Activities and Findings

This section will serve as your report to your program officer of your project's activities and findings. Please describe what you have done and what you have learned, broken down into four categories:

1. Describe the major research and education activities of the project.

   This project is concerned with the development of novel error control coding (ECC) schemes and complementary network-routing mechanisms that (i) require simple circuitry, (ii) are adaptive to various traffic and optical channel characteristics, and (iii) provide flexible QoS management.

   For the past year, the investigators on this project have pursued several research thrusts related to novel forward error correction schemes, adaptive error correction codes, constrained codes and modulation formats, optical CDMA, and algorithms and protocols for constraint-based routing. These activities will serve as a basis for advanced optical network development. Specific accomplishments include:

   1. Development of a novel class of forward error correction codes, generalized low-density parity-check codes suitable for long-haul optical transmission, optical networks and unequal error protection.
   2. Development of a novel class of constrained codes, pseudo-ternary constrained codes, suitable for suppression of intrachannel fiber nonlinearities in high-speed optical transmission (40 Gb/s and above).
   3. Optical system simulator is upgraded to include novel modulation formats such as RZ-DPSK, duobinary modulation formats and M-ary DPSK.
   4. Development of novel transmitter/receiver configurations and novel classes of LDPC codes suitable for multilevel coding in M-ary DPSK transmission with direct detection.
   5. Development of a combined constrained coding and error control coding scheme suitable for high-speed optical transmission.
   6. Development of refined models and channel capacity studies to assess the ultimate performance limits in the presence of intra-channel non-linearities.
   7. Development novel nonlinear ISI cancellation techniques, based on BCJR detection and MP decoding, to tackle the combined effects of dispersion and fiber nonlinearities.
   8. Development of a novel wavelength-time orthogonal code suitable for high-speed optical CDMA, able to support larger number of users than other proposals available in the literature.
   10. Channel capacity studies to assess the ultimate performance limits for atmospheric turbulent channel.
   11. Development of LDPC codes suitable for transmission over turbulent atmospheric channel.
   12. Designed and fabricated a cascaded grating edge illuminated holographic filter for CDMA applications.
   13. Improved the performance of a holographic photopolymer (phenanthrenequinone-doped poly methyl methacrylate) for implementing different types of CDMA spectral filters.
14. Developed packaging and measurement techniques for evaluating the performance of holographic edge illuminated gratings in fiber communications systems.
16. Algorithmic formulation and analysis of the differential delay problem in Ethernet over SONET systems (EOS) supporting dynamic bandwidth management based on virtual concatenation.
17. Development of highly efficient computational algorithms for finding delay-constrained paths in a SONET mesh that supports EOS applications. In contrast to traditional constrained path selection problems, the one investigated in this project is uniquely characterized by two-sided constraints (i.e., the delay of the computed path must satisfy both upper and lower constraints).
18. Development of algorithmic solutions for path selection in EOS systems under probabilistic link-state information. The algorithmic complexities of the proposed solutions are as low as $O(n \log n)$, where $n$ is the number of nodes in the SONET mesh.
19. Development of optimal schemes for wavelength assignment in all-optical networks under imprecise wavelength availability information.

The educational activities include teaching courses in optical communications, optical networks, and digital communications as well as presenting tutorial lectures to various groups on and off campus.
2. Describe the major findings resulting from these activities.

**Novel Forward Error Correction Schemes**

We have recently shown that performance of turbo codes can be matched and improved by LDPC codes, which have additionally very small hardware complexity. However, LDPC decoding is based on a sub-optimal message-passing algorithm, and therefore one may expect to be able to further improve this coding scheme in terms of its distance to Shannon’s limit. Generalized low-density parity-check (GLDPC) coding provides one possible way to achieve this task and improve the overall characteristics of LDPC codes. A novel class of powerful regular and irregular, random-like and structured GLDPC codes is developed [C-2], [J-1]. The proposed codes are suitable for long-haul transmission, optical networks and adaptive error control. The proposed GLDPC codes outperform currently known turbo and LDPC coding schemes with comparable parameters utilized in optical communication systems. For a GLDPC coding scheme with 23.6% redundancy, the largest so far reported coding gain of at least 11.5 dB (at 40 Gb/s) is demonstrated, as illustrated in Figs. 1-2 taken from [J-1].

GLDPC decoding is based on a combination of simple and fast Soft Input-Soft Output decoding of short, linear block codes, such as Hamming codes, BCH or Reed-Muller codes. Time efficient MAP decoding algorithms operating on local codes provide accurate estimates for the variable nodes in the global LDPC graph after a very small number of iterations (less than 10). The low complexity of encoding and especially decoding makes FEC schemes based on GLDPC codes an attractive option for high-speed optical transmission.

