider Electrical Engineering as a possibility for their undergraduate studies.
- To set up demonstrations in our laboratories at the Department of Electrical and Computer Engineering of the University of Delaware (and for this the development of the laboratory proposed in section 5.3 is an important milestone,) so that students who got interested in the previous stage could have a first hand knowledge of the activities developed in our Department, and more specifically in the communications group. I think that the interaction of high school students with graduate an undergraduate students (including minorities and women) will serve as a catalyzer to attract top high school students to our field.

Of course, it is not enough to attract undergraduate students to our department. My objective is also to convince undergraduate students to the get more involved in the area of communications, and to prepare some of them (as graduate students) in the field of wireless and multimedia communications. One problem with our current undergraduate curriculum is that the first contact that students have with the fields of signal processing and communications is postponed until their junior year. When they take the first course in this area (Signal Processing I), most of them have already chosen an area of specialization. Comments such as “I would have specialized in communications if I had taken this course before" are not unusual among undergraduate students. The department has realized this problem and plans to offer a course combining circuits, signal processing, and communications in the sophomore year. I am very interested in this course, because I think it is possible to introduce signal processing and communications in an attractive light to allure sophomore students into these areas. Building a wireless communications laboratory is an important step towards this goal. Another way of attracting undergraduate students to our graduate program in communications is through the so called "undergraduate research opportunities". This is a program developed at the University, in which undergraduate students are encouraged to get involved in research projects working with professors and graduate students. I will fully support this early involvement in research, which hopefully will make undergraduate students more interested in pursuing graduate degrees in our field.

5.2 Graduate courses development

The main objective of my educational plan is to strengthen the area of communications in the Department of Electrical and Computer Engineering at the University of Delaware. At this time, communications and signal processing constitute a common area. It is the objective of the department to separate both of them, allowing a greater flexibility for the students. This will involve the creation of new courses, and the modification of the existing ones. The graduate courses that I plan to develop are specified below. The first two courses (*Information Theory: An introduction to channel coding* and *Estimation and Detection Theory*) are more introductory in nature, although some aspects covered in our research will be introduced. The last two courses (*Fundamentals of iterative decoding: The Bayesian approach* and *Advanced topics in coding with applications to wireless communications* will be strongly based in our research, and state of the art results will be presented in class.

5.2.1 Information Theory: An introduction to channel coding

Our current graduate course in Information Theory is more oriented towards source coding. In addition, I plan to offer a new course more focused on channel coding. By offering the two courses, graduate students will acquire a solid formation in both source and channel coding. The topics covered in this new course will include:

- Fundamental concepts in Information Theory: Entropy, relative entropy, mutual information
- Channel capacity. Derivations based on the Asymptotic Equipartition Property (AEP)
- Shannon separation principle. Joint source-channel coding
- Introduction to block and convolutional codes. Trellis-coded modulation

5.2.2 Estimation and Detection Theory

The first course in communications currently offered to our graduate students is *Digital Communications*, which partially covers estimation and detection theory. However, in order to provide students with a strong mathematical background, it is important to increase the depth in which these concepts are covered. This will be achieved by introducing a new course in estimation and detection theory, whose main contents will be:

- Hypothesis testing: Bayes, minimax and Neyman-Pearson criteria
- Detection of deterministic signals in white and colored Gaussian noise
- M-ary digital communications. Coherent and noncoherent detection
- Parameter estimation: Mean-square, maximum-likelihood, maximum a posteriori

5.2.3 Fundamentals of iterative decoding: The Bayesian approach

Iterative decoding is a very novel concept, breaking (in some sense) with traditional schemes based on algebraic decoding. The connections between these decoding schemes and other areas such as artificial intelligence, statistics, and even control and bioinformatics are now beginning to be more clear. This will be a multidisciplinary course: Its main objective will be to present a unified approach to the algorithms used in all these areas utilizing the Bayesian network formalism. Particular applications in all different areas will be presented, with stress in communications. The last part of the course will cover serial and parallel concatenated codes (binary and in combination with trellis-coded modulation schemes,) and binary and non-binary low-density parity check codes.

5.2.4 Advanced topics in coding with application to wireless communications

This course will be presented as a sequel of *Fundamentals of iterative decoding: The Bayesian approach*. Once students have grasped the concepts covered in this previous course, the Bayesian formalism presented there will be expanded to cover wireless channels. This will allow to introduce in a natural way the concept of decoding using channel information (and present state of the art results from our research.) After an introduction to the fundamental aspects of modeling wireless channels, such as Doppler spread, time delay spread, shadowing and path loss (and some information-theoretic aspects,) traditional coding and equalization techniques for fading channels will be presented. The main part of the course will focus on specific topics of our research.

5.3 Building a wireless communications laboratory

An important objective in my educational and research plan is to build a wireless communications laboratory. The purpose is two-fold. First, in order to develop our proposed research, it is important to have good and realistic models of wireless communications systems. Second, the wireless laboratory will improve the undergraduate and graduate curriculum. It will also expose sophomore students to the area of wireless communications, serving as a magnet to attract good students to our field. The central content for this laboratory will include wireless digital mobile communications indoor and outdoor system modeling, channel and source coding, antenna array receivers and software for simulations. Some funding from the industry is expected, and the department will provide the rest of the funds for its development.

