Microcomputers in Civil Engineering **12** (1997) 393–404

Multimedia Services for Highway Infrastructure Management

Kelvin C. P. Wang* & Xuyang Li

Department of Civil Engineering, 4190 Bell Engineering, University of Arkansas, Fayetteville, Arkansas 72701, USA

Abstract: *Photographic logging systems used by highway agencies provide engineers with information in the analysis of traffic accidents, design improvements, and highway pavement management. However, there exist limitations for such systems in the areas of accessibility, search capability of the image library, and synchronization video data with traditional engineering site data. More important, there are situations in which multiple users may need to examine the video footage at the same time. This capability cannot be provided by current systems. The analog nature of the video signals also presents difficulties in integrating the visual information with other types of data. This paper introduces a type of multimedia service that can be applied in a state highway department environment for highway infrastructure management. This multimedia-based information system utilizes state-of-the-art technologies in digital video, high-speed networking, and video server. This paper discusses the requirements of high-speed networking systems and presents a new computer network that has the potential to become a dominant technology for the transmission of multimedia data. In addition, design concerns regarding the video server and its structure are also discussed. A data-synchronization algorithm is also presented on how to dynamically display digital video frames with traditional engineering data sets that contain information such as as-built data, pavement condition and performance, traffic safety, geometric features, and other infrastructure data.*

1 INTRODUCTION

Visual information is used frequently in highway departments for their traffic engineering and infrastructure management. Another type of information is the tabulated site data organized in traditional engineering databases on pavement history and layer information, pavement width and type, average daily traffic (ADT), accident history, and signing and marking inventory. These two types of information (roadway images and traditional engineering databases) can be of daily benefit to the needs of various divisions in state highway departments. In order to improve data accessibility in a highway department, it will be very beneficial to combine these two information sources into one comprehensive database that can be accessed simultaneously.

However, virtually all the existing photographic logging systems used by various highway departments are analog-based and located at specific location(s) within the department. Simultaneous multiple accesses to the video data are not possible. Searching for site data is cumbersome. Traditional engineering site data are contained separately from the video databases. There were a few studies that tried to exploit new technologies to improve the accessibility and usability of video information collected from the photographic logging process. Wang et al.[6] presented general concepts and design issues for the development of a distributed multimedia-based highway information system (MMHIS) and discussed the economic and technical feasibility of using digital video and new networking technologies for such a system. It was concluded in that study that the latest technology allows such a system to be developed cost-effectively. This paper presents further studies in the areas of high-speed networking, video server technology, and data synchronization that are essential for implementation of an MMHIS. It is demonstrated that a future digital video–based highway information system will be efficient and productive through use of such technologies as Asynchronous Transfer Mode (ATM) and state-of-the-art video server devices.

* To whom correspondence should be addressed.

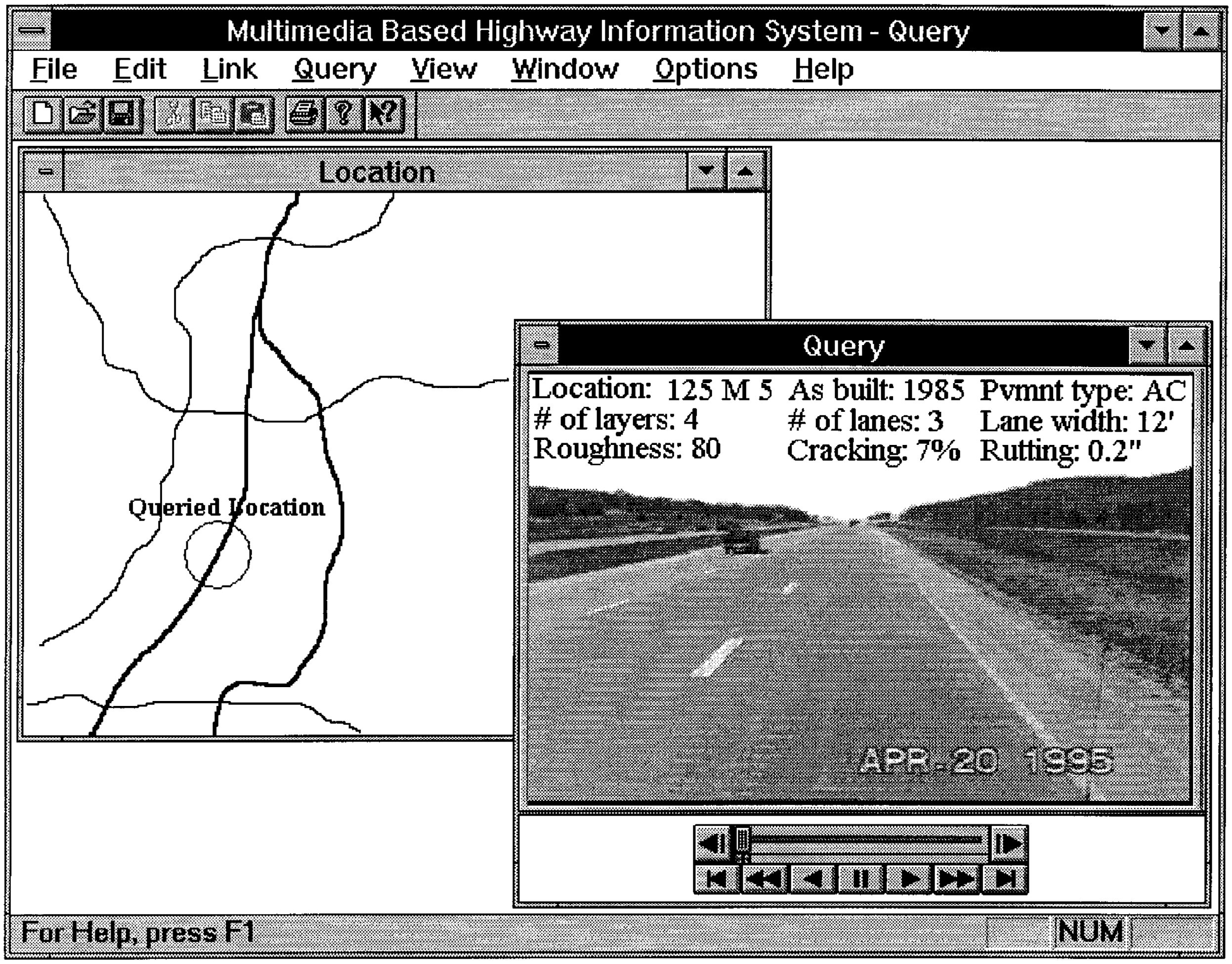

Fig. 1. An example of the MMHIS in a GIS shell.

