Perception-Based Methods for Spatial Audio

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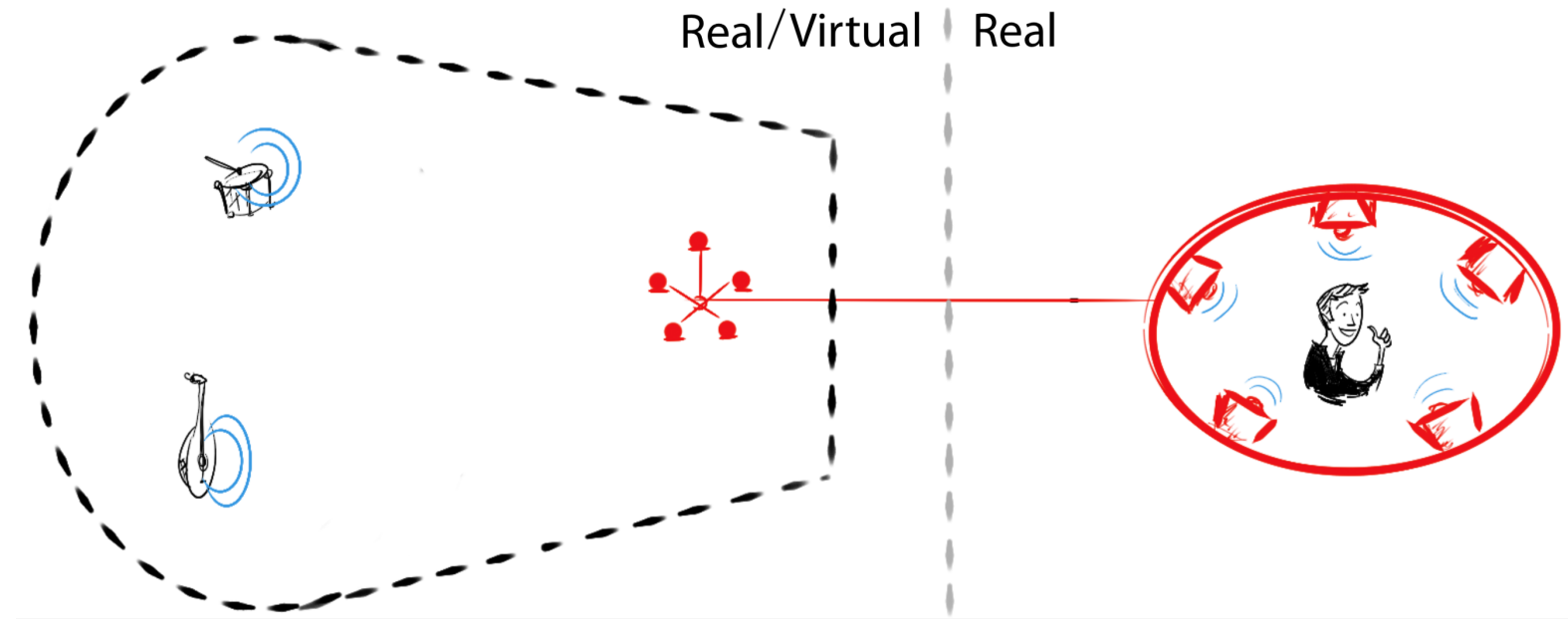
Objective

- Making listener feel transported to a different auditory scene, which can be
  - a real recorded one (live music performance, sporting event..)
  - a virtual one (video games, VR/AR, architectural acoustics..)



Physical and cross-talk cancellation methods

	SFR	**Multichannel**	**2-Channel**
Channel count	50+	< 10	2
Equipment Load	High	Commercially viable	Low
Psychoacoustics	None	Required	Critical
Sweet Spot	Large	Medium, small group	Small, individual

- Sound Field Reconstruction (SFR) provide mathematically elegant solution (e.g. HOA, WFS)...
  - but large number of loudspeakers: $r = \frac{c}{f}\frac{N}{2e\pi}$, e.g. $f = 10$ kHz, $r = 0.1$ m $\Rightarrow N = 56$
- 2-channel (cross-talk cancellation) binaural methods, only two channels...
  - but small sweet spot (e.g. [Rose et al., 2002] report ≈ 3 cm)
- We'll focus on multichannel systems with limited equipment load, which need to leverage somehow psychoacoustics

Outline

Acknowledgements

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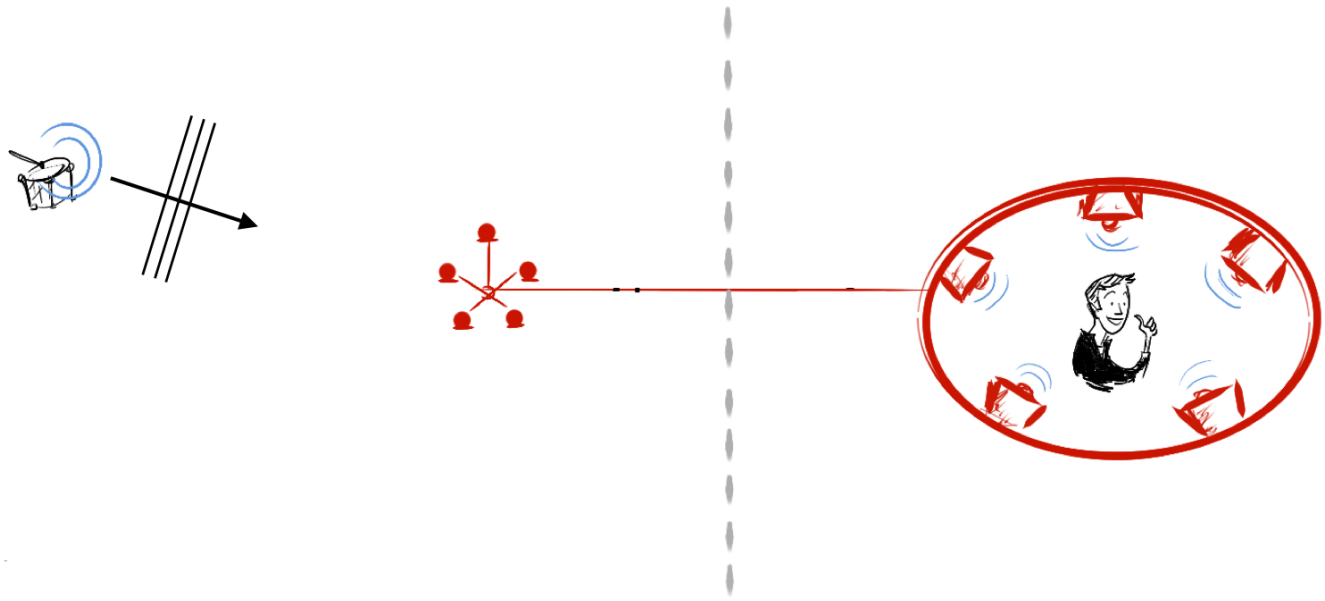
About this talk