5.4 Outreach to students of other disciplines

One of the dangers with the current very specialized knowledge in science and technology is that some research topics can get more and more focused, losing contact with developments in other related areas. A clear example of this situation can be found in the parallel development of artificial intelligence (Bayesian networks) and coding (turbo codes and low-density parity check codes.) Until very recently, communications between these two communities have been very small, and most of the times one community was completely unaware of the developments produced by the other one. Not surprisingly, the flourishment in Coding Theory in the last years has been partially produced by the increased awareness between both communities.

In order to avoid this kind of situations, it is important to look at a given research problem from different perspectives. This is why I think that (especially for the research proposed here) it is important to attract students not only from Electrical Engineering, but also from related fields such as Computer Science, Mathematics, and Statistics. They will bring fresh air to our field, and different ways of looking at the problems. At the same time, they will also benefit by acquiring new skills. Therefore, I plan to encourage the enrollment of students from other related areas in our graduate program. I will also try to make students in our program aware of opportunities in other related fields.

References

[1] F. Babich, O. E. Kelly, and G. Lombardi, "A Context-Tree Based Model for Quantized Fading," *IEEE Communications Letters*, vol. 3, no. 2, pp. 46-48, February 1999.

[2] F. Babich, O. E. Kelly, and G. Lombardi, "Generalized Markov Modeling for Flat Fading," *IEEE Trans. on Communications*, vol. 48, no. 4, pp. 547-551, April 2000.

[3] L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate," *IEEE Trans. on Information Theory*, vol. 20, no. 2, pp. 284-287, March 1974.

[4] G. Bauch, H. Khorram, and J. Hagenauer, "Iterative Equalization and Decoding in Mobile Communications Systems," *Second EPMCC'97 together with Third ITG-Fachtagung "Mobile Kommunikation"*, pp. 307-312, Bonn, Germany, October 1997.

[5] G. Bauch, "Concatenation of Space-Time Block Turbo Codes and 'Turbo' TCM," *Proc. ICC'99*, pp. 1202-1206, June 1999.

[6] L. E. Baum and T. Petrie, "Statistical Inference for Probabilistic Functions on Finite State Markov Chains," *Ann. Math. Stat.*, vol.37, pp. 1554-1563, 1966.

[7] L. E. Baum and G. R. Sell, "Growth Functions for Transformations on Manifolds,"*Pac. J. Math.*, vol.32, no. 2, pp. 211-227, 1968.

[8] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "A Soft-Input Soft-Output APP Module for Iterative Decoding of Concatenated Codes," *IEEE Communications Letters*, vol. 1, no. 1, pp. 22-24, January 1997.

[9] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Bandwidth Efficient Parallel Concatenated Coding Schemes," *Electronics Letters*, vol.31, no. 24, pp. 2067-2069, November 1995.

[10] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Parallel Concatenated Trellis Coded Modulation," *Proc. ICC'96*, pp. 974-978, June 1996.

[11] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo-Codes," *Proc. ICC'93*, pp. 1064-1070, May 1993.

[12] C. Berrou and A. Glavieux, "Near Optimum Error Correcting Coding and Decoding: Turbo-Codes," *IEEE Trans. on Communications*, vol. 44, no. 10, pp. 1261-1271, October 1996.

[13] A. Beverly and K. S. Shanmugan, "Hidden Markov Models for Burst Errors in GSM and DECT Channels," *Proc. Globecom'98*, pp. 3692-3698, November 1998.

[14] E. Biglieri, D. Divsalar, P. McLane, and M. Simon, "Introduction to Trellis Coded Modulation with Applications," *Mcmillan*, 1991.

[15] E. Biglieri, J. Proakis, and S. Shamai (Shitz), "Fading Channels: Information-Theoretic and Communications Aspects,"*IEEE Trans. on Information Theory*, vol. 44, no. 6, pp. 2619-2692, October 1998.

[16] N. Chomsky, "Three Models for the Description of Language,"*IRE Trans. on Information Theory*, vol. 2, no. 3, pp. 113-124, September 1956.

[17] N. Chomsky, "On Certain Formal Properties of Grammars,"*Information and Control*, vol. 2, pp. 137-167, 1959.

[18] J.-Y. Chouinard, M. Lecours, and G. Delisle, "Estimation of Gilbert's and Fritchman's Models Parameters Using the Gradient Method for Digital Mobile Radio Channels," *IEEE Trans. on Vehicular Technology*, vol. 37, no. 3, pp. 158-166, August 1988.

[19] K. M. Chugg, "MLSE for an Unknown Channel-Part I: Optimality Considerations,"*IEEE Trans. on Communications*, vol.44, no. 7, pp. 836-846, July 1996.

[20] C. Cook, A. Rosenfeld, and A. Aronson, "Grammatical Inference by Hill Climbing," *Information Sciences*, vol.10, pp. 59-80, 1976.

[21] M. C. Davey and D. J. C. MacKay, "Low-Density Parity-Check Codes over GF(q)," *IEEE Communications Letters*, vol. 2, no. 6, pp. 165-167, June 1998.