2 DESCRIPTION OF MMHIS

Multimedia contain more than one type of data, such as a combination of video, graphics, and text. The combination of roadway visual data with traditional highway engineering databases results in a multimedia-based information system. If the multimedia-based databases can be distributed through the highway agency's computer networks, access to both types of information becomes immediate. This information system is therefore named a distributed *multimedia-based highway information system* (*MMHIS*).[6] The MMHIS can be integrated with a geographic information system (GIS) in order to give users visual information about the queried section of pavement. A user-friendly interface lets users select locations from one window and quickly view the associated video and its site data from another window. Figure 1 demonstrates a prototype of such a user interface at a client station.

2.1 Digital Video for MMHIS

The video quality associated with consumer television and videotapes, including video from super-VHS and laser disks, is determined by the analog video standards set by the National Television Standard Committee (NTSC) in 1953. Even though analog video signal can be transmitted and copied through narrow bandwidth, it is difficult to manipulate, copy, and distribute without introducing electronic *noise* into the original signal, resulting in the deterioration of image quality. Without the use of high-end video production equipment, the integration of analog video with other types of data, such as text and graphics, is very difficult.

Additionally, in an MMHIS, multiple users need simultaneous and random access to video data. For data stored in an analog system, multiple and unsynchronized access to video data is a problem. For instance, it is difficult to view two different sections of the same video tape simultaneously and then decide to freeze one while running the other. Routing of multiple analog video data to users is also complicated. If video signal is presented in digital format, as the digital sound in compact discs, it can provide much better image quality, can be duplicated easily and can be incorporated into other media without introducing artifacts or losing fidelity. Since digital video data are stored in disk files, it is possible to allow simultaneous multiple accesses to the same digital video files through computer networks. Digital video is necessary when high fidelity and fast and multiple user accesses are required of the MMHIS.

2.2 Compression and decompression (CODEC)

For the vast majority of digital video applications, data compression is needed to reduce data storage requirements, on the one hand, and to improve data flow rate, on the other. The amount of compression ranges from 2:1 to 200:1, depending on the type of algorithm, the implementation of the algorithm, the level of video quality, and the presence of hardware assistance. Most image-compression algorithms are *lossy*, meaning that information is lost during the compression of the data, due to the fact that the compression ratio based on *lossless* encoding algorithms is low, around 2:1. The objective for most applications is to retain visually faithful representations of the original images and discard any visually insignificant information. The process of *co*mpression and *dec*ompression (for playback) is called *CODEC* for encoding and decoding. Some approaches require more operations to be performed in encoding than in decoding. This type of CODEC is referred to as *asymmetrical*. If both processes require the same amount of processing, it is called *symmetrical* CODEC.

Motion JPEG and MPEG are the two dominant types of digital video CODECs, both of which are used in this MMHIS research. The Joint Photographic Experts Group (JPEG) developed the JPEG compression algorithm for still images based on discrete consine transformation (DCT), the quantization approach and Huffman encoding. The standard was then widely adopted as Motion JPEG for video sequences, each frame of which is compressed based on the JPEG standard. Motion JPEG allows easy random access to any frame in a digitized sequence. Compression for Motion JPEG is conducted exclusively on redundant data in individual frames without condensing any data between frames. Hardware-based JPEG CODEC can capture full-screen, full-rate video in real time. When a high compression ratio (over 20:1) is not required, this symmetrical CODEC is very effective in preserving the details and fidelity of single video frames.

Unlike JPEG, which condenses information only within each frame, the standard developed by the Motion Picture Experts Group (MPEG) compresses information based on data within a frame and frame-to-frame motion. It should be noted that the compression within frames in MPEG is also based on DCT and related algorithms.

MPEG allows compression ratios over 100:1 while still retaining good visual quality. Due to its high compression ratio, MPEG is a desirable delivery format for applications that require narrow-bandwidth transmission, such as CD-ROM and video networks. However, due to the asymmetrical nature of MPEG, the encoding process requires very high computing power. For example, a state-of-the-art MPEG encoding device can consist of 8 RISC-based compression processors. The decoding process of MPEG needs relatively less computing power. At similar levels of video quality, a Motion JPEG stream will require a much higher data rate than an MPEG compressed stream.

3 NETWORK PERFORMANCE REQUIREMENTS

A single digital video stream based on the NTSC standard has a data rate of about 0.5 to 2 Mb/s for the NTSC-resolution MPEG signals and 3 to 5 Mb/s for Motion JPEG. Common networks based on Token Ring or Ethernet have the shared data bandwidth of 16 and 10 Mb/s (2 and 1.25 Mb/s), respectively. The effective actual bandwidth available to a station can be much less than the specified rate of 16 Mb/s or 10 Mb/s, due to (1) the nature of bandwidth sharing for both Ethernet and Token Ring and (2) network overhead. In addition, the two types of networks are optimized for carrying packet and bursty data and do a poor job of carrying full-motion video, which requires guaranteed bandwidth. In order to provide multiple streams of video data (more than 10), the throughput of the traditional networks needs to be improved drastically, and the bandwidth for individual stations needs to be guaranteed. Furthermore, it is required that video streams be delivered in a particular order with very small and consistent latency. Otherwise, frame drop and unsynchronization occur. Both Ethernet and Token Ring cannot guarantee the timely delivery of motion video. Even though FDDI and some other fast-network technologies provide a 100-Mb/s data rate, they have similar disadvantages of using a shared medium and of not being capable of carrying motion video in a timely fashion. Therefore, the challenge is to design a proper network to provide both high bandwidth and guaranteed video delivery.

The MMHIS-capable computer network in a highway department should be able to carry a number of services, including low-speed data transmission for regular data sets and mail, medium-speed transmission for CAD files, and high-speed transmission for the distribution of high-quality video footage of highway sections (see Fig. 2). Therefore, the network system cannot be designed specifically for one service. Figure 3 shows a range of services with an estimated bit rate of a few bit per second up to some hundreds of megabits per second. The holding times (continuous transmission period) vary from seconds to hours.

