WLAN trilateration for musical echolocation in the installation 'The Network Is A Blind Space'

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ABSTRACT
This paper presents the system and technology developed for the distributed, micro-telematic, interactive sound art installation, *The Network Is A Blind Space.* The piece uses sound to explore the physical yet invisible electromagnetic spaces created by Wireless Local Area Networks (WLANs). To this end, the author created a framework for indoor WiFi localization, providing a variety of control data for various types of 'musical echolocation'. This data, generated mostly by visitors exploring the installation while holding WiFi-enabled devices, is used to convey the hidden properties of wireless networks as dynamic spaces through an artistic experience.

Keywords
Network music, mobile music, distributed music, interactivity, sound art installation, collaborative instrument, site-specific, electromagnetic signals, WiFi, trilateration, traceroute, echolocation, SuperCollider, Pure Data, RjDj, mapping

1. INTRODUCTION
1.1 Concept
We make wide use of WiFi electromagnetic radiation in our daily lives and depend on it increasingly to wirelessly transmit and receive information of all sorts, for all sorts of uses. However, despite relying on this Hertzian space[1] that surrounds us, it can be difficult to truly understand its nature or even acknowledge its very physical presence in a manner that involves our bodies directly. Moreover, even though wireless network spaces co-exist with physical spaces, they follow their own rules, which are not always intuitive from the point of view of every-day experience. While vision is all we need to explore physical spaces, it falls short in electromagnetic ones. In nature, many animals inhabiting environments where vision is not a sufficient navigational tool – such as bats and dolphins – have developed echolocation, transmitting sound and listening to the echoes of a space. Humans can achieve something similar through the mediation of electrical devices that can help translate the properties of radio space to audible sound in a perceptually and cognitively meaningful way.

The Network Is a Blind Space [2] is a distributed, micro-telematic, interactive sound art installation that creates a type of 'musical echolocation' to explore the WLAN as an electromagnetic space within the particular spatial configuration it is installed in. It aims to convey an artistic experience, rather than to directly sonify data, allowing visitors to sense in a poetic and visceral way the invisible and intangible world of WiFi communication that engulfs us through the use of ordinary, WiFi-enabled, mobile electronic devices (smartphones, iPods, tablets, laptops, etc). The piece addresses the physicality of electromagnetic waves together with the deeply social nature of computer networks. It explores how a WLAN behaves inside a space, how it modulates the psychogeography of that space affecting visitor behaviors and interactions, but also how it reacts itself to visitor presence. To this extent, the piece reveals the network as a dynamic, navigable space, as an open score spread in that space, and as a large, invisible, collective idiophone – a collaborative distributed instrument which devices of connected visitors excite into resonance.

1.2 Configuration
The piece is meant to be installed in a space with multiple rooms, with one functioning as a central listening area. It extends as far as its WLAN can reach, inside the exhibition building, as well as outside it. Layout specifics depend on the particularities of the site; for example, during its first exhibit two computers were installed near the opposite sides of a long corridor - the most prominent architectural feature of that building - to create an electromagnetic line-space that could be transversed and examined (Figure 1).

Visitors can log into the network with their devices and walk around the building to explore its electromagnetic properties. Devices joining the network become part of its space as active nodes and resonant objects. Each device's view of the network can be heard individually, synthesized in real-time and diffused from a dome of speakers hanging from the ceiling of the main area. Additionally, by installing an application devices become sound-producing echolocation sonars directly exposing the electromagnetic properties of a space – together with its acoustics - while a visitor moves inside it. The state of the network itself, as perceived by each of its computers/nodes, can be listened to as well: In the first exhibition, two speakers were located on the floor of the listening room at the respective positions of the computers they represented within a scale model of the building's architectural plan. This semi-cryptic navigational road-map was duplicated in the mobile application's interface, as a further aid for visitor exploration.

The system is implemented in the SuperCollider real-time audio programming language[2], which interfaces with various OSX command line tools functioning as the project's networking backbone. Mobile devices can download and run an application ('scene') for RjDj[3], a free iOS port of the Pure Data audio programming environment[4].

