Chapter 2
Networked Music Performance

Abstract Networked music performances have been considered since a few decades in contemporary music composition. More recently, the enabling technologies for NMP have been also considered as a way to deliver classes to facilitate rehearsal or conduct proper music improvisation. Unfortunately after a few years of experiments through the Internet the interest has shifted toward the use of NMP for composition only and advancement in avant-garde music practice. NMP is also a means of reflection for the artists and the composer over new media technologies. For these reasons planning a NMP requires an interdisciplinary approach, evaluating both aesthetic and technical issues. In this book, intended for the technical reader, only the latter shall be addressed. However, to ease the exchange and expedite collaboration between technologists and artists an introduction on historical and current practices in NMP is provided. The lexicon and the dissertation on technical issues are intentionally left as simple as possible to facilitate readers with no specific technical background on digital signal processing, audio processing, and networking.

Keywords Networked music performance · Network computer music · Laptop orchestra

2.1 Definition and Taxonomy

One of the first definitions of networked music performance dates back to 2001 [1]:

> A Networked Music Performance occurs when a group of musicians, located at different physical locations, interact over a network to perform as if they would, if located in the same room.

Such definition carries an implicit bias, as the network is seen as a surrogate for the natural propagation of sound and light in the space between musicians sharing the same ambience. Other researchers, e.g., those of the SoundWire group at Stanford CCRMA, showed rather the opposite interest, i.e. to explore the network as a new medium for interaction and making its inherent shortcomings, such as the propagation delay, as a feature, or at least something musicians have to "*live with*" [2].

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A more neutral and ample definition of NMP is thus,

> the practice of conducting real-time music interaction over a computer network.

This definition, thus, does not suggest limitations on the way the interaction is conducted, the distance, or the instruments to be employed. Many category of NMP fall under such a broad definition. We may thus build a taxonomy of networked music performances based on the instruments employed: *computer-only*, *human performers-only*, or *mixed*. We shall see later in Sect. 2.2 that the first usage of networking was conducted between computers employing algorithms for sound generation, with limited human intervention. We shall also see that in the recent years fiber-optic networks for research institutions allowed simultaneous low-latency transmission of audio and video, making it possible for acoustic musicians displaced at remote location to perform and interact in a feedback fashion. One reason why computer-only NMP is first seen in NMP history is that it can be carried out by transmitting control data only, or some form of compressed representation of audio data, thus it has been feasible since the inception of computer networking, given the limited bandwidth available at the time. NMPs can be, thus, classified whether the network carries *control data only*, *audio data only*, or both. Computer networking is often employed in the *laptop orchestra* paradigm. Technical and musical discussion of laptop orchestras is a topic on its own, which is already treated by textbooks and reviews. Not all laptop orchestras employ networking. Indeed, they seldom employ networking and most of the times it is based on TCP/IP data exchange over a wired connection.

Another means to discriminate between different NMP practices is the distance and position of the performers and their instruments. Most NMP literature at the moment deals with remote performers, i.e., performers located at distances much larger than 1 km. In this book, the use of wireless technologies enables, instead, to connect musicians located in the same room, in a large indoor space or in outdoor spaces. We may, thus, distinguish between *indoor local*, *outdoor local* or *remote* NMP. In the former two cases local area networking (LAN) technologies are employed, while in the second wide area networking (WAN) is necessary. The level of interaction also defines different kinds of performance: the musicians can be *tightly synchronized*, as they are when they improvise in a shared space, they can be *loosely synchronized*, i.e. aware of each other's actions, but not able to respond as they were separated by a negligible latency or *disconnected*. In the latter case, they may be disconnected *aurally* or *visually*, or both. If there is not aural or visual connection a click track or similar means must be employed to synchronize them (Table 2.1).

To conclude, there are a number of different approaches for musical interaction between human performers, depending on latency constraints, proposed by Carôt in [3]:

- Realistic Interaction Approach (RIA),
- Master Slave Approach (MSA),
- Laid Back Approach (LBA),
- Delay Feedback Approach (DFA),

Table 2.1 Taxonomy of a networked music performance

Human role	Instrument performer, laptop performer, supervisor only (autonomous computer network)
Network topology	Start, point-to-point, mesh
Transmitted signals	Audio, video, control (e.g. OSC), text chat
Distance of performers	Remote (tens to hundreds of km), outdoor local (up to a few km), indoor
Networking area	LAN, MAN, WAN
Networking technologies	Wired LAN, wireless LAN, fibre-optic WAN, copper WAN, satellite link
Latency and synchronization	Tight synch, loose synch, click synch (no aural/visual cue), disconnected (only the audience is aware of the performers actions)
Audio and video	Aurally and/or visually synchronized, aurally and/or visually aware but not synchronized, no aural and/or visual connection

- Latency Accepting Approach (LAA),
- Fake Time Approach (FTA).

