Audio Engineering Society

Convention e-Brief 129

Presented at the 141st Convention
2016 September 29 – October 2, Los Angeles, CA, USA

Digital Waveguide Network Reverberation in Non-Convex Rectilinear Spaces

Aidan Meacham[1], Lauri Savioja[2], Sara R. Martin[3], and Julius Orion Smith III[1]

[1]*Center for Computer Research in Music and Acoustics, Stanford University*
[2]*Department of Computer Science, Aalto University*
[3]*Acoustics Research Centre - Dept. of Electronics and Telecommunications, Norwegian University of Science and Technology*

Correspondence should be addressed to Aidan Meacham (`ameacham@ccrma.stanford.edu`)

ABSTRACT

We present a method to simulate the late reverberation of a non-convex rectilinear space using digital waveguide networks (DWNs). In many delay-line-based reverberators, diffraction effects and even occlusion are often neglected due to the need for hand-tuned, non-physical mechanisms that complicate the extreme computational economy typical of such systems. We contend that a target space can be decomposed into rectangular solids following a succinct set of geometric rules, each of which correspond to a simple DWN reverberator. By defining the interactions between these systems, an approximation of diffraction and occlusion can be achieved while maintaining structural simplicity. This approach provides a promising engine for real-time synthesis of late reverberation with an arbitrary number of sources and receivers and dynamic geometry.

1 Introduction

Digital waveguide networks (DWNs) are a framework on which many late reverberation schemes have been built. One of the shortcomings of reduced DWNs (à la [1] and [2]) is a lack of a mechanism to simulate diffraction in non-convex spaces. Thus, deriving a physically informed approximation of this phenomena in the context of the computationally inexpensive DWNs, for applications with dynamic sources and receivers, extends the capabilities of these structures to far more complex situations.

2 Methods

For simplicity, the late reverberation problem will be treated in a two-dimensional context. The first step is to decompose the space into a minimal number of overlapping rectangular "rooms." Each of these rooms must have some portion of each of their four "walls" coincident with the actual walls of the space or an occluder in the room.

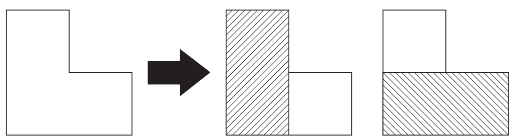

Fig. 1: Decomposition of a non-convex room into two overlapping rectangular spaces, each of which has some portion of each edge along the original room's walls.

For example, an “L” shaped room can be decomposed into two overlapping rectangular areas: one which covers the entire vertical extent (in plan view), and one which covers the entire horizontal extent, overlapping at the “knee” of the full room. For the purposes of this e-Brief, this model will be examined in detail.

For each of these rectangular spaces, a simple DWN consisting of six waveguides is allocated. One pair of waveguides are perpendicular, terminating on opposite walls. The other four waveguides connect the terminations of the first two waveguides on adjacent walls, forming a diamond. This allows for the development of cross-modal behavior and can be thought of as a discretization of wave propagation direction.

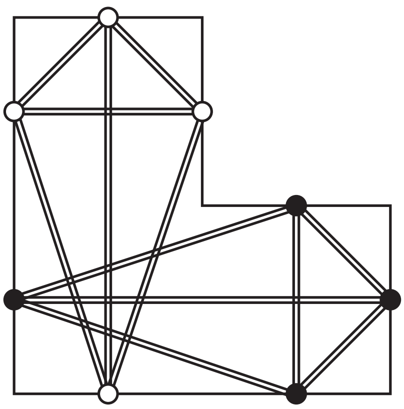

Fig. 2: The reduced digital waveguide networks for each rectangular space.

