

**Annual Report for Period:** 04/2000 - 04/2001

**Submitted on:** 04/01/2001

**Principal Investigator:** Elmagarmid, Ahmed K.

**Award ID:** 9972883

**Organization:** Purdue Research Foundation

CISE Research Infrastructure: MSI: A Research  
Computing Environments

Infrastructure for Integrated Quality of Service Management in Multimedia

**Project Participants**

**Senior Personnel**

**Name:** Elmagarmid, Ahmed  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Korb, John  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Ghafoor, Arif  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Spafford, Eugene  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Park, Kihong  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Aref, Walid  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Fahmy, Sonia  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Prabhakar, Sunil  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Yau, David  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Blair, Shane  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Delp, Ed

**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Szpankowski, Wojtek  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

#### Post-doc

**Name:** Kim, Jisoo  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Kim, Jae-Kwan  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Bahk, Saewoong  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Vakali, Athena  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

**Name:** Lee, Heejo  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

Heejo Lee has begun preliminary work on ascertaining Cisco's network security framework for subsequent adaptation to the AdSec network security architecture advanced in the project. Lee and Park (co-PI) have written a paper on probabilistic packet marking for distributed denial-of-service attack (DoS) prevention, which puts forth an effective technique for dealing with an important security and QoS threat.

**Name:** Hacid, M.  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

M. Hacid (Ph.D., Post-Doctorate) recently joined the MSI project. His main role will be to design and oversee the implementation of the QoP/QoS Interface.

**Name:** Fan, Jianping  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

Jianping Fan (Ph.D., Post-Doctorate) is pursuing his research in providing low-level support in video databases including, feature extraction, spatial and temporal segmentation, object detection and recognition, object motion tracking, and multimedia database indexing.

#### Graduate Student

**Name:** Hammad, Mustafa  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

Mustafa Hammad (Purdue Fellowship, Ph.D. student) is pursuing his research in developing access control mechanisms for video database systems both at the frame and object levels.

**Name:** Ilyas, Ihab  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**

Ihab Ilyas (RA, Ph.D. student) is pursuing his research in developing multimedia indexing techniques to support fast content-based retrieval of multimedia objects in the context of video databases.

**Name:** Rezgui, Abdulmounaam

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Abdulmounaam Rezgui (RA, Ph.D. student) is pursuing his research in developing scalable multimedia servers that support real-time streaming of video data, quality of service, and quality of presentation.

**Name:** Terzi, Evimaria

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Evimaria Terzi (RA, Ph.D. student) will begin as an RA on the multimedia database project in August 2000.

**Name:** Fahmi, Husni

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Husni Fahmi (RA, Ph.D. student) is pursuing his research in developing the overall framework for a proxy-based real-time distributed multimedia document system (RTDMDS) to allow searching and retrieval of distributed multimedia documents. He is being trained in the area of resource scheduling in a distributed multimedia environment.

**Name:** Al-Khatib, Wasfi

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Wasfi Al-Khatib (RA, Ph.D. student) completed his doctoral studies and has been trained in the area of multimedia databases. In particular, he has developed models for indexing and content-based retrieval of video data. He has published papers in several conferences and journals.

**Name:** Latif, Muddasar

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Muddasar Latif (RA, M.S. student) is pursuing his MS thesis in multimedia document delivery over the Web. He is involved in the development of different modules of RTDMDS.

**Name:** Shafiq, Basit

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Basit Shafiq (RA, M.S. student) is pursuing his MS thesis in multimedia document modeling and search mechanism. He has completed the development of several modules for RTDMDS. Currently, he is pursuing his work on the synchronization and integration aspects of heterogeneous multimedia databases.

**Name:** Joshi, James

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

James Joshi (RA, Ph.D. student) is pursuing his research in the area of multimedia database security. Currently he is developing a framework that will allow integration of heterogeneous security and access control mechanisms in a distributed multimedia document environment. The framework will integrate both Role-Based Access Control (RBAC) models and Task-Based Access Control (TBAC) models.

**Name:** Chari, Rahul

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Rahul Chari (RA, Ph.D. student) is developing a simulator for the storage management aspects of MSI, and developing and testing alternative schemes.

**Name:** Xia, Y.

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Y. Xia is a graduate student working on an independent study project in the storage area.

**Name:** Li, Jiangtao

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Jiangtao Li (RA, Ph.D. student) is implementing different storage management schemes for their testing and evaluation.

**Name:** Chen, Shaogang

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Shaogang Chen (RA, Ph.D. student) has graduated May 2000, with his Ph.D. dissertation 'Stratified Best-effort QoS Provisioning in Noncooperative Networks' advancing the state-of-the-art in the area. Chen has joined CPlane, a start-up company that focuses on QoS and network management switching products.

