

ANGKOR: A Real-time Remote Classroom on Research and Education Networks

ANGKOR: 学術研究ネットワークにおける
リアルタイム遠隔教室

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In this paper, we describe our experiences from a collaborative project, called ANGKOR. We conducted real-life experiments on setting up remote teaching and learning in medical sciences, which comprises of rich media contents with mandatory interactive sessions. Remote teaching experiments were conducted from the School of Medicine, University of Pierre et Marie Curie (UPMC) in France to the University of Health Sciences in Cambodia (UHSC). The network being used for the project poses a real technical challenge, where a combination of very high speed connectivity from France to Japan with relatively low speed satellite Internet from Japan to Cambodia. Rich multimedia content for medical lessons is sent using digital video transport system, or DVTS, from UPMC. Three main technical contributions from this project include the use of IP multicast in heterogeneous environment; the real-time media stream frame reductions and the provisions for mobile classrooms. Based upon our experimental results from this project, we propose a framework for a remote classroom system over heterogeneous network environment.

本稿では、ANGKOR プロジェクトにおける成果を解説する。本プロジェクトでは、リッチメディアと双方向のインタラクティブセッションを用いて、遠隔地からの医学教育を実施した。この遠隔医学教育実験は、フランスの University of Pierre et Marie Curie (UPMC) 医学部と、カンボジアの the University of Health Sciences in Cambodia (UHSC) の間で行った。この実験では、利超広帯域回線と狭帯域回線を通してビデオ画像を送信するという技術的な試みを行った。フランス～日本間は超広帯域回線を、日本～カンボジア間は衛星を用いた狭帯域回線を利用し、医学教育用リッチメディアコンテンツを DVTS を用いて送信した。また、様々な受講環境における IP マルチキャストの利用、リアルタイムなビデオフレーム数間引き技術を用いた狭帯域ネットワークへのストリーム配信、携帯端末を用いた移動教室環境の整備といった点について、技術的検証を行った。本プロジェクトによる実験の結果、様々な受講環境下での遠隔教育環境構築の手法を提案できた。

Keywords: Medical education, Real-time classroom, IPv6, IP multicast, VDO streaming

1 Introduction

A request from the University of Health Sciences Cambodia (UHSC) was made through the University Pierre et Marie Curie (UPMC)'s Office of International Affairs to develop distance teaching during the first, second and third medical cycles on some subjects of medical education that are not covered locally at UHSC. UHSC is the only French speaking medical university in Cambodia, a country urgently in need of qualified medical manpower, thus their request was given a serious consideration by UPMC; a feasible technical and economical solution had to be sought out. A similar request was also made by some faculty members in the UPMC School of Medicine who have to travel long distances at high costs to deliver lectures in overseas French speaking institutions.

Medical science distance education provides students with specialized education not available in their own schools, which as up to now, been provided by foreign specialists who need to travel to provide the courses consuming both time and travel expenses. In response to the requests for long distance education above, the ANGKOR Project was launched as a collaborative research project, to experiment on the deployment aspects of IP multicast for real-time classrooms. The project was set up to explore the technical as well as the educational issues raised by the use of the Internet for education over a long distance in real-time with interactions. Its long term objective or ultimate aim is to be able to share ongoing classes being offered at UPMC on local high speed network with those students with low speed network at remote sites, such as at UHSC, simultaneously using IP multicast.

The paper is organized with the project description of the ANGKOR in Section 2 with a discussion of its design considerations and the conceptual framework. Section 3 describes the experiments of this project in setting up real-time

classrooms over long distance network using IP multicast, problems encountered and experiences. As an outcome from the project a real-time distant classroom model is being proposed in Section 4 to maintain sufficient IP multicast deployment for efficiency while a mixture of multicast and unicast as well as IPv4 and IPv6 can be adopted to reduce deployment complexity. Section 5 surveys some related works, and Section 6 contains a summary and discussion.