[22] J. Deller, J. Proakis, and J. Hansen, "Discrete-Time Processing of Speech Signals," *Mcmillan*, 1993.

[23] C. Douillard, M. Jezequel, C. Berrou, A. Picart, P. Didier, and A. Glavieux, "Iterative Correction of Intersymbol Interference: Turbo Equalization," *European Transactions on Telecommunications*, vol. 6, no. 5, pp. 189-192, September-October 1995.

[24] A. Drukarev and K. P. Yiu, "Performance of Error-Correcting Codes on Channels with Memory," *IEEE Trans. on Communications*, vol. 34, no. 6, pp. 513-521, June 1986.

[25] R. Durbin, S. Eddy, S. Krogh, and G. Mitchison, "Biological Sequence Analysis," *Cambridge University Press*, 1998.

[26] E. O. Elliott, "Estimates of Error Rates for Codes on Burst-Noise Channels," *Bell System Tech. J.*, vol. 42, pp. 1977-1997, September 1963.

[27] C. Fragouli and R. D. Wesel, "Turbo Encoder Design for Symbol Interleaved Parallel Concatenated Trellis Coded Modulation," *submitted to IEEE Trans. on Communications.*

[28] B. J. Frey, F. R. Kschischang, and P. G. Gulak, "Concurrent Turbo-Decoding," *Proc. ISIT'97*, p. 431, July 1997.

[29] B. D. Fritchman, "A Binary Channel Characterization Using Partitioned Markov Chains with Applications to Error Correcting Codes," *Ph.D. dissertation*, Lehigh Univ., Bethlehem, PA, 1966.

[30] B. D. Fritchman, "A Binary Channel Characterization Using Partitioned Markov Chains," *IEEE Trans. on Information Theory*, vol. 13, no. 2, pp. 221-227, April 1967.

[31] R. G. Gallager, "Low-Density Parity-Check Codes," *IEEE Trans. on Information Theory*, vol. 8, no. 1, pp. 21-28, January 1962.

[32] R. G. Gallager, "Low-Density Parity-Check Codes," *M.I.T Press*, 1963.

[33] J. Garcia-Frias and P. M. Crespo, "Hidden Markov Models for Burst Error Characterization in Indoors Radio Channels," *IEEE Trans. on Vehicular Communications*, vol. 46, no. 4, pp. 1006-1020, November 1997.

[34] J. Garcia-Frias and J. Villasenor, "Simplified Turbo Decoding for Binary Markov Channels," *Proc. ISIT'00*, p. 67, June 2000.

[35] J. Garcia-Frias and J. Villasenor, "Low Complexity Turbo Decoding for Binary Markov Channels," *Proc. VTC'00*, May 2000.

[36] J. Garcia-Frias and J. Villasenor, "Turbo Codes for Continuous Markov Channels with Unknown Parameters," *Proc. Globecom'99*, December 1999.

[37] J. Garcia-Frias and J. Villasenor, "Simplified Methods for Combining Hidden Markov Models and Turbo Codes," *Proc. VTC'99*, pp. 1580-1584, September 1999.

[38] J. Garcia-Frias and J. Villasenor, "Combined Blind Equalization and Turbo Decoding," *Proc. ICC'99 (Communications Theory Miniconference)*, pp. 52-57, June 1999.

[39] J. Garcia-Frias and J. Villasenor, "Blind Turbo Decoding and Equalization," *Proc. VTC'99*, pp. 1881-1885, May 1999.

[40] J. Garcia-Frias and J. Villasenor, "Exploiting Binary Markov Channels with Unknown Parameters in Turbo Coding," *Proc. Globecom'98*, pp. 3244-3249, November 1998.

[41] J. Garcia-Frias and J. Villasenor, "Turbo Decoders for Markov Channels," *IEEE Communication Letters*, vol. 2, no. 9, pp. 257-259, September 1998.

[42] J. Garcia-Frias and J. Villasenor, "Joint Source Channel Coding and Estimation of Hidden Markov Structures," *Proc. ISIT'98*, p. 201, August 1998.

[43] J. Garcia-Frias and J. Villasenor, "Turbo Codes for Binary Markov Channels," *Proc. ICC'98*, pp. 110-115, June 1998.

[44] J. Garcia-Frias and J. Villasenor, "Turbo Decoding of Hidden Markov Sources with Unknown Parameters," *Proc. DCC'98*, pp. 159-168, March 1998.

[45] J. Garcia-Frias and J. Villasenor, "Markov Structures in Turbo Decoding," *Proc. of the Winter 1998 IEEE Information Theory Workshop*, pp. 54-55, San Diego, California, February 1998.

[46] J. Garcia-Frias and J. Villasenor, "Joint Source-Channel Decoding of Turbo Codes," *Proc. of the International Symposium on Turbo Codes and Related Topics*, pp. 259-262, Brest, France, September 1997.

[47] J. L. Gersting, "Mathematical Structures for Computer Science," *W. H. Freeman*, 1993.

