We developed an asynchronous transfer mode-based environment for distributed musical rehearsals in an immersive teleconference environment. This article describes the technical specifications of the installations and the organization and studio setup of these rehearsals. We present our implementation of the environment and give the results obtained from the organized distributed musical rehearsal trials.

The past few years have seen the rapid evolution and wide availability of high-quality communication networks and powerful, inexpensive computers. Consequently, new communication applications and ideas have appeared in different disciplines, ranging from networked medical applications to distributed music performances. A common denominator of these applications, and a communication system in high demand, is teleconferencing. Currently, telephone operators offer videoconference services, and Internet users can communicate with Internet protocol (IP)-telephony and Webcams. However, the video and audio quality of these applications is low, and demanding users want more than small, low-resolution video images and telephone-quality audio. They need immersive systems like Teleport and Immersive High Quality Communication (IHQC) that can accurately reproduce images and sounds, allowing observation of gestures and voice changes as if talking person-to-person.

Musicians and composers were among the first artists interested in the new communication technologies and the artistic possibilities they offer. Various experiments and applications have addressed distributing a musical creation or a performance environment. Applications ranged from Musical Instrument Digital Interface (MIDI) synchronization over the Internet, like Distributed Music and NetMusic, tools for interactive control of virtual instruments in virtual environments, like the Hypercello, up to real-time, high-quality, interactive music networks over asynchronous transfer mode (ATM), like NetMuse. Also, researchers in industry and academia conducted a large number of music performance experiments using telephone and ISDN lines at various conferences and expositions, like the Lemma One performance.

To study problems and issues related to teleconference applications in the framework of the Distributed Video Production (DVP) project of the European Union ACTS (Advanced Communication Technologies and Services) research program, we designed and developed an immersive ATM based teleconference environment. A pilot application, called Distributed Musical Rehearsal (DMR), tests and evaluates the DVP teleconference environment. The Distributed Musical Rehearsal aims to let small groups of geographically separated actors and musicians conduct rehearsals as if face-to-face in the same rehearsal room. We implemented a two-site setup with one installed at the German National Research Center for Information Technologies (GMD) at Saint Augustin, near Bonn, Germany and the other at the University Center of Information Science (Centre Universitaire d’Informatique, or CUI) of the University of Geneva, Switzerland.

The distributed musical rehearsal system used video walls, digital sound and video encoding, and ATM technology. The major design and development goals were reproducing, as accurately as possible, the remote sites as an extension of the local conference room. We did this by using a video wall (a 2 × 3-meter screen with back projection) in place of one of the conference room walls and by 3D recreation of the sound space.

Overview of an immersive teleconference environment

One major project goal involved studying and evaluating the distributed musical rehearsal system’s usability for organizing musical rehearsals and measuring its performance in actual working conditions. We developed a methodology to measure the distributed musical rehearsal system performance and compare it, qualitatively and...
quantitatively, with a localized face-to-face rehearsal. Our performance measurement methodology doesn’t rely on technical data, like time delay and video quality, but on the participants’ perceptions. Therefore, the results stem directly from using the system in actual working conditions and provide an accurate measurement of overall system performance.

In contrast to similar experiments investigating communication technology use for an artistic performance, we targeted the technology limitations, the environment’s usability, and concrete results regarding the distributed rehearsal environment’s overall performance. We planned to evaluate if, and up to which level, the existing technology could provide the tools for setting up a working environment for distributed musical rehearsals.

Also in contrast to past experiments, our project used the most advanced technology available, for example ATM networks instead of ISDN lines for communication, and high-performance dummy heads instead of simple microphones, for re-creating the sound space.

Requirements
An immersive teleconference environment minimally needs a large video wall (2 x 3 meters), high-resolution video projection, and a good audio system. These facilitate the participants’ impression that they physically occupy the same room. However, for a musical rehearsal we need not only a high quality of audio (at least 20 to 22 kHz) but also an accurate 3D re-creation of the sound space and very low transmission latency. Participants need to identify and relate acoustically and visually the exact position of other participants. For example, the conductor of a musical rehearsal identifies acoustically the exact position of each musical instrument in order to correct the appropriate musician.