The **RIA** is the most demanding, as it tries to simulate the conditions of a real interplay with the musicians in the same space. The general latency threshold for this approach is set by Carôt at 25 ms for the one-way delay (or latency), following an early technical report from Nathan Schuett at Stanford in 2002 [4], although more accurate studies exist in literature which suggest slightly different (but comparable) values. In the **MSA**, a master instrument provides the beat and the slave synchronizes on the delayed version that is coming from the master. The audio is in sync only at the slave side, while the master does not try to keep up with the slave's tempo, but he can barely get a picture of what is going on at the slave's side, trying not to get influenced in his tempo by the incoming delayed signal. Clearly, the interaction gets reduced in this approach, but the acceptable latency increases. The **Laid Back Approach** is based on the laid back playing manner, which is a common and accepted solo style in jazz music. Playing laid back means to play slightly behind the groove, which musicians often try to achieve consciously in order to make their solo appear more interesting and free. Similarly to the MSA, at the master side the beat is built and at the slave side, a solo instrument can play. At the master side, the round trip delay, if higher than 25 ms but below 50 ms, creates an artificial laid back style of playing. LBA of course does not work for unison music parts in which both parties have to play exactly on the same beat at the same time. A commercial software Musigy exist that implements LBA. A **DFA**, tries to fill the latency gap between the two ends by introducing an artificial delay in the listening room at the master end (if one of the ends have a master role), or at both ends (if interplay is not hierarchical). In the first case, e.g., delaying the master's signal in the room allows to make it closer to the slave's delayed signal. Similarly for the non-hierarchical case. The approach however, introduces a latency between the user action (e.g., key press) and aural response (in case of an electronic instrument) or simply adds a delayed version to an acoustic instrument, which can deteriorate playing conditions, however, is suitable with turntables or sound sources with little human interaction. A commercial software, eJamming, employs this approach. The **LAA** simply neglects synchronization and is used for contemporary avantgarde music, music with very low timing constraints or computer music which employs the network as part of the performance. The SoundWire group promoted this approach with several performances of contemporary music.

Finally, an approach that accepts latency but allows for tempo (but not beat) synchronization is the **FTA**. In this case the latency is artificially adapted to be one measure or multiples. This way, any performer plays on the previous measure executed by the other performer. This approach requires a tempo to be known a priori and fixed. A further hypothesis is needed, that the music does not change drastically from measure to measure, which is the case for many improvisational genres, such as blues, funk, etc. The Ninjam open source software employs this approach. For a different, more aesthetics-related classification of NMP, refer to [5].

2.2 A Brief Timeline

Transmitting music over a distance by technological means was accomplished at the outset of telephone and radio technologies, for technological display and entertainment. One of the first wired music transmission was possible due to Thaddeus Cahill, inventor of the Telharmonium (patent no. 580035, 1896), an "apparatus for generating and distributing music electrically," which since 1906 was employed in performances and could drive 15,000–20,000 telephone receivers, according to its main capital investor, Oscar T. Crosby [6]. Its demise was soon to come,[1] as radio broadcast was going to spread in the subsequent years. And annoyed mistresses were not ready for electronic music yet.

The first radio broadcast dates back to 1910, with an experimental transmission of Mascagni's *Cavalleria Rusticana* and Leoncavallo's *Pagliacci* featuring the Italian tenore Enrico Caruso from the Metropolitan Opera House, in NYC, USA. The amplitude-modulated broadcast, provided by the American inventor Lee De Forest's Radio Telephone Company had some issues, especially with the scarce microphone signal loudness, but the path was set. In Fig. 2.1 a New York Times advertisement for the radio (called *wireless*, despite De Forest's preference for the former term) is

[1] Cable radio was anyway employed all along the twentieth century, with a varying degree of success from country to country and different developments. Its main advantages over radio transmission are a more capillary reach, a higher quality compared to AM transmission and reduced costs compared to digital transmission. Music broadcasting services by means of cable radio are still in use in several countries including Italy.

Fig. 2.1 An advertisement of *wireless music* well before the WeMUST project

shown. Although other musical wireless transmission were experimented before,[2] the one from 1910 was the first to address a public.