2 ANGKOR: a next generation Internet for remote medical science classroom project

The ANGKOR Project (or Next Generation Internet for Remote Medical Science Classroom) is a collaboration led by the Faculty of Medicine of the University Pierre et Marie Curie (FMPMC), France, and the Asian Institute of Technology (AIT), Thailand, funded in part by ICT-Asia project of the French Ministry of Foreign Affairs. It involves active participations and support of several research and education networks, namely, RAP (Réseau Académique Parisien), Renater (Réseau National de pour la Technologie l'Enseignement et la Recherche)^{1*}, GEANT2^{2*}, TEIN2^{3*}, APAN-JP^{4*}, and the Asian Interconnection Initiative, or AI³, satellite test bed^{5*} of the WIDE Project, Japan. Other members of the ANGKOR Project include the School on Internet Asia (SOI Asia)^{6*}, which conducts real-time classrooms in many countries in Southeast Asia. SOI-Asia lectures are delivered over the satellite Internet test bed run by the AI³ Project whose coverage reaches UHSC, providing 13 Mbps unidirectional downlink.

The ANGKOR Project has been applying high quality digital video transmission using the Digital Video Transport System (DVTS)^[6] and VClass E-Education Platform^{7*} developed by AIT to broadcast lectures with interactive sessions from FMPMC Paris

6 and UHSC. The main tasks in this project are to develop and test some means to distribute lectures from a distance over the next generation Internet (IPv6, multimedia and mobile or wireless Internet). Next we will explain the design and implementation of ANGKOR classrooms, starting with the requirements.

2.1 Distance medical classrooms requirements

Typical medical teaching and learning includes rich multimedia contents with interactive sessions with high quality video and audio, thus we need to consider the following requirements:

(a) *Communication Model.* We assume that our long distance classroom is intended to bring lectures from France with rich networks to developing countries with limited bandwidth and connectivity. Ultimately, medical lectures from the lecture rooms should be shareable, at the same time, among local medical schools and by those at the remote sites. With this assumption, we have to deal with drastically different network scenarios upon which our distance teaching and learning is expected to operate and is expected to reach as many classes around the world as possible simultaneously.

The choice of multicast, or one-to-many communication model, became obvious as opposed to unicast in order to reach a large number of remote classes or receivers with better bandwidth utilization. For effective teaching and learning over very long distances, we have to be concerned over minimizing delay, packet loss and jitters of bandwidth greedy lecture streams, thus IP multicast^[3] with multicast routing are handled by the routers fairs better than application layer multicast (ALM)^[2].

Our solution is therefore to adopt IP multicast crossing over many research and education networks with heterogeneous environment. However, these research and education networks are more

cooperative and are more prepared to co-ordinate than the normal commercial Internet Service Providers (ISPs). Deployment of IP multicast by commercial ISP's has not been common because IP multicast is resource intensive on the network, all routers must be supporting IP multicast for native IP multicast and more importantly inter-ISP coordination is required. However, on research and education networks, IP multicast is expected to be one of the standard services offered.

(b) *Video Streaming.* Since our main focus is in the field of medicine, where distance learning is becoming increasingly important, high quality video streams should flow seamlessly with as little delay as possible. The current techniques of broadcasting on the Internet are generally sufficient for traditional lectures but it cannot handle the delivery of high quality video images needed for broadcasting medical lectures with detailed images from radiology, scanner, histology, anatomical pathology and from surgical demonstration. For medical education, the use of Digital Video (DV) format^[1] or even higher quality video stream has thus become essential. The Digital Video Transport System (DVTS) can accommodate these requirements while providing full NTSC/PAL quality without encoding delay using bandwidth up to 33 Mbps with 30 frames per second. DVTS is an IETF standard protocol (IETF RFC 1394) that allows sending a DV stream over the Internet directly from standard digital video cameras. There are open source implementations of DVTS available for both Windows and Linux.

DVTS is an attractive choice; as it does not require special equipments, except a commercially available DV video camera connected to a PC with an IEEE1394 interface. It has been commonly used for telemedicine^[7] where images from an operating theater can be fed directly as DV streams to DVTS.

(c) *Interactive Sessions.* Student participations or interactive sessions for medical lectures are

an important component of medical teaching and learning where discussions are strongly encouraged. With the resource consuming DVTS streams, we need to adopt a more economical conversational system, which may not be of high quality but nevertheless sufficient in terms of the audio and low quality video streams. Such interaction is to be provided by a chatroom, a shared whiteboard as well as a small group video conference system provided by the VClass system. VClass was developed by a team at the Internet Education and Research Laboratory at AIT, a member of our ANGKOR project, using the Session Initiation Protocol (IETF RFC 3261) to handle users' mobility, hence each remote class can change its locations without having to reconfigure.

