The MusiNet project: Addressing the challenges in Networked Music Performance systems

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Abstract—This paper presents the progress in the MusiNet research project, which aims to provide a comprehensive architecture and a prototype implementation of a Networked Music Performance (NMP) system. We describe the Musinet client and server components, and the different approaches followed in our research effort in order to culminate in the most appropriate scheme in terms of delay and quality for the audio and video streams involved. We also describe the MusiNet user interface, which allows an integrated communication between the participants and the proposed NMP system.

I. INTRODUCTION

Networked Music Performance (NMP) systems can have a catalytic effect in music creation and social interaction, since they allow collaboration between musicians in geographically remote and disparate locations. Lowering the cost of collaboration, such systems can promote music creativity, education and cross-cultural interaction, enabling live performances, rehearsals, improvisation or distant music learning.

The appearance of high speed research/educational computer networks, such as Internet2 in the USA and GEANT in Europe, triggered the appearance of NMP system projects, such as Jacktrip [1], Distributed Immersive Performance (DIP) [2], SoundJack [3] and DIAMOUSES [4]. However, these systems either pose significant limitations to NMP interaction, or require excessive amounts of resources and direct access to high speed networks.

In our previous work [5] we introduced the MusiNet project, which aims at significantly reducing the resource requirements of NMP and studying in depth the sociological and musico- logical aspects of such systems. The central objective of the MusiNet project is to address the main challenges of NMP systems. The most crucial one is the elimination of latencies during the capturing, transmission, reception and reproduction of the audiovisual information. The maximum delay between any two endpoints must be kept below 25 msec [6] in order not to hinder musicians participating in an NMP session. Other challenges include the elimination of network bandwidth bottlenecks, the synchronization of the exchanged information, and handling the high sensitivity of NMP to network data loss. In this work we present the progress accomplished towards unraveling the full potentials of NMP systems, by outlining implementation aspects of the primary components of MusiNet, i.e., the client, server and user interface.

The remainder of this paper is structured as follows. Section II-A presents the Musinet client, Section II-B presents the different implementation approaches for the MusiNet server, while Section II-C describes the user interface of the proposed system and Section II-D describes a novel method for real-time delay estimation of audio streams. We present evaluation and comparative results for the proposed schemes in terms of delay in Section III. We conclude and refer to future work in Section IV.

II. ADVANCES IN THE MUSINET SYSTEM

In this section we describe our work on the primary components of MusiNet, i.e., the MusiNet client and the MusiNet server, shown in Fig. 1. We also describe in Section II-C the user interface that we designed, which enables a natural interaction between the system and the remote participants.

A. The MusiNet Client

For the MusiNet client, we based our implementation on BareSIP [7], an open-source portable and modular Session
processes, for a conference room with a downmix process of numerous streams. For a conference room, we have to modify BareSIP’s architecture. Specifically, a single BareSIP instance should be used, with a single session established between the user and the server. Depending on the architecture of the server (discussed in Section II-B), either a single encoding and decoding process should be performed at each user’s terminal, or one encoding and decoding processes for a conference room with a N + 1 participants.

In a typical conferencing application, the server mixes the multiple audio and video streams in a single stream which is transmitted to the clients. However, in a NMP system it is better for the participants to be able to create their own local downmix. For this reason, the system architecture of MusiNet involves the connection of multiple users to a conference room, we have to modify BareSIP’s architecture. Specifically, a single BareSIP instance should be used, with a single session established between the user and the server. Depending on the architecture of the server (discussed in Section II-B), either a single encoding and decoding process should be performed at each user’s terminal, or one encoding and decoding processes for a conference room with a N + 1 participants.

B. The MusiNet Server

For the MusiNet server we have pursued three parallel lines of development: (a) modifying FreeSwitch [12], an existing SIP server that offers audio Multipoint Control Unit (MCU) functionality, (b) developing pktswitch [13], an ultra-low delay Selective Forwarding Unit (SFU) and (c) modifying the BareSIP client so as to operate as a transparent server with minimal operations; we will refer to this server-oriented BareSIP modification as BareServer.

