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Project Summary

My career goal is to use my roles as a researcher as an educator to contribute to the understanding of the fundamental limits of reliable communications in networked environments. The complexity, diversity and transient nature of official and *de facto* standards in the networking world can easily obscure the intrinsically important issues for reliable transmission of information in networked environments. The purpose of contributing to the fundamental understanding of such networks is to provide lasting tools and guidelines for the analysis and design of robust and reliable networks. In my research, teaching and advising, I seek to establish a solid theoretical framework to analyze problems strongly rooted in engineering applications.

My proposed research activities over the next few years are in the area of packetized wide-band communications and in the area of network robustness and recovery. The first area is applicable to wireless multiple access packetized networks. The second area is applicable to a wide variety of multi-terminal environments where failures are of concern, whether these failures be infrequent but possibly catastrophic, as in optical and high-speed networks, or frequent, as in wireless *ad hoc* networks.

In the area of packetized wide-band communications, I propose to study the applicability of different types of coding and signaling. Results for a single user have shown that spread spectrum techniques which do not allow for high power, low duty cycle signals (peaky signals), suffer in performance when used over very large bandwidths for channels decorrelating in time and frequency. Such poor performance is due to the fact that the impossibility of measuring well a wide-band channel using limited energy can override the diversity gains from spreading. I propose to study the performance of packetized wide-band systems when signals are peaky and when they are bandwidth-scaled (the second and fourth moments scale with bandwidth). In particular, I am interested in determining over which bandwidths the different signaling schemes can be used advantageously. I also wish to investigate whether training sequences or pilot symbols are beneficial and whether the fact that spreading reduces packet size can be used to improve performance of packetized multiple access systems.

In the area of network robustness and recovery, I propose to investigate the fundamental limits of network recovery schemes. Recent developments in coding over networks have considerable implications in the area of recovery from link and node failures. In particular I show that it is possible to map current means of preplanned recovery from link failures onto coding systems over networks. Moreover, certain networks which cannot be recovered using current means of preplanned recovery can be recovered using more advanced network coding techniques. An important question is that of the role of network supervisory signaling. Different network recovery methods and coding schemes require different information about the state of the network. I propose to investigate whether we can establish fundamental principles about the recoverable capacity of a network under different types of network supervisory information. I also propose to investigate whether coding to combat ergodic error processes over links in a network should be combined with coding for network capacity and recovery. Recent results showing that link coding and network coding may be considered separately for a single connection over a network rely on principles that may not extend to more general networking situations.

As an educator, my goals are to teach and supervise undergraduate and graduate students in a way that promotes intrinsic motivation in the students, encourages collaboration while maintaining individual accountability, and recognizes the different strengths and styles of the students. I propose several efforts in the area of curriculum development at the undergraduate and graduate level, by developing a class in networking at the undergraduate level and a class in stochastic processes at the graduate level. My approach in teaching and advising is to encourage students to seek motivation in engineering applications, but to develop their understanding through theoretical considerations. I also seek to allow students to perform research within their set of abilities and interests.

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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.

Career Development Plan

1 Introduction

The rapid development of communication networks involving a variety of domains, components, protocols, and physical media have allowed the deployment of many services, from Internet services to wireless applications, which have rapidly become part of the fabric of our lives. At the same time, the same proliferation of technologies that has enabled these services has also rendered the reliability of these services more difficult to assess and control. The rapid changes in standards and protocols, as well as the wide variety of implementations and network infrastructures, makes the analysis of specific systems both difficult and limited in applicability. In order to assess the reliability of communication networks and to guide the design of networks with reliability in view, a more fundamental understanding of the intrinsic limitations of reliable transmission of information across networks is needed. In the area of communications across a single link, there exists a wide body of information theoretic work, which has had direct and dramatic impact in coding over wireless and wireline links. Despite the existence of several fundamental information-theoretic results in the area of networked communications (multi-terminal systems) [Ahl71, Lia72, Cov98, Gal76], the impact of communication theory and information theory upon the networking field has been comparatively minor [EH98].

My goals in the areas of research and education are :

- to contribute to the understanding of the fundamental limits of reliable communications in networked environments
- to establish, based upon theoretical understanding, applications to enhance the reliability of networks
- to provide teaching and research services which will train our future engineers in a way that directly connects theoretical understanding to practical implementations.

Within these broad goals, the present career plan presents a list of endeavors which, over the next five years, will enable me to establish a research and teaching program. In Section 2, I present an overview of relevant work in the two main areas of research I propose, namely wireless packetized multiple access networks and reliable transmission over networks. In Section 3, I present four specific new topics of research within those areas and my planned technical rationale for these research topics. In Section 4, I present my plan for teaching and supervising at the undergraduate and graduate level, as well as outreach programs for high school students. The remainder of this section presents a broad description of my career plan in terms of research and education.

1.1 Research Goals

My proposed research broadly falls in the area of network capacity. My goal is to provide some fundamental insight into problems which are intrinsic to certain networked applications. I consider two different aspects of robustness in networks

- robustness to multiple user interference and to channel fading in wireless packetized multiple access networks
- robustness to link and node failures in multi terminal networks.

My research and educational goals are to provide understanding of capacity issues embedded in the above topics. By considering theoretical as well as operational aspects networks, I aim to bridge some of the gap between, on the one hand, network architecture and protocol development and, on the other hand, the theoretical study of such networks.

1.1.1 Packetized Multiple Access Networks

The increasing use of wireless link for packetized data applications promises to overtake traditional wireless applications. Currently, different types of packetized wireless protocols exist. The need for more bandwidth also has prompted new bands of spectrum to be considered for commercial wireless communications. These sections of spectrum, usually at higher carrier frequencies, typically display worse channel characteristics than the bands currently allotted to wireless telephony. In particular, higher carrier frequencies affect the Doppler spread and hence the rate of change of the channels' impulse response.

As the need to accommodate more packetized traffic in the wireless domain grows, so does the motivation to investigate the capacity of wireless multiple access networks. Of particular interest is how wider spectrum bands can be effectively used. The concurrent successful deployment of time-division multiple access (TDMA) and of code-division multiple access (CDMA) schemes has shown that determining an "optimal" scheme may be difficult. However, several recent developments point to the fact that certain theoretical bounds may be derivable for wide-band packetized systems.

The first set of results concerns spreading in bandwidth over time-varying channels using bandwidth-scaled signals, which we defined to be signals whose second and fourth moments scale with bandwidth [GM97, M9́5, M0́0a, ET, SH98, GM99a]. These results point to the fact that such signals perform poorly as the bandwidth becomes very large, unless there exist specular paths. The deleterious effect of spreading grows as the rate of change of the channel increases. Peaky distributions (we use the term loosely here and detail its meaning in Section 3.1) can yield capacity for a variety of fading channels in the limit of very large bandwidth [Ken69, Gal68, Tel88, AFTS97]. However, we must spread over an excessively large bandwidth to approach the limits.

The second set of recent results concerns the capacity of ALOHA-style multiple access packetized systems. In the simple case of a time-slotted system where several users share an additive white Gaussian noise channel, a type of capacity region can be determined [MG99a, MMHG00] using results from degraded broadcast channels and from multiple access channels [GRUW95, RU96, Cov72, Cov75, Cov98].

A natural question is to consider whether we can establish capacity results akin to those of [MG99a, MMHG00] under fading channel conditions. Peaky distributions achieve, over certain types of fading channels, the same capacity as would be achieved over non-fading WGN channel of the same average received power. I first propose to investigate this issue. Peaky signals however, may exhibit undesirable characteristics, leading to receiver saturation or violation of the environmental rules regulating peak powers for handheld devices. The second issue I propose to investigate is under what conditions spreading using bandwidth-scaled signals is attractive for packetized systems. Such signals, which we refer to as bandwidth-scaled signals and which include traditional CDMA schemes, do not suffer from the implementation drawbacks of peaky signals.