- Interrupt me
- Just want to give main ideas
- Details and maths left to references (at the end)
- Will share slides (or find them later today at desena.org)

Outline

Reproduction of a single plane-wave

- Let's start from a simplified case
- Rendering a single plane-wave source
- Plane wave could represent e.g. single source or reflection
- (Multiple plane waves will use superposition)



Reproduction of plane waves

- Assume for now that plane wave direction, θ_s, is known
- Relevant case for computer games, music post-production, spatial audio objects (MPEG-H)

Objective–Reproduced plane wave should be:

1. perceived in correct direction (low localization error)
2. easy to localize (low localization uncertainty)

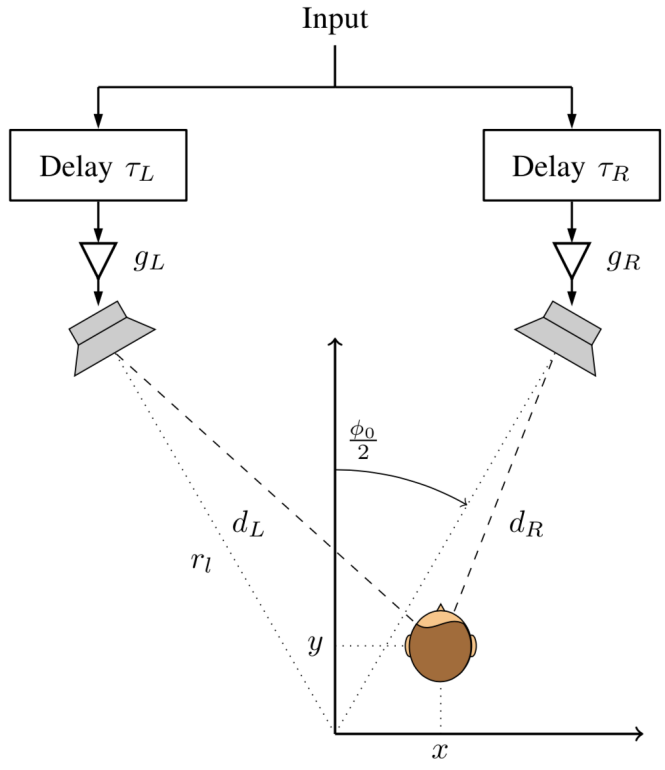
- in the largest possible area (large sweet spot)

How many loudspeakers to use to reproduce plane wave?

- **Question**: how many loudspeakers should we use for a single plane wave?
- Objective analysis in [De Sena et al., 2013] based on active intensity vector field (direction of energy propagation)
- Spatial fluctuations increase with angle between loudspeaker pairs
- **Answer**: use only the two loudspeakers closest to direction of plane wave
- This reduces problem to good ol' stereophonic reproduction

Frequency-independent inter-channel differences

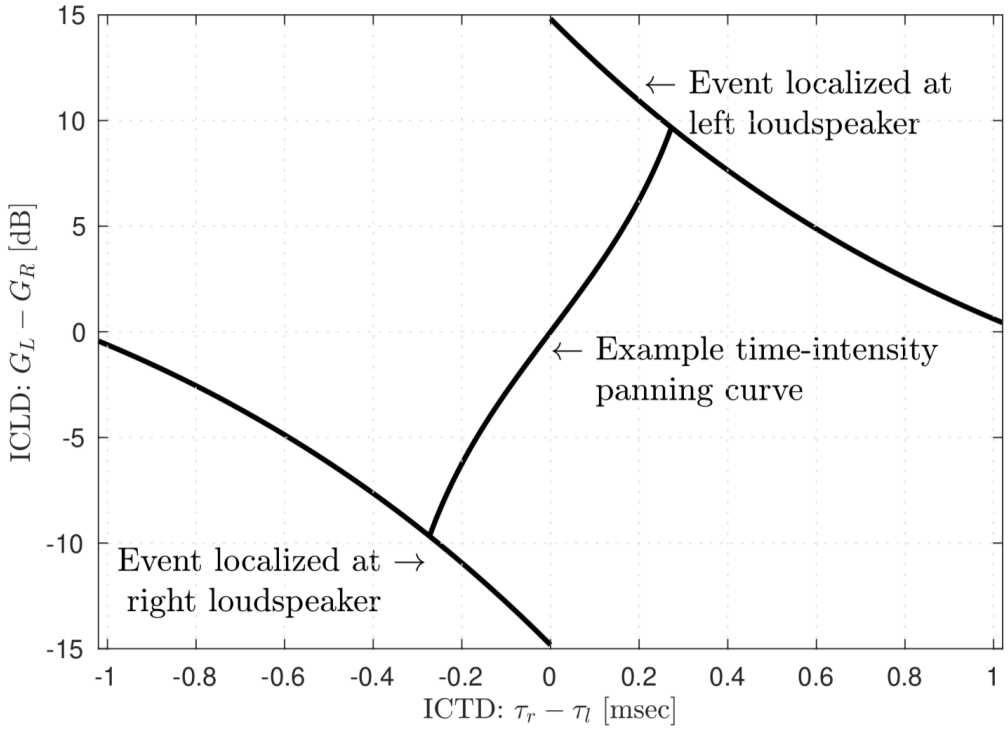
- What should we do with those two loudspeakers?
- Consider frequency independent inter-channel time differences (ICTD) and level differences (ICLD)
- ICTD/ICLDs lead to low coloration [Spors et al., 2013], which is most important attribute for sound quality [Rumsey et al., 2005]



- As long as ICTD below echo threshold, listeners will perceive a fused "phantom source" (summing localization effect)