The data rate of MPEG video streams is variable in nature,

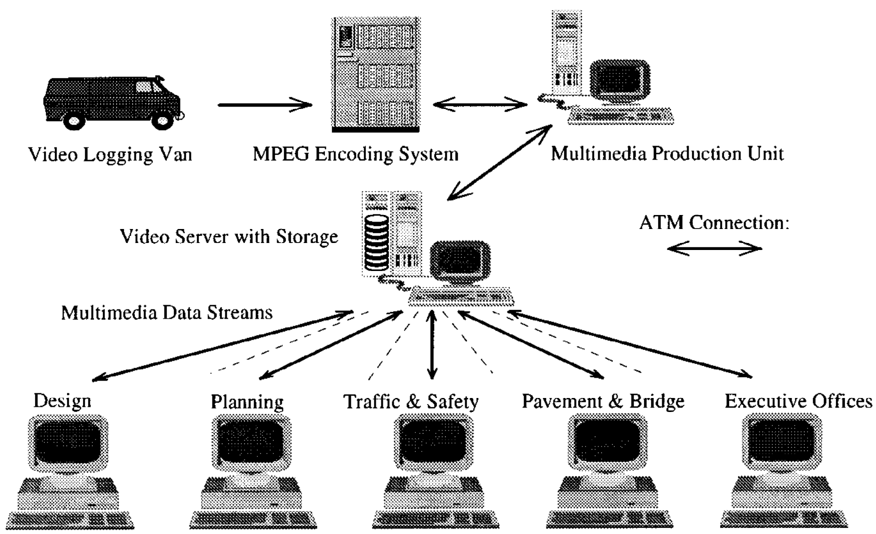

Fig. 2. Video data flow in the MMHIS for a state highway department.

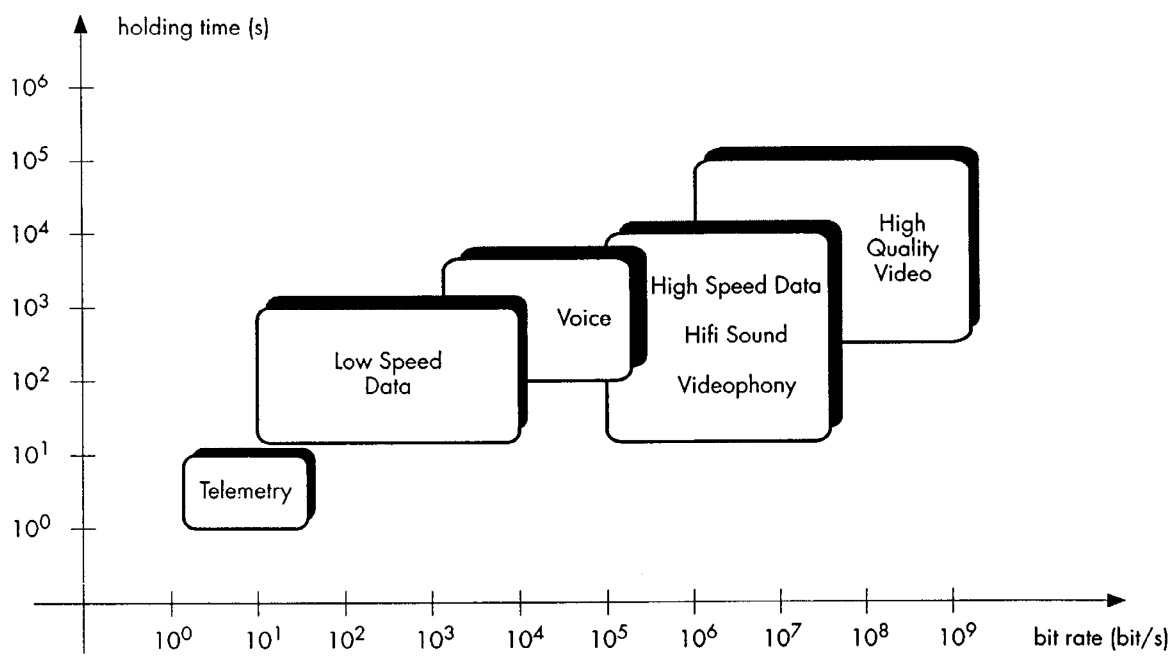

Fig. 3. Range of services in a multimedia network. (*Based on Prycker.*[3])

as illustrated in Fig. 4. It can be represented by a stochastic process $s(t)$. Assuming this stochastic process lasts for duration T of the video transfer, the peak bit rate S and average bit rate $E[s(t)]$ can be obtained over duration T:

$$S = \max s(t) \tag{1}$$

$$E[s(t)] = \frac{1}{T}\int s(t)\,dt \tag{2}$$

The ratio of the maximum rate over the average rate is called the *burstiness* B:

$$B = \frac{S}{E[s(t)]} \tag{3}$$

Even though the stochastic process $s(t)$ has different characteristics for each session of a service, the average and peak rates are typical of a service. For instance, an MPEG stream

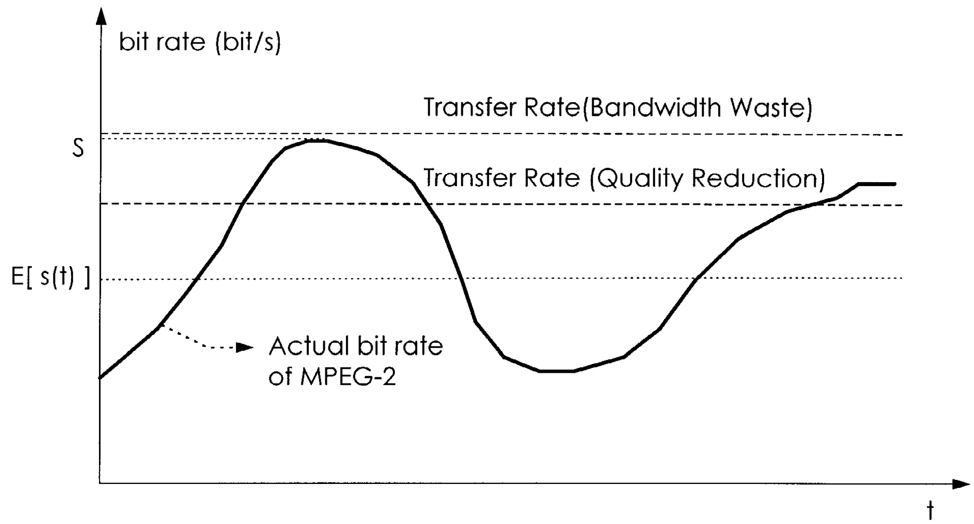

Fig. 4. Fluctuation of video stream rate.

