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Concatenated Systems and Cross-Layer Design

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***Abstract*— With high data rate wireless communications networks, new applications relying on high quality audio, video or control become viable. Examples of such applications are remote tele-medicine, collision avoidance systems, and audio/video entertainment at CD/DVD quality. These applications all demand high data rates, but have different quality-of-service (QoS) requirements in terms of reliability and latency. Currently, mobile communications networks have only limited provisions for QoS implementation and control. The conventional functionality separation in network design may be inhibiting effective implementation of guaranteed QoS. In this paper, we propose and review a system design paradigm based on concatenated system models and iterative signal processing. The novelty of the paradigm is to propagate methodologies of physical layer design across disciplinary boundaries within wireless network design in a bottom-up cross-layer approach. The paper is tutorial in nature, promoting the new view through presenting a series of examples of successful application of concatenated systems design from the physical and link layers. The purpose of the paper is to inspire new research directions.**

I. Introduction

The continuing development of the Internet, wireless communication and wireless Internet is rapidly increasing the demands on enabling communication networks. The current generation of wireless and mobile communications systems, such as UMTS, cdma2000 and the series of wireless IEEE 802 standards, are the first steps towards bringing true wireless Internet to the market. The quality expected by the general consumer from wireless mobile Internet is dictated by the quality currently experienced for conventional wireline systems. This expectation represents a significant challenge when designing future wireless communications systems. In addition, the increasingly wide variety of wireless services on offer has resulted in mixed communication traffic in wireless networks, representing an equally wide range of data-quality requirements. Future wireless communications networks will therefore require vast improvements in data rates, user-mobility and capability to cater for the diverse demands of advanced data services implied by the emerging heterogeneous traffic.

The service quality needed for each particular application can be quantified in terms of data rate, latency, reliability and priority. These quantities are commonly referred to as Quality of Service (QoS) parameters. For example, data services such as emailing and web browsing are sensitive to transmission errors, but relatively tolerant to transmission delay. In contrast, telephony is delay sensitive but relatively error tolerant, while many new wireless services such as audio and video at CD/DVD quality are both delay and error sensitive and require high data rates. Mission-critical applications such as intelligent vehicle safety systems and remote tele-surgery are two examples where failure to meet QoS requirements may have fatal consequences.

The challenge for future wireless networks is to accommodate large densities of highly mobile users demanding services and applications with a wide range of QoS requirements. This requires optimization of network protocols to cater for specific QoS requirements while using a minimum of the limited resources available in a wireless network. Joint optimization of all network functionalities is an immensely complex problem to solve. In fact, it is a significant challenge just to define an overall optimization problem, encompassing all network functionalities. As a convenient alternative the joint network design problem has been partitioned into smaller components (layers) that can be optimized independently.

The layered model is as such a realization of the divide-and-conquer principle. An example is the ISO/OSI model (see e.g., [1]). Within each layer, the principle is typically further applied, leading to individual optimization of separate layer functionalities. The introduction of the layered model was to some extend based on practical implementation issues. For example, a layered model with strictly defined interfaces between layers allows for technology upgrades at any layer

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of the network without impact on other layers. Also a layered model assures inter-operability as for example the operation of IP-networks over many different physical layer channels. Although practical, the divide-and-conquer principle rarely leads to a close approximate solution to the joint optimization problem.

The separation of functionalities in the network design based on the conventional layered model may be inhibiting effective implementation of guaranteed QoS. Often QoS parameters are only allowed to influence the upper layers in the communication stack. In order to meet the challenging demands on future wireless networks, it may be required to adopt new approaches leading to more accurate approximate solutions closer to a well-defined joint optimization across layers and functionalities. A design approach with no layer-constraints may prove more flexible in accommodating QoS guarantees.

A truly joint optimization approach can be revolutionary in nature, requiring disruptive implementation changes to existing layered systems. A more non-intrusive systems approach is preferred from a practical point of view. Cross-layer design within the layered model provides additional flexibility to address some limited joint optimization problems, e.g., joint transport and link layer performance optimization of best-effort TCP flow in case of data file delivery. The potential benefits of cross-layer design have been summarized in the overview paper [2], while a cautionary approach has been promoted in [1]. The main concern in [1] is that independent cross-layer design approaches may counteract each other and thus lead to network performance losses rather than gains. Further, uncoordinated cross-layer designs may lead to loss of transparency and scalability in network implementation. Therefore, cross-layer design should be based on an overall design paradigm, aiming to solve the joint optimization problem in a coordinated fashion.