Position of phantom source

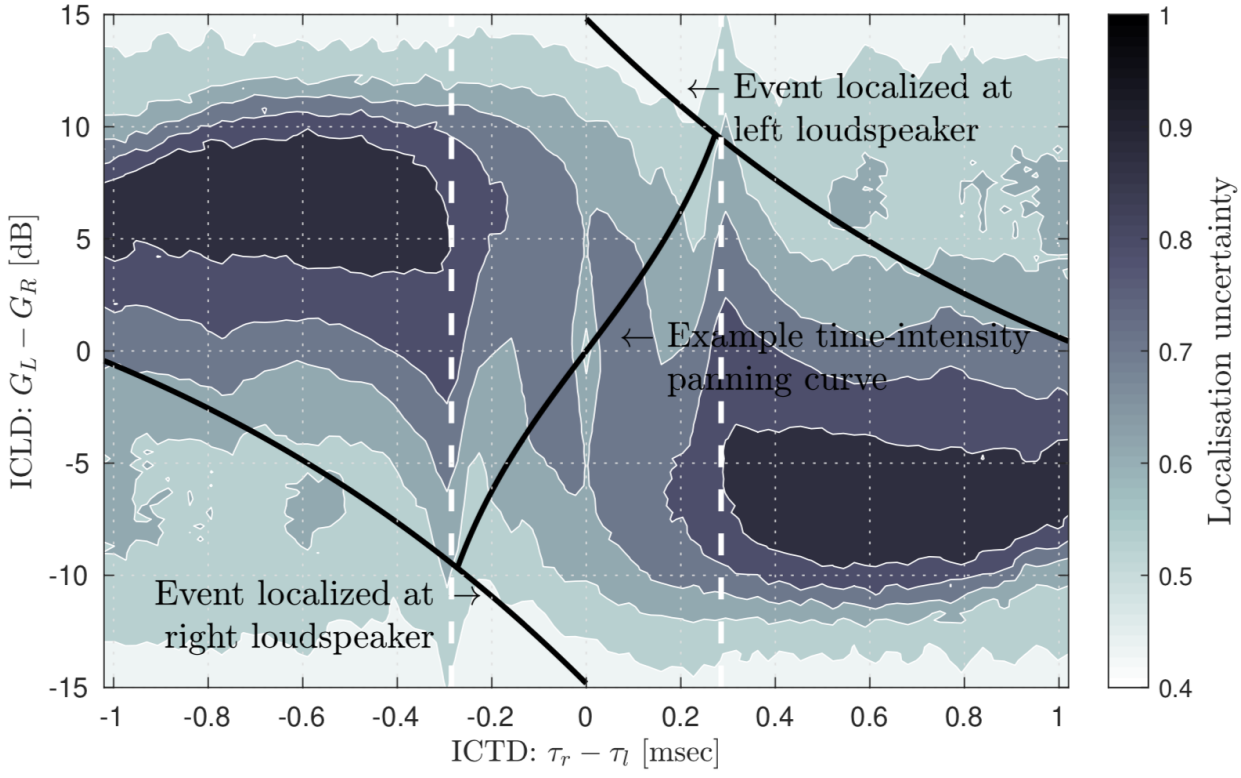
- Position of phantom source depends on ICTD/ICLD pair
- Same position can be achieved with different ICTD/ICLD pair
- One can use e.g. intensity only (most commercial sound recordings), time only, or time-intensity



Adapted from [Williams, 2004]

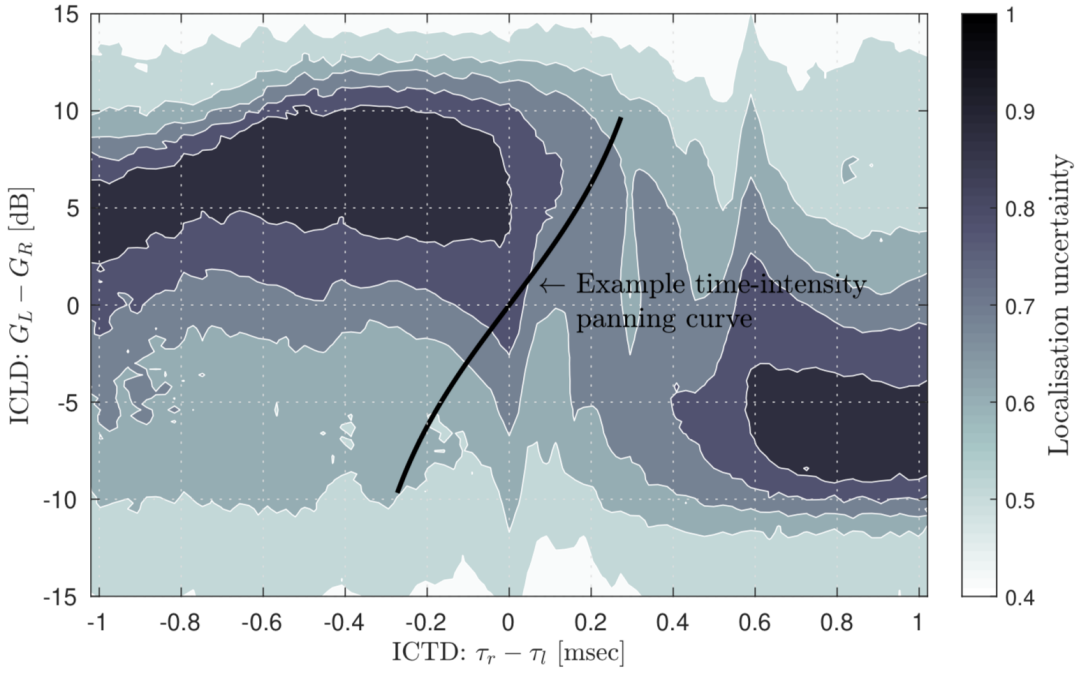
Not all ICTD/ICLD pairs are created equal

- ICTD/ICLD pairs lead to different localization uncertainty
- Computational model in [De Sena et al., 2020]:



- Inconsistent ICTD/ICLD lead to high uncertainty
- The vertical bands correspond to cases where 2 replicates at one ear, but only 1 at the other

Localization uncertainty in off-center positions



- Listener moves 10 cm to the right, then entire plot moves (approximately) to the right
- Now intensity methods lie in area with high uncertainty!
- Time-intensity largely avoids this area

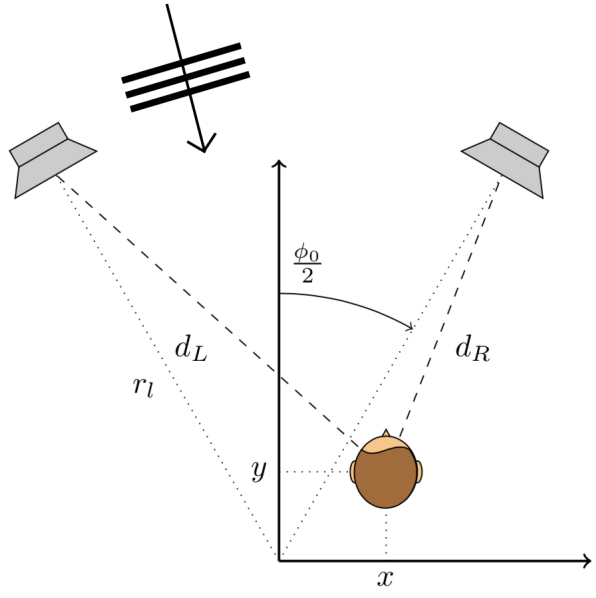
What is happening?