On the FreeSwitch front, our work has focused on replacing the existing audio mixing functionality with a straightforward packet relaying functionality for both audio and video streams. While FreeSwitch has the advantage of supporting SIP functionality required for the MusiNet system, such as user presence notifications, its basic design as an audio mixer

1SSRC, which stands for synchronization source identifier, is an integer number that uniquely identifies a stream in an RTP session [11].
Network socket call can only pass a single packet from the custom protocol and pre-configured settings. Therefore, our research has focused on pktswitch, which follows the latest research developments in high performance network I/O systems but lacks SIP support, and on BareServer, which complies with the project’s strict latency constraints, according to our preliminary experimental results, and also supports SIP functionality.

1) The pktswitch SFU: The basic concept behind pktswitch is to exploit the netmap [14] packet handling framework in order to minimize packet processing delay [15]. In order to assess the validity of our approach, we first implemented a baseline, socket-based, SFU which handles a single type of control packet, indicating new client registrations, and three types of media packets, audio, video base layer and video enhancement layer. A pre-configured table in the SFU shows which media packet types each client wishes to receive. The SFU consults that table for each incoming packet and sends a copy of the packet to each interested client. A final copy is sent back to the originating client as an “echo” packet. A test client periodically transmits packets of each type to the SFU, tracking the time until each “echo” packet arrives. Note that the test client and server do not support SIP but rely on a custom protocol and pre-configured settings.

The disadvantage of the socket-based SFU is that each socket call can only pass a single packet from the Network Interface Card (NIC) to the SFU and vice versa, requiring a context switch between kernel and user space; one call is needed to receive the packet and one call is needed to send the packet to each recipient. This overhead grows with the number of clients. Since the SFU barely modifies the media packets, we have resorted to the netmap framework to minimize this overhead. With netmap, the SFU waits for packets from either the netmap RX (NRX) ring, connected to the NIC, or the host RX (HRX) ring, connected to the host networking stack. The SFU issues a poll system call to wait for new packets. When this call returns, if there are new packets in the NRX ring, they are all moved to user space, without further kernel mediation.

![Fig. 2. The netmap-based pktswitch.](image)

Media packets are passed to a media handler, which inspects the packet header and consults the SFU table to determine which clients should receive it. The packet is copied as many times as needed to the netmap TX (NTX) ring, connected to the NIC, simply changing its destination address to that of the desired client. The incoming packet is also moved to the NTX ring, to be sent as an “echo” packet to the originating client. Control packets are processed by a control handler, updating its lookup table. Finally, packets destined to the host OS are copied to the host TX (HTX) ring, i.e., the host networking stack, for processing by other applications. As a result, packets are always moved to/from user space in large batches, eliminating redundant context switches. An overall view of the application layer SFU is given in Fig. 2.

2) The BareServer: Since BareSIP already supports multiple concurrent peer-to-peer calls and has a modular design which simplifies extensions, we have modified it to behave as a server, the BareServer. The BareServer is a minimal SFU, simply relaying packets, with no transcoding or mixing.

Each BareSIP client makes a peer-to-peer call to the BareServer as it would normally do with another plain BareSIP client. All necessary protocol negotiations needed in order to establish the call are supported by default. When a connection is established between a BareSIP client and the BareServer, the client transmits its own local audio and video streams, but BareServer’s default local audio and video transmit is disabled. In Section II-A we referred to two possible ways for media stream demultiplexing, one based on SSRCs and one based on user IDs. In the first case, the BareServer simply retransmits a received packet to all other clients. In the second one the BareServer, after the RTP header is decoded, re-encodes it including the user ID in the first CSRC slot of the RTP header, which is not used for any other purpose in our implementation, and transmits the packet to all participants involved.

Using either approach, every client connection to the BareServer will be handled as a different call, so it is important to increase the maximum number of calls according to the anticipated maximum number of participants, which by default is set to four. The side information (e.g., the user ID) about room participants is transmitted every 1 sec through Real Time Control Protocol (RTCP) application-specific messages. For each client, its user ID, its uniform resource identifier (URI) and its alias name are included in the side information.