In single user systems, under certain channel conditions and for certain types of bandwidth-scaled signals, spreading is advantageous as long as it remains above a certain threshold of received power per Hertz. In multiple access systems where the users continuously share the same bandwidth, the threshold of received power per Hertz is increased over the single user case. In packetized multiple access systems, however, spreading may reduce the amount of time required to send a packet of a given length. Thus, the advantages of spreading in multiple access packetized systems may be evident over a wider range of bandwidths than in the single user case. Since our inability to perform channel measurement is the cause for the poor performance of bandwidth-scaled signals at large bandwidths, I also propose to investigate the use of a training sequence or pilot symbols to measure the channel when we use bandwidth-scaled signals.

1.1.2 Robustness to link and node failures in multi terminal networks

The issue of network reliability to failures of links or nodes emerges in many different aspects of networking. In high-speed networks, such as optical networks, links may carry tens of Gigabits/second, which need to be rerouted rapidly and reliably. Links, particularly in metropolitan area networks, are occasionally cut by construction accidents or other mishaps. Such events, while rare, are catastrophic if robustness to such failures is not built into the network. In *ad hoc* networks, links and nodes may disappear as a user moves away from the area of coverage or decides to remove himself/herself from the network. Link or node failure will entail a lesser loss of information flow than in an optical network, but the event of a failure will be very frequent.

My proposed research in this area is to investigate the applicability of coding over graphs to recover from link or node failures in networks. Recent results in the area of network information flow establish the use of coding over networks to distribute information from a source to several recipients, i.e. have multicast connections, over a network that has links with limited capacity [ACLY99, LY99]. These results relate the cut-set theorem to the number of bits that can be passed through a network in the case of multicast connections.

Coding is not only applicable to networks in order to achieve capacity, but can also be used to recover from network failures. Such failures are different from link errors, described by ergodic processes, which would be typically dealt with by using channel coding. The failures we consider entail the permanent removal of an edge, such as would occur in a network if there were a long-term failure due to a link cut or other disconnection. Currently, link failures are dealt with, in the networking literature, through the use of link protection or recovery, which I overview in Section 3.2. While a large body of work exists in this area, we can reduce the means of recovery to three major classes of algorithms, namely live path protection, link recovery and failure-induced path protection. All of these classes of algorithms are actually reducible to codes over the networks, as I describe in Section 3.3.

The fact that known algorithms for protection and recovery are but a subset of codes that may be applied to recover from a link failure is a strong motivation to examine whether other types of codes may perform better than traditional protection and recovery methods. Indeed, I show in Section 3 that, for certain networks, recovery is not possible using any of the traditional recovery and protection algorithms, but is possible using a different network code.

I propose, in Section 3.2, two different areas of research in the domain of network coding for recovery. The first area concerns the extent to which network management signaling is of use in networking coding for failure recovery. The second area of research I propose seeks to elucidate the interaction between network coding and link coding.

When we consider recovery from link failures, the issue of network supervisory signaling arises. Let us consider that a link which is in a path from a source to a receiver is upstream of that receiver. The ability for a receiver to know whether an upstream link is down significantly affects the capacity that, in the network, must be devoted to recovery from link failures. When a receiver knows that an upstream link is down, it can apply an erasure-correcting code, if such a code is feasible. The lack of information about upstream link failures may lead to the inability to recover from a failure or to the use of an error-correction code, which requires more bits than an erasure-correcting code. The response to a link failure may be not only for a receiver to apply a different code to the bits it receives, but also for the coding over the whole of the network to be changed. I show in Section 3.2 that, for certain networks, traditional recovery schemes are insufficient to guarantee recovery, while appropriate network coding can achieve recovery.

Network codes may be combined with link coding. Over links which exhibit ergodic error processes, coding over individual links may be used to assume that links are in effect error-free as long as they are used below capacity. Recent results [SY00] show that for a single point-to-point connection, link coding may be done independently from network coding, in effect yielding a separation between link coding and network coding. However, it is not clear that, for general connections that combine several point-to-point connections and multicast connections, combining network codes with link codes designed to overcome ergodic error processes over the links, such separation holds. The results concerning network supervisory signaling indicate that a single point-to-point connection or a single multicast connection may behave very differently from general connections.

1.2 Educational Goals

In my research, I attempt to consider reliability in networks both from an information theoretic and network management point of view As an educator, I consider this integrated view of communications to be important in teaching and advising students. When teaching, I attempt to show students the relevance of the material to different areas of communications. When I advise students, I encourage them to broaden their interests and to consider pursuing research which brings together different sets of skills, for instance combining information theory and protocols to assess the theoretical limits of certain packetized multiple-access schemes. I believe that providing students with a broad view of communications and with intellectual flexibility is crucial to train engineers who will be able to manage, and benefit from, the increasing convergence of different types of technology.

My educational goals are to teach and advise undergraduate and graduate students in the areas of networks, communications and information theory. My main purpose is to teach students in a way that is theoretically sound but strongly motivated by examples. My other main goal as an educator is to help students establish goals for themselves, whether it be in taking a course or in pursuing research, so that the activities they undertake become part of their own professional development plan rather than extrinsically motivated assignments.

My educational goals over the next few years include course development to complement the existing syllabus at MIT. Over the next two years, I propose to develop, along with other faculty in the area, a new course in the are of networks geared towards undergraduates and a graduate course to complement our syllabus in the area of stochastic processes. In Section 4, I give further details on my educational philosophy, and describe in further details my proposed courses and advising goals.

2 Overview of Relevant Work

In this section, I present come of the background relevant to the research topics I discuss in Section 3. The two first subsections are relevant to my proposed research in robustness to multiple user interference and to channel fading in wireless packetized multiple access networks. The last two subsections concern robustness to link and node failures in multi terminal networks. In the first subsection, I overview relevant work in very wide bandwidth spread spectrum communications. In the second subsection, I discuss results in capacity for multiple access packetized systems. In the third subsection, I overview relevant work in the areas of network protection and recovery and in coding over graphs. In the last subsection, I overview results in the area of network coding. Given the space constraints, these overviews are not meant to be exhaustive but to sketch the results which set the background for my research topics.

2.1 Overview of Results in Wideband Spread Spectrum

The use of spreading over frequency for time-varying channels has been studied at length. Loosely speaking, the time-varying nature of the channel is responsible for fading and dispersion and, by transmitting over a wider bandwidth, we reduce our vulnerability to fades. For fading dispersive channels, ([Gal68, pp. 431–419], [Ken69]), capacity may be achieved by transmitting high power pulses with a low duty factor. However, the bandwidth over which we must be able to transmit to approach capacity may be extremely large [Tel88]. Such signaling schemes assume large bandwidths and create marked spikes in power. Hence, such schemes may not be appropriate for many applications. A more common approach, which we term bandwidth-scaled spreading, spreads energy evenly over the available spectrum.

The issue of what sort of signaling is desirable for high-bandwidth channels is complicated by the fact that, even if we can determine what type of signaling achieves capacity, we do not know whether a different type of signaling might also achieve capacity. For channels without fading, such as an AWGN channel, we can achieve capacity by sending a signal which is WGN over all the bandwidth we have available. On the other hand, for certain types of fading dispersive channels, there are several results indicating that impulsive types of transmissions, using a discrete set of input signals, are optimal [AFTS97, Ken69, Ric67, Gal68, Tel88]. However, the fact that such signals may be optimal does not preclude the fact that signals which are not impulsive may also be optimal or near-optimal. Indeed, for certain classes of channels, which include AWGN channels, both WGN signaling and impulsive binary signaling are optimal as the bandwidth increases [Gal87].