[48] M. J. Gertsman and J. H. Lodge, "Symbol-by-Symbol MAP Demodulation of CPM and PSK Signals on Rayleigh Flat-Fading Channels," *Trans. on Communications*, vol. 45, no. 7, pp. 788-799, July 1997.

[49] E. N. Gilbert, "Capacity of a Burst-Noise Channel," *Bell System Tech. J.*, vol. 39, pp. 1253-1265, September 1960.

[50] A. Glavieux, C. Laot, and J. Labat, "Turbo Equalization over a Frequency Selective Channel," *Proc. of the International Symposium on Turbo Codes and Related Topics*, pp. 96-102, Brest, France, September 1997.

[51] S. L. Goff, A. Glavieux, and C. Berrou, "Turbo Codes and High Spectral Efficiency Modulation," *Proc. ICC'94*, pp. 645-649, May 1994.

[52] A. J. Goldsmith and P.P. Varaiya, "Capacity, Mutual Information, and Coding for Finite-State Markov Channels," *IEEE Trans. on Information Theory*, vol. 42, no. 3, pp. 868-886, May 1996.

[53] E. K. Hall and S. Willson, "Design and Performance Analysis of Turbo Codes on Rayleigh Fading Channels," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 2, pp. 160-174, February 1998.

[54] C. Heegard, "Turbo Coding for Magnetic Recording," *Proc. of the Winter 1998 Information Theory Workshop, pp. 18-19*, San Diego, California, February 1998.

[55] J. E. Hopcroft and J. D. Ulman, "Introduction to Automata Theory, Languages and Computation," *Addison-Wesley*, 1979.

[56] G. K. Kaleh and R. Vallet, "Joint Parameter Estimation and Symbol Detection for Linear or Nonlinear Unknown Channels," *IEEE Trans. on Communications*, vol. 42, no. 7, pp. 2406-2413, July 1994.

[57] L. N. Kanal and A. R. K Sastry, "Models for Channels with Memory and Their Application to Error Control," *Proc. of the IEEE*, vol. 66, no. 7, pp. 724-744, July 1978.

[58] J. H. Kang, W. E. Stark, and A. O. Hero, "Turbo Codes for Fading and Burst Channels," *Proc. Globecom'98 (Communications Theory Miniconference)*, pp. 40-45, November 1998.

[59] J. C. Kieffer and E.-H. Yang, "Grammar Based Codes: A New Class of Universal Lossless Source Codes," *IEEE Trans. on Information Theory*, vol. 46, no. 3, pp. 737-754, May 2000.

[60] C. Komminakis and R. D. Wesel, "Pilot-Aided Joint Iterative Data and Channel Estimation in Flat Fading Channels," *Proc. Globecom'99 (Communications Theory Miniconference)*, December 1999.

[61] C. Komminakis and R. D. Wesel, "Non-Pilot-Aided Joint Iterative Decoding for Joint Data and Channel Estimation in Fading," *33rd Asilomar Conference on Signals, Systems, and Computers*, October 1999.

[62] F. R. Kschischang and B. J. Frey, "Iterative Decoding of Compound Codes by Probability Propagation in Graphical Models," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 2, pp. 219-230, February 1998.

[63] F. R. Kschischang, B. J. Frey, and H.-A. Loeliger, "Factor Graphs and the Sum-Product Algorithm," *submitted to IEEE Trans. on Information Theory.*

[64] A. Lapidoth and P. Narayan, "Reliable Communication Under Channel Uncertainty," *IEEE Trans. on Information Theory*, vol. 44, no. 6, pp. 2148-2177, October 1998.

[65] K. Lari and S. J. Young, "The Estimation of Stochastic Context-Free Grammars Using the Inside-Outside Algorithm," *Computer Speech and Language*, vol. 4, no. 1, pp. 35-56, 1990.

[66] L. Li and A. J. Goldsmith, "Decision-Feedback Maximum-Likelihood Decoder for Fading Channels," *Proc. Globecom'97*, pp. 332-336, November 1997.

[67] Y. Liu and M. P. Fitz, "Space-Time Turbo Codes," *Proc. 37th Annual Allerton Conference on Communication, Control and Computing*, Monticello, Illinois, September 1999.

[68] J. H. Lodge and M. J. Gertsman, "Joint Detection and Decoding by Turbo Processing for Fading Channel Communications," *Proc. of the International Symposium on Turbo Codes and Related Topics*, pp. 88-95, Brest, France, September 1997.

[69] D. J. C. MacKay, "Good Error-Correcting Codes Based on Very Sparse Matrices," *IEEE Trans. on Information Theory*, vol. 45, no. 2, pp. 399-431, March 1999.

[70] D. J. C. MacKay and R. M. Neal, "Near Shannon Limit Performance of Low Density Parity Check Codes," *Electronic Letters*, vol. 33, no. 6, pp. 457-458, March 1997.

[71] D. J. C. MacKay, S. T. Wilson, and M. C. Davey "Comparison of Constructions of Irregular Gallager Codes," *IEEE Trans. on Communications*, vol. 47, no. 10, pp. 1449-1454, October 1999.

