Improving Patient Care by Unshackling Telemedicine: Adaptively Constructing Rich Wireless Communication Channels to Facilitate Continuous Remote Collaboration

Improving Patient Care by Unshackling Telemedicine: Adaptively Aggregating Wireless Networks to Facilitate Continuous Collaboration

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Abstract
Telemedicine has had a positive impact on some aspects of patient care. However, existing telemedicine systems that use high-quality video are inflexible, requiring investment in fixed infrastructure. We have overcome a number of technical challenges to build a mobile telemedicine system that can reliably deliver high-quality video from both stationary sites and moving vehicles. Our system is constructed using custom software and off-the-shelf hardware, and opportunistically aggregates wireless data connections from different providers. We have evaluated the communication capabilities of our system in a number of realistic experiments. We are about to launch an evaluation of the clinical utility of our system. The system will be used to allow neonatal specialists to participate in the care of critically ill infants at remote sites and during transport.

1. Introduction

Telemedicine can be roughly characterized as either synchronous or asynchronous. *Synchronous telemedicine* involves caregivers acquiring and acting upon information about a remote patient in near real-time. *Asynchronous telemedicine* does not require the simultaneous availability of the source and recipient of patient information (e.g., medical imaging data analyzed by a specialist at a later time).

Interest in synchronous telemedicine has increased as healthcare has become increasingly specialized and clinical resources have been consolidated in large medical centers. Often, the medical personnel who make first contact with patients—paramedics, nurses, and primary care physicians—have the ability to initiate therapies, but lack the specialized training to recognize certain conditions or determine the correct management. Before treatment can begin, a specialist must be consulted.

Synchronous telemedicine has been shown to improve the effectiveness and reduce the cost of health care, particularly in situations in which the state of the patient may be changing rapidly—e.g., neonatal care, cardiology, and trauma [1, 2, 3].

Historically, synchronous telemedicine has required substantial investment in immobile resources and dedicated communication links. A mobile telemedicine system that uses existing infrastructure, could remove many hurdles, dramatically expanding the reach of telemedicine as a clinical tool.

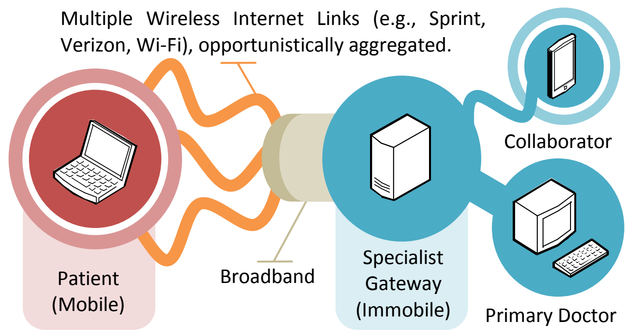

Figure 1. MIT Ambulatory Neonatal Telemedicine System Overview

Our research has focused on developing such a tool. Our system uses off-the-shelf hardware components and standard cellular network data connections, to provide reliable, high quality interactive video communication from moving vehicles. The heart of our system is a novel technology that adaptively and dynamically aggregates available wireless networks, intelligently encodes and distributes video over those networks, and degrades gracefully in the presence of network disruptions. We leverage the multiplicity of cellular providers to achieve reliable high-bandwidth end-to-end communication in the presence of network contention and highly variable signal strength.

Our ongoing investigation is focusing on leveraging our system to enhance neonatal care. We aim to establish an innovative "real-time" telepresence clinical network that allows online collaboration between: primary care physicians working in community hospitals, neonatology specialists at perinatal care centers, and critical care transport teams on moving vehicles. These participants will be able to work collaboratively during the evaluation, stabilization and transfer of critically ill newborns.

To this end, we have created MANTiS (the MIT Ambulatory Neonatal Telemedicine System). See Figure 1. MANTiS will be deployed for testing in the summer of 2010 at Children's Hospital Boston (CHB), a tertiary care pediatric hospital with a dedicated neonatal transport team.

A major contribution of our work is the way in which our novel video and networking technology radically reduces the barriers to entry for telemedicine. In our system, the hardware required at the patient end-point can fit inside a briefcase and consists of easily available and affordable off-the-shelf components: a laptop, cellular data cards, and webcams. MANTiS can operate in any area where there is adequate Internet connectivity, be it cellular, Wi-Fi or Ethernet. It can continuously transmit television quality video from a moving vehicle. This combination of affordability, availability of components, and large potential deployment area promises to greatly increase access to tertiary specialists.

Another contribution is our use of *ad hoc* communication hubs to allow remote specialists to be invited to examine recent patient data and aid in the ongoing diagnosis and treatment. This mimics one of the advantages of large medical centers, where many different specialists under one roof can conveniently be consulted for their opinions. MANTiS can extend this dynamic to situations where specialists are physically dispersed, by leveraging the increasing ubiquity of Internet devices (e.g., smartphones).