Such cautionary cross-layer approaches can also allow QoS implementation through limited joint designs. By enabling a high level of QoS resolution (providing a variety of tailored solutions within a specific range of QoS), the cross-layer approach inherently addresses another important problem in wireless communications, namely the problem of optimizing the use of limited resources. The resulting protocols allow for a high level of flexibility for resource allocation by providing a wide range of supported QoS options, thus moving closer to optimal use of strictly limited bandwidth in wireless networks.

An example of a limited-intrusive cross-layer approach is found within the High Speed Downlink Packet Access (HSDPA) application [3] evolved for wireless Internet access as part of the UMTS system. HSDPA includes adaptive modulation and error control coding, hybrid automatic-repeat-request (ARQ) retransmission protocols, fast scheduling and multiple-input-multiple-output (MIMO) antenna solutions. Higher order modulation and higher rate error control coding provide higher spectral efficiency. In the current UMTS radio access network architecture, the control of scheduling, transmission formats and ARQ is with the radio network control layer. Unfortunately, meeting latency requirements for delay and error sensitive traffic poses a challenge with QoS control residing in such higher network layers. Thus, cross-layer designs extending further down in the layer hierarchy have been suggested as potential solutions, where some control and allocation functionalities are transferred to lower layers closer to the radio channel. Still, HSDPA has only limited provisions for providing a wide range of QoS options. A current limitation of such cross-layer designs is that each component technology is designed independently and operates in a conventional sequential and non-recursive fashion.

In this paper, we promote the use of concatenated systems design as a natural approach for joint optimization of functionalities across conventional layers. The novelty of the approach is to propagate methodologies of physical layer design across the disciplinary boundaries within wireless network design in a bottom-up cross-layer approach. The resulting design may enable more efficient use of limited resources and can possibly facilitate simpler implementation of QoS enabling strategies distributed across layers. The paper is tutorial in nature, arguing the approach through a series of successful applications of concatenated systems design in the physical and link layers. The purpose of the paper is to inspire new inter-disciplinary research directions.

II. Concatenated Systems

Results from communication and information theory have shown that joint optimization of different functionalities in a communications system can lead to significant improvements. Examples are joint designs of modulation and error control coding (coded modulation) [4], forward error control coding and retransmission protocols (hybrid ARQ protocols) [5] and joint source coding and channel coding. The discovery of turbo codes in 1993 [6] further accelerated the application of joint designs. Parallel and/or serial concatenation of simple error control coding components, combined with iterative signal processing techniques at the receiver provides a revolutionary new level of performance very close to fundamental physical limits. The concatenated systems approach with the concept of inference-based iterative signal processing have since been successfully applied to joint designs of many physical layer functionalities. Some examples are joint error control coding and multiple access interference reduction, joint error control coding and inter-symbol interference equalization, joint error control coding and channel estimation, joint error control and space-time coding.

Further, the inference-based iterative approach has been shown to be closely related to well-known algorithms from statistical inference, providing high-quality solutions to large inference and optimization problems. Although these methods do not provide the optimal solution to the joint optimization problem, practical experience has shown that solutions very close to optimal can be expected in many cases. The success of this approach has inspired a new cross-layer design paradigm based on concatenated system models and iterative inference-based signal processing. The new approach moves network

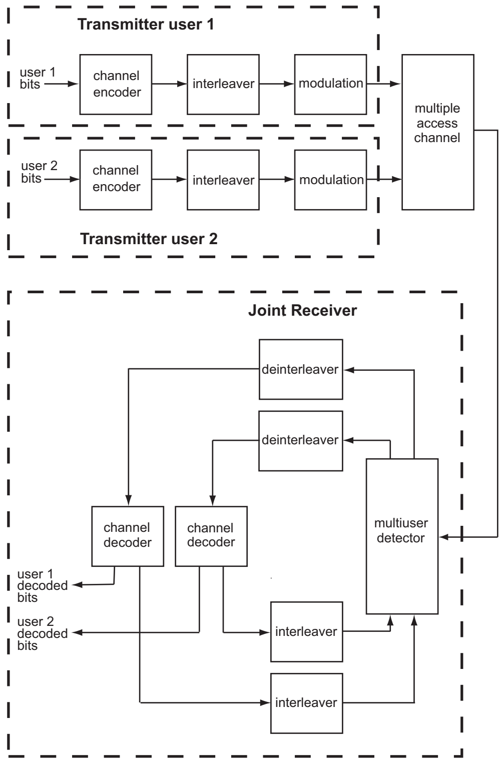


Fig. 1. A concatenated system model for joint multiuser detection and error control decoding.