**Name:** Cruz, John

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

John Cruz (RA, Ph.D. student) has performed end system scheduling work for end-to-end QoS using, in part, the Purdue Infobahn network QoS infrastructure.

**Name:** Ren, Huan

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Huan Ren (RA, Ph.D. student) has published two recent papers on differentiated services QoS with a third paper presently in submission.

**Name:** Tuan, Tsunyi

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Tsunyi Tuan (RA, Ph.D. student) has published one journal paper, one book chapter, and two conference papers based on traffic control work related to the project.

**Name:** Ferreira, Ronaldo

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Lei, Shan

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Li, Wei

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

#### **Undergraduate Student**

**Name:** Stanton, Spencer

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Spencer Stanton (senior) did an independent study with Park (co-PI) in the spring semester where he assisted graduate students with implementing the MPEG audio part of AFEC for Optibase real-time compression board under Windows NT.

#### **Organizational Partners**

**Cisco Systems Inc**

**Clarian Health**

**Indiana University Medical School**

**Florida A&M University**

**Indiana Health Industry Forum**

**Med Institute**

**Methodist Hospital of Indiana Inc**

**Micro Data Base Systems Inc**

**Ohio State University**

**Siemens Corporate Research**

**Spelman College**

**University of Delaware**

**University of Notre Dame**

**Internet2**

**Santa Fe Institute**

**Tuskegee University**

We have purchased and delivered to Tuskegee University a videoconferencing system to help them participate in our research seminars.

**Xerox Corporation**

**Other Collaborators or Contacts**

Fred Baker (Cisco)

E. Bertino (University of Milan)

Jennifer Hou (Ohio State University)

Andrea Lawrence (Spelman College)

Peiya Liu (Siemens Corporation)

Jon Reid (MDBS)

V. Verykios (Drexel University)

Deidre Williams (Florida A&M University)

Ashfaq Khokhar (University of Delaware)

Ben Teitelbaum (Internet2)

Suzanne Dulle (Santa Fe Institute)

Hira Narang (Tuskegee University)

Paul Barford (Univ. of Wisconsin)  
 Azer Bestavros (Boston Univ.)  
 Walter Willinger (AT&T Research)

### Activities and Findings

#### **Project Activities and Findings:**

We are pleased to report great strides in several areas. We have ordered most of the equipment on schedule for the first year and a half, we have been successful in getting the proper staffing, and we continue to involve faculty and students from historically black colleges and universities in our research activities. We continue to be successful in leveraging the NSF CISE RI funds in several significant and noticeable ways.

Equipment purchases to date, summarized by project area, include:

#### Networking

Cisco routers (4) for QoS experiments	\$100,520
Intel workstations (12)	\$26,935
Sun workstations (2)	\$6,990

#### Databases and Storage

Sun E450/A1000 database server	\$53,197
Intel-based storage server engine	\$4,905
Dell-based multimedia proxy servers (3)	\$20,858

#### Image Compression

SGI high resolution display	\$2,335
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#### Applications

Futuretel MPEG-2 encoder	\$5,520
Sony camcorder	\$3,429
Laptop computers (3) for distance learning	\$10,146
Workstation/printer accessories	\$1,062
Videoconferencing stations (3) and streamer	\$14,338

<b>Total</b>	<b>\$250,235</b>
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We have been extremely successful in obtaining research funds and grants from numerous sources. Noted among them is our recently awarded grant from the State of Indiana for supporting faculty and graduate students to conduct research and experimental development of a multimedia system for the telemedicine application. These funds are in direct support of this effort. The total funding from the State is over \$1.7 million for two years, starting February 1, 2000.

In addition, we have received the first year of cost sharing promised by Telcordia and we are in the process of obtaining the second year of funding. We have also established research collaboration in the area of multimedia document delivery with Siemens Corporation.

We have also received internal funding from the Center for Education and Research in Information Assurance and Security (CERIAS) to support one post doctoral fellow, a visiting scholar, and two graduate research assistants.

We are also pleased to report that our group has recently received two large grants, one from NCR/Wal-Mart and the other from Hewlett Packard (HP). The NCR grant is an unprecedented 1.6 terabyte parallel database engine valued at approximately \$7 million. This system will help augment the other storage and compute servers we are purchasing through the NSF grant. This state-of-the-art parallel server has 80 processors and 400 disk drives. The grant from HP allows us to have 20 workstations and one server to use as desktops for the researchers in this project. The NCR machine arrived on campus in late April and the HP machines are scheduled to arrive at the beginning of June.

We have received an National Science Foundation ITR grant (joint with Ohio State Univ. who is a subcontractor) for studying multiple time scale traffic control aspects of the network research component.

We have received a gift grant from the Xerox Foundation for studying the relationship between quality of service, network security, and fault-tolerance.