2.2 Real-time and remote classrooms in the ANGKOR project

Our proposed system is organized as in Figure 1; the source of the broadcast stream comes from the main lecture theater where the stream gets sent over a multicast channel to a number of subscribers. Each subscriber may be on different networks with different network capacity thus they may not be able to receive the video with the original stream quality; some subscribers who are on the high bandwidth network can receive the high bandwidth stream while those at the lower ends may not. If the source delivers video stream with low bandwidth in order to satisfy the lower ends, the higher ends would unnecessarily lose the opportunity to view high quality video that could have been sent from

the source. It was therefore decided that the source sends the video in DV format at full rate (30 frames per second) using DVTS to all its subscribers over IP multicast and find a solution for those lower ends to be able to view the lectures with sufficient quality. Our solution is to introduce a relay to be placed on the multicast tree at the critical point where the bandwidth reduction is needed. This relay is called *DVrelay*^[8] which was developed by our project member from the Internet Education and Research Laboratory (intERLab) of AIT. DVrelay is a modification of DVTS where a frame-dropping module was added, as shown in Figure 1; to randomly drop frames until the output bandwidth requirement is achieved.

For the ANGKOR Project environment, FMPMC, as a member of RENATER, has a gigabit connectivity to the national network RENATER via RAP and subsequently to its international pan-European GEANT2 network with gigabit connectivity to Japan through the TEIN2 network; while from Japan to Cambodia, a 13 Mbps unidirectional satellite link run by AI³ is available. All these networks support IPv6 multicast. In order to satisfy subscribers with lower bandwidth like UHSC, a DVrelay can be placed in Japan to reduce the bandwidth from 30 Mbps to 5 or 6 Mbps. Though a reduction to 1 or 2 Mbps is feasible, the output stream risks quality downgrade especially when the original video contains movements and or when packet loss occur on the network. DVrelay reduces the bandwidth requirements by dropping the frames on the DVTS stream thus reducing the frame

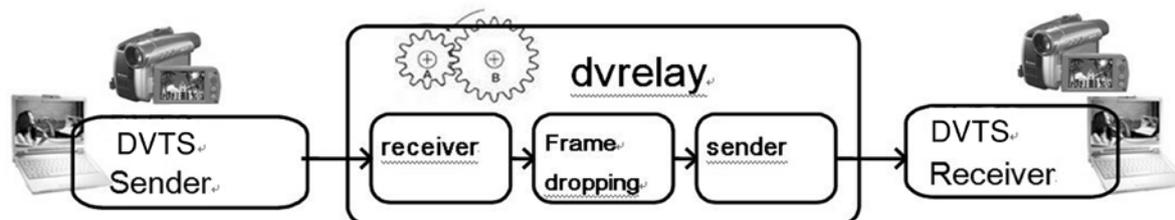


Figure 1 DVrelay is simply a DVTS with frame dropping

rates without affecting the original frame contents. The quality of still images remains mostly without degradation while video with movements may suffer from frames dropping in DVrelay. To optimize the performance, DVrelay performs additional motion detection^[4] and adjusts the frame dropping rates such that when there are a lot of movements detected, DVrelay will avoid the frame dropping as much as possible and it would increase the frame dropping rates as much as possible when little movement was detected or still images detected on the input video. The audio stream is kept as originally sent by DVSend component of DVTS.

In our environment for the ANGKOR Project, a remote real-time class is thus organized using IP multicast with DVrelay machines placed on the multicast path between the lecture theater and the receiver site where the bandwidth reduction must be performed, as shown in Figure 2. The network used

for the ANGKOR Project represents a real technical challenge; since we use the combination of a link at very high speed (2 Gbps) from France to Japan (RAP, RENATER, GEANT2 and TEIN2), with a satellite downlink rate relatively low (13 Mbps satellite link) between Japan and Cambodia. With this environment, FMPMC streams video using DVTS at 30 Mbps to all subscribers with IP multicast. As the video stream arrives at AI³ in Japan, the DVrelay located in AI³ receives the stream then drop some video frames to reduce the bandwidth into 6Mbps, and relay the video stream to the remote class UHSC in Cambodia using AI³ satellite link test bed. As the stream is using IP multicast, other receivers on the AI³ satellite link test bed can receive the stream as well, and they can join the class by signing up to the VClass.