Investigating whether bandwidth-scaled signals are effective for communicating over channels is not only a matter of theoretical interest. The widespread deployment of direct-sequence code-division multiple access (DS-CDMA) systems in commercial wireless telephony applications [Vit95, GJP+91, Sch94] has triggered great interest in spread-spectrum communications using bandwidth-scaled signals.

In AWGN channels, the diversity gains from spreading decrease with increased spreading. In the case of fading channels that decorrelate over frequency, the ability to measure the channel, however, is decreased by the fact that we have less energy per degree of freedom and that the channel decorrelates in time and frequency. In the case of the AWGN, the multiplicative part of the channel is perfectly known, therefore we only observe the advantageous effect of spreading. In fading channels that decorrelate in frequency, the benefit from diversity gains is eventually overtaken by the disadvantages from poorer estimation of the channel.

Some recent work has examined this effect. In [GM97, GM99a], a general result was presented, stating that capacity goes to 0 with infinite bandwidth for bandwith-scaled spreading over frequency in channels which decorrelate in frequency and vary over time. The results of [GM97, GM99a] have also been considered in the context of capacity per unit cost [SH00a]. In [SH98, SH00a], similar results to those in [GM97, GM99a] are given when the constraints are not on the input signal but rather on the noise-free portion of the output signal. Other authors have considered broadband fading channels with a finite number of time-varying paths and shown that the capacity of the channel for white-like signals is inversely proportional to the number of resolvable paths [ET]. The effect of spreading over fading channels has been considered for specific signaling constraints beyond the second and fourth order scaling constraints, such as WGN signaling [Mé95], certain types of direct-sequence (DS) CDMA signaling [Mé00a, Mé99, SH00a] and small peak power constraints [SH00b].

2.2 Overview of Results for Multiple Access Packetized Systems

The flexibility of ALOHA systems, which were first proposed in 1970 by Abramson [Abr70], makes such systems an attractive option for wireless applications, such as data transfer for nomadic computing. In the original ALOHA system, users transmit packets. If a collision among packets occurs at the receiver, those packets are discarded and the users retransmit those packets. The capacity of ALOHA systems and related collision systems has generally been considered in terms of packet throughput [Pip81, MM85]. The stability region of the ALOHA system has been extensively studied. For an infinite number of users, the system is unstable for any input rate [Kap79]. For a finite number of users, there exist bounds and some exact results for only two users or particular arrival processes [Ana91, RE88]. Several different control mechanisms have been established to stabilize the operation of the ALOHA system [Riv87] or to perform conflict resolution [Hay78, TM78, Cap79, MH85, Gal78, KG85, HB85, PTW85, KG85, Mas81].

In order to avoid total loss of packets to collisions, several coding schemes have been proposed for ALOHA packets [OW99, Ray81, BM94, PS87, HW98, BGB97]. The purpose of such coding is to allow at least part of the data in the packets to weather out one or several collisions. When the packets are coded, it is possible to consider capacity in terms of maximum reliable received rate. In [MG99a, MMHG00], a type of capacity region is considered for time-slotted AWGN channels. Furthermore, [MG99a, MMHG00] assume that Bernoulli processes decide transmissions at nodes at each time slot and we assume that the packets have sufficient length that rates at capacity can be achieved over the duration of packet. The capacity computation combines concepts from multi-access communications [Lia72, Ahl71], rate splitting [GRUW95, RU96] and broadcast channels [Cov72, Cov75]. The rationale behind our approach springs from the following observation. In multi-access channels, rate splitting achieves capacity by creating virtual users and decoding all users using interference cancellation. Thus, a set of users appears as noise to other users during decoding. After a user is decoded, his contribution to the signal is eliminated. In a degraded AWGN broadcast channel, the low resolution code is decoded by considering the high resolution code as noise. Once the low resolution code is decoded, its contribution is eliminated. Hence, there is similarity between the decoding mechanism for achieving capacity in multiple-access and in degraded broadcast channels.

Recent results [Sha00] confirm those of [MG99a] using a generalization of the broadcast strategy for the single user Gaussian channel [Sha97]. Note that, in the same way that rate splitting does not help with maximization of individual rates or rate sums in the traditional multiple access channel, rate splitting is not necessary to find the capacity region for [MG99a]. However, rate splitting allows to achieve any point on the boundary of the capacity region. The results of [MG99a] have a pleasing parallel in the uncoded case. For the uncoded collision channel with a finite number of users and a geometric distribution for the packet transmissions [Ana91], the capacity region, in terms of packet throughput, is the same, for each user, as for the case when the queues of all the other users are full. Recent extensions of [MG99a] show that the same result holds true, albeit in very different model. The results, using fluid models for queueing systems, show that, for Bernoulli probabilities of packet arrivals, the feasible rates are the same as for a multiple access channel without packetization.

2.3 Overview of Results for Robustness to Link and Node Failures

Methods commonly employed for link protection in high-speed networks can be classified as either dynamic or pre-planned, though some hybrids schemes also exist [SOOH93]. The two types offer a tradeoff between adaptive use of back-up (or "spare") capacity and speed of restoration [CBJ$^+$94, KA93]. Dynamic restoration typically involves a search for a free path using back-up capacity [HKSM94, GK93, Bak91] through broadcasting of help messages [CBMS93, FY94, Gro87, JBB$^+$94, KA93, Wu94]. For dynamic link restoration using digital cross-connect systems, a two second restoration time is a common goal [FY94, Gro87, KA93, Sos94, Wu94, YH88]. Pre-planned methods depend mostly on look-up tables and switches or add-drop multiplexers. Thus high speed networks generally employ pre-planned methods, even though pre-planned methods suffer from poorer capacity utilization than dynamic systems.

Within pre-planned methods, we may distinguish between path and link or node restoration. Path restoration refers to recovery applied to connections following a particular path across a network. Link or node restoration refers to recovery of all the traffic across a failed link or node, respectively. An overview of restoration and recovery can be found in [RM99a, RM99b]. Path restoration may be itself subdivided into two different types: live (dual-fed) back-up and event-triggered back-up. In the first case, two live flows, a primary and a back-up, are transmitted. The two flows are link-disjoint if we seek to protect against link failure, or node-disjoint (except for the end nodes) if we seek to protect against node failure. Recovery is extremely fast, requiring action only from the receiving node, but back-up capacity is not shared among connections. In the second case, event-triggered path restoration, the back-up path is only activated when a failure occurs on a link or node along the primary path. Backup capacity can be shared among different paths [WLH97], thus improving capacity utilization for back-up channels and allowing for judicious planning [BPG92, HBU95, GBV91, HB94, GKS96, SNH90, VGM93, Fri97, NHS97]. However, recovery involves coordination between the sender and receiver after a failure event and requires action from nodes along the back-up path.

Pre-planned link restoration is not as capacity-efficient as event-triggered path restoration [CWD97, RIG88, LZL94], but is more efficient than live back-up path restoration, since sharing of back-up bandwidth is allowed. The traffic along a failed link or node is recovered, without consideration for the end points of the traffic carried by the link or node. A comparison of the trade-offs between end-to-end and link recovery is given in [DW94]. Comparisons between path protection and event-triggered path protection are given in [RM99a, RIG88, JVS95, JAH94, XM99].

For pre-planned link restoration, the main approaches have been through the use of covers of rings. The most direct approach is to design the network in term of self-healing rings (SHRs) and diversity protection (DP) [WCB91, Was91, WB90, SWC93, SGM93, SF96, STW95, GHS$^+$94, WW92, TYKK94, Wu94, Wu92, WKC89, HT92]. SHRs are unidirectional path-switched rings (UPSRs) or bi-directional line-switched rings (BLSRs), while DP refers to physical redundancy where a spare link (node) is assigned to one or several links (nodes) [Wu92] pp. 315-32. Figure 1 illustrates UPSRs and BLSRs. The rerouting action around a failure in BLSR is termed loop-back.