To achieve higher throughput for the BareServer, a threaded implementation is applied. For each client, two threads are created, one for audio and one for video. The task of each thread is to relay its client’s packets to all other connected clients. A producer-consumer model is used, i.e., when a new audio or video packet from a client is received, it is appended at its audio or video packet list respectively. The threads read those lists and relay the packets sequentially, in the same order they were received.

C. The MusiNet HCI design and media configuration

With respect to interaction design, the approach followed rests on the “material turn” in human-computer interfaces (HCI) [16]–[18]. In terms of design commitments, the material-turn in HCI signifies a redirection of attention from

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2CSRC, which stands for contributing source identifier, is an integer number that uniquely identifies one of the sources contributing to a translated stream, identified by the SSRC of the translating entity.
digital artifacts or the application layer of interaction design toward the materials from which digital products and services are built in the first place. For our purposes, a material turn entails configuring different genres of digital technologies implicated in computer-mediated collaborative music making and performance in such a way that they operate interdependently, as the need arises. Thus, a prominent issue is treating technologies such as BareSIP, file sharing services, an augmented graphical toolkit for music composition and 2D visualization, as digital materials from which virtual experiences are built.

At the core of this effort has been the appropriation (or crafting of new) Application Programming Interfaces (APIs) to ensure that these technologies act interdependently and constitute a coherent whole. As Fig. 3(a) indicates, this layering of different digital materials enables loose coupling of distinct functionalities that may be invoked as needed either prior, during or after network music performance sessions.

To address the challenges, several lines of technical developments have been undertaken. Firstly, dedicated container objects were implemented (see Fig. 3(b)) to host media types from BareSIP. In addition, a multithreaded dialogue manager was designed on top of the window manager to handle the users’ entry to and exit from the workspace, as well as the in-coming events to be delegated to appropriate container objects for rendering multimedia content. Thirdly, a custom component was used to bridge the gap between the Java User Interface API and the BareSIP core API. Finally, several native modules were implemented to allow configuration of BareSIP parameters and user contact lists. An instance depicting parameter configuration is presented in Fig. 3(c).

D. Real-Time Delay Estimation of Audio Streams

Since audio signal delay is the most significant parameter in enabling music collaboration [19], [20], we need a method to accurately quantify the end-to-end delay of audio streams. In order to measure one-way delay in real-time audio communication between distant endpoints, we have resorted to the use of pilot signals. Taking into consideration the general properties of music and the human auditory system, we designed the pilot signal so as to minimize its audible effects, considering that there is a trade-off between the system’s delay estimation accuracy and the pilot signal’s audibility. We provide the key quantities that can be modified correspondingly, with respect to the targeted/desirable application mode.

At the transmitter, we split the audio signal in time intervals equal to the duration of an audio packet. Then, we perform a spectral analysis and properly adjust the pilot signal, avoiding any undesirable additive noise. We also designed an algorithm to estimate the one-way delay based on the receiver’s local clock, given an initial time reference of the first pilot signal’s injection at the transmitter. The proposed system operates in real-time, adding a negligible delay to the total end-to-end latency of the audio stream due to the pilot signal’s adaptation processing. Additionally, the structure of the pilot provides multiple access capability [19]. Initial simulations verify the effectiveness of the adopted techniques. As a next step, we will embed this technique to the MusiNet system in order to allow each user to get informed about the delay of each audio stream received while the system is actually being used.

III. EVALUATION OF THE MUSINET SYSTEM

In this section we evaluate our proposed system through real experimental setups. In the first set of experiments we measure the delay induced by the pktswitch SFU (Section II-B1). In the second set we compare the default implementation of the BareSIP client with the modified version described in Section II-A, using the BareServer SFU (Section II-B2).