The schools of medicine and pharmacy of the UHSC in Cambodia are equipped with computer rooms for the students with a sufficient number of

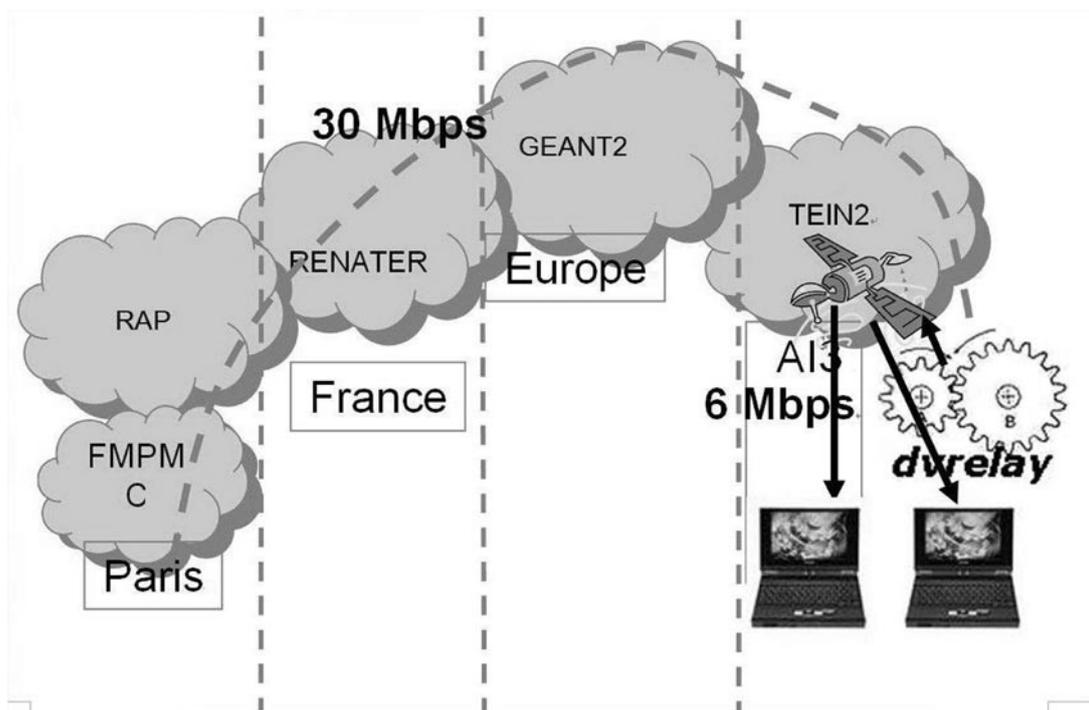


Figure 2 The research and education networks used for the ANGKOR Project where all of them except AI³ can accommodate DVTS at 33 Mbps. A DVrelay is placed at AI³ to reduce the bandwidth to 6 Mbps.

multi-media computers networked at 100 Mbs as well as a lecture hall fitted with video projection. A multicast downstream of the lectures can be organized in the local campus of UHSC reaching more classes, if necessary, within the campus LAN. DVTS streaming as described above allows a one-way broadcast to a large number of remote classrooms simultaneously in real-time. It allows the transmission of image and sound without compression and without loss of quality. In order to provide an interactive session, we extended VClass to provide real-time class interaction with instant messaging, chat, video conferencing via webcam, whiteboard or slideshow, and email. With such environment, we were able to deliver a rich educational content, in real-time (nine hours of the Master one neurophysiopathology course of the FMPMC), in uncompressed DV format using the DVTS through a DVrelay which narrowed down the bandwidth for a unidirectional (UDL) on JCSAT satellite. The lecture streams were channeled to the satellite ground station in UHSC with minimum deterioration or degradation.

3 Experiments on the ANGKOR project

The DVTS and VClass transmission tests were conducted from the Department of Information and Communication Technologies for Education (DPMTICE) laboratory located in FMPMC in Paris with high speed Gigabit IPv4 and IPv6 multicast connectivity. A series of experiments was started at beginning of June 2006 with the following steps:

1. Setting up and assessing the transmission quality of full-rate DVTS between FMPMC (France), Keio-SFC (Japan) and IntERLab (Thailand) both in unicast and multicast, with IPv4 and IPv6, with and without DVrelay.
2. Setting up and assessing the transmission quality of DVTS between UPMC, Keio-SFC, and UHSC through the DVrelay system that uses frame

reduction and motion detection to reduce stream to 5Mbps when sending to the AI³ satellite link both in IPv6 unicast and multicast. AIT-IntERLab could monitor the end results as AIT-IntERLab also has a receiving station for the AI³ testbed. Experimental results are displayed in Appendix 1; the quality of the video stream captured at AIT, at 5 Mbps with no packet loss, is shown in (picture 1) while in (picture 2) there is some small, less than 5% packet loss.