![Fig. 1 BER performance of GLDPC codes with Hamming (31,26) constituent code at 40 Gb/s (line rate) (ten iteration)](image1)

![Fig. 2 BER performance of GLDPC codes with Hamming (63,57) constituent code at 40 Gb/s (line rate) (ten iterations)](image2)

Constrained Coding, Combined Error Control and Constrained Coding, and Modulation Formats

(a) Constrained Coding

Constrained codes are proposed as a means of suppressing detrimental effects of intrachannel nonlinearities in 40Gb/s systems and beyond. Three different constraints, suitable for suppression of intrachannel nonlinearities, are proposed relying on the following ideas: (i) the most troublesome sequences are identified and forbidden, (ii) the zero-symbol in so called “resonant positions” is converted into one-symbol, and (iii) the different contributions to a ghost pulse creation cancel each other in resonant positions. Significant performance improvement is obtained, ranging from 5 dB to 16 dB (in Q-factor), see Fig. 4, depending on number of spans and code rate. These schemes also provide flexibility in selecting the code rate and the factor of suppression of nonlinear effects.

The results of simulations are given in Figs. 3-4, taken from [J-4], [C-7]. The proposed constrained codes are compared against RZ modulation format (of duty cycle 33%). From Fig. 3 it is evident that the constrained codes are successful in suppressing both IFWM (ghost pulse and amplitude jitter) and IXPM (timing jitter). After 60 spans the eye diagram in RZ modulation format is completely closed, while the eye diagrams of constrained codes are widely open.

![Graphs showing power and time for RZ modulation format with 30 and 60 spans](image-url)
Fig. 3 Eye diagrams after 1440 km (left column) and 2880 km (right column):
- RZ format, uncoded signal eye diagram after (a) 30 spans and (b) 60 spans
- Constrained code of rate 0.69 after (c) 30 spans and (d) 60 spans.
- Pseudo-ternary constrained code of rate 0.76 after (e) 30 spans and (f) 60 spans.

Fig. 4 (a) Q-factor improvement over RZ for different number of spans in the absence of ASE noise
Fig. 4 (b) Q-factor improvement over RZ for different number of spans in the presence of ASE noise
(b) Combined Error Control and Constrained Coding

Even though constrained decoding used in sub-section above is conceptually simple (it is based on sliding-window decoder), it decouples the channel and the error correction decoder, because it operates on hard bits and does not produce soft information necessary for iterative (LDPC/turbo) decoding. An alternative scheme that circumvents the above problem is known as reverse concatenation, and it has been recently adapted for soft detectors. In this scheme, the BCJR algorithm is performed on a trellis corresponding to the constrained graph. In our recent submissions [C-6], [S-8], the reverse concatenation scheme is used to suppress the intrachannel nonlinear effects.

The results of simulation are shown in Fig. 5. After 80 spans the electrical eye diagram of uncoded signal (shown in Fig. 5) is completely closed, and the input BER is too high for any FEC scheme to handle (even for the most advanced methods based on turbo or LDPC codes). However, an LDPC code combined with constrained encoder is able to operate error free. The coding gain due to combined constrained and iterative error control coding is 12.1 dB at BER of $10^{-9}$. For BER of $10^{-12}$ expected coding gain is about 13.6 dB.

![Fig. 5 BER performance of combined constrained and LDPC FEC scheme](image)

[C-9] I. B. Djordjevic, B. Vasic, “Combined Constrained and Error Control Coding in Suppression of Intrachannel Fiber Nonlinearities,” submitted to *31th European Conference*
Error Control Codes for Free Space Optical Communications Systems

Wireless communication networks can benefit from the use of the free-space optical channel as an alternative to the radio frequency (RF) channel. The free-space optical (FSO) atmospheric channel may support very high bandwidth allowing many more users than an RF channel. However, the FSO channel is affected by atmospheric turbulence that is caused by temperature variations and wind. This degrades the performance of a communication system and a good model of the channel is required to understand how to utilize this medium in the optimal way. The contributions made in this regard are:

1) We have extended our modeling of turbulence to the strong and the saturation regimes based on a recently proposed a statistical model. This model uses a gamma-gamma distribution and can predict intensity variations of the signal from measurable physical parameters, like propagation distance, turbulence strength and carrier wavelength. This statistical model delivers an excellent match to our numerical propagation model and to other published data. We developed a simulation system that generates statistical samples that permit us to simulate channel conditions from weak to strong intensity fluctuation and evaluate the performance of a FSO communication system and its error-correction codes.

2) We evaluated the performance of finite-geometry/block-circulant regular LDPC and Reed-Solomon error-correction codes under a wide range of turbulence regimes. The coding gains obtained by the use of the LDPC codes (with rates 0.91 and 0.75) range from 7 to 14dB over Reed-Solomon codes of similar rates in the evaluated channels, and from 20 dB and above over the uncoded systems. Coding gains grow monotonically as turbulence strength is increased. In the strong turbulence regime, reliable communications can only be achieved with the use of these powerful LDPC codes as the signal-to-noise ratio (SNR) required to obtain adequately low bit-error rates (BER) goes above practical values (50dB) if Reed-Solomon codes are used. Figures 6 to 8 show the BER performance of the rate 0.91 and the rate 0.75 LDPC codes together with rates 0.94 and 0.75 Reed-Solomon codes. Shannon limits are included in all plots to indicate the maximum achievable coding performance.