Based on the high demands of a distributed musical rehearsal, we defined a set of system requirements:

- Transmission delay requirements. During rehearsal the conductor and the musicians must perceive each other, in terms of vision and sound, as if they occupied the same room. The conductor needs to see and hear the musicians’ reactions to his or her gestures with a maximum delay corresponding to the rhythm of the rehearsed musical piece. Music with slow rhythm and low complexity, like classical music, allows for very long delays, while music with fast rhythm and high complexity, like contemporary music, requires very small delays. Based on a calculation performed during a face-to-face rehearsal, and considering the music we planned to experiment with (contemporary) in the musical rehearsals, we estimated a maximum delay of 160 milliseconds. This corresponds to a one-way transmission delay of 80 ms or, alternatively, to a distance between the conductor and the musicians of 24 meters—the maximum distance between the conductor and the last musician of a very large orchestra.

- Video quality requirements. Since conducting an orchestra uses body language, the video quality must allow musicians to correctly see and interpret the conductor’s signals. Therefore, the distributed musical rehearsal environment requires a high-resolution video that lets musicians see even where the conductor is looking. The conductor, on the other hand, has to correctly identify each musician’s position. Thus the projected video should preserve the natural dimensions and perspective of the orchestra and conductor. Because the conductor and musicians don’t change position during the rehearsal, we can statically calculate the right perspective for the projected video.

- Audio quality requirements. The evolution of the rehearsal demands exact reproduction of the music. Furthermore, because the conductor needs to identify the exact location of an instrument, the sound space must also be reproduced. This requires high-quality microphones placed in well defined positions to reproduce the sound space as accurately as possible.

Rehearsal studio. The rehearsal studio organization and the required equipment layout have major importance for the distributed rehearsal application—to accurately capture and reproduce image and sound.

- Video capture and reproduction.

In a nondistributed rehearsal the musicians and the conductor physically occupy the same room. In the distributed rehearsal the musicians and the conductor logically occupy the same room. Projecting video images on a large screen approximates this. Ideally, the two participants will experience a translucent frame between them.
in the rehearsal studio (Figure 1). Obviously, the video walls' luminosity must be strong enough so that both sites have sufficient ambient light.

To preserve the positional perspective of the musicians and the conductor, video capture takes place between the screen and the participants. Thus, we cannot use large cameras that hide the screen; we need nonintrusive miniature cameras. Furthermore, depending on the cameras' characteristics, accurately reproducing the participants' physical proportions might require a perspective correction of the video. Because the conductor's observed motion is crucial, we must transmit the video at the full video frame rate, rather than at a lower frame rate.

Audio capture and reproduction.

For a distributed musical rehearsal the audio quality is the prime factor for its success. We must not only reproduce the sound in high quality but also preserve the depth and direction information. Thus, a major issue is capturing the sound so that it can be reproduced as accurately as possible.

One method for sound capturing is placing a microphone in front of each musician. However, this suppresses all information regarding the musicians' positions in the sound space, and we would need specialized virtual reality software, like Le Spatialisateur or the Interactor, to re-create the sound's spatial information for the conductor.

A second method uses a number of microphones (two to four, depending on the configuration) that capture the sound along with all its spatial information. When the conductor is at one site and the musicians at another site, the calculations remain relatively simple, and two microphones placed in the right positions suffice. For more complex configurations (more sites or the conductor sharing a site with some of the musicians) this solution won't suffice and virtual reality techniques are needed. However, we didn't study these techniques because they fell outside of the project's scope.

A third method places a dummy head approximately where the conductor's head would be if he were physically present in the room. The microphones capture the sound at exactly the position of the dummy's ears with all the vibrations and interferences that a person's ears would hear.

The sound space needs accurate reproduction for the conductor only. For musicians the only remote sound source is the conductor, who occupies a specific place in front of them. Therefore, a speaker behind the screen suffices. For sound reproduction at the conductor's site two possibilities exist: headphones or loudspeakers. Using headphones with virtual reality technology, we can correctly reproduce the sound and its spatial information. However, this solution requires installing sensors that can capture the position and orientation of the conductor's head.

Using loudspeakers simplifies the audio installations and provides a nonintrusive solution. The disadvantage of loudspeakers is that, without vir-
tual reality techniques and tracking of the conductor, the spatial information is correctly reproduced at one specific point only, and the conductor has reduced localization capability.