We have received funding from the Santa Fe Institute (SFI) and National Science Foundation for holding a joint SFI/NSF Workshop 'The Internet as a Large-Scale Complex System' (Chair: Kihong Park,

co-Chair: Walter Willinger), March 29-31, 2001. More information is available at <http://discuss.santafe.edu/internetcs>

We have received an NSF Career award to study efficient I/O techniques for a broad range of database applications. The project leverages the equipment that is being acquired through the MSI project.

The remainder of this section highlights specific activities in each of the three major areas of the project: multimedia databases and storage management systems, networking, and security.

#### Multimedia Databases and Storage Management Systems

There are four major research activities that we are currently pursuing:

1. Enabling content-based access to video data. We are pursuing activities aimed at developing a video database to allow content-based retrieval of large-scale video data as a critical component of multimedia document management system. We are developing techniques and tools for content-based retrieval, semantic browsing, and querying of video. This includes techniques for partitioning video sources into meaningful segments for providing more effective video representation and indexing, and the development of metadata to support fast and effective search and browse techniques for large-scale video. We are also incorporating MPEG-7 representation of multimedia contents in our system. The support of MPEG-7 will affect the schema representation and query management. We are working on developing a query manager that parses and executes MPEG-7 queries.
2. Adapting traditional databases to handle video data. The large data volume and continuous media properties of video has impact on the design of video database management systems (VDBMS) in the areas of storage, buffering, query processing, indexing and schema representation. We are developing a prototype video database management system that is capable of handling both raw video data as well as the associated meta data. The system uses SHORE, a system developed by Wisconsin, as a storage manager and PREDATOR, which is a value-added server for SHORE. We are also addressing the issue of indexing of video feature data to support similarity searching. Our approach is to develop dimension reduction technique in combination with semantic clustering by exploiting several types of features and the semantics of the video data.
3. Supporting end-to-end quality-of-service. Currently, we are exploring different approaches that will allow mapping of the user-specified Quality of Presentation (QoP) parameters to Quality of Service (QoS) requirements for different system components of the overall MSI architecture, including storage, servers, networking and security subsystems. The implementation of the translation mechanisms will be an integral part of the QoS-based resource scheduling modules that will be implemented using several dynamic and static approaches. We have designed an architecture for a real-time distributed multimedia database system (RTDMDS) for managing multimedia documents with Quality of Service (QoS) guarantees. This system is one of the key components of MSI. The system allows distributed users to author, store, query, and retrieve multimedia documents over a broadband network. We have developed several modules of RTDMDS and continue the development of the whole system using the equipment acquired through the NSF grant. We are also investigating QoS-sensitive storage of video data.
4. Developing techniques for the large scale storage of video data. For physical storage management of multimedia documents, we have designed several novel data placement and scheduling schemes. These schemes are currently being implemented on a Sun E450 server and a Sun A1000 Raid array, acquired through the NSF grant. Also, for video data, due to its unique temporal nature, we are analyzing several techniques for real-time disk scheduling. Managing large volumes of data necessitates the user of cheap tertiary storage. Due to the very high random access cost of tertiary storage, efficient management of data is critical for performance. We are developing data placement, migration, prefetching, caching, and scheduling schemes for the effective retrieval of video from secondary and tertiary storage.

#### Networking

À We have set forth a new unified theory of differentiated services that is implementable on IP networks. It improves on our earlier work on QoS scheduling, facilitating a theory of aggregate-flow QoS control.

À We have benchmarked the new architecture and theory using QSim, our ns-based WAN QoS simulator, confirming the theoretical predictions. Our work shows that differentiated services, following our architecture, can provide scalable and efficient user-specified services.

À We have installed Purdue Infobahn comprised of, presently, four Cisco 7206 VXR routers that form an IP-over-SONET QoS backbone. We have implemented initial signaling and end-to-end controls using both RSVP (Int-Serv) and AS (Diff-Serv) to ascertain the routers' operating capabilities.

. We have performed LAN-scale testing and benchmarking over the IP-over-SONET IP routers differentiated service provisioning, guaranteed service provisioning, and multiple time scale traffic control. Presently 12 PCs have dedicated connections to the testbed and are engaged as QoS flows and background traffic generators.

. We are generalizing the unified differentiated services framework to a queueing framework (m-class G/G/1 queueing system) which will provide the most comprehensive theory of aggregate-flow scheduling.

Security

À We are focusing our efforts to build security-based access control mechanisms for video and multimedia databases. For video databases, we are currently developing an access control system on top of a video database system. At the higher levels, we are developing an access control model that specifies the users' credentials and qualifications as well as the content description of the underlying video. On the other hand, at the lower levels, we are building a toolbox for extracting desired features from the underlying video streams. For multimedia document system, we are developing a security framework to allow integration of heterogeneous access control policies in a distributed environment.