may present a peak rate of 15 Mb/s and an average rate of 4 Mb/s. It should be noted that every type of service has the characteristics of burstiness, with $B > 1$. Figure 4 also illustrates two scenarios for the network transfer rate. One transfer rate is less than S but higher than $E[s(t)]$. Apparently, video quality is affected in this scenario, since some bits are discarded to accommodate the inadequate transfer rate, resulting in transmission errors. In the second scenario, the transfer rate is higher than the peak bit rate of the video stream. However, bandwidth is wasted when the bit rate is less than the peak bit rate. In relation to the transmission errors introduced by limited transfer rate and other hardware and software constraints, the term *semantic transparency* is used to determine the capability of the network to transport data accurately from source to destination. Another critical factor in the transmission of video streams is the timely delivery of requested data, or *time transparency*.

Ethernet and Token Ring technologies are limited in their bandwidth and capabilities of ensuring timely delivery of multimedia data. Recently, switched Ethernet has become a cost-effective approach to increase the available bandwidth from a station to a server. In a switched Ethernet–based network, every station has a dedicated bandwidth of 10 Mb/s to the switch that has a bigger data pipe to the server with 100-Mb/s bandwidth. The 100-Mb/s Ethernet link from the server to the switch is called a type of fast Ethernet technology. Even though data throughput is increased in the switched Ethernet, the inherent limitations of Ethernet still remain in the area of time transparencies. For instance, when an MPEG-2 video stream at 4 to 8 Mb/s is requested from a client and at the same time a CAD file gets transmitted from the server to another client, there is no guarantee that the video stream will be delivered uninterrupted. Most likely jitters will occur in the video stream at the client station. In reality, there could be many data transmissions underway at a particular point in time in the network. Apparently, even switched Ethernet is not a good solution to the problem of providing guaranteed bandwidth for the MMHIS system or for any type of distributed multimedia service with a high video quality requirement.

In the last decade, tremendous research has been conducted by both telecommunications and computer network industries in the area of providing high-quality data service with guaranteed bandwidth in computer networks. A technology called *Asynchronous Transfer Mode* (ATM) has emerged as the dominant approach to solve wide- and local-area data transmission problems by providing very high speed connection with guaranteed bandwidth for various types of services, including bandwidth-hungry video/audio transmissions.

4 ASYNCHRONOUS TRANSFER MODE (ATM) AND GIGABIT MMHIS

ATM is an extremely fast, high-bandwidth packet-switching technology invented by the telecommunications industry. In an ATM environment, computers are connected through adapter cards and network wire to a central ATM switch. ATM breaks all traffic (voice, video, and data) into equal-sized 53-byte short packets known as *cells*. Each cell has a 5-byte header. Therefore, the user data in each cell amounts to 48 bytes, or 90% of the total data. The size of the 48-byte information field in the ATM cell was determined through compromise by the two industry groups in Europe and United States, which preferred 32-byte and 64-byte cell sizes, respectively. In return for the 10% overhead, ATM brings two benefits. First, its short, fixed-length cell makes ATM better than frame relay and existing LAN protocols, which all use variable-length packets, for carrying real-time data and multimedia applications. Second, ATM's short-packet format enables the cells to be formed and routed almost entirely in hardware. This hardware capability is likely to allow far faster network speeds than are possible with today's multiprotocol routers, which rely on software to handle the bulk of the switching task. More important, ATM's speed is scalable up to many gigabits per second.[4] The resulting bandwidth is available from each station to a server or another station, which poses a big advantage over the shared bandwidth technology in Token Ring, Ethernet, and FDDI. *Asynchronous* in ATM comes from the fact that cells headed to a destination appear at varying intervals. Therefore, it is allowed to perform asynchronous operations between the sender clock and the receiver clock. The difference between the clocks can be solved by using empty cells that do not contain useful information.

4.1 ATM performance characteristics

Neither error protection nor flow control is provided on a link-by-link basis in an ATM network. The links in ATM networks have a very high quality, or a low bit error rate (BER). The omission of an error-correction protocol improves data transmission efficiency. In addition, ATM operates in a connection-oriented mode, which allows the network to guarantee a minimal cell loss ratio and therefore maximum quality. As a result, flow control, which is used frequently in other computer networks, is not needed for ATM. At call setup, if enough resources in the network are available, the connection is then realized. When the connection is established, the probability of overflowing the network is very small, less than 10^{-8}.[5]

Delay issues in time transparency are mainly applicable to real-time services such as MMHIS. Other computer data transmissions are not particularly sensitive to delays, such as CAD file transmission. In addition, due to the lack of error-correction protocols in ATM, three sources of error determine the overall BER in an ATM network: error in the information field in the ATM cell, error in the header field in the ATM cell, and queuing overflow resulting in loss of cells in the switch.

In an LAN-based ATM environment, the delay times include (1) the distance dependent transmission delay (TD), (2) packetization delay (PD) at the sender end, (3) depacketization delay (DD) at the receiver end, and (4) switching delay (SD). The size of ATM cell affects the overall network delay, the transmission efficiency, and the implementation complexity. It has been shown that when the size of the ATM cell (packet) is fixed to 53 bytes, the total delay is limited, which is an advantage for real-time services.[5]

4.2 Quality of service (QoS)

Properly implemented ATM networks solve the major problems of existing popular networks in the two areas of high-speed interfaces and multimedia support with video, voice, and data in one transfer. Constant bit rate (CBR) and variable bit rate (VBR) are typically for the transmission of voice and video, respectively. Unspecified bit rate (UBR) and available bit rate (ABR) can be used for regular data traffic. Each traffic type requires a different quality of service (QoS) with properties such as the amount of bandwidth reserved, delay tolerance, and variation.