Despite the long history of music broadcasting, music performance over a distance has a much more recent history. Radio modulated waves had an influence over John Cage, who is credited by some authors to be the first composer for a NMP piece [7], with his "Imaginary Landscape no. 4 for Twelve Radios" in 1951 (see also [8]). The piece does not fall into what has been previously defined as NMP, given the absence of a network. However, disputable whether this can be considered an NMP piece, it is surely one of the first human attempt to explore musical interaction at a distance. The same author in 1992–1993, composed *Helikopter-Streichquartett* a string quartet piece to be played on four helicopters. The piece is the third scene of the opera *Mittwoch aus Licht*. The musicians are separated aurally and visually, and are synchronized by a click track and do not hear each others, while the audience can see and hear all of them through audio and video signals transmitted from each helicopter. Networking was first employed by Max Neuhaus in 1966 in his pieces for public telephone networks. In *Public Supply I*

[2]Most notably, the one from Dr. Nussbaumer at the University of Graz, in 1904, who yodeled an Austrian Folk song from a room to another by means of a receiver and transmitter.

> he combined a radio station with the telephone network and created a two-way public aural space twenty miles in diameter encompassing New York City, where any inhabitant could join a live dialogue with sound by making a phone call. Later, in 1977 with Radio Net, he formed a nationwide network with 190 radio stations.[3]

2.2.1 Early Computer Network Experiments

Computer networking experiments in music were introduced by the League of Automatic Music Composers (LAMC), an experimental collective formed by San Francisco Bay area musicians John Bischoff, James Horton, Tim Perkis, and others. The production of the LAMC was improvisational and the group was open. The group recorded music in the years 1978–83. The LAMC experimented with early microcomputers, and also very primitive computer networking. Specifically, they employed multiple MOS KIM-1 microcomputers programmed by themselves in the 6502 CPU machine language, inputting the assembly by means of a numeric keypad. Programs were stored in audio cassettes. Without getting into the aesthetic and compositional aspects of the LAMC experience, it is of interest here to report on the technical details. The microcomputers were interconnected through parallel ports or interrupt signals, directly handled by the microcode written by the composers. No standard networking was employed. The interaction was based on musical representation data, later fed to analog synthesizers or direct D/A for sound synthesis. The flier from an early concert from band members Bischoff, Behrman, Horton and Gold, depicted in Fig. 2.2 shows the data path and algorithms employed during the then-upcoming event. This picture is still quite representative of laptop orchestra performances taking place nowadays. Please note that audio signals were not transmitted digitally.

In [9], Bischoff, Gold and Horton, report on another performance taking place at the same venue in July 1978, where three KIM-1 are interconnected in a different fashion and output sound through direct D/A or a 8253 programmable interval timer chip. The interconnection is made through serial or 4-bit parallel ports.

The LAMC proposed the term Network Computer Music for their performances. Such performances provided the basis for the typical laptop orchestra paradigm, with different units exchanging musical or audio data which are subsequently processed by other units for synthesis or manipulation. Notably, the setup would algorithmically generate music and sound in a deterministic but unpredictable way, thanks to the feedback nature of the system. The composers themselves claimed to be influenced by some of the intellectual currents of the time, suggesting that complex phenomena could emerge from the interconnection and interaction of simple components. By the way, it is worth citing some of these scientists and writers since their writings were necessary to much computer music theory and practice, still influencing laptop orchestras and NMP composers: Ilya Prigogine (complex system theory and self-organizing systems), Warren S. McCullough (Neural Networks), Gregory

[3] From Max Neuhaus official webpage.