3. We did experiments on the use of VClass to initiate DVTS, sender and receiver, as well as other two-way communication tools such as chat, video conference, messaging, shared whiteboard and shared files. The possibility of student audio-video feedback from UHSC using the VClass video conferencing system on IPv4 using a 256kbps ADSL connection was tested. Appendix 1 also includes another picture showing an interactive session on VClass (picture 3); an image of the lecture stream as captured by another camera at the remote classroom site at UHSC was sent back to the lecturer at UPMC for viewing during the discussions. This demonstrates an acceptable quality of the transmission by comparing the original image quality (large DVTS display on the right hand screen) and the quality of the DVTS stream at the remote classroom (in small display on the left screen) reflected back to UPMC screen via VClass.

From our series of fifteen experiments conducted during 2006-2007, including a successful demonstration at a medical meeting at UHSC where we transmitted DVTS streams from UPMC studio to UHSC lecture hall in October 2006, we can summarize our valuable experiences and learning as follows:

Deployment complexity of IP multicast. Even though IP multicast has been defined almost two decades ago, it has not been widely deployed on most commercial networks due to additional costs and co-ordinations required. On most research and education networks, IP multicast is more readily available but not all research and education network do provide native IP multicast. From our experiments, it was found that the operation of IP Multicast was not stable particularly for inter-domain IPv6 multicast; tunneling had to be applied whenever failures occur. Tunneling is known to compromise the efficiency gains of IP multicast with tunneling gateways and tunneling packets. Most of the failures were due to changes in the network configurations, which need proper co-ordination among network operators of the various networks.

DVrelay. It was found that DVrelay should adopt constant bit rates rather than variable bit rates to avoid peak traffic on the narrow links. This was discovered after unexpected 20% packet loss kept occurring on DVTS streams between Keio-SFC to AIT (and UHSC) while IPv6 multicast was proven to work successful from UPMC to all the intermediate networks and within the AI³. It was later found that such a big loss occurred due to peak traffic of the VDO stream sent with variable bit rates thus we modified DVrelay's bandwidth reduction algorithm adopting constant bit rates for its output streams.

Interactive sessions. Bidirectional communication was introduced with the use of InterERLab's mobile VClass with very small webcam 328 x 244 pixels video images (H.263). It was found that the audio quality and echoes were problematic. The use of echo cancellation microphone was found to fix this problem and hence recommended.

DVTS audio. Though DVrelay leaves the DVTS audio stream untouched, we have found that DVTS audio do suffer from packet loss when we tested sending didactic hepatic surgery video to a surgeons

meeting at UHSC, Cambodia. Packet losses appeared to degrade not only the video precision and the pedagogic impact of the video but also results in scratchy sound at times.

Packet losses. Quality of distant teaching and learning depends heavily on the quality of the video and audio transmissions which in turn suffers when packet losses occur. It was found that apart from satellite transmission losses, which occasionally affect the quality of the output, it was necessary to ensure that bandwidth reservation or the network operators must properly assign prioritized traffic flow.

Pedagogy. In our environment, the receiving institution has very little educational option opened to them because they lack the human expertise in teaching the courses themselves. Though distance teaching offer them less appealing class interactions, the students have no other choice when come to specialized courses which cannot be offered by their own institution, such as the case of UHSC. Technical failures and interruptions do affect the pedagogical impact of distance classes substantially; supplementary technologies and pedagogy must be provided. Archived lecture materials appear to be a valuable resource for the students for subsequent reviews as well as opportunities for tutorials or post-lecture live question and answering sessions.

From our experiences, it was found that the setting up of a successful long distance classes requires stable support from the network operators from end-to-end; and that the co-operations among network operators in the heterogeneous research and education networks appears to be the key component for success. Most technical problems we have found in our experiments were mainly due to configuration mismatches. This could be due to the fact that, unlike unicast, multicast has not been deployed widely so it has not been regularly supported or routinely checked by the network

operators even on research and education networks. In such condition, deployment of multicast cannot be smooth without a strong support from the network operation community.