design beyond the limitations of the current layer protocol paradigm. Recently limited cross-layer designs such as joint optimization of multiuser decoding and power control [7], and QoS-aware hybrid ARQ protocols [8] have been proposed and investigated.

As an example of a concatenated system from the physical layer, consider joint multiuser detection and error control decoding [9]. The corresponding concatenated system model for two active users is depicted in Figure 1, where the transmitters for user 1 and user 2 are found within the upper two dashed boxes and the joint receiver is within the lower dashed box. Each user transmits a sequence of information bits, which is first encoded with an error control code (channel code). The resulting sequence of code bits is then permuted through a pseudo-randomly selected interleaver in order to break up statistical dependencies at the receiver. The final step is to modulate the interleaved code bits onto a signal waveform for transmission. All users transmit over a multiple access channel, which in the simplest case adds the signals from all the users together and imposes additive white Gaussian noise (AWGN) onto the resulting signal.

The overall transmission can be viewed as a hybrid concatenated system in the sense that we have both serial and parallel concatenation. Within each transmitter, the channel encoder and the modulator are serially concatenated through an interleaver, forming a set of parallel concatenated transmitters which in turn is serially concatenated with the *multiple access channel*. The effects of the channel on the transmitted signals can be viewed as yet another level of signal processing, which the receiver can take advantage of. This is in fact the basis for multiuser detection.

Since the noisy multiple access channel signal observed at the receiver is a superposition of signals of all the users in Gaussian noise, it may not be straightforward to retrieve the information bits transmitted by each user. It is only a trivial operation in the case where the modulating waveforms are mutually orthogonal to each other when they arrive at the receiver. In a wireless environment, this is rarely the case. The optimal receiver solves a joint optimization problem and finds the sequence of user bits that minimizes the probability of making a bit error, given the received signal [10]. Finding the sequence of user bits is however a complex task, which in many cases is infeasible.

A. Approximate Joint Optimization through Partitioning

Joint multiuser decoding optimization can be greatly simplified if there exist system components that may be optimized individually. Principles of separation (such as the source-channel separation theorem [11] of information theory) are very powerful tools for system design. Following this idea it is tempting to solve the joint optimization problem by first solving the problem with respect to the joint constraints imposed by the modulation and the multiple access channel, and then use this solution to solve the problem with respect to the constraints imposed by the channel encoders. Unfortunately, it is not as simple as that. The sequence of independent optimal solutions do not in general lead to the optimal joint solution. However, the success of turbo coding and iterative decoding have shown that feedback between the individual optimization problems can lead to solutions close to the joint optimization solution. The formal theory behind this comes from statistical inference [12].

Statistical inference problems may be represented using special types of graphs, e.g., factor graphs [13]. These graphs describe the dependence structure of the problem. Iterative inference algorithms can also be described using these graphs. Given a graphical tree representation, the junction tree algorithm [13] performs optimal inference. Although this algorithm provides a useful framework for design of iterative methods, its complexity is usually too high due to dependencies between variables. Most existing algorithms avoid this problem by ignoring these dependencies. This leads to sub-optimal but computationally efficient algorithms such as belief propagation [13] and the forward-backward algorithm [6], which have been shown to provide high-quality solutions. These arguments support that the receiver should mirror the hybrid concatenated system of the transmission side, and further allow for feedback between the components. Allowing for feedback, a high-quality approximate solution to the joint optimization problem can be obtained by recursively exchanging information between components, solving individual optimization problems based on independent constraints.