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[1] The term was introduced by Anthony Dunne [1].
[2] http://supercollider.sourceforge.net/
[3] http://rjdj.me/
[4] http://puredata.info/

Figure 1: ***The Network Is A Blind Space*** **at the Jack Straw New Media Gallery, Seattle, USA, December 2011 – February 2012**

2. RELATED WORK

2.1 Artistic inspiration

The ideas of exploring communication networks as spaces or using mobile devices to create a distributed or location-based experience are not novel in the fields of music, sound art, or media art. A detailed list or analysis of such pieces is beyond the scope of this paper (for an overview of relevant radio-related art see [3]), but it is worth mentioning some that were an inspiration during the development of this project. Pieces concerned with the Hertzian space include John Cage's *Imaginary Landscape no. 4* (1951) [4] and his proto-interactive *Variations V* (1965) [5], Max Neuhaus's early sound art installation *Drive In Music* (1967) [6], Christina Kubisch's body of sound art work with electromagnetic induction from the late 1970s [7], and Mark Shepard's *Hertzian Rain* (2009) [8]. Pieces using communication networks as musical instruments include Max Neuhaus's radio-based works *Public Supply* (1966-1977) and *Radio Net* (1977) [9], *Global String* (1998) by Atau Tanaka and Kasper Toeplitz [10], the internet acoustics synthesis project by Chris Chafe et al. (2001) [11], and Pedro Rebelo's *Netrooms: The long feedback* (2008-2009) [12]. Finally, inspirational pieces that involve handheld distributed sound include *Vespers* (1967), a particularly inspiring performative sound art piece on echolocation by Alvin Lucier [13], *Dialtones (a Telesymphony)* (2001-2001) by Golan Levin et al. [14] and *Net_Dérive* (2006) by Atau Tanaka and Petra Gemeinboeck [15].

2.2 Scientific research

Current research in the relatively new but growing field of Location-Based Services [16] proved useful, especially during later development stages, through comparisons of this project's heuristic-based, art-centric solutions to commercially oriented WiFi-based indoor positioning models. Most such systems are built on Received Signal Strength Indication, but there are a handful of early experiments using Time of Arrival (TOA) and trilateration – a triangulation variant that uses distances rather than angles - as a cue for deducing the position of a device within an indoor WiFi-enabled space (e.g. [17], [18]).

3. THE PIECE

3.1 Technology basics

3.1.1 On the nature of WiFi radio waves

WiFi radio communication (IEEE 802.11) uses electromagnetic waves of a frequency around 2.4GHz to transmit information wirelessly. Overall, WiFi signals portray typical wave behavior. However, even though they can be generally understood in a similar manner to sound waves, and electromagnetic multipath propagation can be compared to acoustic reverberation, their actual interaction with a space is often counter-intuitive as they move much faster than sound, have much smaller wavelengths and respond differently to objects, depending on the electrical properties of their materials, shape and angle to the transmitter.

3.1.2 Network distance and trilateration

The physical manifestation of the space between two points in a WLAN is the actual path radio signals take to arrive from one place to another. In closed spaces without line-of-sight communication this is impossible to measure. However, we can use instead the time it takes for a data packet to go from one device to another and back as a distance indicator. This is called the Round Trip Time (RTT), the network's latency, or its 'echo'. RTTs form the basis of the echolocation mechanism in *The Network Is A Blind Space.* Two methods are used: *Time of Arrival* (TOA), which is the absolute time it takes a message to arrive from one place to another, and *Time Difference of Arrival* (TDOA), which compares the TOA between different points in the system. TOA shows the distance in µs between two devices, while TDOA can reveal the relative position of one device between two, three or several other devices. Depending on the number of nodes involved in this operation, the precise term is bilateration, trilateration and multilateration - although the term trilateration is most commonly used in the literature to cover all cases. The piece implements an extended, optimized version of TOA and TDOA bilateration by performing various statistical analyses on the RTT data.

3.1.3 Tracerouting

The system presented in this paper is based on the *traceroute* command, a network diagnostic tool commonly employed to reveal the path between a local and a remote device. The data in a traceroute reply contains binary presence (whether a host IP was found or not), discrete data (number of hops, i.e. routers, that separate the two devices) and temporal distance (dt for the RTT between each hop, e.g. 1.673 ms). *Traceroute* is typically used with devices not directly connected to each other – i.e. mostly through the internet – but the fact that it can send bundles of multiple round-trip data-probes makes it extremely useful as a localization tool, even in LANs where connections between devices are direct. Probes in the same traceroute follow each other within a few hundred µs. The gap between separate traceroute requests is adjustable. In a wireless scenario, statistical analysis of the differences between the RTT values of probes – i.e. micro-time differences - can help deduce signal strength and distance between two devices, while differences between the RTTs of separate traceroutes (event-time), or within a history of traceroutes (meso-time) can help trace the movement of a device in physical space or its general behavior. Therefore, tracerouting within a WLAN can help reveal information such as distance, movement, connection stability and overall network congestion. Moreover, inside a space with known obstacles, such data can also give some insights about the possible areas a device may be located.

3.2 System implementation basics

3.2.1 Network echolocation toolbox

A number of SuperCollider classes were developed to interface with command line networking tools, as well as to parse and use the data generated by them[5]. These modules allow automatically setting and querying network settings, retrieving data about the network's topology, handling all tracerouting and micro-time statistics, receiving, handling and storing incoming data from remote trilateration computers, retrieving various types of stored trilateration data, and finally parsing, cleaning, shaping and mapping this data, converting it into control streams for sound synthesis, to be used locally within the system and remotely on connected mobile device clients.