At each of the walls, filters that correspond to air absorption, material absorption and the frequency dependence of diffraction are added. Waveguides that terminate on a wall that is partially “open” to another room send a fraction of the energy that reaches that node (corresponding to the ratio of open / reflecting wall length) to the other DWN along the direction of travel at the point where the bounding rectangle intersects the other axial waveguide. In the “L-shaped” room, this would be the wall node on the right of the vertical rectangle transmitting to the horizontal waveguide of the horizontal rectangle and the node at the top of the horizontal rectangle transmitting to the vertical waveguide in the

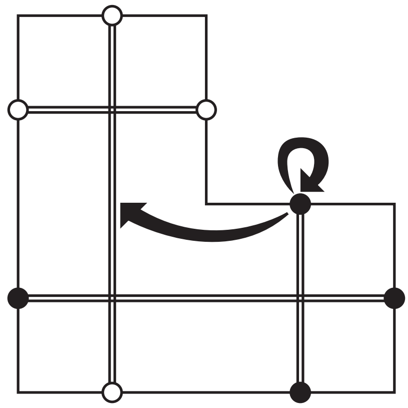

Fig. 3: Diffraction from one network to another and reflection back to itself. (Non-axial waveguides hidden for simplicity.)

vertical room. Therefore, energy that enters into a semi-open wall node is filtered by air, split into reflected and diffracted portions, and filtered appropriately before either returning as a reflection or being sent to the other DWN.

Additionally, based on the diffusive qualities of the materials at the wall nodes, some of the reflected energy may be transferred to the non-axial waveguides. Further, energy that enters a node from one of these non-axial waveguides may be transmitted primarily to the other, simulating an acute angle of incidence and reflection.

An omnidirectional input or output element outside of the region of overlap acts as it would in a typical DWN context, introducing energy into the network (or observing) at a particular point by interacting with the horizontal and vertical waveguides corresponding to its position. In the region of overlap, simply crossfading between axial waveguides as a function of position within the region is proposed. For example, moving from top-to-bottom in the example’s region of overlap would crossfade from the vertical rectangle’s horizontal waveguides to the horizontal rectangle’s horizontal waveguide.

With these structures in place, a simulation of the late reverberation of a non-convex space is possible.

With the addition of low-order image source method techniques for the early reflections and the direct path (given line-of-sight), a complete impulse response can be generated.

3 Results

A rudimentary model (of the "L-shaped" room) is in development, with early but promising audible results. The model is written in C++ using the cross-platform JUCE library, with a GUI that allows dynamic movement of source and listener with arbitrary sound input.

4 Discussion

A major advantage of this model is the lack of need for tuning of any kind. All parameters are generated directly from the room geometry and well-documented materials properties. This allows automatic generation from relatively simple models, such as those that could be generated by a game engine. In addition, note the ease of extension to a third dimension with the addition of an additional waveguide along an orthogonal axis and the corresponding 8 further waveguides to facilitate diffusion. This brings the total number of waveguides per room to 15. The scalability of the decomposition algorithm means that the system is equally valid for small spaces with high complexity and large interconnected spaces, such as winding hallways or multilevel structures connected by stairways.

The inherent modularity of this design lends itself particularly well to gaming and VR contexts in that "rooms" can be dynamically loaded and unloaded according to listener position. Dynamic geometry as well as object destruction are also distinct possibilities, and directional sources and receivers are easily handled.

5 Summary

We have presented a simple model for reverberation in a non-convex space that takes advantage of the simplicity of digital waveguide networks in order to handle a high level of geometric complexity. Furthermore, the model requires no tuning and is entirely based on the materials of the room and its geometry, making it ideal for integration with architectural, video game, or virtual reality rendering engines.

References

[1] Karjalainen, M., Huang, P., and Smith, J. O., "Digital Waveguide Networks for Room Response Modeling and Synthesis," in *Audio Engineering Society Convention 118*, 2005.

[2] De Sena, E., Hacıhabiboğlu, H., Cvetković, Z., and Smith, J. O., "Efficient Synthesis of Room Acoustics via Scattering Delay Networks," *IEEE/ACM Trans. Audio, Speech and Lang. Proc.*, 23(9), pp. 1478–1492, 2015, ISSN 2329-9290, doi:10.1109/TASLP.2015.2438547.