3) We evaluated the Shannon channel capacity of the FSO atmospheric channel under a very wide range of turbulence conditions. This is a very significant contribution towards the design of efficient FSO communication systems for wireless networks. We have determined that atmospheric turbulence reduces the channel capacity for an On-Off Keying (OOK) intensity-modulated direct-detection (IM/DD) system. The FSO channel capacity seems to asymptotically approach that of an additive white Gaussian noise (AWGN) channel at very weak turbulence. The capacity decreases monotonically as the turbulence strength increases, and reaches an asymptotic limit. In our analysis we have assumed that no memory or inter-symbol interference is present in the channel. Figure 9 shows a plot of the capacity curves for ten different turbulent channels, as a function of SNR. Lower capacity if represented by curves shifted to higher values of SNR.
Optical CDMA Systems

We have proposed a new family of unipolar wavelength-time codes with zero out-of-phase autocorrelation and maximum cross-correlation equal to one, based on balanced incomplete block design [C-9]. The system performance was assessed in a realistic simulation environment using VPI modeling, taking into account multi-access interference, transmitter/receiver imperfections. The code constructions employ a greater number of wavelengths as compared to time chips giving rise to potential use in high-speed applications. Simulations demonstrate the excellent performance of the codes in the presence of MAI. The decoding of one 10 Gb/s user in the presence of 6 interferers has a penalty of about 5 dB for a BER of $10^{-9}$ as compared to decoding in the absence of interference from other users. In contrast, optical CDMA systems based on one-dimensional codes exhibit severe performance degradation due to MAI, as bad as severe flooring at a BER of $>10^{-6}$ occurs for even 2 simultaneous users at 622 Mb/s. By using

[C-10] Anguita, Djordjevic, Neifeld, Vasic, "High-rate error-correction code for the optical atmospheric channel", accepted for presentation at SPIE Optics and Photonics 2005, FREE-SPACE LASER COMMUNICATIONS V (OEI121), San Diego, CA, 31 July-4 August 2005.
MAI suppression schemes and additional signal processing at the decoder, the performance may be further improved, and larger number of users can be supported.

![Eye Diagrams](image)

Fig. 10 10 Gb/s eye diagrams. Decoded eye diagram for a) one user, b) two users, c) four users, and d) seven users


**Integrated Optics for Communications and Optical Signal Processing**

Several devices for wave division multiplexing (WDM) systems which utilize mode conversion have been proposed and demonstrated. Tilted Bragg gratings (TBG) have been used to produce the mode conversion in these devices. However, TBGs produce multiple reflections, only one of which provides the desired mode conversion. We have developed a novel anti-symmetric Bragg grating to produce the mode conversion for these types of devices. We proposed the device and provided modeling using both BPM and coupled mode equations [C-10]. We experimentally verified the operation of our design with a silica-on-silicon integrated optic chip [C-11, C-12]. We are currently investigating a variety of aspects of the device performance, including polarization rotation, polarization dependent loss, and cladding mode coupling.

![Device Schematic](image)

Fig. 11(a) Schematic of fabricated device using the anti-symmetric grating. (b) Comparison of anti-symmetric to tilted Bragg grating for mode conversion.
Our design can be utilized in communication and optical signal processing applications such as for optical add drop multiplexers (OADM), optical header recognition [C-12], code division multiplexing access (CDMA) encoders and decoders [C-12] and for optical encryption [C-13].

We have proposed a novel scheme to enhance security in optical systems using pseudo random modulated super structured Bragg gratings (SSBG). This type of SSBG is designed using couple mode theory and transfer matrix methods to produce noisy-like impulses responses. The encryption process is performed in two steps. The first step is the transformation of the data into an optical noise-like pattern by the use of the pseudo-random SSBG. In the second step, the previous encoded signal is masked by quasi-orthogonal noise generated by other set of SSBG. The resultant signal to be transmitted is a noisy-like sequence in which the structure of the bits is lost for an eavesdropper. For decoding, the authorized users use the conjugate SSBG to obtain the information bits. Simulations show that error free communication is possible for authorized users while maximizing the bit error rate of eavesdroppers.

![Diagram](image)

Fig. 12 a) Transmitter (b) encrypted sequence at 2 Gbps (c) decrypted sequence before thresholding.