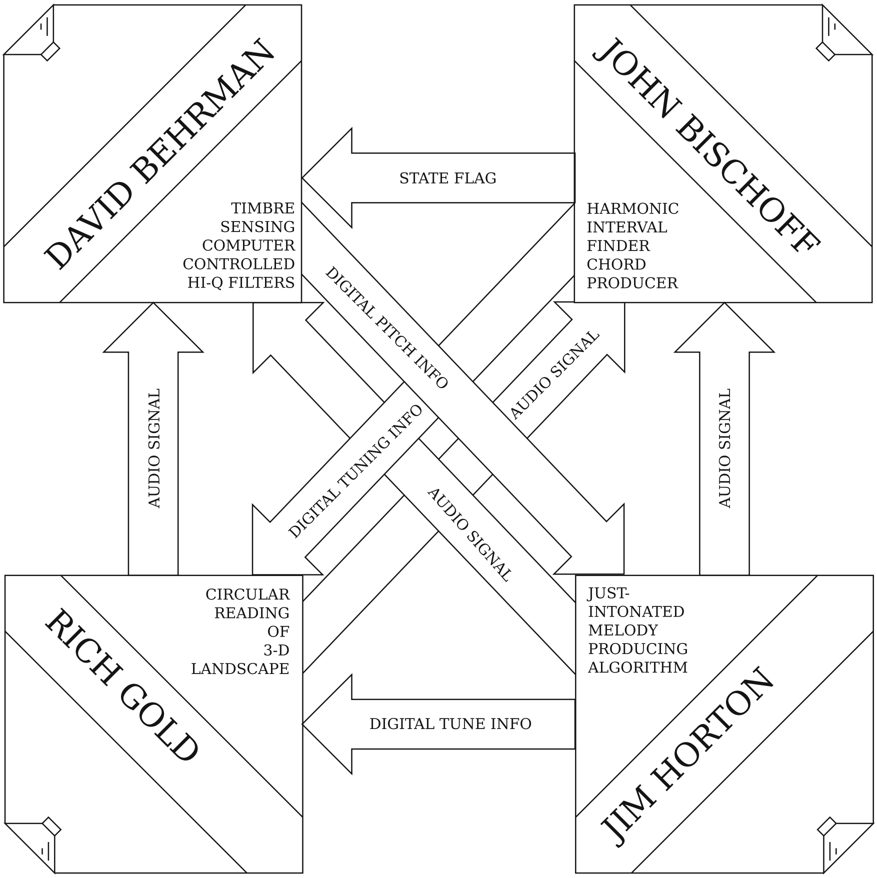

Fig. 2.2 Reproduction of a flier publicizing a concert at the Blind Lemon in Berkeley, USA in Nov. 1978. The flier features a diagram of the data paths between computers and indicates the musical algorithm running at each microcomputer

Bateson (cultural ecology), John Holland (genetic algorithms). More introspection on the LAMC can be found on a document written by Perkis and Bischoff available on the Internet "The League of Automatic Music Composers 19781983."[4] After the LAMC stopped its activities in 1983, due to Jim Horton's health problems, Perkis and Bischoff followed on the same path and worked on a digital system interconnection interface for musical practice called *The Hub*, which eventually led to the creation of a stable group of performers with the same name. The KIM-based Hub had four UARTS to allow four players to network using 300 bps serial connections. This central unit allowed for an easier connection (during the LAMC days the computers were connected by directly wiring and soldering the machines) and standardized

[4] http://www.newworldrecords.org/uploads/fileIXvp3.pdf.

format for data exchange. The musicians would, in fact, employ a shared memory (nicknamed "The Blob") where to store data. This was referred to as "blackboard system" and allowed for asynchronous data exchange. The hub would keep information about each player's activity accessible to other players' computers. As reported in [5], after the 1985 Network Muse festival held in San Francisco, featuring Bischoff, Perkis and more artists, *The Hub* collective would develop and add distance to their networked performances. In a series of concerts in 1987 six musicians would play in two different venues in New York City, split into two groups, connected through a telephone line via a modem. The technical effort was considerable, but successful, although one of *The Hub* members, Gresham-Lancaster in [10] comments

> Although the group performed at separate locations a few times, it created its strongest and most interesting work with all the participants in the same room, interacting directly with each other and with the emergent algorithmic behavior of each new piece

With the advent of MIDI and software sequencers, in 1990, Gresham-Lancaster and Perkis designed a MIDI-based Hub, where each musician's machine was assigned a MIDI port and MIDI messages were employed to exchange data. This way each musician could address privately each other machine, adding flexibility. At the end of the 1990s *the Hub* members explored the use of the Internet as a means to develop their network computer music experiments. Again, the comments by Gresham-Lancaster are not entirely positive,

> In the only test case so far, two of us performed from each of three sites [...]. This formidable test actually ended up being more of a technical exercise than a full-blown concert. [...] In this case, the technology was so complex that we were unable to reach a satisfactory point of expressivity.

Later in 1997, *The Hub* musicians were asked for a new remote performance, which was called "Points of Presence," a live performance produced by the Institute for Studies in the Arts (ISA) at Arizona State University (ASU), linking members of the Hub at Mills College, California Institute for the Arts, and ASU via the Internet. Communication technology was not mature for musical usage at the time and the experience reported by member Chris Brown with networking at a distance was not adequate enough, as he explains in an article[5]:

> ... the performance was technically and artistically a failure. It was more difficult than imagined to debug all of the software problems on each of the different machines with different operating systems and CPU speeds in different cities. In part, because we weren't in the same place, we weren't able to collaborate in a multifocal way (only via internet chats, and on the telephone); and in a network piece, if all parts are not working, then the whole network concept fails to lift off the ground. We succeeded only in performing 10 min or so of music with the full network, and the local audience in Arizona had to be supplied with extensive explanations of what we were trying to do, instead of what actually happened.

Notwithstanding technical difficulties the group reformed after 2–3 years and went on to create new repertoire that took full advantage of the improvements to networking infrastructure in performances throughout the U.S. and Europe.