QoS of a connection is a general indicator relating to cell loss, delay, and delay variation incurred by the cells belonging to that connection in an ATM network. It represents user perception of service quality at the receiving end of the network. It is a function of terminal capability (bit rate) and network performance. The bit rate ranges from videophone at very low rate of 64 Kb/s to high-definition television at over 20 Mb/s. The bandwidth management, key to the support of multiple services on ATM, guarantees QoS for high-priority, delay-sensitive CBR and VBR traffic while providing bursty UBR and ABR traffic with fair access to the remaining network bandwidth.

4.3 Gigabit local networking for MMHIS

In an MMHIS, a number of computers connected through a network medium are used to transmit and receive high-quality video streams and regular engineering databases. The MMHIS needs to be scalable to accommodate the data rate of future digital television standards. For instance, one uncompressed high-definition television (HDTV) stream carries a data rate of over 1 Gb/s. The compression ratio for an HDTV signal can be from 20:1 to 50:1. Based on a study by Kinoshita et al.,[1] the peak rate can be 65Mb/s and average 10 to 20 Mb/s for one HDTV stream transmission in an ATM network. Based on experience with a state highway agency (SHA), the possible number of simultaneous users accessing video and data streams can be as high as 50. Therefore, the aggregated data rate in an MMHIS network will well exceed 1 Gb/s when HDTV-level video streams are used.

A gigabit LAN is a LAN for which the physical communication medium has a peak bandwidth on the order of 1 Gb/s or higher and for which an end user is able to realize this gigabit performance.[2] Clearly, an MMHIS-based network will be a gigabit LAN. In high-speed networks, the specification for transmission protocols follows the SONET (Synchronous Optical Network) standards based on the base signal rate of 51.84 Mb/s, which is commonly referred to as OC-1. The higher speeds are OC-3, OC-12, OC-24, and OC-48, with the speeds of 155.52 and 622 Mb/s and 1.244 and 2.488 Gb/s, respectively. ATM adapter cards at OC-3 speed are widely available. Many LAN-based ATM switches have an aggregated data rate at or over the OC-48 specification.

5 THE VIDEO AND STORAGE SERVER

Transmission of multiple digital video streams requires very high and consistent data throughput for every subsystem in the MMHIS that processes the streams. The subsystems include the desktop's CPU, bus, and display card; the networking devices (adapters and switch); and the video server and storage. Special attention needs to be paid to the capabilities of the video server and video storage. For example, a traditional uniprocessor-based server is not able to handle multiple video streams, and virtually all existing video servers are based on the powerful symmetrical multiprocessing structure with multiple microprocessors. Multimedia also require huge data storage and a very high and sustained data rate. Storage size and sustainable speed are two critical factors for implementation of the storage server of MMHIS.

5.1 Issues related to multimedia-oriented network operating systems

In a multimedia application, it is required that large blocks of digital video/audio data be transferred simultaneously and continuously in order to ensure the high degree of consistency in picture frame and synchronization with audio or other data. The dominant network operating systems used today do not have the capability to coordinate video data flow sufficiently to ensure video quality on the clients' desktops. The current network management software emphasizes data integrity through error control protocols. Therefore, it is imperative to ensure that video/audio data steams flow at consistent latency in the network and that no traffic cloggs for video/audio data occur. It should be noted that even though many ATM standards have been set, some important standards regarding QoS and MPEG-2 video transmission are not ready yet.

Protocols are software layers in the network that ensure that data arrive without errors and that traffic flows are regulated properly. For video/audio data, a special video protocol is necessary to make sure that there is a highly reliable connection for an uninterrupted stream of data. The flow of regular data can be conducted through the normal protocols. With this *parallel-protocol approach*, video/audio data will have priority over other data flows. Normal data flows yield the right of way to video/audio data. The challenge in developing a continuous-media software solution for video lies in managing the large number of data streams leaving the server. A critical technique in developing such a solution is through the use of a set of ATM-specific application programming interfaces (APIs). The new Winsock 2 specification that includes ATM APIs as standard features will be used in the development of MMHIS.

5.2 Requirements for the multimedia storage server

MMHIS consists of client stations, one or more storage systems, a high-speed ATM network, real-time service-oriented operating systems, and customized applications such as shown in Fig. 1. The client stations are able to receive very fast ATM cells, repacketize them, and decode the video data and display the motion video to the computer screen with synchronized engineering data sets. The storage system should be able to simultaneously process multiple requests for video and data streams and send the requested data fast enough to the clients through the ATM network.

There are four fundamental characteristics of the storage server for MMHIS:

- Real-time storage and retrieval of continuous video media
- Large data transfer rate and huge storage space requirement
- Dynamic synchronization with and display of traditional engineering data sets with the video frames
- Multiple simultaneous access to the video and data files

The storage requirement of video footage at MPEG-2 quality (average 5 Mb/s) is about 222 GB for a typical 5000-lane-mile interstate system when the video is recorded at the speed of 50 mi/h. This huge storage needs to be randomly accessed by multiple users at any point of the video footage.

Continuous playback of a video stream consists of a sequence of retrieving video blocks from server disks with scheduled play time. It is possible to fetch the video stream from the server fast enough to be played back at the client station. However, the bursty nature of data retrieval from disks does not guarantee continuous operation of video display. Quite possibly, there will be disruptions of display due to inadequate video data. Therefore, a buffer storage needs to be used at the client station or the server to contain the video stream before it is played, as shown in Fig. 5. Buffering is both expensive and time-consuming. The goal is to design a system that would prevent the client from starvation for video data and at the same time minimize buffer space and initialization latency. Employing modest amounts of buffering enables conventional file and operating systems to support continuous storage and retrieval of isolated video streams.

The multimedia storage server has to process requests from several clients simultaneously. More often than not, different clients may request to view different locations of the highway video footage.