Using only DP and SHRs is a constraint which has cost implications for building and expanding networks [WKC89, BGSM94]. However, rings are not necessary to construct survivable networks [NV91, WH91]. Mesh-based topologies can also provide redundancy [Sto92, JHC93, WKC88]. Covering mesh topologies with rings is a means of providing both mesh topologies and distributed, ring-based restoration. By covering all nodes in the network by rings [Was91], link restoration can be effected on each ring as long as routing is restricted to the covered links. To allow every link to carry protected traffic, other ring-based approaches ensure every link is covered by a ring. One approach to selecting such covers is to cover a network with rings so that every link is part of at least one ring [Gro92]. Minimizing the number of links to provide redundancy using ring covers is equivalent to finding the minimum cycle cover of a graph, an NP-complete problem [Tho97, ILPR81], although bounds on the total length of the cycle cover may be found [Fan92].

A second approach to ring covers, intended to overcome the difficulties of the first approach, is to cover every link with exactly two rings, each with two fibers [ESH97, ES96]. The approach is an application of the double-cycle ring cover [Jae85, Sey79, Sze73]. For planar graphs, the problem can be solved in polynomial-time; for non-planar graphs, it is conjectured that double cycle covers exist

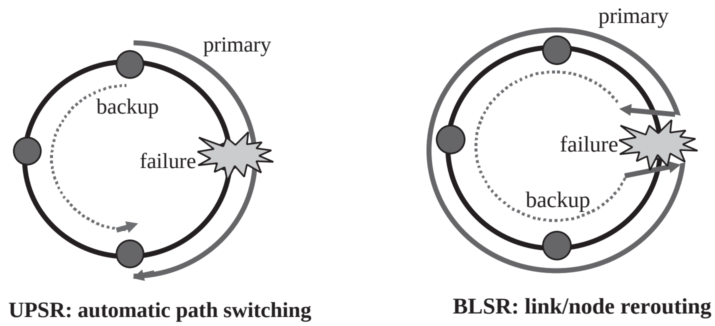

Figure 1: BSLR and UPSR.

[God85]. Node recovery can be effected with double cycle ring covers, but such restoration requires cumbersome hopping among rings.

In order to avoid the limitations of ring covers, an approach using pre-configured cycles, or p-cycles, is given in [GS98]. A p-cycle is a cycle on a redundant mesh network. Links on the p-cycle are recovered by using the p-cycle as a conventional BLSR. Links not on the p-cycle are recovered by selecting, along the p-cycle, one the paths which connect the nodes which are the end-points of the failed link. Some difficulty arises from the fact that several p-cycles may be required to cover a network. Results [Fou85, Jac80, ZLY85] and conjectures [HJ85, Woo75] exist concerning the length of maximal cycles in two-connected graphs.

Recently, Médard, Finn and Barry [MFB99, MBF$^+$00] introduced the concept of generalized loop-back on mesh networks, which allows for link or node recovery without the use of ring covers. Using partial graph node orderings [MFBG99] akin to s-t orderings [ET76, LEC66], they showed that link or node recovery can be done over mesh networks, as long as their corresponding graphs are 2-edge connected (for link recovery) or 2-node connected (for node recovery). As for p-cycles, generalized loop-back allows some links to be protected without requiring that spare capacity be reserved on those links. Unlike p-cycles, network management acts in the same way for all links regardless of whether or not they bear reserved spare capacity. This trait of generalized loop-back enables significant savings in capacity [MLT00].

2.4 Overview of Results for Network Coding

The topic of capacity over networks has generally been considered in the context of networks of nodes and link, where the links experience errors described by ergodic stochastic processes [CT91]. Such networks include, for instance, the broadcast channel (several receivers, a single sender), the multiple access channels, and the relay channel [dM71, SG00].

Recently, coding over error-free networks for the purpose of transmitting multicast connections has been considered [LY99, ACLY99, LY98]. Consider figure 2 from [LY99]. Each link can transmit a single bit error-free (we do not consider delays). On the left-hand side network, the source may easily transmit two bits, b_1 and b_2, to receivers y and z, by using switching at w and broadcasting at t and u. On the right-hand side network, a code is required, where w must code over the arc (w, x). The capacity of such networks is shown to be maximum flow from the source to each receiver in the network. This approach may be generalized from directed acyclic graphs to general directed graphs as long as we consider delays along the links. The concept of using coding for network recovery

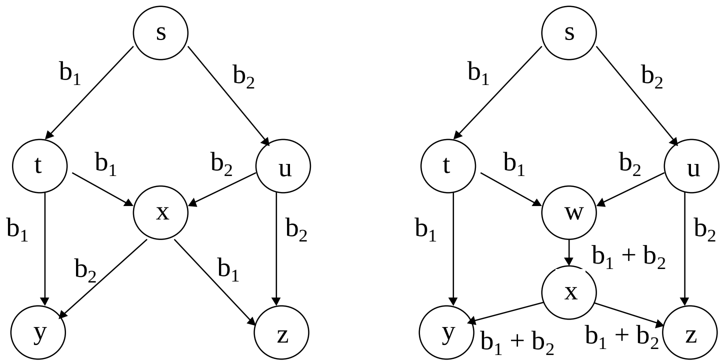

Figure 2: Networks with multicast connection from s to y and z.

is not explored in this work, except to say that, if there exist two redundant paths between two nodes, then only one of those paths needs to be used to achieve capacity. Thus, codes specifically geared towards recovery are not presented. The link between network coding on error-free networks and error-correction coding for networks whose links exhibit ergodic error processes has only been considered for the case of a single point-to-point connection [SY00]. In the single point-to-point connection, the network coding and the link coding can be performed independently.

Very little work aside from [Gal76] has considered the basic limitations of the amount of protocol information that must be transmitted in communication networks. The work in [Gal76] considers the amount of information required to keep track of the source and receiver addresses and the starting and stopping of messages. I do not know of any fundamental work considering the basic limitations of the amount of protocol information required to establish recovery in networks.

3 Research Goals

In this Section, I give an overview of my research goals in the areas of packetized wireless multiple access networks and robustness to link and node failures in multi terminal networks. For each for these general topics, I describe two specific areas of work. I assume the background provided in Section 2.

3.1 Packetized Wireless Multiple Access Networks

3.1.1 Packetized Systems Using Peaky Signals

I propose to investigate the performance of peaky signals for packetized transmissions in wide band frequency-selective fading channels. There are many ways to construct peaky signals [Gal68, Ken69, Gal87]. In order to consider a simple illustrative model, I propose the following simple construction. The decision whether or not to transmit over a time interval $[i\tau, (i+1)\tau)$ is made at the beginning of that interval. A random variable with low duty cycle, $D[i]$ determines whether or not there is a transmission in the i^{th} time sample. $D[i]$ is 1 if a transmission occurs in the time interval $[i\tau, (i{+}1)\tau)$and is 0 otherwise. The signals that are sent are complex signals determined by frequencies from the set $\{\omega_0 + j\omega_1\}_{j=1}^{n}$. We select ω_1 to be large enough to ensure that, even the bandwidth spreading effect of passing through a time-dispersive channel, two different sinusoid signals will not be confused with each other after passage through the channel and before the addition of noise. The random variable $N_j[i]$ is 1 if, in the case transmission occurs during the interval $[i\tau, (i+1)\tau)$, that transmission is the function $f_j(t)$, which has Fourier transform $F_j(\omega) = \frac{1}{\gamma} u\left(\omega_0 + j\omega_1 - \gamma\right) - u\left(\omega_0 + j\omega_1 + \gamma\right)$, for γ small (we denote the step function by u). Otherwise, $N_j[i] = 0$. The lowest frequency at which we transmit is roughly ω_0 and the highest is roughly $\omega_0 + n\omega_1$. We spread in bandwidth by increasing n. In effect, the number n provides the richness of our code words. The amplitude of the signal is given by a scalar A. Thus, the input signal to the channel at time t is $S(t) = AD\left[\lfloor \frac{t}{\omega_1} \rfloor\right] \sum_{j=1}^{n} f_{N_j[i]}(t) N_j \left[\lfloor \frac{t}{\omega_1} \rfloor\right]$. This signaling is in effect an approximation of the signaling described in [Gal68].