[5] http://crossfade.walkerart.org/brownbischoff/IndigenoustotheNetPrint.html.

Several other early NMPs took place in those years. In 1992 Jean Claude Risset and Terry Riley performed from Nice while David Rosenboom and Morton Subotnick performed from Los Angeles. Augmented pianos (Disklavier) were used with sensors and actuators allowing to capture locally and reproduce remotely the exact playing of the musician. The concert, named Transatlantic Concert [11] was based on satellite links, and thus, given the high cost, was not replicated, nor the project was further sustained. Satellite links indeed may seem worth investigating for NMP, if the economic expenses are ignored. Satellite links are able to provide, for extremely distant location a minimal number of switching nodes, and quite direct paths. Unfortunately, the satellite employed for this kind of communications are in the geostationary orbit, i.e., approximately 35700 km from the Earth surface. Approximating signal propagation by the light speed in vacuum, under the hypothesis the points to connect are in visibility with one satellite only, the delay introduced only by propagation uplink and downlink is of the order of 250 ms. This is unacceptable for RIA NMP. In copper or fibre-optic links, the path with wired Internet connections is much shorter, although orography and routing may increase the length of the path. Even though the signal propagates at slower velocity in these materials, it may be convenient to employ copper of fibre-optic backbones even for NMP over locations across the Earth. As an example, the distance between the two farthest points in Europe (Portugal–Finland) or the USA (Washington-Florida) is approximately 4500 km, i.e., 21 ms (under the hypothesis of a direct path and the signal traveling at $0.7c$). This is at least one order of magnitude lower than employing a satellite link (even though the fibre-optic or copper link is never direct, thus may be longer). For reasons of latency and economic expenditure satellite links have not been experimented in other network performances to the best of our knowledge.

2.2.2 Current Networked Computer Music Performance Trends

While at the beginning of the 2000s The Hub collective slowed down its activity, its founders continued to experiment. It is the case, for instance, of Chris Brown, who, among other works, employed networking to create a shared virtual instrument from two ReacTables,[6] one placed in Barcelona, Spain and the other in Linz, Austria. This experiment, *Teleson*, was premiered in 2005 and crosses the borders between computer music and NMP. Similar experiences started being common practice. Nowadays laptop orchestras and NMP are widespread. The LAMC and The Hub experiences were fundamental for the development of current computer music performance trends. Following their activities these two important lines of music research, namely the laptop orchestra paradigm and the networked music performance, were created. They are both of interest in this book as laptop orchestras may employ networking as well. Tens of music schools, universities and conservatories

[6] http://reactable.com/.

run a laptop orchestra. It is not by coincidence that many tutorial books on Computer Music, host a section on Networking or Laptop Ensembles.

The Viennese Farmers Manual in 1995 formed a multi-laptop ensemble, while MIMEO (Music In Motion Electronic Orchestra) mixed acoustic instruments and computers from 1997. An extremely interesting ensemble for the purpose of this thesis is PowerBooks_UnPlugged, a collective of varying number of musicians only employing laptops, started in 2003. Not thriving into the details of their very interesting aesthetic, a point to highlight is the use of laptop and wireless networking to share data, algorithms, and more. The ensemble performance is based on the music programming language Supercollider[7] and a software library developed with the contribution of the ensemble named *Republic*. According to ensemble member Alberto de Campo, Apple Ad Hoc wireless networking was employed, without any wireless Access Point. He also points out that

> [the network topology is] very democratic, everyone can send sounds to everyones server, everyones evaluated code gets sent to everyones History (for reuse, adaptation, etc.), everyone can send chat messages or shout messages to everyone else.[8]

The library allows each musician to *join the Republic* by manually entering a user name and a unique ID number. A GUI showing a chat and snippets of code employed by other musicians is presented. Synth definitions[9] can be shared, allocated, and played on other musicians' laptops. The ability of the musicians to *interfere* with each other coding flow to interact in the real environment and move freely makes this laptop orchestra very interesting.

In the last ten years, however, ensemble laptop performance has become extremely common in the literature and a plethora of papers dealing with the aesthetics, the composition techniques, or the software employed are published yearly on the proceedings of computer music conferences. Stable laptop orchestra are based in Princeton (PLOrk), Stanford (SLOrk), University of Colorado Boulder (BLOrk), Dublin, Huddersfield, Virginia Tech (L2Ork), Carnegie Mellon Laptop Orchestra, and many more. Among these, the PLOrk, reported the use of wireless networking in several setups [12, 13]. A 802.11g LAN was established to synchronize the devices, all running Max/MSP and ChucK applications to synthesize and process sound. The synchronization was, however, not very tight, as it was measured to be approximately 30–40 ms. The authors of the paper, however, stated that this was acceptable as the dislocation of the performers, similarly to an acoustic orchestra took a space of 40 ft (12 m), which naturally incurs in such latencies when the performers play acoustic instruments and the air propagates sound.[10] It is not clear whether the wireless network had a role similar to the conductor of an acoustic orchestra. In that case, indeed, the conductor is required to fill the lag due to the air propagation delays, by visually conducting. To address this issue some researchers are experimenting the use of visual cues in laptop ensembles [14, 15].