À We have advanced and analyzed a denial-of-service (DoS) attack prevention framework based on probabilistic packet marking (PPM), and shown its effectiveness in the presence of single-source DoS attacks. We have used an adversarial framework to derive solutions to optimal decision making in a 2-player environment comprised of the attacker and victim/target.

À We have investigated the distributed DoS attack problem under PPM and general network topologies where the attacker can pick the location and number of attack hosts. We have shown that uncertainty factor amplification --- a measure of the attacker's ability to hide his true location(s) --- is achievable by reducing the attack volume at each individual attack site.

À We have investigated the network security architecture of Cisco's router operating system IOS with the aim of incorporating the adaptive security architecture AdSec into its structure.

Security

. We have proposed a new proactive architecture for distributed DoS prevention called route-based distributed packet filtering (DPF). Route-based DPF is the only known scalable solution to distributed DoS prevention. It is implementable in both inter- and intra-domain routing protocols (e.g., BGP, OSPF, RIP). It is expected that this component of the network security research will be funded by DARPA under the FTN program.

### **Project Training and Development:**

The findings in this section are organized according to the three major areas of the project: multimedia databases and storage management systems, networking, and security.

#### Multimedia Databases and Storage Management Systems

##### 1. Content-based Access to Video

À Video Content Analysis: We have developed a novel video shot detection and key frame extraction technique that can automatically adapt the threshold for shot detection according to the activities of different video sequences. Video objects and their trajectories are also exploited by a seed region aggregation and temporal tracking procedure. We have designed and implemented a system with feature extraction functionality. Two kinds of features are extracted: color histogram and camera motion. HSV color space is used to extract color histogram. The dimensions of each component are, H (quantized with 18 levels), and S and V (both quantized with 4 levels). Nine kinds of camera motion are extracted as camera motion features. With the system developed, the video can be processed with shot segmentation, camera motion extraction, hierarchical browsing and video feature extraction. With the results of the video analysis, two kinds of video retrieval can be performed with the system- Camera motion based video retrieval and key frame based video retrieval. In camera motion based retrieval strategy, user will select one kind of camera motion she/he is interested in, then push the 'Retrieval' button, system will return the shots which fit the query. In key frame based video retrieval, the user can browse the video at first, after he find out a certain frame which he is interested in, he may use it as the input



query. The system will extract the feature of the input frame immediately, then use the distance evaluation function to find out the similar shots in the video database.

À **Browsing Video Data:** We proposed an automated technique that combines manual input and knowledge produced by an automatic content characterization technique to build higher-level abstraction of video content. We developed a method based on description logics for automatically discovering structural associations within and between video sequences. The obtained abstraction of the contents of video sequences can be used, by navigating the graph structure, to decide whether the contents are relevant to the needs of users, and hence save user time and avoid unnecessary downloading of large files.

À **Querying Semi-structured Data:** We have designed a constraint-based framework for querying semi-structured data. We provided a class of path constraints of interest in connection with both structured and semi-structured databases. Our constraint language is inspired by Feature Logics. Feature descriptions are used as the main data structure of so-called unification grammars, which are a popular family of declarative formalisms for processing natural language. They provide for a partial description of abstract objects by means of functional attributes called features. On top of the constraints we allow the definition of relations by means of definite clauses. The query language we propose is based on the general scheme for handling clauses whose variables are constrained by an underlying constraint theory. Constraints can be seen as quantifier restrictions as they filter out the values that can be assigned to the variables of a clause in any of the models of the constraint theory. The language is a hybrid one in the sense that it combines clauses with path constraints. It has a clear declarative and operational semantics.

We have also developed a multimedia authoring, querying and presentation tool (MAQP) to compose, query and display multimedia documents. This tool provides a graphical user interface to compose a multimedia document and specify the QoP attributes of its objects along with their temporal ordering in the document.

## 2. Managing Video in Databases

À **Video Database (VDBMS) Prototype.** We have introduced streaming of video as an integrated functionality inside the database system. We are studying issues like providing fixed bandwidth for each request and modification to buffer management to handle real-time as well as non real-time requests. We have identified some bottlenecks in current DBMS design that are not suitable to process video requests. We have also experimented the current system under many concurrent requests for different streams and we are investigating scalability of the system to growing number of stream requests. Another important aspect in our work is logging and recovery of video data. This requirement is a consequence of storing the raw video data inside the DBMS. We are investigating current limitations of logging and recovery with huge amount of storage and long updates to binary contents. We have performed some experiments to identify the effect of physical logging of video updates on the overall system performance.