**Multisite distributed rehearsal.** In a multisite distributed rehearsal or in the two-site setup with one group of musicians and the conductor at one site and a second group of musicians at the other site, the requirements become more complex. First, the logical layout of the orchestra needs definition in a way that makes a physical representation possible. In a three-site setup, for example, having two sites with musicians and a third with the conductor, we need two projection screens for each musicians’ site: one in front of them for the conductor and one on the side for the second group of musicians. This gives the conductor an image of the two musicians sites merged into one to give the impression of a complete orchestra, as shown graphically in Figure 2.

The most important challenge in multisite setups is synchronization of the music played by the musicians. Assuming even a very small delay in the video and audio transmission, for example 20 ms, it’s impossible to synchronize music from all sites at more than one site. For the three-site example, if the conductor listens to the synchronized music from the two musician sites, then each musician site will hear the other site with a delay of 20 ms. If the first musician site delays its actions by 20 ms, in order to synchronize with the second musician site, then the second musician site will be off sync by 40 ms (round trip), while the conductor will perceive the two sites with a difference of 20 ms. Thus, the musicians cannot synchronize between themselves. This doesn’t mean that it’s not possible to conduct a rehearsal, but that a different way of organizing and conducting the rehearsal is needed.

**Overview of a distributed rehearsal studio installation**

Based on the above requirements we installed two distributed rehearsal studios, one at the Geneva-CUI site and one at the Bonn-GMD. Although the two studios aren’t identical, the basic technology (encoding, video and audio capture and reproduction, and so on) is the same. The major difference between the two studios is that GMD has a far greater processing power and can integrate virtual studio techniques in video production.\(^1\)\(^8\) Studio infrastructure relates directly to the distributed rehearsal environment. A diagram of the studio setup and network installations appears in Figure 3.

**Video capture and reproduction**

We used nonintrusive microcameras (Panasonic) as well as small consumer digital cameras (Sony DCR-VX1000E) for the video capture. The projection used two tritube low-luminosity projectors (Sony-230 ANSI Lumen) at GMD and a high luminosity light-valve projector at CUI (Barco 8100-800 ANSI Lumen). The video wall used standard medium-quality screens of 2\(\times\)2.6 meters.

**Audio capture and reproduction**

To accurately reproduce the sound of the orchestra at the conductor’s site, we tested two sound capture systems: a dummy head and a dual microphone setup, both combined with a matrix for the correct 3D reproduction of the sound.

**Video and audio—encoding and transmission**

We digitally encoded and transmitted video and
audio using ATM lines and the Fore StreamRunner AVA/ATV codecs. The video encoding was in an MJPEG (Motion Joint Photographic Experts Group) stream and the audio was digitized in digital audio-tape (DAT) quality (48 kHz sampling). The bandwidth for transmission of the video (noninterlaced PAL 25 frames per second) ranged between 12 and 14 megabits per second (depending on the image complexity) and the audio (DAT stereo) was 1.5 Mbps. Initially the video encoding-decoding delay was 70 ms while the transmission delay was 11 ms (a total delay of 81 ms). However, experimentation with the codecs allowed reduction of the video encoding-decoding delay to 46 ms (by sending even fields). The audio encoding-decoding delay was 6 ms. We introduced 14-ms buffering to eliminate buffer underflow, which produced an annoying clicking in the audio. Thus the total audio delay was 31 ms.

The total bandwidth required for interlaced PAL video at 25 fps was around 29 Mbps, while the available ATM bandwidth was 24 Mbps. Therefore, we transmitted noninterlaced video (that is, one field per frame), which required half the bandwidth. In total (audio plus video) we used a bandwidth of 15.5 Mbps. The encoded audio and video were transmitted over AAL5 (ATM Adaptation Layer 5), while the codecs could work with cell losses reaching up to 25 percent (which creates some artifacts in the reproduced video and audio). The use of AAL5 for the Geneva-Bonn connection combined with the quality-of-service (QoS) specifications allowed us to sustain constant transmission delay and bandwidth rate despite global network traffic variations.

The ATM switching used a DEC GigaSwitch and Fore switches, while the control and ATM traffic analysis used a Sun Microsystems Sparc station and a Hewlett-Packard ATM traffic analyzer.