[72] I. D. Marsland and P. T. Mathiopoulos, "Multiple Differential Detection of Parallel Concatenated Convolutional (Turbo) Codes in Correlated Fast Rayleigh Fading," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 2, pp. 265-275, February 1998.

[73] R. J. McEliece, D. J. C. MacKay, and J. F. Cheng, "Turbo Decoding as an Instance of Pearl's 'Belief Propagation' Algorithm," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 2, pp. 140-156, February 1998.

[74] P. Meshkat and J. D. Villasenor, "New Schedules for Information Processing in Turbo Decoding," *Proc. ISIT'98*, p. 118, August 1998.

[75] M. Mushkin and I. Bar-David, "Capacity and Coding for the Gilbert-Elliott Channels," *IEEE Trans. on Information Theory*, vol. 35, no. 6, pp. 1277-1290, November 1989.

[76] K. R. Narayan, "Turbo Decoding of Concatenated Space-Time Codes," *Proc. 37th Annual Allerton Conference on Communication, Control and Computing*, Monticello, Illinois, September 1999.

[77] J. Pearl, "Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference," *Morgan Kaufmann*, 1988.

[78] J. G. Proakis, "Digital Communications," *McGraw-Hill*, 1995.

[79] L. R. Rabiner, "A Tutorial on Hidden Markov Models and Selected Applications on Speech Recognition," *Proc. of the IEEE*, vol.77, no. 2, pp. 257-285, February 1989.

[80] D. Raphaeli and Y. Zarai, "Combined Turbo Equalization and Turbo Decoding," *IEEE Communications Letters*, vol. 2, no. 4, pp. 107-109, April 1998.

[81] T. Richardson, A. Shokrollahi, and R. Urbanke,"Design of Provably Good Low-Density Parity Check Codes," *submitted to IEEE Trans. on Information Theory.*

[82] T. Richardson and R. Urbanke,"The Capacity of Low-Density Parity Check Codes under Message Passing Decoding," *submitted to IEEE Trans. on Information Theory.*

[83] P. Robertson and T. Worz, "Coded Modulation Scheme Employing Turbo Codes," *Electronic Letters*, vol. 31, no. 18, pp. 1546-1547, August 1995.

[84] P. Robertson and T. Worz, "A Novel Bandwidth Efficient Coding Scheme Employing Turbo Codes," *Proc. ICC'96*, pp. 962-967, June 1996.

[85] P. Robertson and T. Worz, "Bandwidth Efficient Turbo Trellis-Coded Modulation Using Punctured Components Codes," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 2, pp. 206-218, February 1998.

[86] T. Sato, K. Tokuda, M. Kawabe, and T. Kato "Simulation of Burst Error Models and Adaptive Error Control Scheme for High Speed Data Transmission Over Analog Cellular Systems," *IEEE Trans. on Vehicular Technology*, vol. 40, no. 2, pp. 443-452, May 1991.

[87] A. Semmar, M. Lecours, J. Y. Chouinard, and J. Ahern, "Characterization of Error Sequences in UHF Digital Mobile Radio Channels," *IEEE Trans. on Vehicular Technology*, vol. 40, no. 4, pp. 769-776, November 1991.

[88] S. Srinivas and K.S. Shanmugan, "An Equivalent Markov Model for Burst Errors in Digital Channels," *IEEE Trans. on Communications*, vol 43, no. 2-4, pp. 1347-1355, February-April 1995.

[89] F. Swarts and H. C. Ferreira, "Markov Characterization of Channels with Soft Decision Outputs," *IEEE Trans. on Communications*, vol. 41, no. 5, pp. 678-682, May 1993.

[90] F. Swarts and H. C. Ferreira, "Markov Characterization of Digital Fading Mobile VHF Channels," *IEEE Trans. on Vehicular Technology*, vol. 43, no. 4, pp. 977-985, November 1994.

[91] J. S. Swarts and H. C. Ferreira, "On the Evaluation and Application of Markov Channel Models in Wireless Communications," *Proc. VTC'99*, pp. 117-121, September 1999.

[92] C. C. Tan and N. C. Beaulieu, "First Order Markov Modeling for the Rayleigh Fading Channel," *Proc. Globecom'99*, pp. 8-12, November 1998.

[93] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-Time Codes for High Data Rate Wireless Communications: Performance Criterion and Code Constructions," *IEEE Trans. on Information Theory*, vol. 44, no. 2, pp. 744-765, March 1998.

[94] W. Turin, "Performance Analysis of Digital Transmission Systems," New York: Computer Science, 1990.

[95] W. Turin and M. M. Sondhi, "Modeling Error Sources in Digital Channels," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 3, pp. 340-347, April 1993.

[96] W. Turin and R. Van Nobelen, "Hidden Markov Modeling of Flat Fading Channels," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 9, pp. 1809-1817, December 1998.

[97] M. C. Valenti and B. D. Woerner, "Refined Channel Estimation for Coherent Detection of Turbo Codes over Flat-Fading Channels," *Electronics Letters*, vol. 34, no. 17, pp. 1648-1649, August 1998.

[98] M. C. Valenti and B. D. Woerner, "Performance of Turbo Codes in Interleaved Flat Fading Channels with Estimated Channel State Information," *Proc. VTC'98*, May 1998.