À **High-Dimensional Data.** In the VDBMS prototype we are developing, we have implemented the GiST indexing framework to realize the R\*-tree and the SR-tree as our high-dimensional index structure. In the literature, the SR-tree proved to outperform other R-tree variants. We are now investigating developing a general framework for high-dimensional indexing to flexibly choose the most suitable index structure for video data. On the other hand, we are investigating the use of semantic data clustering (using seed-based clustering algorithm) to build a semantic-aware index structure for video. Semantic clustering can serve as an efficient dimension reduction technique without the loss of the underlying semantics of video units.

## 3. Quality of Service in Video Databases

À **Quality-of-Service Aware Repository (QuaSAR) Architecture:** We have designed a system architecture that supports user quality-sensitive queries within a database framework. The proposed architecture relies upon the notion of QoS aware interfaces to the various components of the system such as the network layer and the operating system (encompassing CPU, main memory, and disk storage). These interfaces enable real-time determination of the status of the components with respect to the satisfaction of QoS constraints. In addition these interfaces will support reservation of resources to guarantee the ability to satisfy the user's requested level of quality. A key component of QuaSAR is the enhanced query processing capabilities in contrast to traditional databases. Based upon the content component of the query and the content metadata, alternative plans are generated for the retrieval of the relevant objects. Each plan is annotated with QoS parameters relevant to each component based upon translation of the user's quality parameters for the given plan. Each of the constraints represented by the annotations are tested through the interfaces, and if necessary reserve resources. If no feasible plan is found a negotiation step is invoked to adjust the constraints and re-evaluate the feasibility of the plan.

À **QoS Constraint Specification Language:** A language, in the style of constraint database languages, for formal specification of QoS constraints has been developed. We have shown that constrained rules are a valuable tool for specifying and managing quality of service in time-based media databases. We also described an algorithm for deciding whether a query 'matches' a specified quality of service. We show that the satisfaction by the system of the user quality requirements can be viewed as a constraint satisfaction problem, and that the re-

negotiation can be viewed as constraint relaxation.

À Distributed Proxies: We are developing distributed proxy architecture to allow QoS-based synchronization and caching of multimedia documents in a network environment. The key feature of this architecture is a centralized load balancing mechanism for the network proxy servers that uses a stochastic scheduling approach. Currently, we are simulating our approach using network traffic traces from the Lawrence Berkeley National Laboratory and the Technical University Berlin. In addition, we have implemented a media stream synchronization technique for distributed multimedia document servers.

À Security Constraints: In the area of multimedia database security, we have proposed a colored Petri-net based formalism to provide a multilevel security mechanism. In particular, the model allows specification of security attributes of multiple levels to manage access control to multimedia documents in a distributed multi-domain environment. The MAQP tool can provide such specifications as a part of the overall QoS requirements.

#### 4. Large Scale Video Storage

We have developed a novel hot prefix caching scheme for continuous media placement across the secondary-tertiary boundary. The key idea is to reserve a portion of secondary storage for storing the initial segments of continuous media objects in lieu of the traditional use as a cache for tertiary storage. These segments serve the purpose of masking the extremely high latency of random access to tertiary storage. In order to reduce jitter during playback of documents that are stored on tertiary storage, we propose the use of full replication. The proposed schemes are tested using a simulation of the system under conditions of concurrent access. Our results show that these two techniques result in significant reductions in the startup latency as well as jitter during playback. We are also investigating placement schemes for tertiary storage based upon access patterns that show relationships between documents or objects.

Popularity-based models have been proposed such that multimedia (video) data representation guides data placement on a tertiary storage subsystem. A two-level representation model is considered to capture the frequencies of accesses at external (video objects) and internal (video clips) levels. Video data placement is employed on a tertiary storage topology under three well known placement policies governed by the Organ-pipe, the Camel and the Simulated Annealing algorithms. The latter approach proves to be the most beneficial for the overall multimedia system's performance. Furthermore, QoS has been proposed in storage subsystem management towards effective disk space utilization and request servicing. A QoS based storage model for effective user negotiation in terms of scheduling, redundancy and number of storage devices has been developed. Users can create their own profile with respect to certain QoS attributes in order to specify their requirements. A hierarchical storage model with data elevation among various levels of the storage hierarchy has been simulated. Algorithms of placement among different levels of storage hierarchy and elevation issues have been investigated.