The channel can be considered to be a fading channel, dispersive in time and frequency. The model may be the dispersive channel of [Gal68, Ken69], or the Gauss-Markov model of [M9́9, M0́0a], or a block fading model as in [SH00a].

The main points of the proposed research are the following:

- to consider how the number of users scales with bandwidth. In the case of a single user, the capacity approaches that of an AWGN channel. I wish to consider whether, as bandwidth increases, the multiple access capacity region approaches that of the case where we have several users sharing an AWGN channel.

- To investigate the sensitivity of our results to the channel model. In particular, I wish to investigate how the results change when there are possibly specular paths as in [ET].

3.1.2 Packetized Systems Using Bandwidth Scaled Signals

I propose to investigate under what conditions spreading using bandwidth-scaled signals, whose second and fourth moments scale with bandwidth, is attractive for packetized systems. Existing results in the area of bandwidth spreading using bandwidth-scaled signals show that there exists a threshold, say λ_{low} of energy per Hertz below which spreading is detrimental. However, preliminary results show that, for a frequency selective block-fading channel model, we can establish that, when we use bandwidth-scaled signals, spreading is advantageous as long as we remain above another threshold, say λ_{high}, of energy per Hertz. Above the threshold of λ_{high}, the beneficial effects of diversity outstrip the deleterious effects of our inability of to estimate the channel at the receiver. In the case of packetized multiple access, there may be further advantages to spreading. Spreading may reduce the probability that packets collide, by requiring less time to transmit the packet. From our brief discussion, two areas of research emerge.

- I propose to investigate the effect multiple use interference in a packetized system has upon capacity when we spread using bandwidth scaled signals. The multiple access interference when packets collide should worsen the receiver's ability to measure the channel. Thus, spreading should lower the achievable rate over a packet and may require that packets be longer to accommodate higher redundancy in the codes required to transmit a packet's payload. On the other hand, the probability of collision may be lowered by spreading, since packets may take less time to transmit. I propose to investigate the interaction of these different effects.

- The second area of research I propose concerns the use of training sequences in packets for the purpose of estimating the channel. Packets generally include some header for acquisition and identification. Training sequences, whether in the header or embedded in the coding, may improve the estimate that the receiver has of the channel, but they come at the expense of packet length and energy consumed. In effect, training sequences or pilot signals take resources

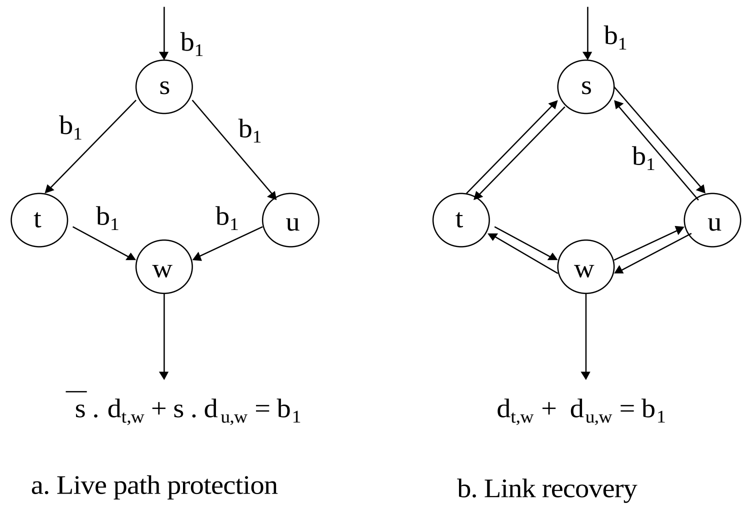

Figure 3: Ring networks illustrating path protection and link recovery.

from the transmission of information and provide only an improved channel estimate at the receiver.

3.2 Link and Node Failures in Multi Terminal Networks

3.2.1 Role of Network Management in Recovery Using Network Coding

My proposed research in the area of the role of network management is strongly motivated by the fact that the three types of preplanned recovery from failures discussed in Section 2.2, namely live path protection, link recovery and failure-induced path protection, can all be reduced to codes. I illustrate this fact over a ring, although all other types of preplanned recovery discussed in Section 2.2, including generalized loopback, can be similarly reduced when we consider a mesh rather than a ring. Figure 3 illustrates our discussion. We have a single sender s transmitting b_1 to a single receiver w. The simplest scheme to illustrate is live path protection, shown in figure 3.a. The primary path is $s \rightarrow u \rightarrow w$. At the receiver, the only network supervisory signal required is a signal indicating whether or not the primary path is live. The supervisory signal is denoted by s, where s is 1 if the primary path has had no failures and is 0 otherwise. Let $d_{i,j}$ denote the data being sent along directed link (i, j). For links (s, u), (u, w), (s, v) and (v, w), the data is b_1. The code at w is shown in figure 3.a. For link recovery, we need to have a supervisory signal $s_{i,j}$, where $s_{i,j}$ is 1 if the primary path has had no failures and is 0 otherwise. We have primary links, which are the links in the clockwise direction and backup (secondary) links, which are the links in the counterclockwise direction. For each node i, the code is $d_{i,h} = d_{k,i} + d_{h,i}$ for the primary link (i, h) emanating from i (if i is w, then the output is $d_{k,i} + d_{h,i}$), where (k, i) is the primary link into i and (h, i) is the secondary link into i. For the secondary link emanating from i, the code is $d_{i,k} = d_{h,i} . s_{i,h} + d_{i,h} . \overline{s}_{i,h}$. Finally, we may consider failure-induced path protection as a code. The sender knows s. The code is similar to the one in figure 3.a. The links in the backup path carry the same signal as for the live path, but multiplied by $\overline{s}$, which means that nothing is carried except in the case of failure. The links in the primary path see their data multiplied by s. The receiver need not have knowledge of s. It simply outputs $d_{u,w} + d_{v,w}$.

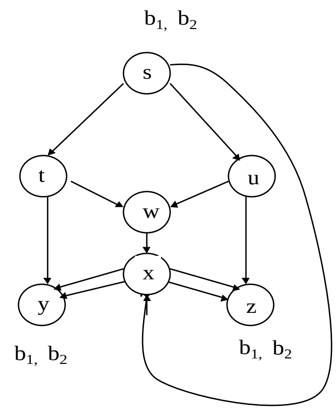

Figure 4: Network with multicast connection from s to y and z where path recovery and link protection are not sufficient for failure recovery .

In recent results, R. Koetter and I show that the case of a multicast connection over a network exhibits a very different behavior from a collection of point-to-point connections. In the case of a multicast connection over a network, if a network is robust to a single link failure, then a single network code can be used to handle all single link failures. This result implies that, for multicast connections, the only useful supervisory signaling over the network is signaling informing a receiver of failure of an upstream node. The network itself need not change its code in response to a failure. While existing means of protection and recovery can be reduced to codes, codes for recovery exist which cannot be reduced to traditional protection and recovery. The simple network in figure 4 illustrates this fact. The source s broadcasts bits b_1 and b_2 to nodes y and z. If the link (s, x) fails, then we must resort to network coding as in the left hand side of figure 2 to perform recovery.

I propose one main area of research motivated by the above discussion. I propose to investigate the role that network supervisory signals play in recovery, when recovery is considered using codes over networks. In particular, I wish to explore whether there exits fundamental limits, akin to those in [Gal76], in the number of bits that must be devoted to supervisory signals for recovery.