[99] H. S. Wang and P. C. Chang, "On Verifying the First-Order Markovian Assumption for a Rayleigh Fading Channel Model," *IEEE Trans. on Vehicular Technology*, vol. 45, no. 2, pp. 353-357, May 1996.

[100] H. S. Wang and N. Moayeri, "Finite-State Markov Channel: A Useful Model for Radio Communication Channels," *IEEE Trans. on Vehicular Technology*, vol. 44, no. 1, pp. 163-171, February 1995.

[101] N. Wiberg, H.-A. Loeliger, and R. Kotter, "Codes and Decoding on General Graphs," no. 440, Dept. of Electrical Engineering, University of Sweden, Sweden 1995.

[102] N. Wiberg, "Codes and Iterative Decoding on General Graphs," *European Trans. on Telecommunication*, vol. 6, no. 5, pp. 513-525, September 1995.

Biographical Sketch of Javier Garcia-Frias

a. Professional Preparation

Universidad Politecnica, Madrid	Electrical Engineering	B.S.&M.S.1992
Univ. Nacional de Educacion a Distancia, Madrid	Mathematics	B.S.&M.S.1995
University of California, Los Angeles	Electrical Engineering	Ph.D.1999

b. Appointments

University of Delaware	Assistant Professor	9/99-now
University of California, Los Angeles	Univ. fellowship & research assistant	8/96-7/99
Telefonica I+D, Madrid	Research assistant	6/94-7/96
Universidad Politecnica, Madrid	Fellowship from Spanish government	1/93-5/94
Telefonica I+D, Madrid	Research assistant	5/92-12/92

c. Publications

(i) Publications most closely related to the proposed project

J. Garcia-Frias and P. Crespo, "Hidden Markov Models for Burst Error Characterization in Indoors Radio Channels," *IEEE Trans. on Vehicular Technology*, vol. 46, no. 4, pp. 1006-1020, November 1997.

J. Garcia-Frias and J. D. Villasenor, "Turbo Decoders for Markov Channels," *IEEE Communications Letters*, vol. 2, no. 9, pp. 257-259, September 1998.

J. Garcia-Frias and J. D. Villasenor, "Exploiting Binary Markov Channels with Unknown Parameters in Turbo Coding," *Proc. Globecom'98*, pp. 3244-3249, November 1998.

J. Garcia-Frias and J. D. Villasenor, "Turbo Codes for Continuous Markov Channels with Unknown Parameters," *Proc. Globecom'99*, December 1999.

J. Garcia-Frias and J. D. Villasenor, "Low Complexity Turbo Decoding for Binary Hidden Markov Channels," *Proc. VTC'00*, May 2000.

(ii) Other significant publications

P. Crespo, R. Mann, J. P. Cosmas, and J. Garcia-Frias, "Results of Channel Error Profiles for DECT," *IEEE Trans. on Communications*, vol. 44, no. 8, pp. 913-917, August 1996.

J. Garcia-Frias and J. D. Villasenor, "Combining Hidden Markov Models and Parallel Concatenated Codes," *IEEE Communications Letters*, vol. 1, no. 4, pp. 111-113, July 1997.

J. Garcia-Frias, and John D. Villasenor, "Turbo Decoding of Hidden Markov Sources with Unknown Parameters," *Proc. DCC'98*, pp. 159-168, March 1998.

J. Garcia-Frias and J. D. Villasenor, "Turbo Codes for Binary Markov Channels," *Proc. ICC'98*, pp. 110-115, June 1998.

J. Garcia-Frias, and J. D. Villasenor, "Combined Blind Equalization and Turbo Decoding," *Proc. ICC'99 (Communications Theory Miniconference)*, pp. 1881-1885, June 1999.

d. Synergistic activities

1. IEEE Member (Information Theory, Communications, Vehicular Technology, and Signal Processing Societies.)
2. Reviewer for IEEE Trans. on Information Theory, Trans. on Communications, Trans. on Vehicular Technology, Trans. on Image Processing, and several conferences.

e. Collaborators & Other Affiliations

(i) Collaborators

Dan Benyamin; Ph.D. student; University of California, Los Angeles

Pedro M. Crespo; Technology Director; Jazztel SA, Madrid

John D. Villasenor; Professor; University of California, Los Angeles

(ii) Graduate and Post Doctoral Advisors

John D. Villasenor (Ph.D. advisor); Professor; University of California, Los Angeles

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor

Felipe Cabarcas, M.S. expected June 2001

Zhao Ying, Ph.D. expected June 2003

SUMMARY PROPOSAL BUDGET YEAR 1

ORGANIZATION: University of Delaware	FOR NSF USE ONLY	
	PROPOSAL NO.	DURATION (months): Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Javier Garcia-Frias	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. Javier Garcia-Frias - Principal Investigator	0.00	0.00	2.00	$ 14,914	$
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	14,914	
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. (1) GRADUATE STUDENTS				20,000	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				34,914	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,486	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				39,400	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) Computer Workstations $ 10,000					
TOTAL EQUIPMENT				10,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,750	
2. FOREIGN				1,750	
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				500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				53,900	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.0000, Base: 43901)					
TOTAL INDIRECT COSTS (F&A)				22,389	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				76,289	
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)				$ 76,289	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $	
PI / PD TYPED NAME & SIGNATURE*: Javier Garcia-Frias	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 2