#### Networking

À Advance foundations of effective differentiated services architecture. We have developed a framework for reasoning about the 'goodness' of various differentiated services architectures, which considers both the per-hop behavior (PHB) and edge control parts when provisioning user-specified QoS-sensitive network services. In the PHB part, we have formulated the problem of optimal aggregate-flow per-hop behavior and solved it by showing the optimal aggregate-flow classifier that dominates all other per-hop behaviors with respect to both efficiency and fairness. We have shown that the optimal aggregate-flow classifier--implementable over IPv4 and IPv6 in modern routers and performing stateless per-hop control scheduling in linear time--satisfies certain properties (called (A1), (A2), and (B)) which allows desired end-to-end QoS to be achieved using edge control, both open-loop and closed-loop. Our framework, analysis machinery, and tools allows pressing questions such as 'what is the loss of power due to flow aggregation?', 'what is the impact of a discrete, bounded label set (DSCP in the DS field) on QoS?', 'what edge control can achieve setting of end-to-end TOS label values to achieve system optimal QoS?' to be answered both qualitatively and quantitatively. We have benchmarked the architecture over QSim, an ns-based WAN QoS simulation environment, and shown that optimal aggregate-flow per-hop behavior can export efficient differentiated services commensurate with user requirements.

À Configure Purdue Infobahn QoS Testbed and perform initial tests and exploratory implementations. As a starting point to implementing a full-fledged version of our optimal aggregate-flow classifier inside Cisco 7206 VXR routers with system support from Cisco, we have implemented end-to-end signaling controls, both for current IETF Diff-Serv specifications (i.e., Assured Service) and IETF integrated services (Int-Serv) using RSVP. Our end-to-end signaling platform can be adapted, with modular changes, to the optimal aggregate-flow per-hop control architecture advanced in our theoretical and simulation work. We have tested the real-time scheduling and switching capabilities of a network of Cisco 7206 VXR routers connected as an IP-over-SONET internetwork with 100 Mbps network interfaces tapping end station PCs -- serving both as QoS end points and traffic generators -- and ascertained their operating dimensions and properties with respect to yielding predictable performance. The latter include saturation effects stemming from processor scheduling and software switching overhead at the router. We are in the process of implementing the first version of optimal aggregate-flow PHB inside Cisco 7206 VXR routers, which will then be tested with respect to its QoS provisioning properties when incorporating all software and processing overheads associated with routers and end stations.

À Advance end-to-end traffic control for QoS shaping. We have developed and implemented end-to-end QoS amplification techniques

using adaptive packet-level forward error correction and multiple time scale traffic control. Adaptive FEC (AFEC) allows invariant end-to-end QoS to be exported over variable network conditions stemming from shared bottleneck routers and congestion effects. Since differentiated services-even in the presence of optimal aggregate-flow PHB-is subject to occasional variability due to imperfect QoS protection resulting from abstaining from per-flow reservation and admission control, AFEC can provide QoS amplification over varying degrees of imperfect QoS channels which can further improve the operating range and usefulness of differentiated services on top of scalability. We have advanced the multiple time scale (MTS) traffic control framework that exploits large time scale correlation structure present in bursty-in particular, self-similar-network traffic for traffic control purposes. An important consequence of MTS traffic control is the ability to mitigate the cost of feedback traffic controls in high delay-bandwidth product networks that which is especially pronounced in high-bandwidth wide area networks. By exploiting predictability structure resident at time scales exceeding the round-trip time (RTT) or feedback loop by an order of magnitude or more, timeliness of reactive can be achieved by bridging the 'uncertainty gap' inherent in reactive actions. Thus, MTS traffic control facilitates a much needed measure of proactivity, which, in turn, facilitates scalable end-to-end traffic and QoS control. MTS traffic control has been implemented both for QoS (a multiple time scale extension of AFEC called AFEC-MT), and throughput maximization for TCP (MTS extension called TCP-MT over Reno, Tahoe, and Vegas) and rate-based control for ATM. Multiple time scale redundancy control (i.e., AFEC-MT) has been benchmarked over UDP/IP internetworks that transport real-time MPEG I & II video and audio. The systems run both for UNIX and Windows NT. In the latter, the sender interfaces with a real-time MPEG compression board (Optibase I for MPEG I video/audio and Futuretel for MPEG II video/audio), which is fed by high-end digital and analog video cameras.

. We have implemented and tested both differentiated services and guaranteed services functionalities on Purdue Infobahn. We have observed that RSVP-based per-flow resource reservation shields user flows from the detrimental effects of cross-traffic whereas for differentiated services the achieved service level is more variable. The influence of processing speed of the router can be significant when subject to high load, and it is a characteristic that needs to be explicitly incorporated when computing end-to-end QoS assurances. The first service parallels the standardization effort under the auspices of the Internet2 QoS Working Group (co-PI Kihong Park is a member of the Architecture Design Team) which seeks to achieve robust Premium Service using IETF's Expedited Forwarding (EF) specification, however, using conventional per-flow reservation.