- Useful to define "relative" ICTD/ICLD as observed by the listener:

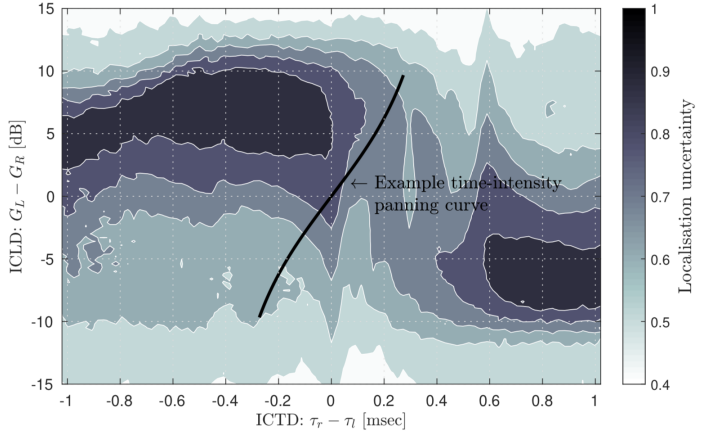
$$\text{RICLD} \approx \text{ICLD} - \frac{x}{r_l} \frac{20 \sin\left(\frac{\phi_0}{2}\right)}{\log_e(10)} ,$$

$$\text{RICTD} \approx \text{ICTD} - x \frac{2}{c} \sin\left(\frac{\phi_0}{2}\right) .$$

where c speed of sound



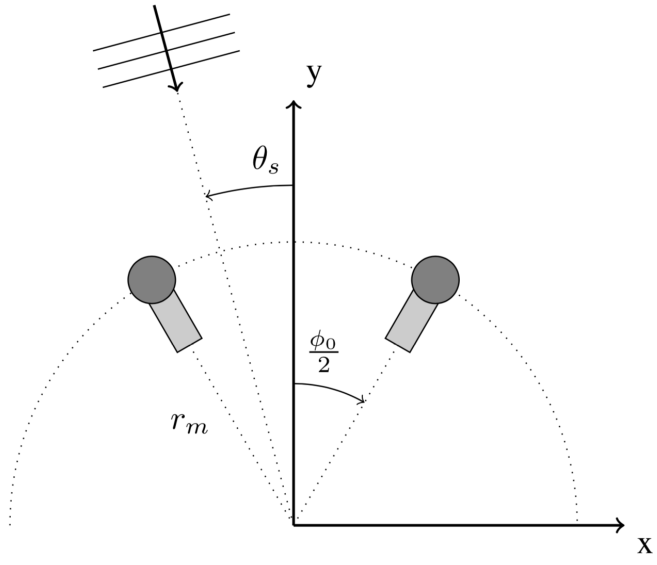
- E.g. consider ICTD $= 0$ ms and ICLD $= 5$ dB (left leading)
- RICTD $= -0.29$ ms and RICLD $= 4.78$ dB, i.t. contradicting
- Adding a small ICTD will delay the onset of contradictory RICTD/RICLD



Parametrization of ICTD (time-delay microphone array)

- Convenient now to specify ICTD and ICLD functions of θ_s, including a parameter taking into account how much we rely on ICLD compared to ICLD (time-intensity trade-off)

- Let the ICTD be defined according to the delay that would be observed on two spatially separated microphones as in figure:

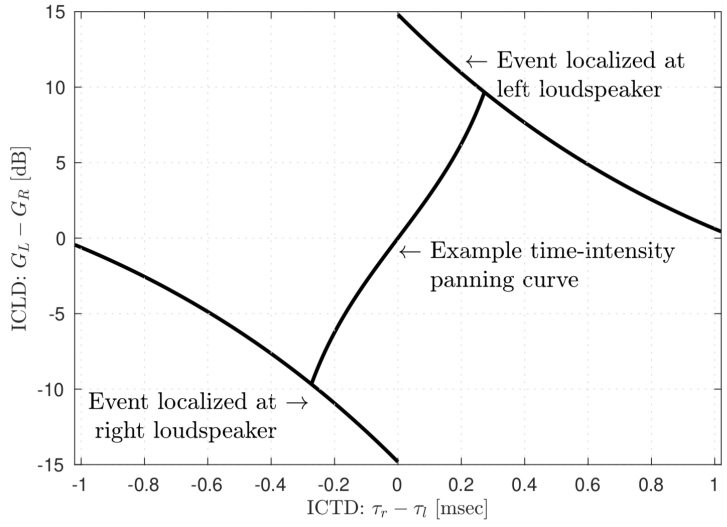


$$\mathrm{ICTD}(\theta_s, r_m) = 2\frac{r_m}{c}\sin\left(\frac{\phi_0}{2}\right)\sin\theta_s$$

where r_m is the array radius

- This parametrization is convenient since it allows to easily extend to the case of recording with circular arrays

Parametrization of ICLDs



- Psychoacoustic curves give only extreme positions
- Could use different curves, for instance [De Sena et al., 2013]:

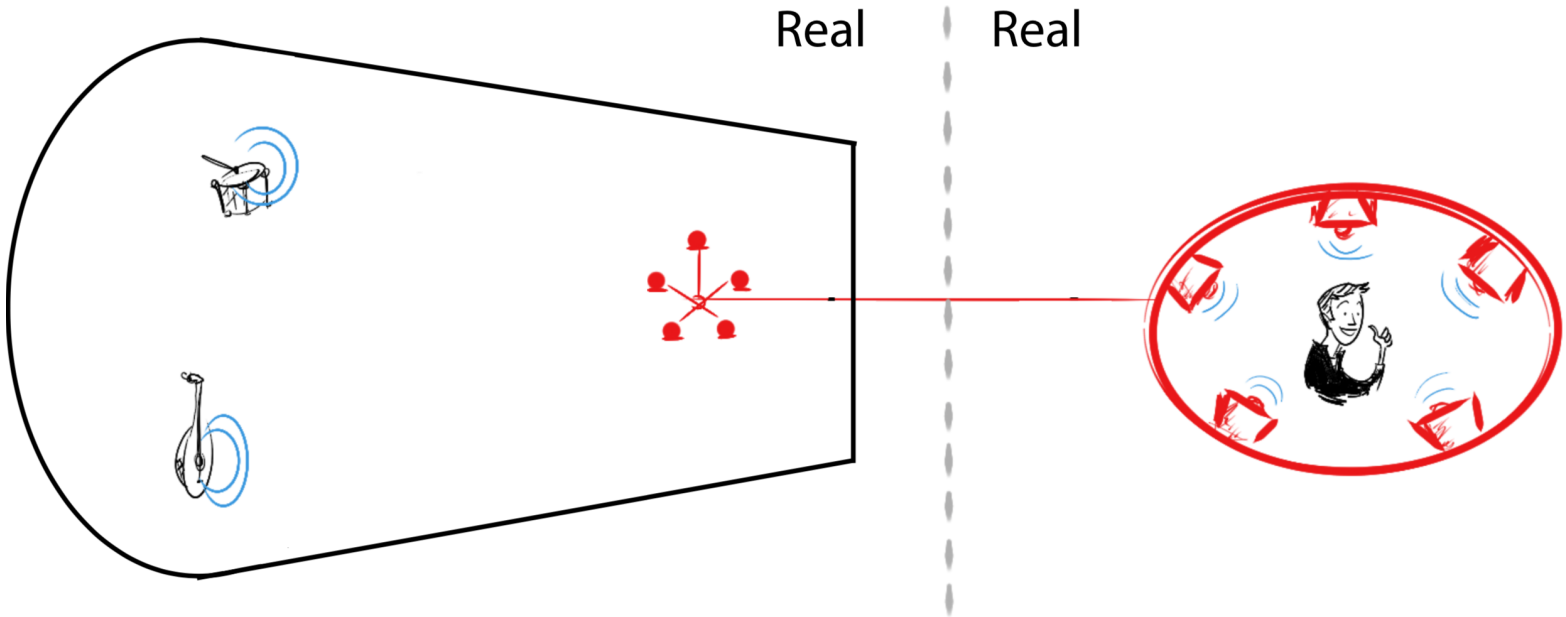
$$\mathrm{ICLD}(\theta_s, r_m) = 20 \log_{10} \frac{\sin\left(\frac{\phi_0}{2} + \beta(r_m) + \theta_s\right)}{\sin\left(\frac{\phi_0}{2} + \beta(r_m) - \theta_s\right)}$$