7 http://supercollider.sourceforge.net/.

8 From a private correspondence with the authors.

9 A SynthDef or Synth definition is a Supercollider object that represent a signal processing units.

10 The speed of sound at sea level is 340.29 m/s, i.e., approximately 35 ms for a space of 12 m.

In another more recent paper, the SLOrk reported the use of an IEEE 802.11n wireless access point for an indoor and outdoor performance [16]. The performance seems to have taken place in a garden with high trees, and the performers had to place the access point at an elevated position in order to guarantee good signal coverage for all the performers. No other information is provided regarding technical issues or the outcome, besides the remark that powering all the devices required some engineering. It is generally difficult to gather information regarding the technical issues that the orchestras encounter for their performances, since often they are barely mentioned, given the aesthetic focus of the papers. In the literature, technical aspects are often disregarded as computer musicians and composers prefer to focus on the artistic aspects and rely on widely adopted technologies. A greater understanding is gathered only by direct discussion with the involved subjects.

The lack of technical focus has probably led to withdrawal of challenges and opportunities offered by the new technologies, such as audio streaming between performers, the use of wireless networking, off-stage performance (with the notable exception of the aforementioned PowerBooks_UnPlugged ensemble and few others), the shift from laptop to embedded/embodied instruments and more. For more historical information on laptop orchestras refer to, e.g., [17].

2.2.3 Current Acoustic Networked Music Performance Experiences

Albeit the human interaction potential is much higher than that available in a networked laptop performance [14, 15], human–performer NMP has had relatively fewer occurrences reported in the literature. This is probably due to the greater technical and management effort in delivering a performance between remote locations. The Internet has been explored for NMP since its boom in the late 1990s. Early experiments, however, were unsatisfactory given the best-effort delivery nature of the Internet and later academic works mainly dealt with reserved fibre-optic links, as already mentioned. No standard has been proposed for the purpose of NMP and some software products were developed with dim success. At the outset of our research work some of these were tested, proving the impossibility of conducting performance following the RIA approach previously described, due to the latency introduced by the large network delay and buffering for jitter, even at distances of 10 km line-of-sight in a urban area, due to relatively large number of switching nodes. As a general purpose network, however, the Internet has been explored for compositional purposes (see e.g. [18]).

A *purist* approach to human–performer NMP is the use of high-bandwidth, low-latency fiber links allocated on purpose, which, although available at few institutions, provide much insight for research. Needless to say, the effort and challenges of this kind of NMP are numerous. First envisioned in the late 1990s [19], audio–video low-latency transmission has been experimented on both LAN and WAN since more than

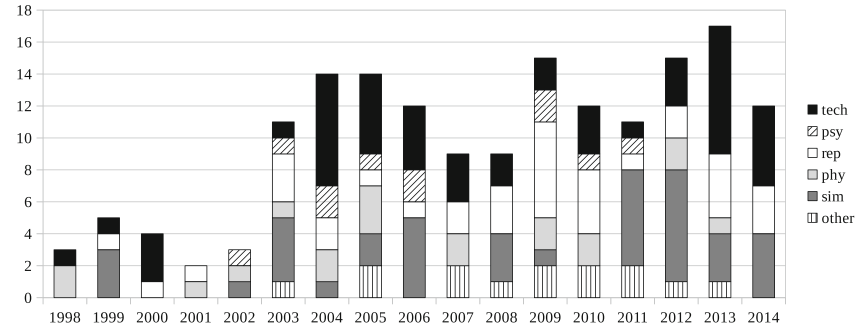

Fig. 2.3 Statistical findings from an NMP academic literature survey, years 1998–2014

a decade. Technically speaking, the first consistent attempt to address NMP over the Internet was conducted by the SoundWire group at CCRMA starting from year 2000 [20], which introduced bidirectional uncompressed audio streaming at low latency, employing the US Internet2 network. At McGill, the Ultra Video-Conferencing Research group started reporting about a similar approach, also including video, from the same year [21]. A first wave of experiments were spun in 2000 and following years. In those years the use of remote servers was often suggested (see, e.g., [22], or the Ninjam software project[11]), following similar use cases, e.g., that of remote gaming. Audio compression was also often suggested, yielding very high results in terms of latency.