. We are generalizing the unified differentiated services framework to a queueing framework -- m-class G/G/1 queueing system -- which is the most general framework upon which to establish a theory of aggregate-flow scheduling. We have shown that aggregate-flow scheduling theory can be derived from the foundations of per-flow scheduling theory -- the same approach as followed in the previous optimal per-hop behavior work without queueing -- which uses the conservation law (a dot product functional which applies to all work-conserving schedulers and their queueing systems) as the basis upon which further refinements are carried out that incorporate ever more structure induced from the stochastic nature of the arrival process (e.g., m-class M/G/1, G/M/1, and M/G/infinity input). In terms of relevance, the new theory plays a similar role as RMS and EDF do for real-time scheduling where they are shown to be optimal for fixed and variable priority schedulers, respectively.

## Security

À For video databases, we have developed an access control mechanism that can allow different users to view different contents based on their qualifications and credentials. The units of access control can either be a sequence of one or more frames, or parts of a frame, e.g., objects in a frame. For multimedia document system, we have developed a Petri-net based model for role-based access control mechanism that allows selective viewing of different parts of document by authorized users.

À We have advanced a framework for probabilistic packet marking for distributed denial-of-service attack (DoS) prevention which puts forth an effective technique for dealing with an important security and QoS threat. Instead of logging path information at routers which makes traceback of DoS attack overhead-prone and ineffective in high-speed networks where routers are expected to switch at Gbps or higher rates, the complexity is pushed to the edge following the end-to-end paradigm, and 'logging' is carried out by probabilistic sampling of path information in an end-to-end manner. This method can be easily implemented in IP routers. Our work provides a comprehensive analysis of the power of probabilistic packet marking (PPM) with respect to DoS, both single-source and distributed. We use a 2-player adversarial framework to analyze the minimax and maximin optimal strategies of the attacker and victim, and show that PPM is effective at preventing DoS attacks. We show using numerical results the outcome of optimal strategies when using typical Internet based configurations including hop count, topology, spoofing, and marking probability.

. We have proposed a new proactive and scalable network architecture for distributed denial-of-service (DoS) attack prevention on the

Internet called route-based distributed packet filtering (DPF). We have shown that DPF achieves proactiveness and scalability, and we have shown that there is an intimate relationship between the effectiveness of DPF at mitigating distributed DoS (DDoS) attack and the recently discovered power-law Internet topology. The salient features of this work are two-fold. First, we have shown that DPF is able to proactively filter out a significant fraction of spoofed packet flows and prevent attack packets from reaching their targets in the first place. The IP flows that cannot be proactively curtailed are extremely sparse such that their origin can be localized--i.e., IP traceback--to within a small, constant number of candidate sites. We show that the two proactive and reactive performance effects can be achieved by implementing route-based filtering on less than 20% of Internet autonomous system (AS) sites. Second, we have shown that the two complementary performance measures are dependent on the properties of the underlying AS graph topology. In particular, we have shown that the power-law structure of Internet AS topology leads to connectivity properties which are crucial in facilitating the observed performance effects. As a DDoS prevention architecture, DPF is able to emulate the IP traceback prowess of probabilistic packet marking, while alleviating the latter's three principal weaknesses: (i) need to inscribe link information in the IP packet header, (ii) reactiveness--traceback occurs after the impact of DoS attack has been felt--and (iii) scalability where the effort needed to achieve IP traceback grows proportionally with the number of attack hosts engaged in a DDoS attack.

### Research Training:

The advanced multimedia course 'Multimedia Information Systems' taught by Ghafoor (co-PI) in Fall 1999 used the multimedia database servers (video data server) and exposed graduate students to state-of-the-art multimedia database and document management techniques.

The exploratory advanced networking course 'Multimedia and High-Speed Networks' taught by Park (co-PI) in Spring 2000 used the evolving Purdue Infobahn QoS Testbed, and exposed graduate students to state-of-the-art network QoS techniques and implementations.

Leveraging the QoS and traffic control work carried out in the Network Systems Lab, co-PI Kihong Park has forged a collaborative relationship with Internet2 to perform wide area network (WAN) QoS amplification experiments over Abilene/QBone, the Gbps backbone of Internet2.

### Outreach Activities:

Our outreach efforts have been more successful than we anticipated in the proposal. We have been able to involve four HBCUs instead of only one originally planned. Our efforts have been in getting faculty and students from Fisk, Florida A&M, Spelman, and Morehouse to get involved in this research project. To this end, we have organized a workshop for department heads at these schools at Purdue. We have plans underway for a larger summer program including:

À A two week workshop at Purdue to be held May 21 to June 1, 2001. This workshop will be attended by faculty representatives from each of the participating schools and up to five students from each institution. The two week program will consist of five two-day short courses: intensive review of programming languages and systems, database systems, computer networking, security, and multimedia computing. These courses will be taught by Professors Korb, Elmagarmid, Park, Spafford, and Ghafoor, respectively.

À Summer internships will be arranged for students from the workshop with Telcordia Technologies for the entire summer.

À Faculty from Purdue and faculty from the participating schools will visit periodically with the students during their internship.