4 A real-time remote classroom network model

The ANGKOR Project has given us a much clearer picture of how real-time classrooms can be realized on a semi-autonomous and heterogeneous network environment. We identified that the most important factor to the success of the ANGKOR classroom is based upon the network operation support. In order to realize a real-time classroom for a day-to-day operation, such dependencies on the network operation team must be reduced to a bare minimum, namely reducing the deployment complexity of IP multicast.

The set up of distance classrooms should be scalable to be economical and the classrooms must be real-time with many possible types of communication channels: multicast (one-to-many and many-to-many) and unicast (one-to-one) enabling one-to-one or multipoint conferencing/meetings. We have found that native IPv6 multicast, though efficient in bandwidth utilization and consuming less host processing power, it needs heavy co-operations from and co-ordination among all the network operation centers (NOC) involved. End-to-end NOC support for each distance classroom set up appears to be unrealistic for a day-to-day operation, let alone the scalability issue.

We can view our heterogeneous network as a set of networks connecting to one another either directly or indirectly. The core backbone of the network has to be identified which connects all member networks, in the same way as a minimum spanning tree, and is to be maintained by the network engineers such that native IPv6 multicast is guaranteed. The core or backbone should, as far as possible, be confined to a

minimal backbone, in term of the number of nodes, in order to reduce the support of the NOC engineers as much as possible. Native IPv6 multicast is efficient but it should be adopted on the common backbone connecting many as many neighboring networks as possible. The backbone IPv6 multicast must be maintained and guaranteed to work on 24/7 basis, while it is not compulsory for the remaining networks to provide IPv6 multicast. Streaming channels are managed or routed via DVrelays whose main task is to forward streams within its network to the common multicast backbone to efficiently deliver the streams to the wider community through the backbone. In this was, only the core NOCs have to routinely check the operation of their multicast setup and provide emergency trouble shooting when necessary.

Our proposed real-time classroom network thus comprises a common area or domain, which connects to all members, networks, as shown in Figure 3. Each connecting network set up a gateway with a DVrelay whose function is not only to adjust the bandwidth but also to convert multicast to/from unicast and IPv4 to/from IPv6 streams. These gateways uniformly send out IPv6 multicast streams to the common pool, for example TEIN2 AS24490 in Figure 3, while the common pool is expected to have IPv6 multicast operational all the time. Gateways are placed in any neighboring networks, within which no native IPv6 multicast is necessarily supported. Our overlay network is not an application level multicast (ALM) overlay network as it does not perform multicasting at the application layer; it is simply a patchwork of different network environments using the native communication protocol (IPv4 vs IPv6 and unicast vs multicast) for DV streaming. As shown in Figure 3, a real-time class may consist of a path of DVrelays on the overlay network with a combination of native IPv4/IPv6 and multicast/unicast depending on the available underlying networks.

This proposed model has been adopted for

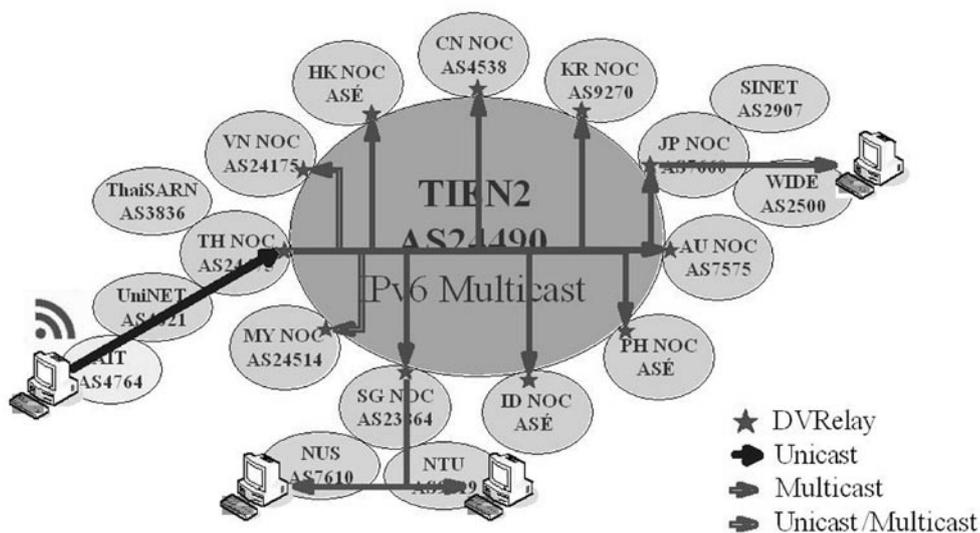


Figure 3 A real-time classroom model with IPv6 multicast core spans over the Pacific and DVrelays at each national research and education network gateway to the common TEIN2 core network.

deployment by a digital streaming CanalAVIST^{8*} project where the common TEIN2 network connects all member national research and education networks in Australia (AU), China (CN), Japan (JP), Korea (KR), Malaysia (MY), Philippines (PH), Singapore (SG), Thailand (TH), and Vietnam (VN) together with the national gateways running DVRelays placed at respective point of attachment.