In 2007, Carôt reported a decreased interest in the research communities after the first attempts in the beginning of the 2000s [7]:

> Most projects undertaken in the field of real-time high-quality networked music performance took place around and after 2000 and went very quiet afterwards. In the last year or so, a revival of interest for the subject has emerged not only on the technological side but also on the cultural side, where researchers are seeking to understand the cultural implications of providing such facilities to musicians and producers as well as seeking ways to increase the level of interactions between musicians collaborating over network connections.

To test this statement and gather further information on the literature, the authors conducted a statistical research on the corpus of academic literature from 1998 to 2014. The research, does not aim to be complete, but is thorough enough to possibly outline the trends of the NMP field since its early years up to the last year. The results are summarized in Fig. 2.3. First, academic contributions in the NMP fields have been very large from year 2003 to 2006. If we want to give account to Carôt's statement we can speculate that in years 1998–2002, the NMP was new and much hype was projected around this research field, with new projects being started. Those may have been under a phase of development around these years, and were not able to yield academic outcomes until years 2003–2006. At the time when his paper was published a decrease in NMP publications can be observed (2007 and 2008). Again, this may

[11] http://www.cockos.com/ninjam/.

not reflect the perceived interest in the academic communities, nor a decrease in the number of actual performances conducted. In the years 2008–2014 a certain degree of fluctuation can be observed.

For a deeper introspection, published papers have been separated in several distinct categories. Ph.D. degree theses, diploma theses. and master's theses have been included. The categories chosen by the authors follow:

- **tech**: technical improvements in networking, hardware, DSP, and software; new solutions and architectures for networking and management of audio and control data.
- **sim**: papers dealing with collaborative use of networks for music composition, cooperative performance also involving the audience; networking in laptop orchestras; multimodal and immersive reality for remote music performance, installations, and choreography.
- **psy**: psychoacoustic findings relevant to the field or directly targeted at NMP.
- **rep**: reports on performance experiences, reviews and surveys on performances, projects and installations.
- **phy**: philosophical works and conceptual frameworks, aesthetics dialectic of the NMP paradigm.
- **other**: development of NMP technologies for educational purposes; human–computer interfaces and visual cues; papers without specific findings or low degree of novelty.

Please note that works dealing with wireless mobile phone interface design, participatory mobile phone usage in performances, and not implying the networked performance paradigm have been discarded.

All the categories can be seen to be subject to a certain degree of random fluctuation. Specifically, by clearing out from the picture the works categorized as *sim* (Fig. 2.4), which are loosely related to NMP in that they use networking for collaborative composition and audience participation, a slightly different picture emerges, showing fewer academic outcomes in the years 2006, 2011, and 2012. The works of

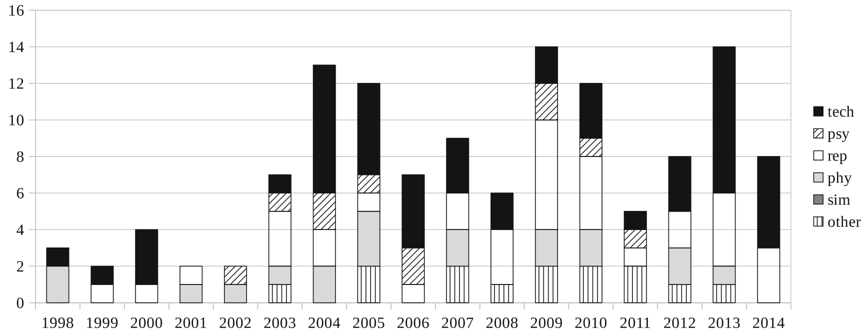

Fig. 2.4 Statistical findings from an NMP academic literature survey, years 1998–2014, showing only those works tightly related to NMP

technical nature have been numerous in the years 2004–2007, and increased again after 2011, with a peak in 2013.

In the last 5 years, a number of projects involving a large effort in technical and framework development can be seen. The DIAMOUSES framework [23], developed in Crete, provides a scalable architecture for both synchronous and asynchronous collaboration, with a web portal to share information and organize performances and the exploitation of DVB-T (digital TV broadcast) for distributed music performance on-demand replay. The MusiNet project was started at the end of 2012 and is still ongoing at the time of writing. It is funded by the European Union and involves several Greek institutions. It involves a complex network architecture involving clients and a server (*MusiNet Center*). The server can relay session information, audio/video data and further information, and textual data [24]. The choice of this architecture is motivated by a more scalable delivery, with clients responsible of sending their data to the server only and relieved of multiple transmission when more clients need to receive the same streaming. This, however, introduce additional latency. Spatial audio is taken into account by recording spatial information and estimating the direction of arrival of the sound source. Audio data is encoded with low delay and possibly acoustic echo cancelation is performed if needed. Video is also encoded, but in [24] a mechanism to reduce the latency of video streams down to 25 ms was still being investigated. This project has already provided an amount of technical outcomes related to network architectures and the use of Information-Centric Networks (ICN) [25] and Content-Centric Networks (CCN) [26] for NMP, software and cloud services for remote music collaboration [27], packet delay reduction by direct access to the network hardware [28] and more.