À We will encourage students to apply to the masters and Ph.D. programs at Purdue.

Three additional programs have also evolved out of our workshop on May 22, 2000:

À Joint weekly seminar: Purdue will help the participating institutions to develop capabilities to attend a weekly seminar using video conferencing. The goal is to allow students and faculty at the participating institutions to attend the 'Advances in DBMS' weekly seminar. This will be first attempted in the fall semester to start in August 2000. Some institutions in close proximity will be encouraged to share the site such as Spelman and Morehouse.

À Joint colloquia program: Purdue faculty will periodically visit participating institutions and faculty from those institutions will be encouraged to visit Purdue to give seminars on research topics related to the subject of this project.

À Invite participating institutions to participate in our Web portal currently under development using state funding.

Kihong Park has interacted with members of the Santa Fe Institute in the capacity of Fellow-at-Large. Park is also organizing a workshop at the

Santa Fe Institute (for February 2001) called 'The Internet as a Complex System', which looks at scaling, performance, and control issues related to the Next Generation Internet. It is a by-invitation only meeting, and selected contributions will be published by Oxford Press as part of the SFI book series.

### **Journal Publications**

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### **Web/Internet Sites**

**URL(s):**

<http://www.cs.purdue.edu/msi>

**Description:**

The MSI site connects all the researchers and associated organizations working on this project. Additional URLs, linked from the MSI web page above, include...

Indiana Telemedicine Incubator

<http://www.cs.purdue.edu/icds/iti>

Indiana Center for Database Systems

<http://www.cs.purdue.edu/icds>

Distributed Multimedia Systems Lab

<http://shay.ecn.purdue.edu/~dmultlab>

Network Systems Lab

<http://www.cs.purdue.edu/ns1>

Center for Education and Research in Information Assurance and Security (CERIAS)

<http://www.cerias.purdue.edu/>

## Other Specific Products

### Contributions

#### **Contributions within Discipline:**

The RTDMDS architecture for the MSI framework is based on some of the most advanced techniques and models developed for multimedia document management and content-based retrieval of multimedia information. In particular, several novel techniques have been proposed by the PIs for the QoP-based specification of complex multimedia objects, video data modeling for efficient searching and querying of multimedia data and access control mechanisms for multimedia database systems. These techniques have the potentials of significantly advancing the Web-based multimedia information technology. In addition, the new techniques for multimedia storage management and access control will allow the development of high performance secure Web-based multimedia servers.

The network QoS architecture contains the some of the most advanced theory developed for differentiated services, with the potential to impact the design and implementation of the Next Generation Internet.

#### **Contributions to Other Disciplines:**

Several science and engineering disciplines can considerably reap the benefits from our research related to the MSI framework. In particular, the results and the products from the RTDMDS architecture can be directly extended to the GIS-based applications for the civil engineering discipline, to electronic publication and management of manuals and documents in industrial and mechanical engineering, and to telemedicine and digital library related science and engineering disciplines.

The optimal aggregate-flow switching theory in the networking area significantly advances the state-of-the-art in scheduling (electrical engineering, operations research, industrial engineering, applied mathematics), and the network QoS game theory advances the state-of-the-art in noncooperative game theory (economics, management science, applied mathematics).

#### **Contributions to Human Resource Development:**

Both our graduate students (Ph.D. and Master's) and undergraduate students get exposed to cutting edge material, encompassing both theory and implementation, related to the design and development of advanced multimedia database systems and broadband multimedia networking technologies. In the area of database the students learn the state-of-the-art techniques for storing, accessing, and delivery of multimedia documents in a distributed environment.

In the networking area, the leading edge research allows students to understand and experiment with the novel techniques needed for the design and development of the Next Generation Internet and its QoS provisioning architecture.

#### **Contributions to Science and Technology Infrastructure:**

Collaborative efforts, in particular, with industrial organizations foster technology transfer as well as collaborative research at the national and international scale. As a part of this project, we have been extremely successful in establishing collaboration with the several leading organizations that include Cisco, Sprint, Siemens, and many Indiana-based telemedicine and database companies. We also have close interaction with several academic organizations as listed at the beginning of the report.

#### **Beyond Science and Engineering:**

The success of the Next Generation Internet is one of the most pressing and important problems facing technological advancement of society today. The knowledge and experience gained from the network QoS project can have a significant impact on the development of the core international infrastructure critical to all other electronic infrastructures. The integration of secure multimedia document capabilities with this network infrastructure will have significant economic and social impact-and will help protect the environment by reducing our dependence on distribution media for videos, software, and data.

## Special Requirements

**Special reporting requirements:** None

**Change in Objectives or Scope:** None

**Unobligated Funds:**

\$0.00

**Animal, Human Subjects, Biohazards:** None

**Categories for which nothing is reported:**

Any Product