B. Joint Multiuser Detection and Decoding

In the joint multiuser detection and error control decoding example, we can partition the problem into separate multiuser detection and error control decoding. It is then the task of the multiuser detector to detangle the independent signals from the different users. In turn, the channel decoder for a particular user takes as input the corresponding detangled output from the multiuser detector and performs the decoding process. The results of the decoding operations are the corresponding improved estimates of the sequence of code bits and the sequence of information bits. The outputs from the decoding operations are then forwarded as input to the multiuser detector, completing one iteration of the iterative joint multiuser detection and decoding scheme. The exchange of information between the components is based on uncorrelated probability distributions on individual code bits. Thus, the multiuser detector determines the probability distribution of each code bit for each user, given the corresponding received multiuser signal. Assuming binary codes, the distributions are just the probability of the code bit being equal to one and zero, respectively. We can therefore alternatively use log-likelihood ratio (LLR) representation to improve the dynamic range of the representation.

Given an uncorrelated LLR input sequence, each channel decoder computes corresponding LLRs of the interleaved sequence of code bits as well as of the interleaved sequence of information bits, given the encoding constraints. The LLR sequence corresponding to code bits is forwarded to the multiuser detector, while the sequence corresponding to information bits is only forwarded to the user sink when the iterative detection/decoding process is completed.

In the second iteration, the multiuser detector takes the interleaved outputs from all the channel decoders (*a priori* LLRs) as additional inputs and re-computes the LLRs of the interleaved code bit sequence (extrinsic LLRs). This iterative process continues until convergence or for a predetermined number of iterations. With an efficient multiuser detector, the iterative scheme is able to provide a low bit error rate (BER) even when a high number of users share a narrow-band channel. This is demonstrated in Figure 2 for an example where each user applies a rate $1/2$, four-state $(5, 7)$ convolutional code, user-unique interleavers and QPSK modulation formats (no spectrum spreading) [14]. The channel is a simple random-phase AWGN channel and the iterative receiver contains an optimal multiuser detector concatenated with optimal channel decoders. The performance for a single user is also shown in the plot.

C. Analysis and Design Tools

The behavior of the iterative receiver can be modelled as a dynamic system. The common approach for predicting the behavior of dynamic systems has been to characterize the components using scalar transfer functions, and to track the evolution of the iterative process via composition of these functions. The transfer function for each receiver component shows how some parameter of interest, for example signal-to-noise ratio

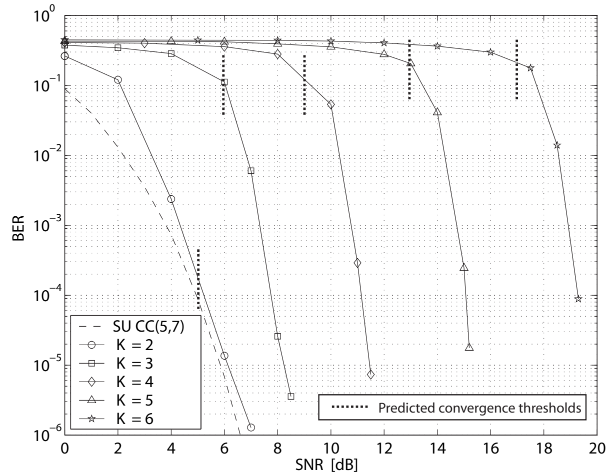


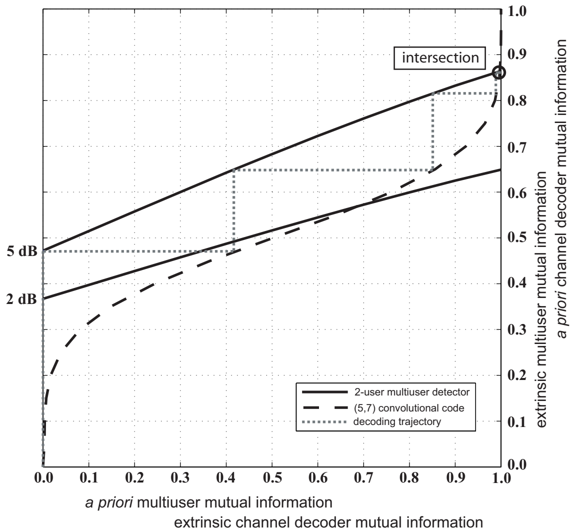
Fig. 2. Bit error rate (BER) performance as a function of the SNR.