3.2.2 Network and Link Coding

I seek to establish whether network coding and coding over network links which exhibit ergodic error processes can be in general separated. The results in [SY00] show that they can be separated for the case of a single point-to-point connection. The coding over the links renders those links in effect error-free and network coding can then be used to achieve capacity or recovery over an error-free network. Network coding can be thought to be akin to source coding and the result in [SY00] can therefore be viewed in some respects as a separation theorem. Different types of connections, be they multicast connections or combinations of point-to-point connections, may not exhibit the same separation properties.

4 Educational Goals

In this section, I give some background to my teaching philosophy and present my goals for teaching and advising.

4.1 Teaching Philosophy

My teaching and advising philosophy has been considerably shaped by my experience as an educator over the last two years. Before entering academia, I had had a variety of teaching experiences in altogether different areas - as an aerobics instructor, as a teaching assistant during my graduate school days and as Sunday school teacher. Upon entering academia I believed that surely those experiences would not transfer to my new occupation. I started teaching assuming that students learnt in the same way that I prefer to, namely by reading the book, and that in class I should strive mostly to answer questions and point to more advanced material. I taught the class by simply following the curriculum. During my first year at the University of Illinois Urbana-Champaign, I was fortunate, as a GE Fellow, to have the opportunity to participate in the Faculty Teaching College. Through that program, I took a year-long class from the Academy for Excellence in Engineering Education, led by professors in the School of Engineering and the School of Education. The class designed for academics to learn more about teaching. Although it was a considerable time commitment, this class helped me understand the different types of learning styles of students and the way to motivate students. In particular, I started to realize that most students had very different learning styles from my own and that a syllabus was not in itself motivation. However, I did not really internalize these ideas until the end of my first term. One morning, my eldest daughter announced, after a long struggle with her shoelaces, that she would never be able to learn to tie her shoelaces. I reassured her of her ability, helped her set some goals for herself (tying a simpler knot) and talked to her about why it was important to tie her shoelaces. Soon after, I had office hours. I now was faced by a despondent graduate student who announced that he would never be able to learn to solve stochastic differential equations. Although these words were coming from a 6'6" man rather than little six year old girl, I was suddenly struck by the similarity of the complaints. I started thinking about how I acted as a parent and how I acted as an educator and started realizing that maybe I was wrong in viewing my two roles as completely distinct.

In fact, the lessons I was learning from my Excellence in Teaching course were the methods I applied to parenting as a matter of course, but had not transferred into my teaching. I realized there were three principles, all of which I considered important in parenting or teaching little children, that I needed to transfer to my teaching:

- Create intrinsic motivation for performance
- Encourage collaboration while maintaining individual accountability
- Recognize the different learning styles of students.

Over the next terms, I began to incorporate these principles into my teaching. I began by stating clearly the goals for the class. I distinguished lower level goals, such being able to apply certain formulas, from higher level goals such as being able to read a paper and think critically about it. I placed all the assignment and class work in the context of the class's goals, and placed the class's goals in the context of the students' professional careers. At the beginning of a term of teaching undergraduate probability, I even asked students to make a goal for themselves by having each student come up with some problem which was relevant to him (I had no women that term in my class) and which he hoped to be able to understand better at the end of the class. At the end of the term, we revisited those problems and discussed how we could apply what we had learned to those problems.

In order to encourage collaboration, I introduced group exercises in class. Even in a graduate information theory class, I found such exercises motivated students to be alert and feel more engaged in the class. The group exercise might be filling in some steps in a proof, or trying to guess the right formulation of a theorem before I presented it. Individual testing helped me maintain individual accountability. I have also tried to present material in more than one way, when possible, in order to engage students with different learning styles. I have found this last endeavor to be the most challenging of my three goals.

4.2 Teaching Goals

My teaching goals are to integrate my teaching philosophy to improve my teaching of existing courses and to develop new courses to complement our undergraduate and graduate syllabus at MIT.

My first priority is to offer a new course to address the needs of advanced undergraduates and of Master students interested in networks. The purpose of this course is to provide an introduction to the broad and expanding area of networking. Many of our graduates are entering this field and almost all of them will require some familiarity with it throughout their careers.

While our graduate offerings in the area of networking have successfully fulfilled the needs of graduates interested in advanced network applications and network performance analysis, these courses have lately been very heavily subscribed. Many students, particularly undergraduate students or students interested in taking a single introductory course, have found the offerings to provide too much depth and less of the breadth they are seeking. The graduate courses, however, should maintain their current substance in order to service appropriately the graduate student population requiring theoretical in-depth understanding of networking issues.

My goals in developing this undergraduate network course are the following:

- To introduce students to the field of networking in a way which logically integrates computer networking, protocols, network management, network optimization algorithms, network performance analysis and traditional telecom applications. My purpose is to integrate traditional EE and CS approaches so students understand that computer networks and traditional telecoms are not disjoint entities. Indeed, as Gigabit Ethernet and 10 Gigabit Ethernet move into the metropolitan and local area networks, and as IP moves out into wide area networks, run directly over carrier-class protocols, the distinction between computer networks and traditional telecoms becomes increasingly blurred.

- To provide students with relevant projects in various areas of networking. The projects should not be mere examples, but should allow students to understand in depth a few selected aspects of networking. Examples could include practical demonstrations of IP denial of service attacks, managing queues in a simple ATM switch emulator, measuring traffic loss for voice over IP, designing SONET networks using rings to minimize length of fiber, and establishing link budgets for inter-satellite connectivity. These projects should help the students feel engaged in the class and realize that the class gives them tools to tackle problems that are relevant, significant and interesting.

- To introduce students to network performance analysis in a way that is simple but sound, preparing them for further analytical treatment of network performance analysis. I propose to introduce simple probabilistic modeling of systems (Markov chains, simple queueing). My goal is to create students who have enough analytical maturity to avoid blind reliance on simulations, who apply the knowledge they derive from analysis to create intelligent simulations, and who are able to decide how best to combine simulations and analysis to obtain understanding of the problems they face.

Students successfully completing the class would be well prepared to take advanced networking classes at MIT or at other institutions. Moreover, for our students taking this as their sole class in networking, the class should provide them with the right tools not just to be able to "hack" their way around networking applications (most of our students can figure that out without our help). Rather, this class should lead them to understand the changing structure of networks and to be able to evaluate critically developments in networking.

My second priority is to supplement the material in stochastic processes for our graduate students. My teaching experience at the University of Illinois made me reflect an the strengths and weaknesses of MIT's curriculum. I am currently helping to develop a class to address some important topics, such as different aspects of stochastic calculus, which our graduates need and have expressed a concern to learn about. My longer term goal is to create a class in the area of wireless communications for advanced undergraduates and Master students.

4.3 Advising Goals

My advising goals are to advise undergraduate and graduate students in the areas of networks, communications and information theory. As part of advising, I try to encourage intrinsic motivation from the student by finding an intersection between the student's interest and my own. I try to refrain from assigning a topic but try to encourage the student to help define the topic.

I have advised undergraduate and graduate students in research projects. I am also involved in the Research Science Institute, run by the Center for Excellence in Education, through which I advise promising U.S. high school students by working with them on a research project over the summer. In advising a student, I seek to understand the student's strengths and limitations and gear the research towards the former. I also attempt to ensure that, for a terminal Master student, the thesis is not viewed as a botched attempt towards a Doctorate, but rather as an important goal, set by the student himself or herself. My goal is to establish a balanced research group incorporating undergraduates, Master students and Doctoral candidates. As an advisor, I have been fortunate to be able to attract a fair number of female students (half of my students have been women) and I have often felt a close mentoring relation with them. My role with them often expands beyond academic counseling. I find my students struggle with the same issues, such deciding whether to delay starting a family to pursue further studies, with which I was confronted.