The ATM connection from the CUI to GMD used permanent virtual circuits (PVCs). We were unable to use switched virtual circuits (SVCs) due to incompatibilities in the UNI3 signaling protocols between the DEC and Fore switches.

We chose MJPEG encoding over other standards, like MPEG or H.261. The most important reason was that all existing MPEG codecs had encoding delays of more than 200 ms, whereas we require at most 80 ms. A second reason for choosing the specific MJPEG codecs was their lower cost. We rejected other low-bandwidth encoding standards like H.261 because of low audio/video quality, which was inconsistent with our major consideration of high audio/video quality (not reduction in network bandwidth).

Distributed rehearsal trials

From the several tests and trials performed at the GMD and CUI sites, the most characteristic ones were a distributed singing rehearsal and two distributed musical rehearsals.9 The singing rehearsal used a large (117 cm) television screen, instead of the video wall, at the CUI location. The two full-scale distributed musical rehearsal trials lasted six hours each with the Grame Contemporary Music Orchestra (Grame-EOC) orchestra. In the singing rehearsal we performed trial objective evaluation tests, while in the musical rehearsals we organized trial designation tests.

Distributed singing rehearsal

The distributed singing rehearsal trial was a duet with a piano. The pianist and one singer were at CUI-Geneva while the second singer was at GMD-Bonn (Figure 4). The rehearsal lasted two hours total.

Because we didn’t need spatial sound information for this rehearsal, we used monophonic audio channels for the audio transmission. The audio sent to GMD from CUI mixed the audio signals of the piano and the singer, while the audio from

Figure 4. Singing rehearsal, CUI setup (a) and video from GMD (b).
GMD to CUI was the audio signal from the singer. This trial used an early version of the codecs' control software that didn't allow control over the audio delay and buffering. As a result, the audio delay was the same as the video delay—approximately 80 ms. For the distributed singing rehearsal, we wanted to get an initial idea of technical problems and issues related to the organization and setup of the rehearsal. We also wanted to gain a subjective appreciation of the feasibility and limitations of a distributed rehearsal.

The most critical issue in the singing rehearsal trial was synchronizing the singers. With the delay of about 80 ms (one way) in the transmission of sound and image, we couldn't achieve synchronization at both sites. If the local singer at one site was synchronized with the remote singer, then the remote singer would perceive his peer with a 160 ms delay. Using a central point where singing is synchronized offers one way to resolve this problem. This central point can be located at either of the sites or at a third site.

Using a central point replicates a singing situation (long delays and synchronization of the audio at a central point) that first appeared and was mastered during the Renaissance with the cori spezzati of St. Mark's cathedral in Venice, Italy. A conductor stood in the middle of a large church, and the singers ranged around the church's balconies. Because of the church's large size, the sound delay between singers could reach 200 ms or more (60 meters distance), and the only point where the sound was synchronized was the center of the church where the conductor stood. Of course, the distributed rehearsal not only has a delay in the sound but also in the image. Therefore, singers must anticipate the conductor (or the other singers). A similar situation occurs in some operas when singers singing behind the stage are invisible to the conductor. The singers behind the stage must anticipate the conductor in order to synchronize with the singers in the scene.

The degree to which we can achieve synchronization in the presence of delays also depends on the musical piece played. In the distributed singing rehearsal, two different songs were rehearsed: Handel's Israel in Egypt and Britten's Abraham and Isaac. The Handel piece, having a regular rhythm, was easier for the remote singer to anticipate. The Britten piece didn't have a regular rhythm, being free-time music, and thus the remote singer had more trouble anticipating and synchronizing. However, in both cases after some trial and error, the singers managed to synchronize their singing.

In the distributed singing rehearsal setup at CUI, the image received and displayed was a mix of the GMD and CUI singers (Figure 4). The two images were mixed at GMD and sent to CUI. As a result, the image of the CUI singer projected at CUI had a delay of 160 ms. This confused the CUI singer, since he saw himself with a noticeable delay.

An important technical problem we faced in the distributed singing rehearsal was fine-tuning the audio signals to fit the studios' acoustics. The sound from the remote site was reproduced using loudspeakers. This way the singer's microphone also captured the reproduced sound from the remote singer, which was then transmitted back to the remote site. As a result, each singer heard the remote singer and his own voice delayed by approximately 160 ms. These artifacts and echo confused the singers. Since we couldn't use echo-cancelers (the echo delay was too long and had small variations on the order of 0.5 ms), we adjusted the microphone's gain and the loudspeakers' volume to eliminate the effect.