(SNR), improves as the signal passes through. These analytical methods therefore require a scalar parameterization of the decoding process, and a method for computing the transfer functions. Candidate parameters include the posterior mean or variance, error probability and mutual information [15]. These methods share a common deficiency. To date the component transfer characteristics are almost exclusively obtained by Monte-Carlo simulation. This is however an improvement as compared to having to simulate the entire iterative process.

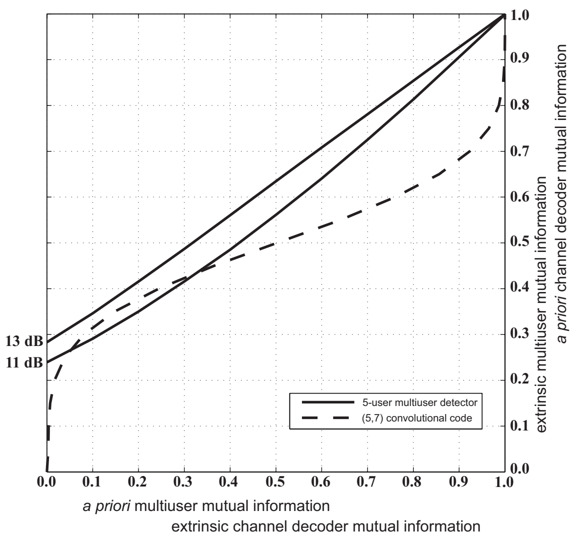
Extrinsic information transfer (EXIT) charts [15], (parameterizing using mutual information) have emerged as a leading candidate for the design and analysis of iteratively decoded systems. EXIT charts accurately predict the SNR convergence threshold, and also the speed of convergence. Further, they provide a good visualization of the decoding trajectory. The evolution of extrinsic information over iterations is the determining factor for convergence of an iterative decoder. The convergence threshold is the SNR at which the decoder rapidly transitions from high to low error rate, as exemplified in Figure 2.

To demonstrate the use of EXIT charts, we consider the joint multiuser decoder from the above example. The transfer function for the multiuser detector takes as input the mutual information between the channel observations and the transmitted code bits, and the mutual information between the *a priori* LLR values (the output of the channel decoders) and the transmitted code bits. The output of this transfer function is the mutual information between the multiuser detection output LLR values and the transmitted code bits. The output mutual information of the multiuser detection transfer function is in turn the *a priori* input to the channel decoder transfer function. The output of this transfer function is then again the mutual information between the channel decoder output LLR values and the transmitted code bits, which is also the *a priori* mutual information input to the multiuser detection transfer function.

For the joint multiuser detection and decoding example, the corresponding EXIT charts for two active users and five



a) Two-user system.



b) Five-user system.

Fig. 3. EXIT charts for two and five active users.

active users, respectively, are shown in Figures 3a and 3b. In these charts the multiuser transfer function is plotted as a solid line with the *a priori* input on the abscissa and the extrinsic output on the ordinate. Received SNRs of 2 and 5 dB, 11 and 13 dB, respectively are used as parameters for the multiuser transfer functions. The corresponding SNRs are shown on the left in the plots. The channel decoder transfer function for the $(5, 7)$ convolutional code is plotted as a dashed line with the *a priori* input on the ordinate and the extrinsic output on the abscissa, i.e., the plot is flipped along the diagonal as compared to the multiuser transfer function. This way, it is possible to plot the decoding trajectory as an alternate activation of each concatenated receiver component.

In Figure 3a, the trajectory of the iterative decoder is shown as the dotted staircase for the case of an SNR of 5 dB.

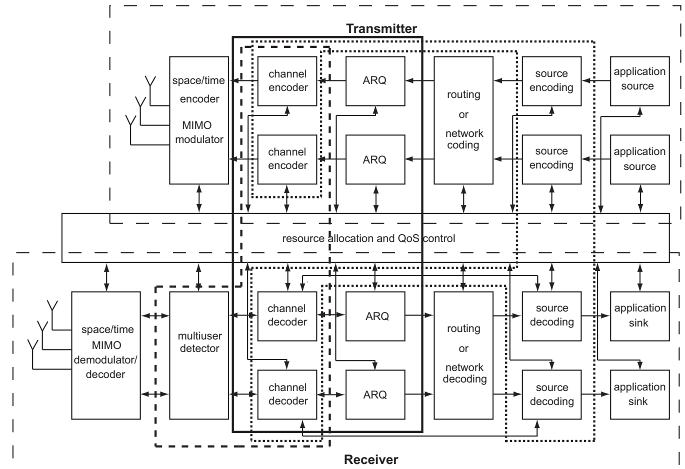


Fig. 4. A concatenated system model for a simplified base station transmitter/receiver.