We have investigated the design and formation of cascaded filters for use as OCDMA encoders and decoders using edge illuminated holographic gratings in optical polymers. Gratings implemented in optical polymers are less expensive to fabricate than fiber Bragg gratings because they can be recorded using visible rather than UV illumination. In our work we have been using phenanthrenequinone (PQ) doped poly methyl methacrylate (PMMA) for making holographic Bragg filters. The material can be used to make thick samples that can be molded into different forms and it has reasonably high efficiency at telecommunications wavelengths. One of the attractive aspects of this polymer is the ability to rapidly prototype new types of fiber communication devices. One device that we have experimented with is a time-wavelength OCDMA encoder/decoder. A preliminary step in this development is the recording of two cascaded gratings with different Bragg wavelengths separated by a fixed distance. The separation introduces a time delay between the two reflected wavelengths. The basic configuration for the
edge illuminated hologram and the mask used to form the cascaded gratings are shown in Figure 13. The reflectance spectra for the two filtered wavelengths are illustrated in Figure 14. The cascaded grating device was directly coupled into a fiber communication system allowing direct measurement of the resulting system eye diagram (Figure 15). These experiments showed the potential for using edge-illuminated holograms in fiber communication systems to test theoretical concepts developed by other investigators in this project. The next step in this work is to fabricate a matched pair of wavelength filters to form an encoder/decoder combination. A simple technique was developed to fabricate matched sets and will be investigate during the next year.

Figure 13 Edge illuminated hologram (a) and mask used to form two cascaded gratings with different periods $\Lambda_1$ and $\Lambda_2$ separated by distance $d$ (b). $K$ is the grating vector that is perpendicular to the grating fringe planes.
Figure 14 Reflectance spectra from cascaded edge illuminated holograms.

Figure 15 `Eye’ diagram obtained using the reflectance signal from an edge illuminated grating. The resulting $Q \sim 11$.


Unequal Error Protection Error Control Coding

JPEG2000 is the latest international image coding standard. Comparing to its predecessor JPEG, it delivers superior compression performance and provides many advanced features including scalability, flexibility, and error resilience, etc. We have proposed a framework for iterative joint source-channel decoding of JPEG2000 codestreams [C-16], [C-17]. In this scheme, images are encoded by JPEG2000 with certain error resilience (ER) modes, and low-density parity-check (LDPC) codes are used to perform channel coding. At the decoder, the source decoder uses the ER modes to identify corrupt sections of the codestream and provides this information to the channel decoder. The channel decoder modifies its decoding algorithm according to the feedback information. The decoding is thus carried out jointly in an iterative fashion. Figure 1 illustrates how the proposed method improves the convergence rate as well as the overall system performance. Average Peak Signal-to-Noise Ratio (PSNR) is plotted against iteration numbers for gray scale Lena image 512x512. The three subplots in Figure 16 correspond to three different codeblock sizes used in the JPEG2000 encoding.

JPEG2000 codestreams are highly scalable, which enables progressive transmission and also allows truncation of codestreams without making the correctly received data useless. Different parts of the codestreams have different importance in terms of the distortion reductions they contribute to the reconstructed images. We presented an unequal error protection (UEP) scheme based on the Plotkin construction for channel (error control) codes [C-18], [S-10]. The images are encoded into different quality layers by JPEG2000. Different layers are protected by different component codes of the constructed Plotkin code. The resulting scheme offers the novel ability of using one long channel codeword to protect an entire image, yet still allowing progressive decoding. Progressive quality improvements occur in two ways: the first is the usual progressive refinement, where image quality is improved as more data are received; the second is that residual error rates of earlier received data are reduced as more data are received. Figure 17
shows the progressive quality improvements and superior UEP gains. The horizontal axis represents the number of layers used to reconstruct the image. The asterisks show the traces of PSNR values being refined during decoding, and the final PSNR values are reached after the progressive decoding (top solid line). The bottom solid line is obtained when equal error protection (EEP) is used.

Because of the high compression efficiency and error resilience, JPEG2000 is a good candidate for wireless multimedia applications. It also facilitates a wide range of quality of service (QoS) strategies due to its scalability. Our future work will include joint source-channel coding problems in DS-CDMA (Direct Sequence Code Division Multiple Access). In addition to optical networks, this work will have applications in 3rd generation mobile communication systems. UEP solutions will be obtained by optimizing the source rate and the parameters of the CDMA sub-channels jointly.

![Graph showing PSNR vs. iteration for channel SNR = 4.3 dB. FB: with feedback; no FB: without feedback.](image1)

![Graph showing PSNR vs. number of received packets.](image2)


Path Selection Algorithms

(a) Path Selection Algorithms for Ethernet over SONET Systems Under Exact Link-State Information

We developed highly efficient, low-complexity path-finding algorithms for EOS systems. EOS is a popular approach for interconnecting geographically distant Ethernet segments over a SONET transport infrastructure. It typically uses virtual concatenation for dynamic bandwidth management. When more bandwidth is needed, a new virtual channel (VC) is dynamically added to the existing virtually concatenated group (VCG) that represents the current bandwidth demand of the EOS application. The differential delay between the new VC and each existing VC in the VCG must be within a certain limit that reflects the available memory buffer of the destination node. Given the network topology and given precise information about the delays and available bandwidth of the fiber links, we considered the problem of finding the route for the newly added VC such that the differential delay is minimized. In contrast to traditional constrained path selection problems, the one at hand is more sophisticated, as it involves finding a path whose delay lies between a lower and upper bounds. Even for the case of exact link-state information, we showed that the resulting Two-sided constrained path (TSCP) problem is NP-complete [S-12] (as it turns out to be a more restrictive version of the longest-path problem). Accordingly, we proposed two computationally efficient approximate solutions for this problem [S-12], [C-21]: the modified-link-weight K-shortest-path (MLW-KSP) and the backward-forward (BF) algorithms. MLW-KSP assigns to each link a weight that represents a linear combination of the link delay and its inverse. The selection of this link weight was inspired by theoretical findings showing the optimality of such a weighting function when applied to the complete path. As for the BF algorithm [S-12], it uses the idea of graph pre-labeling in the backward direction followed by a forward search that attempts to minimize an approximate objective function. Table 1 depicts the average number of iterations required to obtain a feasible path for various sizes of the solution space (reflected in the value of the parameter A). Both MLW-KSP and BF are compared with the traditional KSP algorithm. The results clearly demonstrate the high efficiency of both algorithms (and particularly, the BF algorithm).