5 Results from Previous NSF support

I have received support for a graduate student under NSF grant 99-79381. This NSF program is in the area of wireless communications. The results from this research, performed jointly with Professor Meyn of the University of Illinois Urbana-Champaign, Professor Goldsmith of Stanford Univerity and my student Jianyi Huang of the Univerity of Illinois Urbana-Champaign, have been in the area of capacity of time-slotted ALOHA systems [MMHG00]. Our work demonstrated how to select coding strategies to attain the capacity region of time-slotted ALOHA systems given in [MG99a].

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Biographical Sketch of Principal Investigator

I received the B.S. degree in Electrical Engineering and Computer Science and the B.S. degree in Mathematics in 1989, the B.S. degree in Humanities in 1990, the M.S. degree in Electrical Engineering in 1991, and the Sc.D. degree in Electrical Engineering in 1995, all from the Massachusetts Institute of Technology (MIT), Cambridge. Since January 2000, I have been an Assistant Professor in the Electrical Engineering and Computer Science at MIT. I was previously an Assistant Professor at the Electrical and Computer Engineering Department and the Coordinated Science Laboratory, University of Illinois Urbana-Champaign, which I joined in September 1998. From 1995 to 1998 I was a Staff Member at MIT Lincoln Laboratory in the Optical Communications and the Advanced Networking Groups.

My main research accomplishments include:

1. Derivation of the fact that, for channels decorrelating in time and bandwidth, bandwidth-scaled signals (in which the second and fourth moments scale with bandwidth) have a capacity that go to 0 (joint work with R.G. Gallager) [GM97, GM99a]. Also established the first such results for white Gaussian signaling and certain types of direct sequence CDMA [M0́0a, M9́5].

2. Contributions to the understanding of the effect of channel uncertainty at the receiver on the capacity of single user and multiple user systems [M0́0b].

3. Derivation of the capacity of time varying channels with sender and receiver channel side information in which the interaction of the ISI and the channel time variations is explicitly taken into account (joint work with A.J. Goldsmith). These results have led to the ability to establish the capacity and optimal distribution for a class of time varying ISI channels with perfect sender and receiver channel side information, for which traditional decomposition techniques are not applicable [MG99b, GM99b].

4. Derivation of capacity regions [MG99a] and codes to achieve such regions [MMHG00] (joint work with S.P. Meyn, A.J. Goldsmith and student J-Y Huang) for the time-slotted ALOHA channel.

5. Derivation of the effect of decoupling fast fades from slow fades in finite-state Markov channels where the sender has knowledge of the slow fades and the receiver has knowledge of the fast fades as well (joint work with R. Srikant) [MS00].

6. Development of a new algorithm for redundant trees over redundant graphs (joint work with R. Barry, S.G. Finn and R.G. Gallager) [MFBG99]. This algorithm allows for path protection on multicast routings on arbitrary 2-edge or 2-node redundant graphs. The algorithm yields more solutions than the previously best known algorithm [IR88].

7. Development of the first and, I believe, only algorithm which allows for link and node recovery on arbitrary 2-edge or 2-node redundant graphs, respectively, without the use of rings (joint work with R. Barry and S.G. Finn) [MFB99, MBF$^+$00]. This algorithm allows for wavelength-to-wavelength protection in wavelength-division multiplexed systems.

8. Development of an algorithm to perform bandwidth efficient link recovery while maintaining performance with respect to several types of double failure metrics (joint work with S.S. Lumetta and student Y.C. Tseng) [MLT00].

9. Development of algorithms for network failure/attack detection [MMC98, MCS98] (joint work with S.R. Chinn and student P. Saengudomlert) and failure attack localization (joint work with R. Bergman) over optical networks [BMC98]. I also established a framework for defining security issues, in particular for denial of service, over optical networks [M´, MMBFa, MMBFb] (joint work with R. Barry, S.G. Finn and D. Marquis).

10. Development of an optical cryptography scheme for use in high speed TDM optical systems [MCM+, CM97, YCM98] (joint work with A. Chan and others). This technology is currently under commercial license as a patent for which I am principal inventor.

My teaching experience includes teaching a graduate course in stochastic processes, a graduate course in network performance analysis, an undergraduate course in probability (all at the University of Illinois Urbana-Champaign) and a graduate course in information theory (at MIT). In order to improve my teaching methods, I took, while a GE Fellow at the University of Illinois Urbana-Champaign, a year-long course from the Faculty Teaching College, offered by the Academy for Excellence in Engineering Education. In the course, I learnt about active learning methods, different learning styles, testing goals and techniques, syllabus design, lecture delivery and preparation, different levels of learning and other pedagogical foundations. I was also able to received feedback on my lectures from members of the Academy for Excellence in Engineering Education and benefited from their advice in the classes I teaching. I also participated in a two-day workshop for Effective Teaching, also sponsored by the Academy for Excellence in Engineering Education.

I have supervised undergraduate and graduate students. As a staff member at MIT Lincoln Laboratory, I supervised an undergraduate student in a Co-op program both over the summers and during the school year. I have supervised and am supervising Master students at the University of Illinois and at MIT (as a staff member MIT Lincoln Laboratory and currently as a faculty member). The thesis topics spanned optical network monitoring, rerouting for network recovery and coding schemes and computation capacities for ALOHA systems. I am also involved in supervising the summer project of a high school student in the area of network algorithms through the Research Science Institute, run by the Center for Excellence in Education.

SUMMARY PROPOSAL BUDGET   YEAR 1

ORGANIZATION **Massachusetts Institute of Technology**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR				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.	0.00	0.00	0.00	$	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				15,162	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				2,285	
TOTAL SALARIES AND WAGES (A + B)				17,447	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				709	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				18,156	
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)				7,243	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				9,925	
TOTAL OTHER DIRECT COSTS				9,925	
H. TOTAL DIRECT COSTS (A THROUGH G)				35,324	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **%of MTDC (Rate: 65.5000, Base: 22405)**					
TOTAL INDIRECT COSTS (F&A)				14,675	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				49,999	
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)				$ 49,999	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $	
PI / PD TYPED NAME & SIGNATURE*	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

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Muriel Medard

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. Muriel Medard - none	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				15,693	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				2,260	
TOTAL SALARIES AND WAGES (A + B)				17,953	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				701	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				18,654	
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)				6,463	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				10,371	
TOTAL OTHER DIRECT COSTS				10,371	
H. TOTAL DIRECT COSTS (A THROUGH G)				35,488	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) % of MTDC (Rate: 65.5000, Base: 22156)					
TOTAL INDIRECT COSTS (F&A)				14,512	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				50,000	
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)				$ 50,000	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI / PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
Muriel Medard		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

SUMMARY PROPOSAL BUDGET YEAR 3

ORGANIZATION: **Massachusetts Institute of Technology**				FOR NSF USE ONLY		
				PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Muriel Medard**				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. Muriel Medard - none	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				16,242	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				2,233	
TOTAL SALARIES AND WAGES (A + B)				18,475	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				692	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				19,167	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				5,652	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				10,840	
TOTAL OTHER DIRECT COSTS				10,840	
H. TOTAL DIRECT COSTS (A THROUGH G)				35,659	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) %MTDC (Rate: 65.5000, Base: 21894)					
TOTAL INDIRECT COSTS (F&A)				14,340	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				49,999	
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)				$ 49,999	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI / PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
Muriel Medard		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

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

SUMMARY PROPOSAL BUDGET

YEAR 4

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Muriel Medard

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. Muriel Medard - none	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				16,810	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				2,205	
TOTAL SALARIES AND WAGES (A + B)				19,015	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				684	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				19,699	
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)				4,808	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				11,333	
TOTAL OTHER DIRECT COSTS				11,333	
H. TOTAL DIRECT COSTS (A THROUGH G)				35,840	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) %MTDC (Rate: 65.5000, Base: 21618)					
TOTAL INDIRECT COSTS (F&A)				14,159	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				49,999	
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)				$ 49,999	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI / PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
Muriel Medard		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date Of Rate Sheet	Initials - ORG

SUMMARY PROPOSAL BUDGET — YEAR 5

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months) Proposed	Granted
AWARD NO.		