Differently, the LOLA project [29] aims at minimizing latencies by employing large bandwidth stable links and avoiding every step that is not essential, such as servers and compression techniques. LOLA was conceived by GARR (the Italian research institutions network) and G. Tartini Conservatory of Trieste (Italy) in 2005 and steadily developed since 2008 up to the time of writing. In LOLA, a great effort has been spent to deliver high-quality and low-latency video signals, which are interleaved and synchronized with the audio. The audio and video acquiring devices supported are limited to a small number of very high performance ones and have software drivers written to satisfy the strict time constraints. A typical setup involves a capable PC, a dedicated audio card, a USB 3.0 camera with high resolution and a gigabit network card. The monitors employed to watch the performers at the other end, must have very low latency, thus many current LCD cannot be employed given their response time of 5 ms or higher. The additional latency added to acquisition and local packet switching is the signal propagation over the fiber link, typically of the order of 1 ms per 100 km. A network administrator must guarantee at the participating institutions where the performance takes place that bandwidth is reserved for the performance. Typical bandwidth may range between 170 Mbps (640×480, 60 fps B/W video) to 1700 Mbps (Full HD, 30 fps color video). Video compression may be employed, reducing the bandwidth down to 20 Mbps best case, but introduces a large computational load at both ends and latency.

In the past various research projects employed video together with audio for NMP, but with very low technical demands (e.g., video link based on commercial conferencing software, of low quality and high latency, not synchronized to the audio signals). As an example, the 2008 performance of Terry Riley's *In C* between Stanford and Peking [30], made use of a 220 ms latency uncompressed audio link, while the video was streamed employing a software for multimedia movie coding and decoding (VLC) with MPEG4 compression, yielding a delay of about 1 s at 720×480 pixel resolution. The authors claimed that

> our previous experience in network performance shows that musicians usually dont look at the video when they perform; it serves primarily the purpose of providing an experience for the audience - while also adding additional reassurance and comfort to the musicians during setup, discussion and other communication needs.

This is probably in contrast with the view of the researchers behind LOLA, and a study to assess the importance of tight video requirements for the performers would be needed. Another technically challenging project in terms of video transmission is that from the McGill Ultra-Videoconferencing research group,[12] which since year 2000 started investigating the subject and in the subsequent years released a software with good results in terms of latency called UltraVideo for Linux PCs and published several works in the field [31, 32].

A similar project started in the same years is UltraGrid.[13] Ultragrid was started by CESNET, the Czech academic network operator, and SITOLA, a networking technologies laboratory established by academic partners and CESNET. The software is under active development by a team of engineers, which reportedly enables end-to-end audio and video communication at minimum latencies of 83 ms. This software is also employed for remote surgery and other uses.

Besides the few aforementioned projects focusing on technical improvement, although technical progress in communication technologies is highly relevant to NMP, most of the development efforts from the music computing research and artists communities have gone into software architectures and frameworks for NMP [23, 33, 34] or analysis and speculation of the NMP paradigm and aspects of Human–Computer Interaction [35–37]. One application close to NMP, but of different nature is music composition, editing, and collaboration by means of software and network technologies. Some of these works are, e.g., included in the *sim* category in the literature survey reported above. Only those projects (e.g., DIAMOUSES, MusiNet) and papers, that include aspects of remote music collaboration but are not limited to it, have been considered in Fig. 2.4. Collaborative composition and asynchronous NMP approaches are not considered in this book as they have different finalities and technical requirements.

A fundamental field of investigation for the feasibility of NMP is psychoacoustics. Psychoacoustic studies related to the effect of latency on synchronization and tempo keeping have been addressed by several authors [38–41] and shall be reported later

[12] http://ultravideo.mcgill.ca/.

[13] http://www.ultragrid.cz.

in Sect. 3.2. This represent a good base for the development of NMP, although many other perceptual aspects need to be evaluated in order to achieve an informed view on best practices for NMP.

To conclude, compression, coding, and error concealment DSP algorithms are covered sparsely in the literature and shall be highlighted in the respective sections.

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