A. Server-induced delay estimation

To assess the delay induced by the SFU (see Section II-B1), we measured the difference between the time a media packet was picked for processing and the time its final “echo” packet was scheduled to be sent. We used a set of identical machines using the Realtek RTL8111/8168B Gigabit Ethernet controller and running Linux kernel 3.2.63, connected via an isolated Gigabit LAN, with one machine acting as the SFU. Each experiment consisted of a warmup period, followed by a 60 s period of measurements. For efficient and high-resolution delay measurements, we counted CPU cycles. To ensure repeatability, we ran each experiment multiple times and verified that results had very low variance. Figure 4 shows the packet processing delay measured for sessions with 6 and 8 clients. The media payload sizes are set to 80, 160 and 320 bytes for the audio, video base and video enhancement streams,
respectively, and a new packet per stream is transmitted every 4 ms, leading to or 750 packets per second (pps), or a combined data rate of 1.12 Mbps per client. The netmap-based SFU shows significant improvements, with a delay that is on average only 11.3% of the delay of the socket-based SFU. Further experiments show that the netmap-based SFU requires only 25% of the packet processing overhead of the socket-based SFU, which means that it can handle four times the load of the socket-based SFU before packet queuing is needed to handle the increased load [13].

B. Delay estimation experiments of the MusiNet System

In this experimental set we compare the default implementation of the BareSIP client with the modified version described in Section II-A, considering sessions with two to five participants. With two users we can directly compare two different but equivalent systems, while with more than two users we can evaluate the performance of the multi-threading receiver developed to support conferencing. We also estimate the time delay of the server processing per received packet.

The total time for media transmission at each client is the sum of the individual time delays for capturing media, encoding media and transmitting the corresponding RTP packets. Media capture is performed by an external module, using appropriate APIs. Thus, a video or audio handler is responsible for transferring captured data to the main BareSIP code to be encoded, packetized and transmitted. For audio transmission, the recording buffer used to store the samples from the audio source is of size equal to the packet duration, i.e., (ptime); when filled, the specified handler is called. The captured data correspond to a single packet, and thus, the encoding, packetization and transmission of a single packet is performed directly by BareSIP’s main code. For video, when a frame is captured, the corresponding handler is called. BareSIP undertakes the encoding, packetization and transmission of video packets, as well, but in this case, the video encoder receives an entire frame and returns the encoded data that may be included in one or more fixed size (pktsize) RTP packets. In both cases, using the system call gettimeofday, we estimate the time needed for the transmission of a single packet, excluding the functions responsible for audio and video capturing. Therefore, these numbers reflect the performance of BareSIP’s main code.

Another parameter affecting delay is the packet size. A larger buffer means that bigger intervals of the audio source are captured, increasing the end-to-end delay, since we have to wait more for the buffer to fill. As mentioned above, in our performance evaluation we ignored capture delay. Increasing the packet size, however, also means handling larger packets, which leads to increased processing delay per packet, although there are fewer packets transmitted per stream.

The experiments were conducted on a LAN, where we made a set of calls with nearly identical video/audio content lasting \( \approx 60 \) sec; all results refer to average values. The measurements were performed on an Apple Mac mini, running a single instance of BareSIP, with additional participants hosted on a second one that ran one instance of BareSIP for each participant. The client computer configuration involved an Intel Core i5 processor at 2.5 GHz running MacOS X version 10.9.5. The Opus codec was used for audio coding and H.263 for the video coding. CoreAudio for audio capture and playback, AVCapture API for video capture, and OpenGL for video display. The server was built on a MacBook Pro with an Intel Core i7 processor at 2.7 GHz running MacOS X 10.9.5.

In Table I we present the processing delay per packet in microseconds (\( \mu \)sec), for audio and video. “P2P” indicates the use of the default, peer-to-peer version of BareSIP; without an intermediate server. The abbreviation “VC” stands for our video conferencing mode, with the integer next to it denoting the number of participants. In this configuration all streams are routed through a media server.