ORGANIZATION **University of Delaware**				**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Javier Garcia-Frias**				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. Javier Garcia-Frias - Principal Investigator	0.00	0.00	2.00	$ 15,511	$
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	15,511	
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. (1) GRADUATE STUDENTS				20,800	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				36,311	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,665	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				40,976	
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)				1,750	
2. FOREIGN				1,750	
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				500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				45,476	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.0000, Base: 45478)					
TOTAL INDIRECT COSTS (F&A)				23,193	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				68,669	
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)				$ 68,669	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Javier Garcia-Frias**	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 **University of Delaware**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted		
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Javier Garcia-Frias**	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. Javier Garcia-Frias - Principal Investigator	0.00	0.00	2.00	$ 16,131	$
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	16,131	
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. (1) GRADUATE STUDENTS				21,632	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				37,763	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,852	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				42,615	
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)				1,750	
2. FOREIGN				1,750	
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				500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				47,115	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.0000, Base: 47117)					
TOTAL INDIRECT COSTS (F&A)				24,029	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				71,144	
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)				$ 71,144	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				
PI / PD TYPED NAME & SIGNATURE* **Javier Garcia-Frias**	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 4

ORGANIZATION **University of Delaware**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Javier Garcia-Frias**				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. **Javier Garcia-Frias - Principal Investigator**	0.00	0.00	2.00	$ 16,776	$
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	16,776	
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. (1) GRADUATE STUDENTS				22,497	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				39,273	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,046	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				44,319	
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)				1,750	
2. FOREIGN				1,750	
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				500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				48,819	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 51.0000, Base: 48816)**					
TOTAL INDIRECT COSTS (F&A)				24,896	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				73,715	
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)				$ 73,715	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE* **Javier Garcia-Frias**	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 University of Delaware	FOR NSF USE ONLY				
	PROPOSAL NO.	DURATION (months) Proposed	Granted		
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Javier Garcia-Frias	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. Javier Garcia-Frias - Principal Investigator	0.00	0.00	2.00	$ 17,447	$
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	17,447	
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. (1) GRADUATE STUDENTS				23,397	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				40,844	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,248	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				46,092	
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)				1,750	
2. FOREIGN				1,750	
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				500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				1,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				50,592	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.0000, Base: 50594)					
TOTAL INDIRECT COSTS (F&A)				25,802	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				76,394	
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)				$ 76,394	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI / PD TYPED NAME & SIGNATURE* Javier Garcia-Frias	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 — Cumulative

ORGANIZATION: **University of Delaware**			FOR NSF USE ONLY		
			PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Javier Garcia-Frias**			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. Javier Garcia-Frias - Principal Investigator	0.00	0.00	10.00	$ 80,779	$
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	10.00	80,779	
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. (5) GRADUATE STUDENTS				108,326	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				189,105	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				24,297	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				213,402	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ 10,000					
TOTAL EQUIPMENT				10,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				8,750	
2. FOREIGN				8,750	
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				2,500	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				2,500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				5,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				245,902	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				120,312	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				366,214	
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)				$ 366,214	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $			
PI / PD TYPED NAME & SIGNATURE*: **Javier Garcia-Frias**	DATE	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

Budget Justification Page

Budget Justification

1. Salary and Personnel
The rate for the principal investigator is based on actual salary, and is estimated for Years 2 through 5 using the rate increased by 4% respectively. Summer compensation for the principal investigator is requested from NSF funds for two summer months in Years 1 through 5 of the research. Associated fringe benefits are calculated for Increments at 27.5%.

A salary budgeted for one (1) graduate student for all five years of the research. The rate for Year 1 is based on the graduate students's actual stipend, and is estimated for Years 2 through 5 using the rate increased by 4% respectively. Associated fringe benefits are calculated for Increments at 7.70% during the summer months only.

2. Travel
Funds requested in this category will be used for both domestic and international travel to attend conferences to be named such as: ICC, Globecom, VTC and ISIT.

3. Equipment
Funds requested in this category will be used to purchase the following:
Year 1: Computer Workstations

4. Supplies & Materials
Funds requested in this category will be used to computer software and upgrades.

5. Publication Costs
Funds requested in this category is based on current IEEE page charge $130/page.

6. Indirect Costs
The University of Delaware's Department of Defense, Office of Naval Research approved Facilities and Administrative Cost and Fringe Benefits Rates for FY years 01 - 03 is 51% of modified total direct costs. The current agreement is dated June 29, 2000.