<table>
<thead>
<tr>
<th>A</th>
<th>KSP algorithm</th>
<th>MLW-KSP algorithm</th>
<th>BF algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>34.47</td>
<td>22.63</td>
<td>1.004</td>
</tr>
<tr>
<td>20</td>
<td>162.15</td>
<td>5.56</td>
<td>1.003</td>
</tr>
<tr>
<td>50</td>
<td>464.0</td>
<td>17.3</td>
<td>1.004</td>
</tr>
</tbody>
</table>

Table 1: Performance of path selection algorithms under exact link-state information.

(b) Path Selection Algorithms for EOS Systems Under Imprecise Link-State Information

There are scenarios in which the link-state information (delay and available bandwidth) is not precisely available at the source node (one that executes the path selection algorithm). In optical networks, the causes of link-state uncertainty are related to the periodic nature of link-state updating protocols (e.g., OSPF), sampling errors, and policy restrictions (e.g., the participating
nodes are managed by different Network Management Systems (NMS) that do not share information). It was previously demonstrated that the reliance on outdated information and considering it as exact can significantly degrade the performance of a path selection algorithm. Accordingly, for EOS systems, we considered the problem of selecting a route subject to two constraints under the assumption that link delays and bandwidths are modeled as random variables. Expectedly, the resulting most-probable TSCP (MP-TSCP) problem is NP-complete. Accordingly, we developed highly efficient heuristic solutions for this problem. Our solutions exploit the backward-forward idea used in the BF algorithm to find the most probable feasible path. Simulations were conducted to evaluate the performance of our proposed algorithms and to demonstrate the advantages of the probabilistic path selection approach over the classic threshold-based approach. Figure 18 depicts a sample of our simulation results, where the hit probability (relative frequency of returning a feasible path by a given algorithm) is plotted against the size of the solution space (reflected in the parameter A).

![Figure 18: Hit rate vs. size of solution space (A) for proposed probabilistic approach (BF_Inaccurate) and the threshold-based approach (parameter L is the differential delay of the EOS system).](image)

(c) Optimal Wavelength Assignment Under Imprecise Network State Information

We have also considered the problem of efficient routing of “lightpaths” in all-optical DWDM networks in which some of the nodes have a limited wavelength conversion capability. Typically, the routing of such lightpaths is performed assuming precise information about the network, including the available wavelengths on each link and the number of unused wavelength converters at each node. In reality, such information is not precisely available (for the same reasons indicated earlier). Accordingly, we considered the problem of identifying the route for a lightpath based on forecasts of the average traffic on a link and previously advertised link-state information. We used such information to estimate the probability of wavelength availability on each link using Markov analysis. Our probabilistic analysis was then used to devise a strategy for selecting the most probable path and its associated wavelength assignment. Compared to the classic random-fit strategy, our simulations (see Figure 19) show that the proposed strategy achieves a significant reduction in the call blocking probability.
Figure 19: Performance of proposed wavelength assignment strategy and random fit vs. advertisement window.


Path Protection Strategies

(a) Failure dependent protection in optical grooming network

Resiliency to link failures in optical networks is becoming increasingly important due to the increasing data rate in the fiber. Path protection schemes attempt to guarantee a backup path for a connection upon a failure in the network, thereby reducing the recovery time for a connection. In [C-24], we develop a failure dependent path protection scheme that dynamically assigns a primary path and backup paths, one for each failure that would affect the primary path. A connection established on the primary path will be re-established on its backup path only if a failure in the network affects the connection. We evaluate the performance of our developed protocol and compare with an alternative approach based on sub-graph routing that achieves high network utilization and low blocking probability at the cost of re-establishing connections even if the failure in the network does not affect the primary path of the connection. We observe that up to a factor of eight reduction in the number of reconfiguration scenarios is achieved with less than 10% reduction in effective network utilization and less than 3% reduction in fairness metrics for tolerating any single link failure in NSFNET and ARPA-2 networks. The failure
dependent protection approach developed in this paper is also applicable to any general failure scenarios that are modeled as shared risk link group failures.