ORGANIZATION: **Massachusetts Institute of Technology**

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Muriel Medard**

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. Muriel Medard - none	0.00	0.00	0.00	$ 0	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				17,398	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				2,176	
TOTAL SALARIES AND WAGES (A + B)				19,574	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				675	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				20,249	
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)				3,930	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				11,851	
TOTAL OTHER DIRECT COSTS				11,851	
H. TOTAL DIRECT COSTS (A THROUGH G)				36,030	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) % MTDC (Rate: 65.5000, Base: 21328)					
TOTAL INDIRECT COSTS (F&A)				13,969	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				49,999	
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)				$ 49,999	$

M. COST SHARING PROPOSED LEVEL $ 0 — AGREED LEVEL IF DIFFERENT $

PI / PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
Muriel Medard		Date Checked	Date Of Rate Sheet	Initials - ORG
ORG. REP. TYPED NAME & SIGNATURE*	DATE			

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **Massachusetts Institute of Technology**					FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Muriel Medard**					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. Muriel Medard - none	0.00	0.00	0.00	$ 0	$	
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	0.00	0		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0		
3. (5) GRADUATE STUDENTS				81,305		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (5) OTHER				11,159		
TOTAL SALARIES AND WAGES (A + B)				92,464		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				3,461		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				95,925		
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)				28,096		
2. FOREIGN				0		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0						
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				0		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				54,320		
TOTAL OTHER DIRECT COSTS				54,320		
H. TOTAL DIRECT COSTS (A THROUGH G)				178,341		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)						
TOTAL INDIRECT COSTS (F&A)				71,657		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				249,998		
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)				$ 249,998	$	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					
PI / PD TYPED NAME & SIGNATURE* **Muriel Medard**	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

****B-6 Other
Administrative Staff
Allocation Base:Yr1=22405. Yr2=22156. Yr3=21894. Yr4=21618. Yr5=21328.
Rate=10.2%
**E. Travel
Travel to professional conference for Professor
**G-6 Other
Expenses include:
Lab allocation
Allocation Base:Yr1=22405. Yr2=22156. Yr3=21894. Yr4=21618. Yr5=21328.
Rate=3.6%
Full tuition=26050 with a 65% subsidy from MIT**

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: **Muriel Medard**

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: **Survivability and Reliability in Direct Access Networks**

Source of Support: **DARPA**

Total Award Amount: $ **370,000** Total Award Period Covered: **06/01/99 - 06/01/01**

Location of Project: **MIT and University of Illinois Urbana-Champaign**

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

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: Sumr:

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

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

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

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

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

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

---

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

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory:

Clinical:

Animal:

Computer: **LIDS has computer facilities available in the same building where faculty, researchers and students are located. They are freely available for this project. Moreover,the PI has her own workstation.**

Office: **LIDS has office space for faculty and students within the same building on MIT campus.**

Other: ____________________

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

LIDS has secretarial and administrative support avaiable for the PI.

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139-4307

Rafael Reif
Associate Head
Room 38-409
(617) 253-7317
Fax: (617) 258-7354
reif@eecs.mit.edu

July 24, 2000

DEPARTMENTAL ENDORSEMENT AND CERTIFICATION: PROF. MURIEL MEDARD

As Associate Department Head of the Department of Electrical Engineering and Computer Science (EECS) at the Massachusetts Institute of Technology, I am delighted to endorse Professor Muriel Medard's NSF CAREER proposal. Together with the department faculty, I fully support Professor Medard in her research activities in communication and networking and in her educational activities.

Professor Medard's career development plan addresses the important issue of integration between the fields of communication theory and of networking. Her plan lays the foundation for allowing communication theory to have a greater impact upon the way wireless and high speed networks are designed and deployed in a robust and efficient manner.

Professor Medard is uniquely well qualified to lead such a research effort. The scope of her research extends from contributing to the information theoretic understanding of wireless communication to the development of routing algorithms for recovery in optical networks. She has contributed fundamental results in the area of very wide band spread spectrum systems and in the area of network recovery. Her broad research background is the attribute needed to consider communication theory and networking in an integrated manner. We fully support her research directions, which fall within the MIT tradition of pursuing fundamental understanding with a clear engineering perspective. Although Professor Medard's work maintains a strong theoretical content, the fact that several of her patents are under license or in the process of being licensed attests to its engineering applicability.

The educational endeavors of Professor Medard are a valuable addition to MIT's educational offerings. She is actively developing two new courses, an undergraduate networks course and a graduate stochastic processes course, which will greatly contribute to the quality of our curriculum. For both these courses, she has involved other members of the EECS faculty across disciplines. Her efforts have brought together faculty in communications with faculty in computer science and in Very Large Scale Integration (VLSI). She is a dedicated educator and advisor with a strong commitment to promoting active learning.

Professor Medard meets the CAREER eligibility criteria. Her first tenure track appointment was at the University of Illinois Urbana-Champaign in September 1998 and she received her Sc.D. from MIT in September 1995.

I have read and endorse this career plan.

Sincerely,

Rafael Reif

Rafael Reif
Professor and Associate Department Head
Electrical Engineering & Computer Science
Massachusetts Institute of Technology

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

Massachusetts Institute of Technology
Cambridge, Mass., 02139-4307, U.S.A.

Room:
Telephone: (617) 253-

Commitment of Laboratory Support and Collaborations

As the Director of the Laboratory for Information and Decision Systems (LIDS) at MIT, I am delighted to commit the necessary support resources for Professor Medard's NSF CAREER Development program. LIDS is an interdepartmental laboratory set up to pursue research in the area of information and decision sciences. Faculty are drawn from the School of Engineering and the Sloan School of Management. The Laboratory faculty and I fully support Professor Medard's research activities and many of us will be active collaborators.

We are especially enthusiastic about her 'return to fundamentals' approach to the analysis of networks. The faculty of two current programs within LIDS, of which I am the PI, would be collaborating with Professor Medard. The first one is a space network architecture program funded by the NRO to look at futuristic space networks that have significant quality of service assurances such as survivability. Professor Medard's research will be very synergistic with this program. The second program in which Professor Medard will also participate is the to be announced "Lucent-MIT Broadband Network Alliance" where under funding from Lucent, the two organizations will take an aggressive stance in the long-term research of future network architectures. The Alliance has shown tremendous amount of interest in the graph-theoretic automatic protection switching algorithms Professor Medard has developed and this interest will no doubt evolve and expand in concert with her career development award if she receives one.

LIDS considers Professor Medard's approach to network research is an important departure from current practice and will lead to more systematic understanding of networks and better architecture. Therefore, all the faculty in the network area will be actively interacting with her in her proposed research.

Vincent W. S. Chan

Vincent W.S. Chan
Joan and Irwin Jacobs Professor of
Electrical Engineering & Computer Science
And Aeronautics & Astronautics
Director, Laboratory for Information and
Decision Systems

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

CAMBRIDGE, MASSACHUSETTS 02139

25 July 2000

LETTER OF SUPPORT CONCERNING PROPOSED

COLLABORATION WITH PROF. MURIEL MEDARD

Professor Medard and I are planning to develop and jointly teach a new graduate course at MIT on stochastic differential equations applied to problems in engineering and finance. MIT currently offers no course on this material, which is a great disadvantage for our students since those who interview on Wall Street are often asked about their ability to apply this material to model financial time series. She has written a course outline that carefully develops the needed mathematics while avoiding the morass of fine mathematical detail that makes most treatments of the subject unapproachable by engineers.

I look forward to developing and teaching this course with Prof. Medard and feel MIT will be much the richer for it.

Sincerely,

John Wyatt

John L. Wyatt, Jr.
Prof. of Electrical Engineering