  where $\beta(r_m)$ is a parameter used to fit the extrema
- With this parametrization, a higher r_m leads to more reliance on ICTDs and lower ICLDs

Outline

Perceptual recording of a real sound scene

- Let's move now to the case of recording a real acoustic scene with multiple sources, reflections etc
- Now direction of sources/reflections is unknown



To DOA or not to DOA

- Possible approach involves two steps:
  - direction of arrival (DOA) estimation (its own field of research)
  - take the signal and artificially add ICTD/ICLD
  - This is the approach followed by many methods, as e.g. Dirac/SDM/SIRR
- DOA estimation is not trivial and carries errors, especially for short time windows
- Let's try to use a different approach...

How to bypass DOA

- Connect each microphone to a corresponding loudspeaker
- We already chose ICTDs parametrisation to be the delay between two microphones
- The pair of microphones will have correct ICTDs by construction (without need to know source direction)

- Microphone directivity pattern $\Gamma(\theta)$: sensitivity of microphone as function of direction θ
- Use the directivity pattern to obtain desired ICLD(θ_s, r_m)
- This process makes DOA estimation unnecessary!

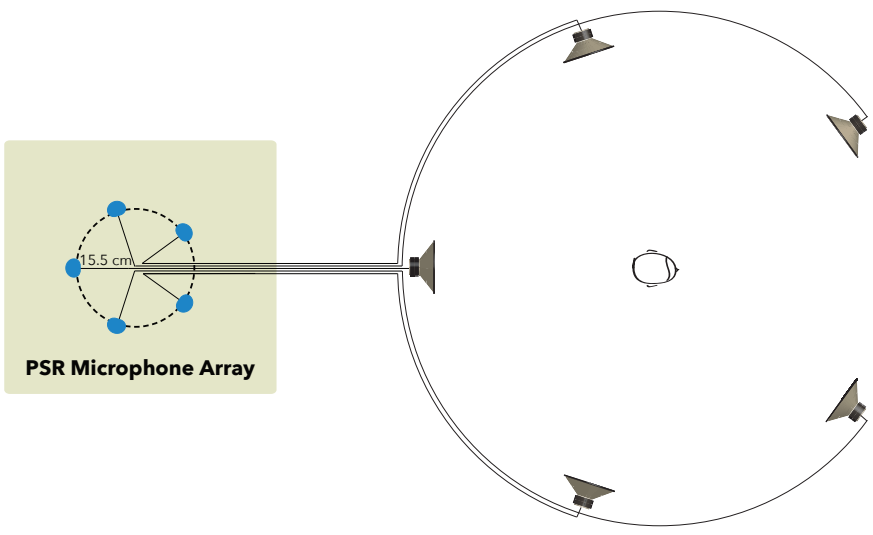
- Rest of this section will describe this design process in more in detail [De Sena et al., 2013]

How many loudspeakers in total?

- 5 channels: minimum for 360° perspective [Fletcher 1953]
- 5 channels: minimum for envelopment [Ando et al. 1986]

Perceptual Soundfield Reconstruction (PSR) Array [Johnston et al., 2000]

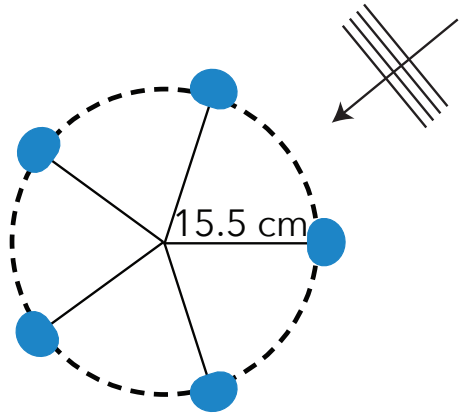
- 5 channels, uniformly distributed



First design step – # constrain only 2 loudspeakers active

How to have only 2 loudspeakers active for each wave?

- Design microphone directivity pattern $\Gamma(\theta)$ such that it does not pick up directions beyond neighbouring microphone



$$\Gamma(\theta) = \begin{cases} 0 & \theta \notin [-\phi_0, \phi_0] \\ ? & \theta \in [-\phi_0, \phi_0] \end{cases}$$

where ϕ_0 is angle between microphones

- From here on we consider microphone pairs
- Design $\Gamma(\theta)$ for $\theta \in [-\phi_0, \phi_0]$ to capture required (ICTD,ICLD) pairs

Second design step – polar pattern

- We know from earlier closed form expression for ICLD(θ, r_m)
- The relation that connects ICLD and directivity patterns is

$$\text{ICLD}(\theta, r_m) = 20 \log_{10} \frac{\Gamma_{l+1}(\theta)}{\Gamma_l(\theta)}$$

  with $\Gamma_{l+1}(\theta)$ and $\Gamma_l(\theta)$ polar patterns of adjacent mics
- We have 1 equation but 2 unknowns
- Add constraint $\Gamma^2_{l+1}(\theta) + \Gamma^2_l(\theta) = 1$ for equal loudness

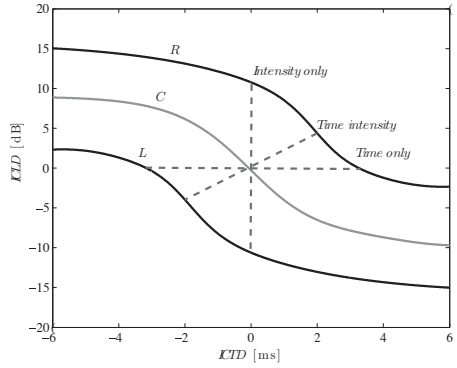
Second design step – polar pattern (cont'd)