5.3 File system for the server

The following factors need to be considered for the server storage:

- Simple, hierarchical directory structure
- Efficient use of low-cost, high-capacity disk drives

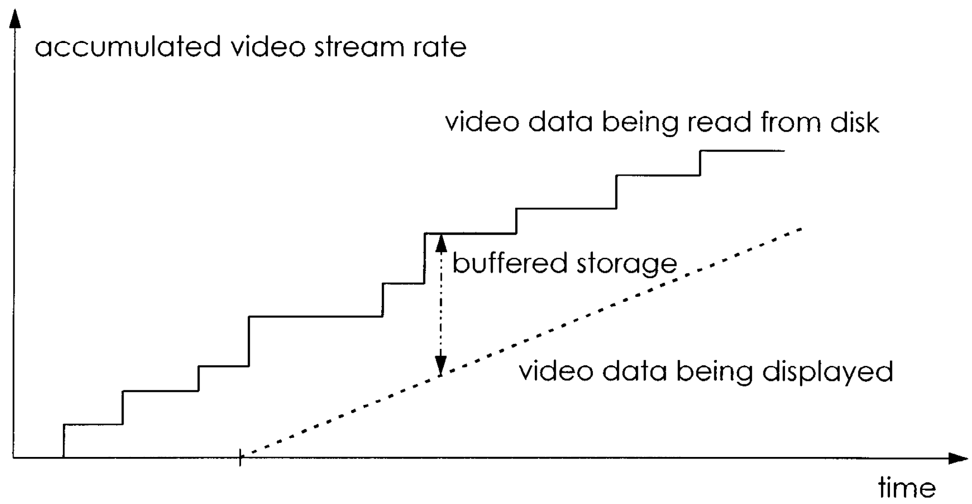

Fig. 5. Buffering scheme for video stream playback.

- Efficient handling of both large and small file system objects
- Optimization for sequential access rather than random access

In addition, it is not necessary nor possible to optimize access based on a drive's physical geometry. It is not even possible to find out the real drive geometry at all: track and sector sparing, automatic sector reassignment, etc. The actual disk layout is completely hidden from the user and optimized for large sequential accesses. Most new drives have large data buffers and perform read-ahead and write-behind. The best way to get optimal performance is to stream large amounts of sequential data in a manner similar to tape handling. Therefore, the filing system for the video server should be able to

- Lay the disk out so that objects are in large, sequential chunks
- Allocate I/O buffers so that transactions are as large as possible
- Minimize the amount of disk seeking

The algorithm to be used is straightforward: assuming that all new files are going to be large and that disk space can then be reserved accordingly. Therefore, when allocating space for a file, reserve a large, contiguous chunk at the beginning, and then use up the reservation as needed. As a video file grows, extra contiguous chunks are reserved. When the file is closed, the unused space is freed. In MMHIS, one large video file can be used to cover a few hundreds of miles of roadway. This file may need to be updated only annually. Therefore, this filing system is applicable for MMHIS. In addition, only read is allowed on video files in an MMHIS system, which simplifies the optimization of the file structure due to the unnecessary frequent "write" capability. Even though this algorithm has a tendency to fragment the space, since the contiguous files are very large with the sizes of gigabytes, the side effect of spare blocks is small.

In the task of optimization for sequential access, it is realized that in an MMHIS system, the accesses to video files are read-only operations and sequential in nature. However, the initialization of viewing request is random in nature. For instance, multiple users may request to view any section of the roadway at the same time.

It should be noted that cache strategies used frequently to improve storage performance do not apply to video files. Video files used in MMHIS are gigabytes in size. The application of cache can only add overhead to a disk streaming operation, and the size of any type of cache is much smaller than a typical video file in MMHIS.

5.4 Disk arrays for server storage

The sustained bandwidth of a single hard drive can be as high as over 10 Mb/s for sequential access. However, when multiple users access the video file(s) in a single drive, the available bandwidth for an individual user's video stream is much less than the average theoretical rate, e.g., 10 Mb/s divided by the number of users. The overhead is due to head-seeking time and disk management. Therefore, the structure of putting a number of drives to a Small Computer System Interface (SCSI) channel will not be able to adequately serve multiple users.

A technology called *Redundant Arrays of Inexpensive Disks* (RAID) is used widely to overcome the inherent limitations of a single disk drive. Various RAID configurations are designed to address either performance or reliability. RAID comes in several flavors from levels zero through five. Each level is optimized for various capabilities, including improved performance of read or write operations and improved data availability through redundant copies or parity checking.

The computer industry's experience with SCSI has brought to light the need for improvements in versatility and throughput. For instance, even in a system based on RAID and SCSI-2, the storage's maximum sustainable rate is about 20 Mb/s. New applications, such as video and image processing, have created a demand for huge increases in storage capacity. Some capacity requirements are so large that it is difficult to configure enough SCSI buses to make sufficient drive addresses available to attach the needed number of drives.

One solution is a relatively new technology called *Fiber Channel*. Fiber Channel is an industry-standard interface adopted by the American National Standards Institute. The existing implementation of Fiber Channel is called *Fiber Channel–Arbitrated Loop* (FC-AL). FA-CL has made it possible for Fiber Channel to be used as a direct disk attachment interface for I/O performance-intensive systems. SCSI-3 (Small Computer Systems Interface-3) has been defined as the disk protocol, which is also technically referred to as the *SCSI-FCP*.

The Fiber Channel interface is a loop architecture as opposed to being a buslike standard SCSI-2. The Fiber Channel loop can have any combination of hosts and disks up to a maximum of 126 devices and provide 100 Mb/s of bandwidth. The maximum cable distance can be as long as 10 km. In addition, Fiber Channel is a generic standard interface supporting many protocols, such as SCSI, Internet Protocol, and ATM. The loop structure enables the rapid exchange of data from device to device. Devices can be removed or inserted without disrupting the operation of the loop. The drives attach directly to the backplane for both signal and power. Neither jumpers nor switches need be set on the drive. The controller determines a drive's address from either the relative position on the backplane or the drive's unique IEEE Fiber Channel address.

6 DEVELOPMENT APPROACH

The current data collection for this MMHIS is conducted in a van, as shown in Fig. 2, which use super-VHS or similar quality system for video recording. The source video is then sent to the compression system for MPEG encoding. Figure 2 also illustrates the multimedia data flow within a state highway department. ATM networking technology is used in MMHIS to link the client stations, the production station, the server, and the encoding system.