While in the ANGKOR Project, a real-time class is constructed using network layer IP multicast throughout, CanalAVIST allows a hybrid model where a real-time class can be constructed using as a string of DVRelays which may be connected by a combination of IPv4/IPv6 unicast/multicast in native mode. In the following, we compare our proposed model against our IP multicast model of ANGKOR in terms of deployment complexity, performance efficiency and scalability.

Deployment complexity. By confining IPv6 multicast within the core network, it provides a

manageable environment for CanalAVIST NOC engineers; in contrast to the end-to-end support from NOC engineers in the ANGKOR to ensure that IP multicast is operational. When IP multicast is not available, which could be caused by one of the configuration mismatch at a router on the multicast tree, the ANGKOR Project has to drop the native IP multicast and adopt tunneling while CanalAVIST can make use of DVrelays without tunneling.

Performance efficiency. CanalAVIST real-time classrooms are arranged and operated on the native network without tunneling. Whenever multicast is not available, a native IP unicast can be adopted until when a DVrelay with multicast output is found, then DVrelay will output a multicast stream. All native communication protocols are used without tunneling, thus achieving better performance efficiency without having to modify any router configurations. In ANGKOR, tunneling is deployed whenever native multicast is not available thus affecting the overall performance. However, each DVrelay does impose

some delays for the frame dropping and motion detection activity, which means that only a limited number of DVrelays can be acceptable for a given real-time class.

Scalability. In this model, we can introduce as many core native IP multicast networks in our model linking the rest of the networks together. Thus the number of simultaneous classrooms is not limited by the introduction of DVrelay overlay in the model but it is limited by the network or bandwidth capacity. Though the distant of the class, or the number of DVrelays being used in the distant class set up, depends on the number of DVrelays used to construct the class, which is thus limited by the acceptable delays. Scalability is subject to the network capacity.

5 Related Work

CanalAVIST and ANGKOR share common objectives with SOI-Asia [5] which is to provide high quality distance education using the Internet technologies. In SOI-Asia, a 13 Mbps unidirectional broadcast satellite covers Asia region enabling lecture sharing among student sites. IPv6 Multicast overlay network is established by UDLR and IPv6 tunnel technologies to create a virtual network connecting lecturer-site and student-sites on top of network heterogeneity. While SOI-Asia mainly focuses on using the AI³ testbed to disseminate real-time lectures to their members within one AI³ network, CanalAVIST and ANGKOR addresses the delivery of lectures over many peering networks with heterogeneous networking conditions, thus higher deployment complexity.

6 Conclusions

In this paper, we have presented our real-life experiments on setting up long distance IP multicast for remote classrooms. It was found that though IP multicast should provide an efficient mechanism

for streaming lecture contents to a large number of audiences simultaneously, its limited deployment has made the support operation unstable. DVTS provides high quality video suitable for delivering distance lectures particularly for medicine. Nevertheless long distance classrooms for medical lectures can never provide lively interaction as in the face-to-face classes; supporting archived lectures as well as organized interactive question and answering or tutorials should be provided to compensate the loss of effective teaching and learning environment.

From these experiments, we have found that in setting up successful delivery of lectures involves substantial support from the network operators due to the deployment complexity of IP multicast and tunneling. We proposed a new model of distance education where we limit native IP multicast to the core or the backbone network and allow for a combination of IPv4/IPv6 and unicast/multicast to co-exist in the model. The core or but with extensive coverage area, like the Asia-Pacific, and also with the ability to support a large number of concurrent multicast groups.