Distributed musical rehearsal

The piece selected for the first distributed musical rehearsal trial, Pierre Boulez' Dérives, required six instruments: piano, vibraphone, violin, cello, flute, and clarinet.

The musicians were installed at CUI while the conductor was at GMD. We placed a dummy head approximately where the conductor's head would be if he were physically present at the rehearsal (Figure 5).

We organized the distributed musical rehearsal trial into four phases. The first phase consisted of tuning and adjusting equipment for the correct capture and reproduction of the sound. The second phase was dedicated to a quantitative quality control of the installation. The third phase was
the main part of the trial, where the orchestra rehearsed the selected musical piece (Figure 6). Finally, in the fourth phase the musicians and the conductor were interviewed independently to obtain a subjective measurement of the distributed rehearsal environment.

An integral part of our work was measuring the distributed rehearsal system’s quality and the limits of its usability. The system quality can be measured subjectively and objectively. Although subjective measurements are very important for the system’s users, we needed objective measurements to evaluate different options and technology choices. Therefore, we developed a methodology for the objective measurement of the system quality. The methodology is based on the musical rehearsal practice where the conductor not only coordinates musicians but also identifies and sometimes modifies notes that are played wrong or don’t sound right for the performance room’s acoustics.

During the second phase of the trial we gave specific scores to the musicians and the conductor. The musicians’ scores contained various errors (like time errors, pitch errors, dynamic errors, and so forth) when compared to the conductor’s score. The errors ranged from very easy to detect to very difficult to detect. The conductor was asked to detect errors in the musicians’ scores. By reproducing the same test in a local situation with different but equivalent musical scores and comparing the errors found in the distributed rehearsal and in the local rehearsal, we established a concrete measurement of the system quality.

Note that the rehearsed piece was later performed in concert without additional rehearsals. Presumably this indicates that the distributed rehearsal effectively prepared the musicians and the conductor.

Second distributed musical rehearsal

In the second rehearsal the selected piece was H.P. Platz’s Piece Noire, for 12 musicians (Figure 7):
two flutes, oboe, clarinet, horn, trumpet, trombone, piano, violin, alto, cello, and contrabass. The rehearsal lasted six hours.

In contrast with the first distributed musical rehearsal, which had a high element of research, this was a professional rehearsal and part of the rehearsal series for the performance of the piece. Based on the observations and analysis of the first trial, we made a number of improvements to the system. The most important changes were a higher quality dummy head, which improved the acoustic diacritical capability of the conductor, and a more detailed perspective correction of the projected video at both sides.

The major goal of this second rehearsal was studying the conductor’s designation capabilities, that is, how well the conductor could identify the musicians’ positions and how well the musicians could identify which of them he designated. For this, we performed a set of designation tests with students from the University of Geneva as subjects. Different groups of students were positioned in specific places in front of the video wall and were designated by the “conductor” in a number of designation sequences.

**Evaluation results**

Analysis of the evaluation results let us identify a number of issues that could contribute to improving the overall system. Nevertheless, the evaluation results aren’t easy to understand and interpret. Further trials with more detailed experimentation are needed to fully understand the implications and related issues.

**Objective quality evaluation**

The objective evaluation results (Figure 8) indicate that overall quality of the distributed musical rehearsal system reaches about 40 percent of a normal localized rehearsal. However, the performance in the distributed versus the local environment differs drastically from instrument to instrument. For example, the performance for the flute is superior in the distributed environment, the performance of the violin is equal for both environments, and the performance of all other instruments is inferior in the distributed environment. In our opinion, this occurs because the audio capture system behaves differently for each musical instrument, depending on its frequency range and its harmonics.

Due to the digitization of the sound it’s probable that some phase information and high-frequency harmonics are lost. Another factor that might contribute to performance degradation of the system is differences in the clock rates between the analog-to-digital and digital-to-analog hardware.

In addition, the acoustics of the local and remote rehearsal rooms contribute to the rehearsal performance quality. While the local rehearsal took place in an acoustically tuned theater, the distributed rehearsal used a room with no special acoustics.