(b) Link protection at connection granularity

In [C-25], we develop a connection establishment framework for protecting connections against single-link failures using link protection at the granularity of a connection, referred to as Connection Switched Link Protection (CSLP). As a connection is routed only around a failed link, the channel assignment for the connection on the backup path of the failed link must be consistent with that of the primary path. Such a consistency is guaranteed at the time of call admission. The advantages of employing link protection at the connection level is established by comparing its performance through extensive simulations against link protection at the granularity of a fiber, referred to as Fiber Switched Link Protection (FSLP). Link protection at the connection level is shown to significantly outperform that at the granularity of a fiber, specifically when some traffic requires protection while others do not.

(c) DIVERSION: A trade off between link and path protection strategies

Path protection strategies achieve better network utilization compared to link protection strategies; however the recovery time of connections in path protection strategies are higher than that in link protection strategies. In [C-26], we develop a new approach, called Diversion, that achieves a trade-off between the connection recovery time and network utilization. Based on extensive simulations, it is demonstrated that Diversion achieves connection recovery times that are closer to, and in some cases better than, link protection while achieving better network utilization and blocking performance than link protection.

(d) Supporting multiple protection strategies in optical grooming networks

In [S-13], we develop a framework to support multiple protection strategies in optical networks, which is in general applicable to any connection-oriented network. The capacity available on a link for routing primary and backup connections are computed depending on the protection strategy. We also develop a model for computing failure recovery time for a connection where notifications of failure location are broadcast in the network. The effectiveness of employing multiple protection strategies is established by studying the performance of three networks for traffic with four types of protection requirement.

(e) Dual-link failure resiliency through backup link mutual exclusion (BLME)

Networks employ link protection to achieve fast recovery. While the first link failure can be protected using link protection, there are several alternatives for protecting against the second failure. This paper formally classifies the approaches to dual-link failure resiliency. One of the strategies to recover from dual-link failures is to employ link protection for the two failed links independently, which requires that two links may not use each other in their backup paths if they may fail simultaneously. Such a requirement is referred to as Backup Link Mutual Exclusion (BLME) constraint and the problem of identifying a backup path for every link that satisfies the above requirement is referred to as the BLME problem.
In [S-14], we develop the necessary theory to establish the sufficient conditions for existence of a solution to the BLME problem. Solution methodologies for the BLME problem is developed using two approaches by: (1) formulating the backup path selection as an integer linear program; and (2) developing a polynomial time approximation algorithm based on minimum cost path routing. The ILP formulation and heuristic are applied to six networks and their performance is compared to approaches that assume precise knowledge of dual-link failure. It is observed that a solution exists for all the six networks considered. The heuristic approach is shown to obtain feasible solutions that are resilient to most dual-link failures, although the backup path lengths may be significantly higher than optimal. In addition, the paper illustrates the significance of the knowledge of failure location by illustrating that network with higher connectivity may require lesser capacity than one with a lower connectivity to recover from dual-link failures.


3. Describe the opportunities for training and development provided by your project.

1. Eighteen graduate and one undergraduate student are working on the project.
2. Information on CDMA techniques was introduced into ECE 430/530, ECE 456/556, and ECE 487/587.
3. Advanced error control coding techniques, LDPC codes, iterative decoding are introduced into ECE 535 and ECE 537.
4. The PI gave a tutorial on constrained coding at the Binational Spring School on April 1-3, 2005. The Binational Consortium of Optics (BNCO) is the partnership of the University of Arizona together with the Instituto Nacional de Astrofísica, the Centro de Investigacion Cientifica y de Educacion Superior de Ensenada, and the Centro de Investigaciones en Optica.

The spring school took place on the campus of the University of Arizona at the Department of Mathematics, room 501. The format of the Spring School consisted of afternoon educational sessions primarily for graduate students and morning research sessions for all participants. The Lectures presented surveys of advances by BNCO partners. It provided an opportunity for graduate students and young researchers to learn more about recent advances from the originators of research in these areas. In addition these sessions allowed identification of research areas for future collaboration of the project partners, encourage participation by young researchers and provide varied opportunities for interaction and
discussion focusing on problems of general and practical importance. More information available at:  http://math.arizona.edu/~nrw/Spring_School_2005/

4. Describe outreach activities your project has undertaken.

Several colloquia, tutorials and invited talks were presented on material developed in this project, including:

a. A colloquium was presented to the public in Tucson on the research activities examined in this project.
b. An exchange with Princeton University was started on the subject material of this research project.
c. Invited talk on Generalized LDPC codes for optical networks was given at University of California-San Diego.
d. A tutorial on constrained coding techniques for suppression of intrachannel nonlinear effects was given at Spring School of Nonlinear and Multiscale Photonics http://math.arizona.edu/~nrw/Spring_School_2005/
Contributions

Now we invite you to explain ways in which your work, your findings, and specific products of your project are significant. Describe the unique contributions, major accomplishments, innovations and successes of your project relative to:

1. The principal discipline(s) of the project;

Novel Forward Error Correction Schemes

We proposed a novel class of FEC for optical transmission systems, the class of GLDPC codes. GLDPC codes, the generalization of both LDPC and turbo codes, demonstrate largest so far reported coding gain of almost 12 dB for 23.6% of overhead (at BER below $10^{-12}$).