Summary of first and second design steps

- Putting together $\mathrm{ICLD}(\theta, r_m) = 20 \log_{10} \frac{\Gamma_{l+1}(\theta)}{\Gamma_l(\theta)}$ (TID) and $\Gamma^2_{l+1}(\theta) + \Gamma^2_l(\theta) = 1$, and symmetry across microphones:

$$\Gamma(\theta) = \begin{cases} \left[1 + \dfrac{\sin^2(\theta + \beta(r_m))}{\sin^2((\phi_0 + \beta(r_m)) - \theta)}\right]^{-1/2} & \theta \in [0, \phi_0] \\ \left[1 + \dfrac{\sin^2(\beta(r_m) - \theta)}{\sin^2(\theta + (\phi_0 + \beta(r_m)))}\right]^{-1/2} & \theta \in [-\phi_0, 0] \\ 0 & \text{elsewhere} \end{cases}$$

- We can still choose r_m: higher r_m leads to larger ICTDs

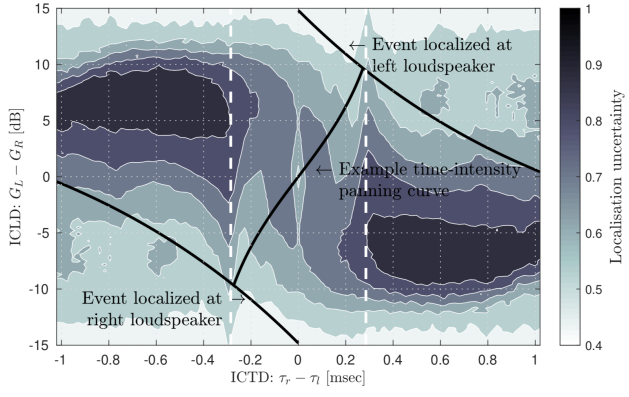


Third design step – array radius

- We saw earlier: larger ICTDs lead to larger sweet spot
- Where do we stop? Two vertical bands in figure
- Array radius such that panning curve end-point touches vertical band [De Sena et al., 2020]:

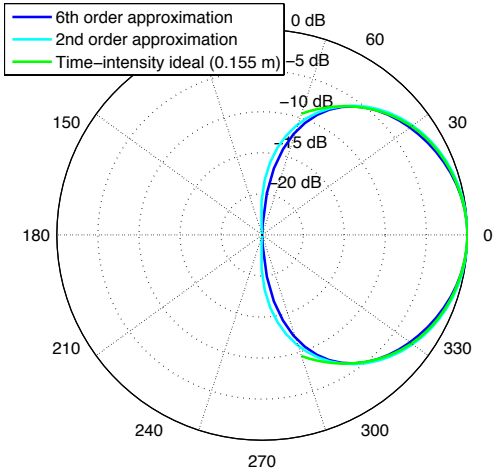
$$r_m \approx r_h \frac{\cos\left(\theta_e - \frac{\phi_0}{2}\right) + \frac{\phi_0}{2} + \theta_e - \frac{\pi}{2}}{2\sin^2\left(\frac{\phi_0}{2}\right)}$$

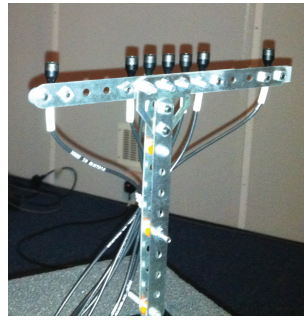
- For $r_h = 9$ cm and 5 loudspeakers, optimal radius $r_m \approx 15$ cm.



Microphone directivity that approximates ICLD(θ_s, r_m)

- Now we have the entire design: microphone positions, orientations and directivity pattern $\Gamma(\theta)$
- Are we done? No... there is no microphone that can implement exactly $\Gamma(\theta)$, but we can get close enough
- Second and higher-order microphones, e.g. differential mics [De Sena et al., 2012], Eigenmike [Elko and Meyer], or filter-and-sum beamformers can be used for this purpose





Subjective listening tests and extensions

Subjective listening tests [De Sena et al., 2013]

- Similar performance to second-order Ambisonics and VBAP in sweet-spot centre
- Lower uncertainty in off-centre positions

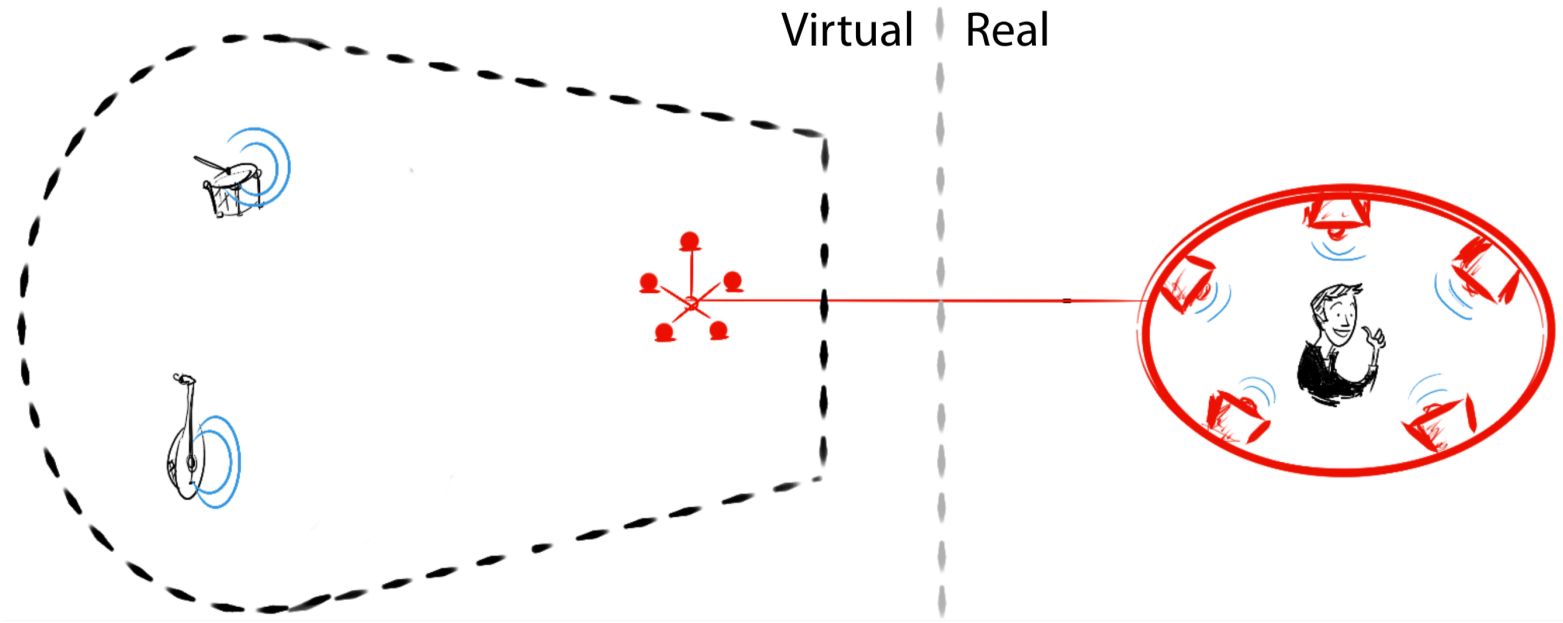
Current work and extensions

- PSR recently extended to third dimension using extrapolation from Eigenmike [Erdem et al., 2019]
- Time-intensity in the vertical dimension leads to a perceived improvement in stability of sweet spot [Andrew-Jones, 2019]