Finally, we must note that because of the small number of trials performed, the statistical data collected don’t provide accurate evaluation results. More trials are needed to obtain higher confidence results—not possible within the budget and time frame of this project.

**Designation tests evaluation**

The second set of evaluation tests, which also affect the overall rehearsal performance, focused on the conductor’s designation capabilities. We used two groups of students instead of musicians (Figure 9). The groups, A and B of nine students each, were divided into subgroups of three students (A1 to A3 and B1 to B3). We tested in an...
environment of three, six, and nine students incrementally, alternating the groups, without changing the sitting position of the subgroups. This way, subgroups A1 and B1 participated in all three runs of their group while subgroups A3 and B3 only in the last of nine persons. As shown in Figure 10, the first subgroups, A1 and B1, improved their performance on the three runs. They achieved their best results in the last situation, which was the most difficult. Subgroups A2 and B2 also improved their performance in the last run, while subgroups A3 and B3, were newcomers and untrained in the most complex run. As expected, they obtained the worst results. The last column in the graph (groups A and B) represents the total normalized number of errors of all groups in the different runs. In the run with nine persons (the most complex environment), the total number of errors is double those of the first two runs (with three and six persons).

Gestural designation through a 2D-image creates an artificial situation where users never feel designated. Without training users can only distinguish left and right designation but no other orientation. With training, it’s possible to distinguish gestural designation in a nine-person group with good to excellent results like subgroup A1 (0 percent errors in the nine-person setup). This is an encouraging result, nevertheless the test conditions were not equivalent to a rehearsal situation in terms of designation speed and participant stress. Therefore, we could not determine, without further experiments, how this result could apply to a real distributed rehearsal environment.

Considering that the musicians had no training in the distributed musical rehearsal environment, we can expect improvement in their future collaboration with the conductor. In fact, we clearly observed this in the second trial where 12 musicians participated, five of whom were present in the first trial. For these musicians, participating in the rehearsal proved easier and more natural, allowing them to concentrate more on their work. Thus, we strongly believe that even a couple of sessions will let the musicians familiarize themselves with the distributed system and thus yield an improvement in the system performance.

**Influence of the delay**

During both distributed musical rehearsals we performed tests to evaluate the influence of the transmission delay. More specifically, we changed the audio and video delays at different points of the rehearsal and observed the musicians and conductor’s reactions. Neither the conductor nor the musicians knew in advance about the delay modifications. In the normal system’s operation the delay was 34 ms for the audio and 57 ms for the video. With these delays the conductor could hear the reaction to his gestures after a total delay of 91 ms (57 ms for the image to arrive to the musicians and 34 ms for the sound to come back to the conductor).

During the first distributed rehearsal the transmission delay was annoying, but acceptable for the chosen Handel piece. The Britten piece played at the second distributed rehearsal was very demanding from the rhythmic point of view, with fast tempi. It was impossible for the conductor to conduct the fastest part of the piece when the tempo was greater than 150 per quarter note. At this speed, sixteenth notes have approximately the duration of the delay perceived by the conductor between his gesture and the sound feedback.

The delay tests let us define a limit between the rhythmic complexity of the rehearsed musical piece and the supportable delay. We estimated that the total round trip delay should not exceed 85 percent of the duration of a sixteenth note. This means that for a delay of 90 ms, the musical piece tempi should be less than 142 per quarter note. Here we must note that in the musicians’ opinion the distributed musical rehearsal system is better adapted to classical music than to contemporary music. The more stable rhythmic structures of classical music seem easier to conduct with the transmission delay of the distributed system.

**Conclusions**

We do not expect, for the time being, that a distributed rehearsal system can completely replace a
localized rehearsal. Apart from the measurable technical characteristics of a rehearsal, other elements that are important to artistic creation cannot be measured, like the relationship between the conductor and the musicians, the feeling of the rehearsal room, and so on. Nevertheless, the advantages of such an environment can be numerous, both in gaining time and reducing costs, and in bringing together artists and ideas from around the world. A distributed rehearsal system can facilitate musicians and conductors in distant countries working together. The system can let music students follow courses given by famous composers and conductors without the need to travel. It can even allow a first-level selection of musicians for an empty place in an orchestra.

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References


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