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: **Javier Garcia-Frias**

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: **THIS PROPOSAL: Iterative Decoding Schemes For Channels With Memory: Application To fading Channels**

Source of Support: **National Science Foundation**

Total Award Amount: $ **366,215** Total Award Period Covered: **09/01/00 - 08/31/05**

Location of Project: **University of Delaware**

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

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

Project/Proposal Title: **New Coding Techniques For Improved Performance In Real Communications Systems**

Source of Support: **University of Delaware Research Foundation**

Total Award Amount: $ **29,950** Total Award Period Covered: **06/01/00 - 05/31/01**

Location of Project: **University of Delaware**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **0.67**

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

Project/Proposal Title: **Advance Techniques For Modeling Customer Behavior (w/Co-P.I.'s: Gonzalo Arce, William Latham and Helen Bowers)**

Source of Support: **Delaware Research Partnership Program**

Total Award Amount: $ **86,100** Total Award Period Covered: **07/01/00 - 06/30/01**

Location of Project: **University of Delaware**

Person-Months Per Year Committed to the Project. Cal: **0.00** Acad: **0.00** Sumr: **1.00**

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.

Facilities, Equipment, and Other Resources

The facilities, equipment, and resources available to this project include those available in the Signal Processing and Communications Laboratory (SpLab) as well as the full resources of the Department of Electrical and Computer Engineering. The SpLab resources include a Viewgraphics High Capacity Digital Video Player, a dozen Sun Ultra 10 workstations, three Macintosh computers, three Pentium workstations, color and monochrome Lexmark laser printers, a dye-sublimation color printer, a high resolution color slide scanner, a flat-bed scanner, and a 2.2 Mbit digital camera.

The Department of Electrical and Computer Engineering (ECE) resources include a joint research laboratory operated with the Department of Computer and Information Sciences (CIS). This laboratory (set up in the early 80's with support from an NSF equipment grant and known locally as the ECE/CIS Lab) radiates from two central facilities, one in Smith Hall where Computer and Information Sciences is housed, and one in Evans Hall where Electrical and Computer Engineering is housed. These two central facilities share common networking elements and are jointly administered. The facilities serve a total of roughly 50 faculty and 200 graduate students, as well undergraduates who are involved in research projects. Provided below are some details on each of the central facilities.

ECE operates 40 Sun, twelve SGI, three DEC alpha, one Mac, and one HP desktop workstations, plus 28 Sun 3's configured as X–terminals for research use by graduate students and faculty. In addition, there is an educational laboratory containing fifteen SGI workstations. The ECE department houses the ECE/CIS NSF Research Infrastructure Computer Cluster which consists of 20 Sun Microsystem Ultra Enterprise 450's each with 4 250MHz Ultra-II processors. Eight nodes of the cluster have 1GB of memory 4-way interleaved. The other 12 nodes have 512MB of memory 4-way interleaved. Each of the 20 nodes have a 4GB system disk. 12 of the nodes also have an 18GB temporary data storage disk available on the cluster. Their primary network interface is fast ethernet, which are connected to a Cisco 2926 Switch. They also have a private high-speed, low-latency network called Myrinet from Myricom. CIS currently operates 75 Sun desktop workstations. This year, ECE has added a "Cave" immersive visualization laboratory for teaching and research.

The core networking elements for both departments are 8-port Ethernet Switches with an FDDI interface. Each switch contains dual IP subnets for the associated department and provides the basis for the desktop support. There are thirteen additional Sun workstations configured as servers for both ECE and CIS, utilized as file and print servers, and servers for email, the World Wide Web, Gopher, FTP, etc. The servers are connected to the FDDI ring and some have additional network connections for research and/or educational requirements. The ECE SGI workstations, for education, have their own Ethernet Switch. The switch has high-speed server/upstream connections of both FastEthernet and FDDI connections. The ECE SGI workstations, for research, have connections to the Ethernet Switch as well as to an ATM switch. The ATM switch is under a private IP subnet and (currently) not used for external communications. The ECE/CIS Lab is currently connected to the campus core network via three Ethernet (IP subnet) connections.

UNIVERSITY OF DELAWARE

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

140 Evans Hall
University of Delaware
Newark, Delaware 19716-3130
Ph: 302/831-2405
Fax: 302/831-4316

DEPARTMENTAL ENDORSEMENT

Javier Garcia-Frias is a first year assistant professor who has spent time at the Telefonica research laboratories of Spain and brings a broad and practical perspective to the university. Very rapidly, Professor Garcia-Frias is building a ``real-channel'' approach to communications research.

Providing the best communications technology education to our students is critical for our program. Professor Garcia-Frias' educational and research thrusts integrate well with the departmental goals and priorities.

We are completely committed to helping new faculty develop their career. We do this by providing generous startup packages. Professor Garcia-Frias start-up package includes $150,000 for equipment plus departmental support for two graduate research assistants, and two summer months of support. In addition, we help them develop their research and graduate education program by keeping their course load to one course a semester for as long as possible – sometimes for several years. We have a very successful undergraduate research program, which provides some very bright undergraduates to starting faculty at no additional cost.

We hope you find Professor Garcia-Frias' proposal suitable for funding.

Professor Garcia-Frias earned his doctoral degree from the University of California at Los Angeles in September, 1999. The official effective date of appointment at the University of Delaware as Assistant Professor is 9/1/99.

I have read and endorse this Career Development Plan.

Gonzalo R. Arce, Interim Chairman
Electrical and Computer Engineering
7/7/2000