The remainder of this paper is structured as follows: section 2 provides an introduction to neonatal care and transport; section 3 provides a brief technical description of MANTiS; and section 4 summarizes our experimental evaluation of the reliability and performance of our MANTiS prototype.

2. Background: Neonatal Care and Transport

The emergence of a regionalized system for the care of ill newborns, with the associated stratification of the levels of neonatal care delivered in hospitals, has improved the delivery of specialized care provided to this high-risk patient population. The identification of prenatal complications and subsequent transfer of expectant mothers to a facility with neonatal specialty services has demonstrably improved outcomes [4].

Unfortunately, unanticipated deliveries of premature and critically ill neonates continue to occur in non-specialty institutions. For most community hospitals, it is not economically feasible to provide the in-house neonatal coverage needed to provide the advanced level of care needed during the initial stabilization of a critically ill newborn. In some cases, it may be in the best interests of a baby to transport him or her to a tertiary care center.

The discipline of neonatal transport medicine has co-evolved with the establishment of regionalized perinatal care centers [5]. Before and during transport, recommendations from the specialty physician at the tertiary care center must be based on the referring physician's and transport team's assessment and interpretation of clinical data, rather than on primary information. Prior to the baby's arrival at the tertiary care center, the state of the baby and the care provided to the baby are largely invisible to the team at the receiving tertiary care hospital.

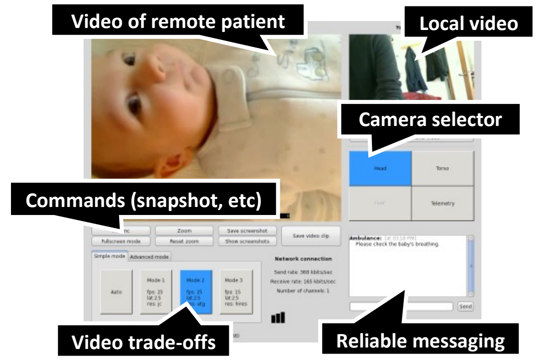

Figure 2. User Interface at specialist node.

Synchronous telemedicine could have a significant positive impact on the care of neonates (e.g., see the pediatric cardiology study in [2]). A collaborative approach between the pediatrician and the neonatologist in the initial assessment of the patient would be useful in separating those patients who should be transferred from those suitable for continued management in the community setting. Continued telemonitoring from the ambulance while in route to a tertiary care center could provide a channel for seamless exchange of information with the neonatal care team that will ultimately manage the patient. Such monitoring would also provide an additional level of subspecialty input should there be deterioration of the patient's condition during transport.

3. MANTiS

MANTiS has two main components. Clinicians interact with a software application specifically designed for the neonatal care scenario [6]. This application is built upon a novel video coding and communication sub-system [7, 8].

In developing MANTiS, we used an iterative process. We started by building the underlying video streaming technology. We then developed the neonatal care application by prototyping, soliciting feedback from neonatal intensivists and transport team members, and modifying the system accordingly.

3.1 Collaborative Neonatal Care Application

We refer to the part of the system co-located with the neonate as the *patient* node, and the fixed computer as the *specialist* node (see figure 1). The patient node may be stationary at the community hospital or mobile in an ambulance. When both nodes are stationary, both can use high-performance broadband networks, and when the patient node starts to move out of the community hospital, the patient node seamlessly switches over to cellular data networks.

Specialists and caregivers communicate within the context of bi-directional video *sessions*, with each session being assigned to a unique patient. The patient node initiates the session, by selecting a specialist node (e.g., from a list of hospitals).

The specialist and patient nodes have different user interfaces, reflecting their contrasting roles in the clinical process. Figure 2 shows the top-level user interface at the specialist node.

Video. At each node, *live* video from the other participant is displayed smoothly as it streams in. At the patient node, we use multiple fixed cameras, with each camera directed at a different part of the infant. Due to network bandwidth limitations, only one camera's video is transmitted. At any time, either session participant can select which camera is active.

When network bandwidth is inadequate, the video encoding process makes tradeoffs between image resolution, color range, and motion detail. Most video-conferencing systems use static rules to manage these tradeoffs. In contrast, MANTiS combines input from users with real-time network measurements to dynamically adapt.

The specialist may adjust the balance between the video's *spatial resolution* (the number of pixels) and *motion detail* (frames per second). For example, to investigate a skin lesion, the specialist can zoom in on one area of the body and increase the resolution, at the cost of degrading the smoothness of motion. In contrast, if the infant is suffering from what appears to be a seizure, the specialist may choose to increase the frame rate at the cost of degrading the resolution.

Audio and Reliable IM. To ensure the delivery of continuous smooth high-quality video over cellular networks, we introduce a few seconds delay between patients and specialists. For audio communications, this latency can be problematic. Therefore, the audio communication between specialist and patient nodes is conducted using conventional cellular phone calls.