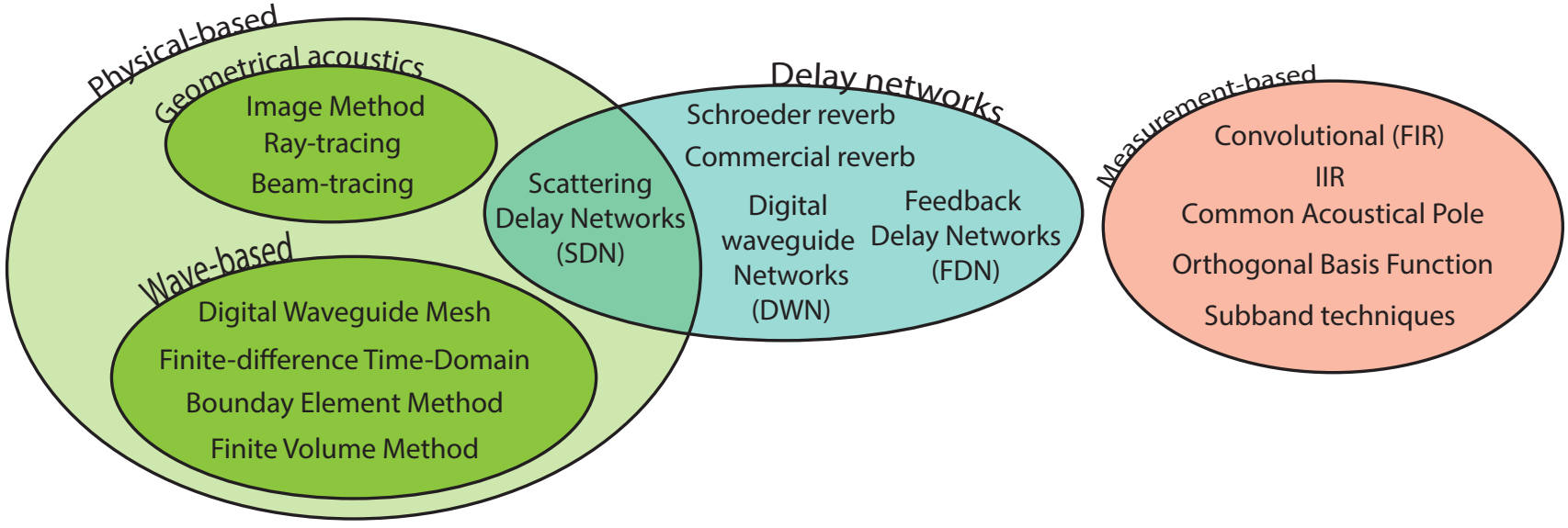
Outline

Perceptual Simulation of Room Acoustics

1. Simulate virtual room acoustics
2. *Virtual* recording and *real* reproduction (simulate microphone array as described in first part of talk)



Overview



- Overview of more than 50 years of room acoustic simulation in [Välimäki *et al.*, 2012], [Välimäki *et al.*, 2016] and [Hacıhabiboğlu *et al.*, 2017]
- Wave-based models are the most accurate ones

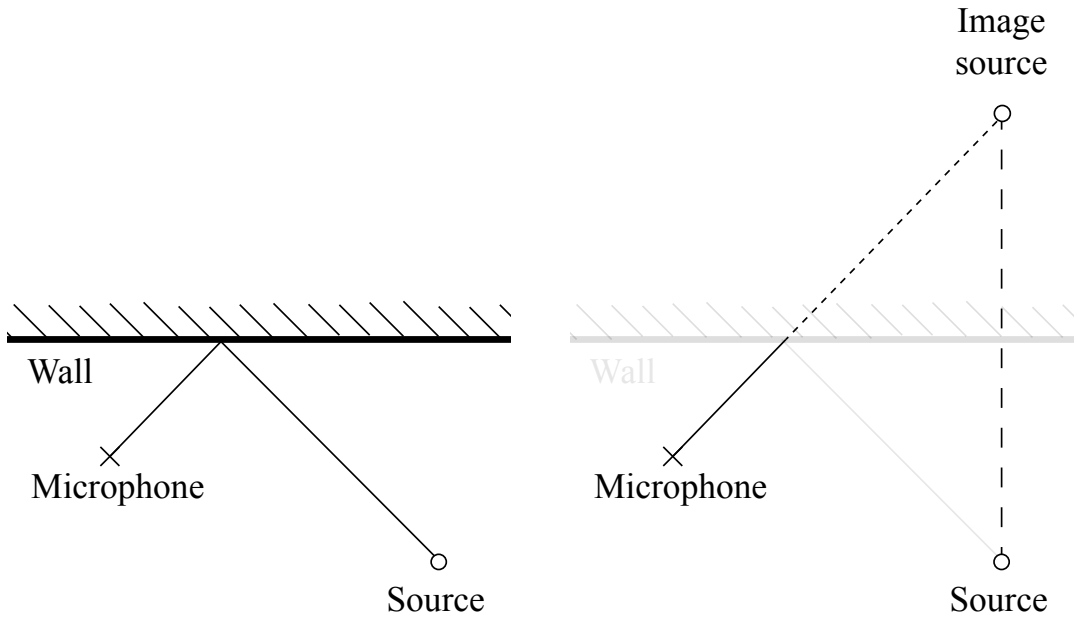
Rendering of dynamic scenes with wave models

- In a complete wave model of a room:
  - sources and listeners can be moved
  - *spatialized* using microphone arrays or "virtual dummy head"

Example: How expensive is a wave-based model?