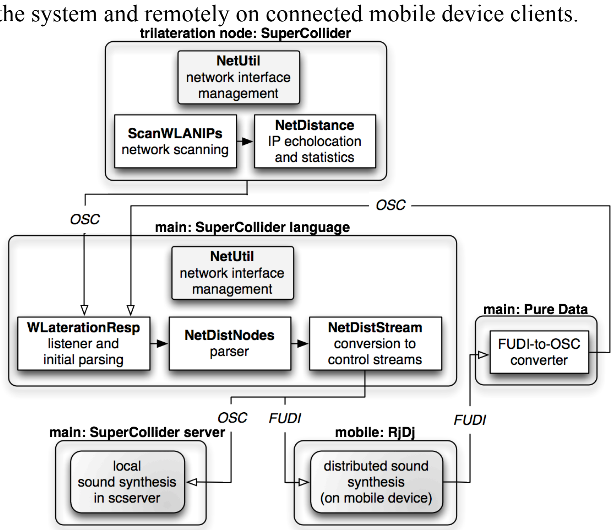

Figure 2: The network echolocation toolbox

3.2.2 Hardware

The hardware of the system includes: a) two computers acting as trilateration nodes; b) another computer as the main 'brain' of the installation, which does most of the number crunching and is in charge of the interaction, mapping, sound synthesis and spatial diffusion; it also makes any compositional decisions required; c) a variable number of WiFi-enabled devices that visitors bring with them (or borrow at the exhibition space).

3.2.3 Trilateration nodes

The trilateration nodes run a standalone application written in SuperCollider. They are responsible for finding devices that join the network. Once a new device is found, they begin sending traceroute probes to it until it disappears. RTT data within each traceroute are statistically analyzed and sent to the main computer via Open Sound Control[6] (Figure 3).

3.2.4 The network from different points of view

The main computer registers all information and can parse it in a number of different ways, exposing all traceroute statistics but also revealing other useful data, such as how many and which IPs are connected overall or per node, when was the last time each was seen, if an IP exists, if it is still active, and various combinations of the above. This functionality permits looking at the network's properties from three different points of view: a) The global, i.e. that of the network in its entirety; b) the local/nodal, i.e. the network as perceived by a specific trilateration node; c) the mobile, i.e. the network as perceived by each mobile device connected to the system.

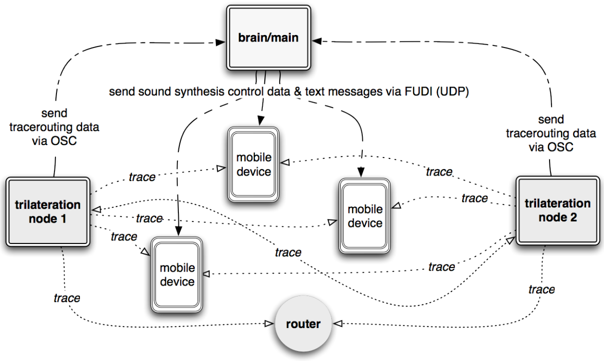

Figure 3: System hardware and communication

3.2.5 Control data as streams

Any of this data can be transformed on demand into a real-time control stream, which can be mapped to sound synthesis parameters. The operation involves (Figure 4): a) sampling the data at regular intervals; b) performing additional statistical operations on the sampled stream; c) choosing between using a TOA statistic, derived from the network distance of a device to a particular node, a TDOA statistic, relating to the relative position of a device in the space, or the sign of a TDOA statistic, showing which node a device is closer to; d) optionally tracking rate-of-change in a stream, detecting peak onsets, or using the density of such onsets (onsets-per-second); e) further shaping the resulting stream through operations such as scaling, applying various distortion methods on values that exceed a threshold, and/or using transfer functions to waveshape the stream. This allows transforming streams in ways most appropriate to the incoming data, to the parameters they are called to control, and to the compositional plan of the piece. This functionality was crucial in fine-tuning the traceroute data to the specificities of the exhibition space and of the sound synthesis algorithms used in *The Network Is A Blind Space.*

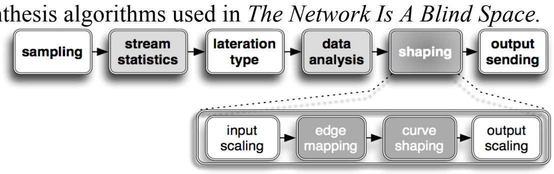

Figure 4: Converting traceroute information to control streams. Operations in grey color are optional.