A Motion JPEG–comparable video stream in MPEG format is normally referred to a type of high-quality MPEG specification that is MPEG-2 of Main Profile at Main Level. A combination of profile and level determines the frame rate and size. For example, MPEG-2 of Main Profile at High Level Type 1 is to be used for U.S. HDTV with the resolution of 1152 lines per frame, 1920 pixels per line, and 30 frames per second.[3] The current mainstream MPEG-2 is Main Profile at Main Level with resolution of 720 by 480. It is determined that in order to provide useful video information for highway engineering work, high-quality digital video for MMHIS is required. Either MPEG-2 or Motion JPEG can provide super-VHS or higher quality, which meets the quality requirement. Even though Motion JPEG–based CODEC provides very high quality video, it requires over 5 times more data throughput than a comparable-quality MPEG video stream. Therefore, MPEG-2 of Main Profile at Main Level is used in the actual development of MMHIS.

6.1 The hardware structure for the MMHIS

Client and server. Based on current practices of highway agencies and the fast-growing capabilities of the Intel x86 processor and related I/O subsystems, the hardware platforms for both the video server and clients are going to be Pentium or better computers. The video server is symmetrically based with four or more state-of-the-art Intel processors to distribute the management of data streams among processors. The computer bus is based on PCI with a peak I/O bandwidth of 132 MB/s.

Storage. The storage requirement of video footage at MPEG-2 quality (average 5 Mb/s) is about 222 GB for a typical 5000-lane-mile interstate system when the video is recorded at the speed of 50 mi/h. The sustained throughput for the video storage is one of the critical elements in the MMHIS to ensure timely delivery of multiple video streams to the desktop computers. Fiber Channel and RAID-3 will be used as the server storage technology.

ATM-based networking devices, including adapter card for each computer and switch(*es*). OC-3 based 155Mbps cards and a 2.5Gbps ATM switch are used in the development.

One MPEG-2 encoder of Main Profile at Main Level. Only one encoder is needed for a production-level MMHIS. A set of MPEG-2 decoder and video cards is used for each client station. Many vendors have developed combo PCI-based video cards that overlay MPEG-quality motion video on the computer screen. New MPEG-2–based combo video cards will be used in this MMHIS, which allow overlay of MPEG-2 video on the computer screen of a client station.

6.2 Software issue of data synchronization in MMHIS

The 32-bit ATM APIs from Winsock Version 2 will be used to develop the video delivery system for the network. Oracle Relational Database Manager will be used in the development. Intergraph's solution to geographical information sys-

Table 1
Frame index file

Field	*Meaning*	*Type*
rowid	Serial number for the current record	Long integer
vfname	Video file name	Character string
sframe	Start frame	Long integer
eframe	End frame	Long integer
rtno	Route number	Character string
dir	Direction	Character string
mp	Mile post	Integer
caption	A name of this section of highway (used as the caption of the application window)	Character string
left1	Row id of the first left turn road (−1 means n/a)	Long integer
left2	Row id of the second left turn road (−1 means n/a)	Long integer
through	Row id of the through road (−1 means n/a)	Long integer
right1	Row id of the first right turn road (−1 means n/a)	Long integer
right2	Row id of the second right turn road (−1 means n/a)	Long integer

tem, MGE, will be used as the visual environment for data query of MMHIS.

A key feature of this MMHIS is the synchronization of tabulated site data with video frames. In Fig. 1, the site data on the upper portion of the video shows various engineering information about the particular highway section. Since video database and site database are separate data files, the synchronization of the two sets of data becomes important.

The approach to dynamically link regular database records with video frames is shown in Fig. 6. In this approach, a database filter is used to connect the traditional engineering databases with the video stream. Each roadway section contains unique data on as-built, pavement condition, ride quality, accident history, and others. The visual presentation of engineering data dynamically synchronized with video frames is a critical feature of this information system. Users will not need to reference a second information source for site engineering data any more. Engineering site data will be displayed dynamically with the moving video frames.

The algorithm to achieve this capability is based on the Open Data Base Connectivity (ODBC) standard, which is the database filter, and proper cache subsystem. In order to make the information system compatible with the major database systems, such as Oracle, dBase, FoxPro, Access, and others, a data filter needs to be applied to the source engineering database. ODBC presents an industry standard to interface a customized application with various relational databases. It is a standard application programming interface (API) for accessing data in both relational and nonrelational database management systems (DBMSs). Using the ODBC API, applications can access data stored in a variety of personal computer, minicomputer, and mainframe DBMSs, even when each DBMS uses a different data storage format and programming interface. ODBC data query can be achieved by using Structured Query Language (SQL) commands. In addition, a software-based cache subsystem needs to be built into the client stations so that adequate video and site data are available to be synchronized and displayed.

In the software program for MMHIS, two databases were involved in the synchronization of the video and site data display. The first database contains engineering site data for roadway sections. The Arizona database file was used as the site data database. This database was created with FoxPro. It contains the following key fields: RTNO (route number), D (direction), and MP (mile post). These fields were used to specify highway sections.

The second database contains frame indexes for the video files. To synchronize the display of the video with the corresponding site data, a frame index file was used. The file was in comma-delimited text format. The restriction with text files is that the database cannot be indexed, so the data retrieval speed is slow. To solve this problem, a different database format can be used in future implementations. The frame index file contains the fields listed in Table 1.

The MMHIS interface and database program were implemented on the Windows NT operating system. Two windows were used in this program to display video and site data, respectively. When the video is being played in video window, the site data window checks the frame number of the video window at fixed intervals using a timer installed at creation