Activating the multiuser detector once, we make a vertical move in the trajectory from the multiuser transfer curve to the channel code transfer curve. Activating the channel decoders, we make a horizontal move as shown in the trajectory. For each activation, we move along the trajectory depending on which component has been activated. Convergence occurs where the multiuser transfer curve and the channel code transfer curve intersect or if either of the output mutual informations reach a value of one. In Figure 3a, the two curves intersect at the circle to the right. To reach a low BER (less than 10^{-5}), a mutual information of more than 0.9999 should be reached. We can therefore only achieve a low BER if there is an open tunnel between the two curves all the way across the plot. We observe in Figures 3a and 3b that with an SNR of around 5 dB for the two-user case and around 13 dB for the five-user case, the EXIT charts predict that it should be possible to reach low BER performance with the $(5, 7)$ code. For 3, 4, 6 users the predictions are 6, 9, 17 dB, respectively. This is confirmed in Figure 2.

III. Cross-Layer Concatenated Systems Model

An adaptive cross-layer communication protocol involves many functionalities and technologies. As an example we consider a cellular-type network. Inspired by the success of concatenated approaches at the physical layer, the interaction between functionalities in a base station transmitter/receiver across layers can be modelled as a hybrid concatenated system with multiple parallel and serial branches. This is demonstrated in Figure 4 for a simplified base station transmitter/receiver model with two active users. Here, the transmitter/receiver components recursively interchange information across traditional layer boundaries emulating a joint optimization solution. Only a limited subset of functionalities has been included in the figure. Important functionalities such as network addressing, data transporting plane, and multi-interfacing have been omitted for clarity.

The difference between a conventional transmitter block diagram and the transmitter in Figure 4 is that, in the latter, each transmitter component is allowed two-way exchange of information with the common resource allocation and QoS control component. The lines with double arrows indicate two-way exchange of information. The same level of interaction between the control component and all components in the receiver is also allowed. In addition, two-way information exchange directly between components is also allowed in the receiver.

The non-intrusive nature of the concatenated systems approach is clear from Figure 4. A conventional design is merely a special case of the concatenated model. Therefore, the approach allows for gradually including functionalities in a joint design. Examples of joint designs are indicated in Figure 4 by the inserted boxes. The dashed box indicates a joint design of iterative multiuser detection and decoding together with power control and error control code selection in order to meet QoS requirements. A design process based on transfer function tools have been proposed for this problem in [7]. The dotted box highlights joint iterative source coding and channel coding, which has also been proposed with impressive performance gains. Finally, the solid-lined box denotes a QoS-aware hybrid ARQ protocol, incorporating error control coding, data link layer retransmission schemes, and some parts of network layer QoS responsibilities [8]. Based on the concatenated approach, an overall joint design of the functionalities in the three boxes is a relatively straightforward exercise, which is yet to be investigated.

The information exchange in the concatenated system defines the cross-layer information flow. In the physical layer, the exchange of information follows directly from the common nature of functionalities. It may not be equally straightforward to recognize the information exchange between different functionalities across layers. Practical examples are suggested in [16]. Typically the information flowing upstream in the layers are soft quality measures of the corresponding functionalities. Examples can be probability distributions, mean squared errors, mutual information levels, delay distributions or throughput. Upstream this information may for example be used for scheduling, code selection, power control, source coding improvements or transmission policies. The information flowing downstream across layers is usually resource allocation and priority information in order to meet QoS requirements in the network.

IV. QoS-aware Adaptive Coding Scheme

To illustrate the joint approach, we consider here in more detail the QoS-aware hybrid ARQ protocol mentioned above [8]. This scheme is based on incremental redundancy hybrid ARQ techniques using concatenated coding and iterative decoding. In a so-called incremental redundancy type-II hybrid ARQ scheme [5], a high rate code is applied for the initial encoding of the information bits. If this is not sufficiently powerful to allow for correct decoding of the information bits, additional parity bits are incrementally transmitted until the information bits are successfully decoded or until all available parity bits have been sent. This scheme is well suited for QoS requirements in terms of latency versus reliability. In an incremental redundancy scheme reliability is assured by selecting an appropriate parent code, while latency is assured by limiting the number of transmissions allowed before a full codeword has been transmitted.