MANTiS also provides a reliable instant messaging interface, allowing communication even when the phone connection is inoperative. Since MANTiS uses multiple cellular providers, significant performance problems related to individual providers (e.g., "dead zones") manifest as momentary hiccups rather than serious disruptions. MANTiS's communication channel is thus more reliable than conventional phones. Text-based instant messaging is also useful when noise in the ambulance (e.g., from the mechanical ventilator or truck engine) renders audio communication ineffective.

Snapshots, Video Clips and Sharing. Specialists can save *snapshots* (still images) and mark video clips. These can be reviewed locally, or shared with collaborators. During a live session, specialists can email individual images, or links to a web server, where collaborators can view the images and clips.

Using a web server as the communication hub allows collaborators to access shared data on any web-enabled device (e.g., smartphones). Specialists at home, at other hospitals, or on their rounds can all be instantly drawn into an active clinical situation, and their opinions integrated by the primary specialist.

Video clips can be marked either on the patient node or at the specialist node. A user specifies how many minutes of past video are part of the clip and provides an annotation. Specifying the end of the clip rather than the start has multiple advantages. Often it is not clear that something important has happened, until *after* it is over. Furthermore, in contrast to traditional teleconferencing systems, which assume that all relevant parties are always online, consultants may not arrive at the specialist node until after the start of the session. With this feature, the transport team can mark video clips capturing significant events the specialist missed and permit them to be viewed later.

3.2. Adaptive Wireless Network Aggregation

The requirements of the mobile telemedicine application drove us to develop the novel communication subsystem used by MANTiS. To facilitate accurate diagnoses, the application requires a reliable video connection, with video quality that is consistently high enough to convey subtle patient cues (e.g., unhealthy skin color and irregular movement). At the same time we need to be able to reach patients in arbitrary locations and to support vehicular mobility.

Conventional video solutions use a single wireless network connection—either a Wi-Fi or a cellular wide-area network (WWAN) data connection. Wi-Fi coverage is still relatively sparse, so relying on Wi-Fi alone would severely limit which patients we could reach. Furthermore, we found that we could not meet our application's requirements using a single WWAN connection, for a number of reasons.

The network performance of a WWAN connection is unstable and unpredictable—connection degradations and disruptions are relatively common. When stationary, WWAN throughput exhibits substantial temporal and geographic variability (see, for example, our measurements in [7, 8]). WWANs also have high and variable network packet round trip times and problematic packet loss rates [7]. Vehicular mobility further exacerbates these problems. Unfortunately, these performance problems interact quite unfavorably with conventional video delivery mechanisms.

Furthermore, WWAN connections have upstream bandwidths that are far less than downstream bandwidths. We are primarily interested in uploading data from the patient node, so this is a serious bottleneck.

Rather than limiting itself to a single connection, MANTiS simultaneously connects to all available networks. Typically, multiple wireless networks have overlapping coverage (Sprint, Verizon, etc.). By adaptively aggregating their bandwidth we can overcome network bandwidth bottlenecks. Additionally, our use of multiple network providers notably improves the system's reliability. Network service disruptions are not well correlated across providers [8].

MANTiS maintains a dynamic pool of wireless connections, continuously scans for new networks, regularly measures the quality of existing connections and aggressively optimizes the way in which video data is being encoded and spread across its connections.

We designed MANTiS to quickly adapt the video encoding to the changing network capabilities. A sudden cellular network disconnection on one provider (a call "drop") may cause MANTiS to experience short-lived video glitches and reduce video quality, but will not seriously affect communication. Conversely, the sudden availability of a high-bandwidth Wi-Fi network (e.g., upon entering a hospital) will cause video quality to improve seamlessly.

The MANTiS neonatal care application is built on top of an adaptive multi-channel video-streaming library, which is in turn built upon a network striping middleware. The middleware [7] handles low-level issues (e.g., network scanning, spreading and reassembling data, network congestion control, etc.). The video library [8] uses a variant of H.264, optimized for multiple network channels, and is built using the `x264` and `ffmpeg` open-source libraries.

MANTiS's network protocol is incompatible with existing video-conferencing clients. This is the unavoidable result of spreading video data over many network interfaces, something that existing video protocols are not designed to support.

4. Experimental Evaluation

We have technically evaluated the video streaming subsystem and network striping middleware in previous work [7, 8]. In this paper, we describe preliminary experiments designed to evaluate the end-to-end quality and reliability of the video. We tested the system with both stationary and mobile patient nodes.

Figure 3. Video from a moving ambulance. The mannequin is being moved back and forth rapidly to simulate a seizure. Relative frame numbers are shown; the video is at 25 frames per second.

Figure 4. Video from a stationary test (over Wi-Fi).