The resulting streams can be mapped to sound synthesis algorithms locally, or remotely by sending them to the mobile devices via User Datagram Protocol (UDP). They can also be used in several non-sound generating manners, e.g. for high-level control of the composition or interaction behavior, etc.

3.2.6 Using the echolocation streams

Different statistics can be used to deduce various useful states and relationships of a device with the network and the space. For example, various types of TOA RTT values (e.g. minimum, mean, maximum) are the standard method for revealing distance from a node. The standard deviation of RTTs is also extremely useful; for example, small values reveal a good connection – therefore closeness – which makes the TDOA of the standard deviation an excellent tool for finding relative position in the actual physical space. A smoothed out version of the sign of the TDOA, in its turn, can be translated to probability of closeness. On the other hand, tracking slope or using onset detection on a mean or standard deviation stream helps to identify, in most cases, when a device moves from one space to another; this is used in the installation to create an audible response when a visitor passes through a door.

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[5] This library is still in beta. A finished version will be released as a SuperCollider extension (Quark) in the future.

[6] http://opensoundcontrol.org/

3.3 Sound

The sound is responsive to interaction, helping reveal properties of the network and the space. To achieve this, the piece makes extensive use of feedback-based synthesis methods, interconnecting control parameters through synthesis in a cross-coupled, many-to-many mapping model [19]. This creates a very dynamic and organically behaving sonic environment, promoting a unified experience rather than concentrating on listening to specific statistics - a goal more appropriate for a pure sonification project. It also makes the various 'instruments' within the network's 'orchestra' very expressive and entertaining for visitors to interact with. An orchestration decision was to assign different sonic and behavioral qualities to each of them, thus allowing visitors to easily distinguish between the 'voice' of the trilateration nodes, that of devices simply connected to the network, the 'voice' of devices running the special application, and the sound emanating from the devices themselves, while ensuring it all works well together.

3.4 Experience and interaction

The rules of engagement are deliberately simple, intuitive, and directly tied to the piece's concept. Visitors activate and navigate the space and the piece through the WiFi interface of their devices and with their bodies, judging how to relate to the network and to the physical space according to what they hear.

Without any devices connected one can listen to the sound of the system itself and the dynamic modulation of the line-space between the two trilateration nodes. Interaction is still possible though minimal, for example by opening and closing doors to add more obstacles to the radio waves. Having a WiFi-enabled device allows visitors to change the properties of the network space more directly. By simply connecting to the piece's WLAN the network space is augmented with the addition of a resonant node thus the system's balance is altered. This creates a new 'instrument' tied to the device, which sounds through the speaker dome; it also modulates the sound of the trilateration nodes and changes the properties of the network itself in purely electromagnetic terms. The modes of interaction with a device running the RjDj scene are similar, except the sound and – to a smaller extent – the mapping is different and, most importantly, the device itself generates audio.

Visitors experience the piece in various manners: by standing still to listen how the network space changes in time; by moving around the main space, exploring the rest of the building, or even walking outside, thus actively changing their distance from the two trilateration computers; by seeking particular spots with interesting radio properties (e.g. blind, shadowy or more electromagnetically resonant areas). As a more direct way of interacting, turning on and off a WiFi card or disconnecting and reconnecting has an audible effect, as it both destabilizes the system but also removes and recreates the device-specific instrument, assigning it a slightly different sound every time it appears in the system, as some randomness in the synthesis algorithms is involved upon initialization to provide greater sonic variety.

4. CONCLUSIONS AND FUTURE WORK

The system presented in this paper makes it possible to interactively navigate WLAN networks as spaces through sound, exploring their inherent properties, their relationship to physical spaces, and their response to actions of connected visitors. The system provides a large variety of user-generated control data through multi-layered analyses, combinations and shaping of various network statistics. For optimal response, it needs to be fine-tuned to the specific site.

Developing the framework introduced in this paper presented many challenges, artistic and technical, the least pleasant of the latter involving long hours of troubleshooting networking hardware while grappling with the network's response to extraneous and unpredictable factors such as humidity and network congestion. Nevertheless, the finished system is robust and versatile, to the point of permitting live-coding instruments, behaviors and mappings - which was very useful when putting on the final touches. Needless to say, there is still much room for improvement and further exploration.

During a 7-week gallery exhibition of *The Network Is A Blind Space* the system proved very successful, intriguing visitors, who listened attentively and engaged with it for extended periods of time, with many coming back to explore and experience it under different circumstances, with friends or by themselves. This framework will be used in a family of related future works. Some ideas involve investigating different found spaces, architectures specifically sculpted for the system, expanding to multiple sites and the internet, but also incorporating performative elements, where visitors and trained performers can engage together through the network.

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