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Notes

- 1* <http://www.renater.fr>
- 2* <http://www.geant2.net>
- 3* <http://www.tein2.net>
- 4* <http://www.apan.net>
- 5* <http://www.ai3.net>
- 6* <http://www.soi.wide.ad.jp/soi-asia/>
- 7* <http://www.vclass.net>
- 8* <http://www.canalavist.org>

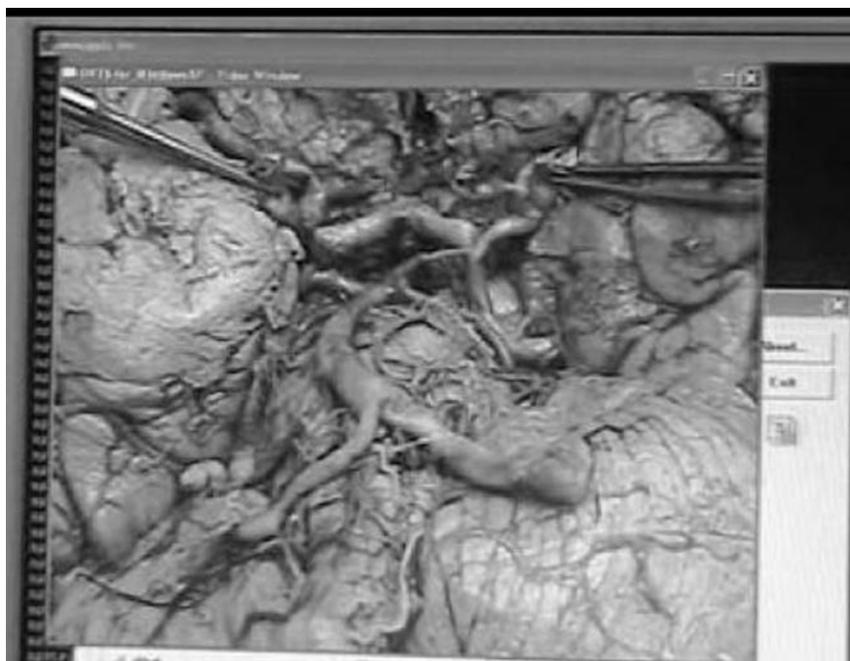
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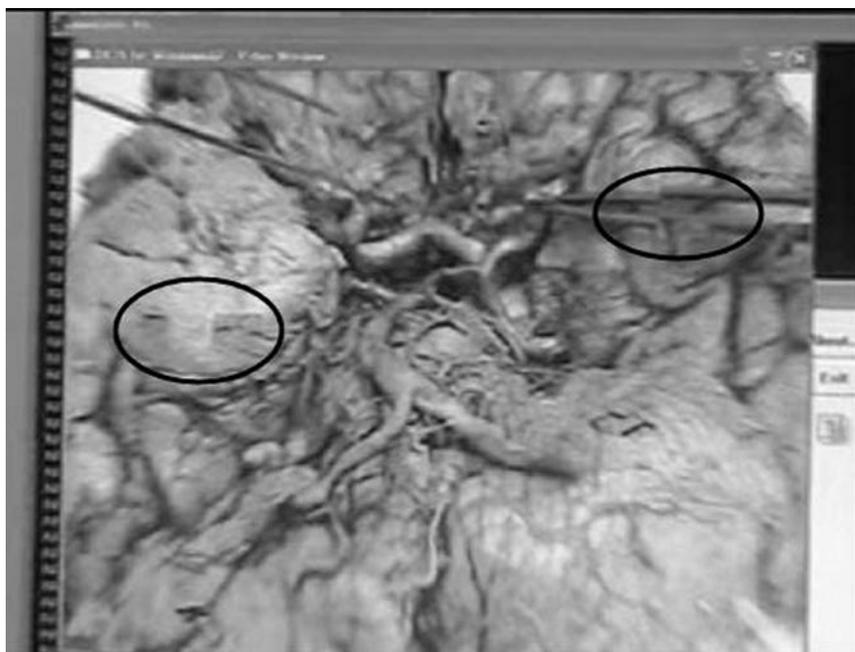
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Appendix: Experimental Results

(1) A screen capture of a lecture stream received at 5 Mbps without packet loss from the AI³ satellite testbed.



(2) A screen capture of the same lecture stream received at 5 Mbps with less than 5% packet loss (as marked) from the AI³ satellite testbed.



(3) Left hand screen shows ongoing interactive session using VClass; the lower right hand image of the left screen displayed the Endoscopic lecture stream from UPMC which was received at USHC and sent back to UPMC using VClass. The original VDO stream being sent by DVTS from UPMC can be viewed on the right hand laptop.