<table>
<thead>
<tr>
<th>Ptime</th>
<th>Delay of audio transmission per packet (( \mu )sec)</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>P2P</td>
</tr>
<tr>
<td>10</td>
<td>166.54</td>
</tr>
<tr>
<td>5</td>
<td>115.39</td>
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<tr>
<td></td>
<td>72.6</td>
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</table>

<table>
<thead>
<tr>
<th>Pktsize</th>
<th>Delay of video transmission per packet (( \mu )sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>P2P</td>
</tr>
<tr>
<td>1663.98</td>
<td>1778.97</td>
</tr>
</tbody>
</table>

For both audio and video transmission, we observe that as the number of participants and the packet size are increased, the processing delay generally increases. In the case of audio, by decreasing the packet duration at each tested mode we notice a significant delay reduction of up to 57%. For both audio and video, by increasing the number of users and keeping the packet size fixed, we observe a delay increase of up to 10% in terms of \( \mu \)sec, which does not depend on the number of clients, making the difference negligible.

At each client, the total time for media reception is the sum of time for receiving RTP packets, jitter buffer processing, decoding and rendering the media. Media rendering is performed by an external module. After the decoding operation, specific handlers are called to either store the decoded audio samples to the playout buffer, or to display the video frame. In the case...
of video, a single packet may include a whole, or a part of a frame. In both cases, using the system call `gettimeofday`, we estimate the time needed for the reception of a single packet, excluding the system functions responsible for audio and video reproduction. Besides the media content and the packet duration, another parameter that significantly affects the receiving operation is the size of the jitter buffer, which is set in terms of frames/packets. In Table II we present the processing delay per packet in msec for audio and video, respectively, including the jitter buffer size as an extra parameter.

<table>
<thead>
<tr>
<th>Buffer size</th>
<th>ptime</th>
<th>pktsize</th>
<th>VC 2</th>
<th>VC 3</th>
<th>VC 4</th>
<th>VC 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>2024</td>
<td>200.087</td>
<td>200.069</td>
<td>199.914</td>
<td>200.083</td>
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<tr>
<td>10</td>
<td>10</td>
<td>99.834</td>
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<td>100.034</td>
<td>100.025</td>
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<tr>
<td>5</td>
<td>5</td>
<td>49.909</td>
<td>50.045</td>
<td>50.025</td>
<td>50.028</td>
<td>50.014</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>99.773</td>
<td>100.099</td>
<td>100.099</td>
<td>100.078</td>
<td>100.048</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>49.959</td>
<td>50.059</td>
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<td>20.003</td>
<td>20.097</td>
<td>20.122</td>
<td>20.098</td>
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<td>1</td>
<td>1</td>
<td>10.029</td>
<td>10.073</td>
<td>10.057</td>
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<td>5.056</td>
<td>5.062</td>
<td>5.059</td>
<td>5.060</td>
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For audio reception (the most critical issue for MusiNet), keeping the packet duration and the jitter buffer size fixed, the estimated delay time is almost identical for each tested mode. Specifically, the estimated delay is approximately equal to the product of the packet duration multiplied by the size of the jitter buffer. For video reception, keeping the jitter buffer size constant, we notice that as the number of the participants is increased, the processing delay increases by up to 38%. Furthermore, at each tested mode, decreasing the size of the buffer we observe that the estimated delays are reduced almost by the same percentage.

Regarding the performance of the BareServer, we demonstrate the per packet relaying delay in Table III. We observe that, as the number of the participants and the packet time are increasing, the system is stressed and its processing delay is increased up to 260%. Note, however, that these measurements are in microseconds.

<table>
<thead>
<tr>
<th>Buffer size</th>
<th>ptime</th>
<th>pktsize</th>
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<th>VC 3</th>
<th>VC 4</th>
<th>VC 5</th>
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<td>5.060</td>
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Aiming at achieving the lowest delay possible, we would naturally choose the lowest value for the `ptime` parameter as well as the jitter buffer size. However there is a trade off between the delay and the perceived audio quality which should be taken into account.

### IV. Conclusion

The goal of the MusiNet project is to integrate ultra low delay audio coding, scalable video coding, low delay relaying and musician collaboration techniques into a unified prototype towards a full potential NMP system for the average user. In this work we have presented the progress accomplished towards this goal in terms of implementation of the primary units of the system. In future work we will present complementary delay measurements as well as objective and subjective evaluation results in real conditions.

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