The excellent BER performance of GLPDC codes in the presence of ASE noise, fiber nonlinearities, chromatic dispersion, and inter-symbol interference selects them as a very promising option for next generation of optical transmission systems and for network applications.

Constrained Codes and Modulation Formats

It is widely accepted that at high bit rates of 40 Gbps or beyond, data transmission through optical channels deployed using dispersion managed schemes is limited by nonlinear effects especially by intrachannel four-wave mixing (IFWM). These effects cause timing and amplitude jitter as well as interactions between the pulses in the channel causing energy transfer between them, making reliable transmission of information impossible.

Significant performance improvements, ranging from 5 dB to 16 dB, are obtained by implementing the constrained codes we proposed. Performance improvement varies depending on constrained code, code rate and number of spans in the link. The constrained codes are capable of improving the FEC threshold in systems with severely degraded performance due to intrachannel nonlinearities. Moreover at 40Gb/s, distances of several thousand kilometers may be reached without employing any FEC.

Combined constrained and error control coding is able to operate in the regime of strong intrachannel nonlinearities when even the most advanced FEC schemes are not able to operate. At $10^{-9}$ it provides the coding gain of 12.1 dB, while expected coding gain at BER of $10^{-12}$ is 13.6 dB, the largest ever reported coding gain for long-haul optical transmission.

Error Control Codes for Free Space Optical Communications Systems

The propagation of an On-Off Keying modulated optical signal through the optical atmospheric turbulent channel is considered. The atmospheric turbulence is modeled using a gamma-gamma distribution. The Shannon’s capacity limits of this channel are calculated under a wide range of turbulence conditions. For a zero inner scale, the capacity decreases monotonically as the turbulence strengthens. However, for a non-zero inner scale, the capacity decreases in a non-monotonic fashion with turbulence strength in the saturation regime. Two error correction schemes, both based on low-density parity-check (LDPC) codes, are proposed for use in free-
space optics communications. The bit-error rate performance of proposed LDPC codes is compared against the conventional Reed-Solomon (RS) codes of comparable code rates and lengths. An excellent coding gain improvement of LDPC codes over RS codes is obtained, ranging from 5.5 dB to 14 dB, depending on the turbulence strength.

**Integrated Optics for Communications and Optical Signal Processing**

We have primarily focused on optical CDMA and optical encoding. We have proposed a new family of unipolar wavelength-time codes and assessed their performance in a realistic simulation environment using VPI modeling, taking into account multi-access interference, transmitter/receiver imperfections. Simulations demonstrate the excellent performance of the codes in the presence of MAI as compared with one-dimensional codes. We are developing a platform technology for integrated optic chips, with applications in communications and signal processing. We have developed and demonstrated a novel anti-symmetric Bragg waveguide grating to produce the mode conversion. Using this new grating, we developing designs with applications such as for optical add drop multiplexers (OADMs), optical header recognition, code division multiplexing access encoders and decoders and for optical encryption.

We evaluate the use of edge illuminated holographic Bragg filters formed in phenanthrenequinone (PQ) doped poly (methyl-methacrylate) (MMA) for optical code division multiple access (OCDMA) coding and decoding applications. Experimental cascaded Bragg filters are formed to select two different wavelengths with a fixed distance between the gratings and are directly coupled to a fiber measurement system. The configuration and tolerances of the cascaded gratings are shown to be practical for time/wavelength OCDMA applications.

**Unequal Error Protection Error Control Coding**

We have proposed a framework for iterative joint source-channel decoding of JPEG2000 codestreams. In this scheme, images are encoded by JPEG2000 with certain error resilience (ER) modes, and low-density parity-check (LDPC) codes are used to perform channel coding. At the decoder, the source decoder uses the ER modes to identify corrupt sections of the codestream and provides this information to the channel decoder. The channel decoder modifies its decoding algorithm according to the feedback information. The decoding is thus carried out jointly in an iterative fashion.

We presented an unequal error protection (UEP) scheme based on the Plotkin construction for channel (error control) codes. The images are encoded into different quality layers by JPEG2000. Different layers are protected by different component codes of the constructed Plotkin code. The resulting scheme offers the novel ability of using one long channel codeword to protect an entire image, yet still allowing progressive decoding.

**Path Selection Algorithms**

We developed highly efficient, low-complexity path-finding algorithms for EOS systems. EOS is a popular approach for interconnecting geographically distant Ethernet segments over a SONET transport infrastructure. When more bandwidth is needed, a new virtual channel (VC) is
dynamically added to the existing virtually concatenated group (VCG) that represents the current bandwidth demand of the EOS application. The differential delay between the new VC and each existing VC in the VCG must be within a certain limit that reflects the available memory buffer of the destination node. In contrast to traditional constrained path selection problems, the one at hand is more sophisticated, as it involves finding a path whose delay lies between a lower and upper bounds. We proposed two computationally efficient approximate solutions for this problem: the modified-link-weight K-shortest-path (MLW-KSP) and the backward-forward (BF) algorithms. MLW-KSP assigns to each link a weight that represents a linear combination of the link delay and its inverse. The selection of this link weight was inspired by theoretical findings showing the optimality of such a weighting function when applied to the complete path. As for the BF algorithm, it uses the idea of graph pre-labeling in the backward direction followed by a forward search that attempts to minimize an approximate objective function.