Incremental redundancy hybrid ARQ schemes are commonly based on rate compatible punctured codes, where high rate codes are obtained by puncturing codewords of a lower rate parent code. Puncturing a codeword implies that certain code bits are removed before transmission so that the overall code rate is increased. The receiver needs to know the so-called puncturing pattern, so that erasures can be inserted instead of the punctured bits before decoding starts. Rate compatible turbo codes have been found particularly suitable for incremental redundancy hybrid ARQ. It is simple to provide multiple coding alternatives that can provide the same required QoS in terms of latency and reliability. This flexibility is found in the trade-off between SNR and bandwidth, i.e., between higher transmission power and additional redundancy. In Figure 5, an example of three codes concatenated in parallel is shown. Each encoder is connected to a puncturer, removing code bits before transmission, and thus increasing the corresponding overall code rate. In this structure, it is very

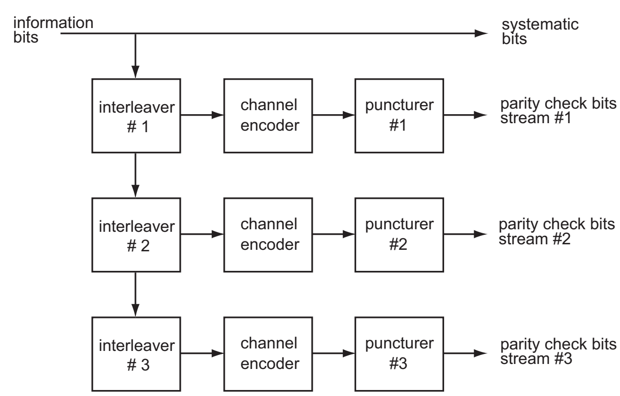


Fig. 5. The structure of a multiple parallel concatenated code with three components.

simple to create codes of lower rates. The same encoder can be replicated as many times as necessary in order to provide alternatives that can reach the required reliability at lower power levels. This useful feature provides a high level of flexibility for resource allocation and scheduling.

Figure 6 shows upper bounds on frame error rate performance for three parallel concatenated $(8, 7)$ single-parity check codes as a function of the number of parity bits included in the decoding process [8]. The parity bits have been punctured according to component codes. Based on this plot, we can see that for a given frame error rate (FER) we have multiple choices for parent code rate and transmission power to accommodate a specific QoS requirement. As the maximum number of transmissions is determined by the acceptable delay or a formal deadline, we can find optimal transmission packet lengths for each incremental redundancy packet such that the overall throughput is maximized.

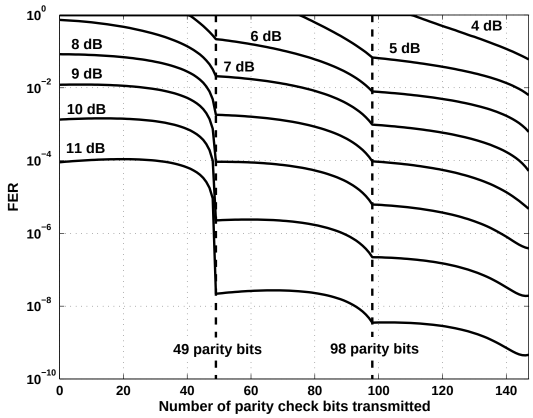


Fig. 6. Analytical upper bounds on frame error rate as a function of the number of parity bits in the codeword.

Combined with the iterative joint multiuser detector and decoder with power control and the iterative joint source decoder and channel decoder, this concatenated approach is a promising paradigm for making joint designs across conventional layers which are close to truly joint optimal designs.

V. Concluding Remarks

In this paper we have reviewed the application of concatenated system models with iterative signal processing as a design paradigm for wireless networks. The paradigm promises a non-intrusive cross-layer approach, gradually moving towards truly joint optimization of network functionalities. The novel approach is to propagate methodologies of physical layer design across disciplinary boundaries in a bottom-up cross-layer approach, representing a bold step towards expanding the level of interdisciplinary research in wireless network design.

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