To evaluate the system, we collected data pertaining to the video and the network as the system was used, and gathered subjective evaluations from transport team members and physicians interacting with the system. Thus far, we have tested the system with neonatal dolls as patients in a transport scenario and with a healthy infant in a stationary setting. We are in the process of deploying the system at CHB, in order to assess the clinical utility of the system.

Vehicular Experiments. In collaboration with the neonatal transport team at CHB, we outfitted an infant transport incubator with our cameras and drove the CHB transport truck through Boston and Cambridge, covering routes between CHB and other hospitals. At the same time, a stationary physician operated the specialist node interface, located at MIT.

In the simulated transports MANTiS had continuous connectivity of high quality. Video was briefly disrupted when traveling through tunnels, but quickly recovered without user intervention. The video connection was more stable than the regular cellular phone connections used to communicate between the transport truck and the specialist node. The phone connection disconnected several times, while the specialist continued to receive good quality video.

Figure 3 shows a sample of the video received from the ambulance, during a period when the doll was being shaken to simulate a seizure. The color wheel provides a frame of reference.

Network errors such as packet losses are unavoidable in the vehicular scenario, so transient glitches did appear in the video, but the system has many automatic mechanisms both to recover quickly and to limit the amount of the image that is affected.

Figure 5 shows the MANTiS network throughput during a vehicular experiment. MANTiS was using three cellular network interfaces (two from Verizon and one from Sprint; all three were CDMA EVDO-RevA). Throughput is a function of both the demand (caused by video scene complexity, degree of motion,

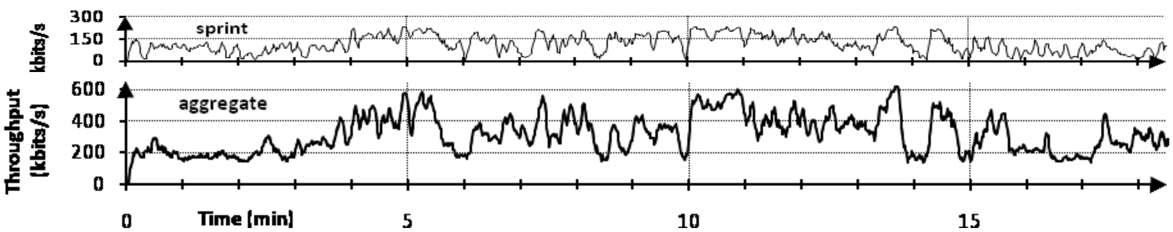

Figure 5. Network throughput during a mobile experiment (July 2009). The top graph shows throughput on a single network channel; the bottom shows the aggregate throughput, using three channels (mean = 280 kbps).

and desired resolution) and the available network bandwidth. The three channels provided a mean throughput of 280 kbps compared to the mean throughput of 101 kbps provide by the best channel (Sprint). Moreover, the lowest aggregate throughput was around 200 kbps—well above the minimum required to deliver video of acceptable quality.

Stationary Experiment. We evaluated performance when the incubator was stationary, inside buildings at MIT and at CHB. In one experiment at MIT, we placed a healthy infant in the incubator. Figure 4 shows video from this experiment. As before, the system performed well.

5. Related Work

Video Conferencing. The most complex part of the MANTiS system is the bi-directional video streaming system. Many video conferencing solutions exist, ranging from popular free services such as Skype to high-end systems that deliver HD video. MANTiS's simultaneous use of multiple unreliable connections differentiates it from other systems.

Mobile Telemedicine. Mobile telemedicine is not a new idea. Several early mobile telemedicine applications utilized satellite technology [9], but the deployment cost and inherently long network latencies associated with satellite technology limited the long-term clinical impact of these applications.

The widespread growth of inexpensive cellular data networks has made them attractive for mobile telemedicine applications. Existing systems either depend on special hardware or use a single network. None of these systems report video quality matching that provided by MANTiS. Examples include systems developed at the University of Massachusetts at Amherst [10] and at the Inter-national Institute of Telecomm in Montreal [11]. However, direct comparisons may not be fair since the tests of these systems were conducted using older technology.

6. Conclusion

Past studies have provided evidence that telemedicine can be used to improve patient outcomes. This is particularly true when clinical expertise is stratified, as in the case of regionalized systems for the care of ill newborns. Typically, existing telemedicine systems suffer from being inflexible—a predetermined set of locations must be selected, and patients cannot be adequately observed during transport. We have overcome a number of technical challenges to build a highly flexible mobile telemedicine system. We have experimentally evaluated our system from a technical standpoint. Our system achieves seamless vehicular mobility and can deliver much higher quality video than comparable systems.

We have embedded our system-level software in a application designed to support remote neonatal care However, an evaluation of the utility of the system in improving medical care awaits the results of a trial that is just starting at Children's Hospital Boston.

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