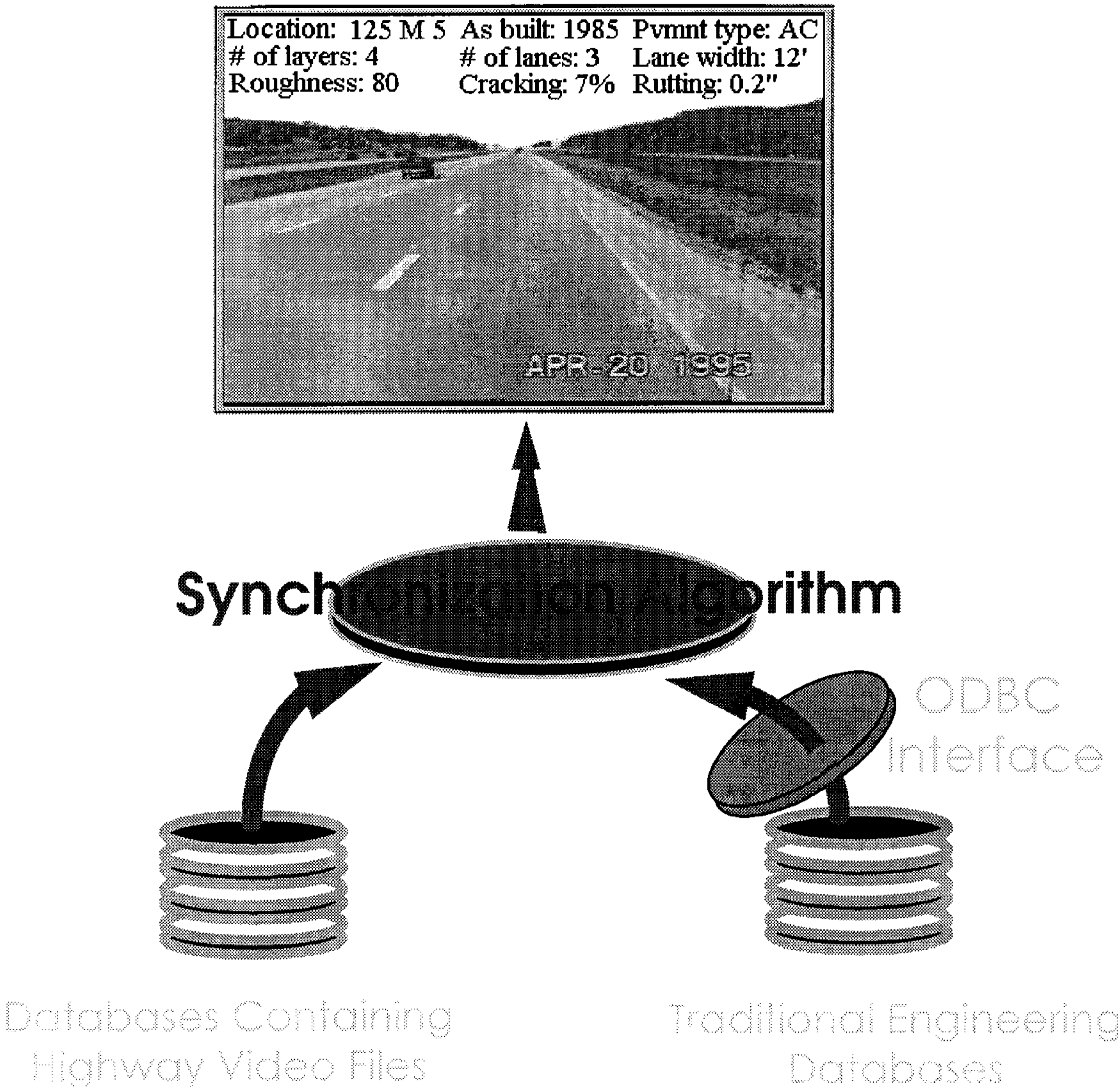

Fig. 6. The approach to synchronize video with roadway engineering database.

time. If the current frame is not in the range currently saved in memory, it does a data query from the index file to find the proper range (defined by sframe and eframe) and updates the range saved in memory. In the meantime, the corresponding route number, direction, and mile post are also retrieved from the same database. Using these values, it opens the site data database to find out the corresponding site data. It then displays the query result in the site data window using one of several predefined formats. A range that is never used by any video file is set at the beginning of program execution to force a first-time retrieval of data from the databases.

It is important for the frame index file to contain accurate information on synchronization. The frame index file used in the prototype MMHIS system was created directly using its internal format. Since this is the first time site data are synchronized with the video, human judgment is needed to initialize the frame index file. In future implementations, the frame index file will be created by a user-friendly system initialization and maintenance module of the MMHIS system.

7 CONCLUSION

High-performance network, powerful video, and storage servers are key components of the MMHIS. In order to supply a high-quality multimedia service for highway infrastructure management, the application of new technologies such as ATM and RAID is necessary. In addition to the installation of ATM network systems in the headquarters in a highway department, the distribution of hard-copy video disks to remote district offices may be a plausible alternative to building a wide-area–based ATM network. For example, the maximum capacity of a new kind of CD, the Digital Versatile Disk (DVD), is 18.8 GB, which can hold 400 lane-miles of video information at MPEG-2 quality. The implementability of an MMHIS needs to satisfy three factors: (1) maturity of hardware and database technologies, (2) acceptable implementation costs, and (3) high video quality and resolution. Implementation costs can be high at this time. However, preliminary highway site inspection normally involves two people and can take as much time as 2 to 3 days. If such trips can be mostly reduced or even eliminated through the use of MMHIS, the funds for 1 year's travel and labor expenses can be used to build an MMHIS. For instance, if a total of 500 preliminary field trips are taken in a state highway department and the average cost for each trip is $500, the total saving over 1 year is $250,000, which is adequate to cover all the hardware cost for a 20-client setup, the network, an ATM switch, and encoding and decoding devices. Therefore, it will not be long when such a system is put to use.

REFERENCES

1. Kinoshita, T., Nakahashi, T. & Maruyama, M., Variable-bit-rate HDTV CODEC with ATM-cell-loss compensation. *IEEE Transactions on Circuits and Systems for Video Technology*, **3** (3) (June 1993), xxx–xx.
2. Kung, H. T., Gigabit local area networks: A systems perspective, in *Advances in Local and Metropolitan Area Networks*, ed. William Stallings, IEEE Computer Society Press, CA, 1994, pp. 49–59.
3. Minoli, D. & Keinath, R., *Distributed Multimedia Through Broadband Communications*, Artech House, MA, 1994.
4. Partridge, C., *Gigabit Networking*, Addison-Wesley, Reading, MA, 1994.
5. Prycker, M. E., *Asynchronous Transfer Mode*: *Solution for Broadband ISDN*, 2d ed., Ellis Horwood, New York, 1993.
6. Wang, K. C. P. & Elliott, R. P., Design Considerations for a Distributed Multimedia Based Highway Information System, Transportation Research Board, National Research Council, Washington, 1995.