**Path Protection Strategies**

We developed a connection establishment framework for protecting connections against single-link failures using link protection at the granularity of a connection, referred to as Connection Switched Link Protection (CSLP). The advantages of employing link protection at the connection level is established by comparing its performance through extensive simulations against link protection at the granularity of a fiber, referred to as Fiber Switched Link Protection (FSLP). Link protection at the connection level is shown to significantly outperform that at the granularity of a fiber, specifically when some traffic requires protection while others do not.

Path protection strategies achieve better network utilization compared to link protection strategies; however the recovery time of connections in path protection strategies are higher than that in link protection strategies. We developed a new approach, called Diversion, that achieves a trade-off between the connection recovery time and network utilization. Based on extensive simulations, it is demonstrated that diversion achieves connection recovery times that are closer to, and in some cases better than, link protection while achieving better network utilization and blocking performance than link protection.

We developed a framework to support multiple protection strategies in optical networks, which is in general applicable to any connection-oriented network. We also developed a model for computing failure recovery time for a connection where notifications of failure location are broadcast in the network. The effectiveness of employing multiple protection strategies is established by studying the performance of three networks for traffic with four types of protection requirement.

We formally classified the approaches to dual-link failure resiliency. We developed the necessary theory to establish the sufficient conditions for existence of a solution to the BLME problem. The ILP formulation and heuristic are applied to six networks and their performance is compared to approaches that assume precise knowledge of dual-link failure. It is observed that a solution exists for all the six networks considered. The heuristic approach is shown to obtain feasible solutions that are resilient to most dual-link failures, although the backup path lengths may be significantly higher than optimal.

2. Other disciplines of science or engineering;

None
3. The development of human resources;
   None

4. The physical, institutional, or information resources that form the infrastructure for research and education; and
   None

5. Other aspects of public welfare beyond science and engineering such as commercial technology, the economy, cost-efficient environmental protection, or solutions to social problems.
   None
Publications and Products

In this section, you will be asked to describe the tangible products coming out of your project. Specifically:

1. What have you published as a result of this work?

Journal publications

Advanced FEC for Optical Transmission and Unequal Error Protection


Constrained Coding and Modulation Formats


Optical CDMA Systems


Optical Packet Switching

Papers Submitted for Journal Publication

**Advanced FEC for Optical Transmission**


**Constrained Coding and Modulation Formats**


**Unequal Error Protection Error Control Coding**


**Integrated Optics**


*Path Selection Algorithms*


*Path Protection Strategies*


Books or other non-periodical, one-time publications

2. What Web site or other Internet site have you created?
http://www.ece.arizona.edu/~opt-com/

3. What other specific products (databases, physical collections, educational aids, software, instruments, or the like) have you developed?
Participants:

1. Ivan B. Djordjevic
2. Bane Vasic
3. Marwan M. Krunz
4. David F. Geraghty
5. Raymond K. Kostuk
6. Srinivasan Ramasubramanian
7. Mark A. Neifeld
8. Michael W. Marcellin
9. Lingling Pu
   Construction and analysis of source-channel codes. Construction and optimization of irregular LDPC codes for unequal error protection.
10. Jaime Anguita
    Theoretical work on free-space optical communications systems. Channel modeling, simulation, and analysis of error control techniques.
11. Satyajeet Ahuja – ¼ time
    Design of computationally efficient algorithms for constrained path selection in optical networks. Design of path selection algorithms for support of virtual concatenation in Ethernet over SONET systems.
12. Chia Hung Chen - 1/4 time
13. Wendy Maeda - 1/4 time
    Developing a holographic photopolymer that can be used form making integrated CDMA optical elements. Design of optical filters for use in CDMA systems.
    Experimental demonstration of optical CDMA codes. This has included construction of the coders and decoders which required the fabrication of accurate fiber delay lines, successful demonstration of coding and decoding a signal, and evaluation of the coded signal in the presence of non-orthogonal channels, both theoretically using VPI modeling software and experimentally in our testbed.
15. Jose Castro-1/2 time.
    The design and development of integrated optic devices that utilize bragg gratings. These devices have applications in optical CDMA encoding/decoding, syndrome calculation for a coded signal, packet header recognition and chromatic dispersion compensation.
16. *Amit Chandak*
Optical networks – Network Design: Research involves design of new networks that have certain protection properties.

17. *Karthikeyan Sathyamurthy*
Optical Networks – Link Protection: Develop methodologies for link protection in optical networks satisfying channel assignment constraints on primary and backup paths.
Have You had Other Collaborators or Contacts?

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