- Audio bandwidth $= 20$ kHz ≈ 1.27 cm wavelength
- Spatial samples every 0.63 cm or less
- $3.65 \times 5.8 \times 2.4$ m room requires > 200 million grid points
- 3D finite difference model requires one multiply and 6 additions per grid point $\Rightarrow$ 70 billion FLOPS at $F_s = 50$ kHz
- $30 \times 15 \times 6$ m concert hall requires $>$ *3 quadrillion FLOPS*

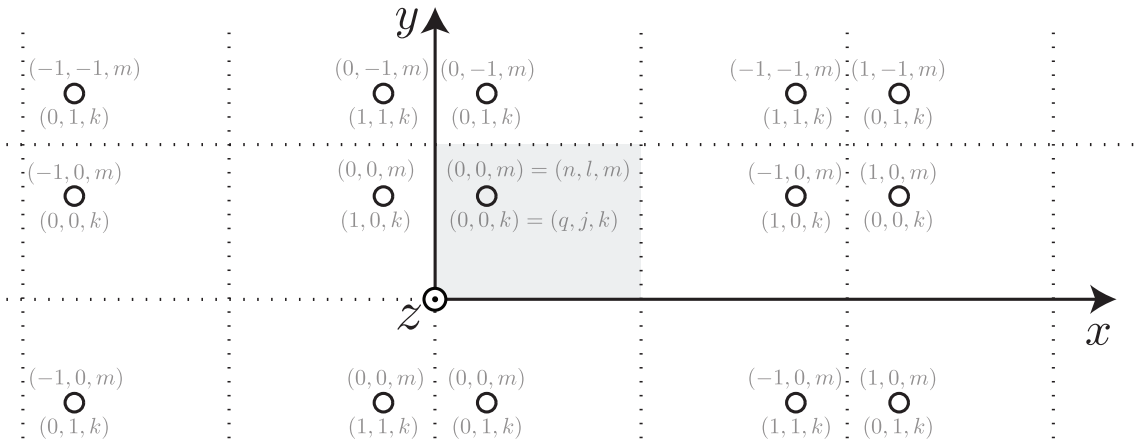
Image method for single reflector



- Wave propagation in half space is equivalent for:
  1. source and wall
  2. source and image source **(no wall)**
- Exact for rigid wall ($\nabla p \cdot \mathrm{n} = 0$)
- Approximation for non-rigid wall

Image method for rectangular room

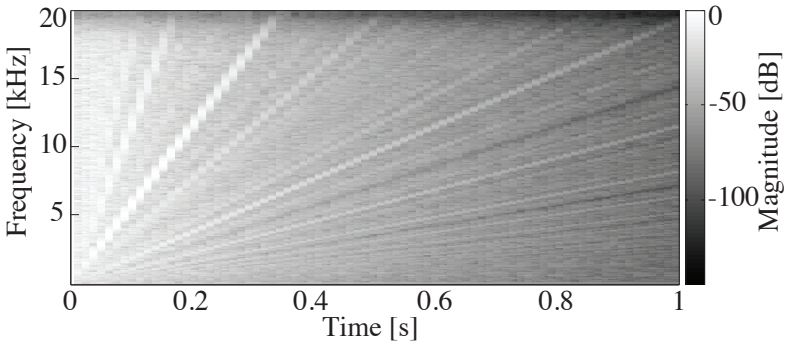
- With multiple reflectors: remove wall, mirror source *and* opposite wall



- Rectangular room: proven to be solution of wave equation for rigid walls [Allen and Berkley, 1979]
- Non-rectangular rooms also possible, but need expensive computations of image source visibility [Borish 1984]

Sweeping echoes in image method [De Sena *et al.*, 2015]

- Perfectly rectangular rooms cause so-called *sweeping echoes*
- Regular simulation setups yield stronger sweeping echoes



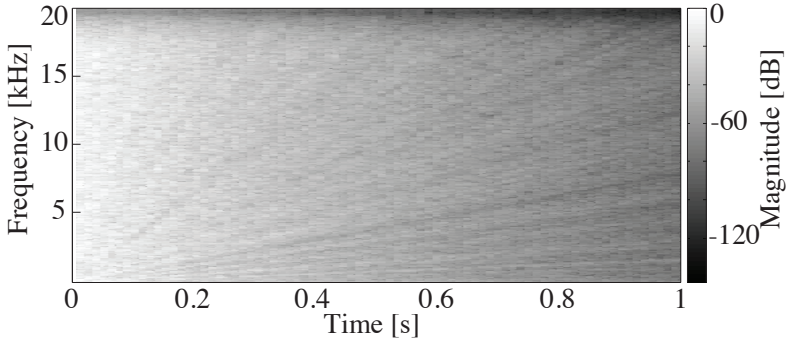
RIR: play

Anechoic: play REV: play

Room dimension: $4 \times 4 \times 4$

Mic. position $[1, 2, 2]$

Source position $[2, 1.5, 1]$



RIR: play

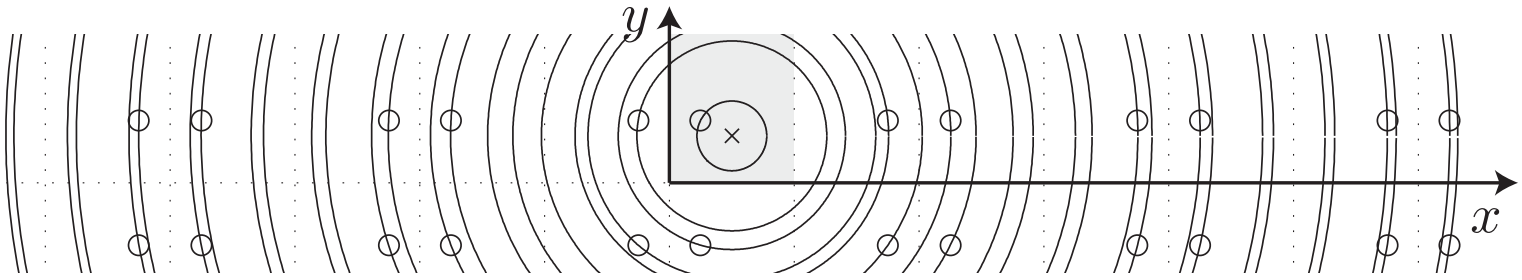
Anechoic: play REV: play

Room dimension: $4.1 \times 4.2 \times 4.3$

Mic. position $[1.4, 2.5, 2.6]$

Source position $[2.7, 1.8, 1.9]$

Cause of sweeping echoes



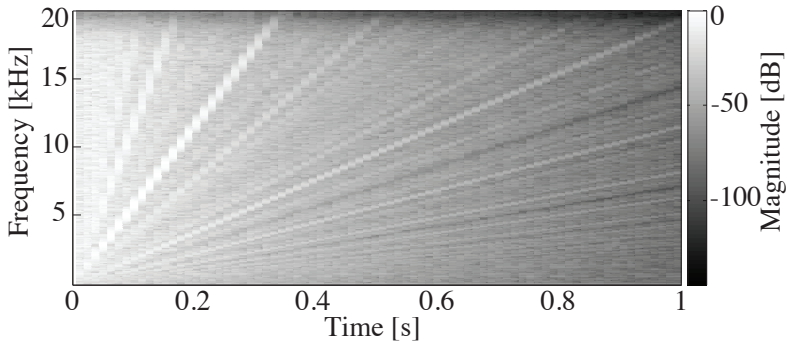
- Due to orderly alignment of images along 3 axes
- Pairs get closer like $1/t$, thus freq. resp. stretches with t
- Does not happen in most real rooms due to small imperfections

How to avoid sweeping echoes

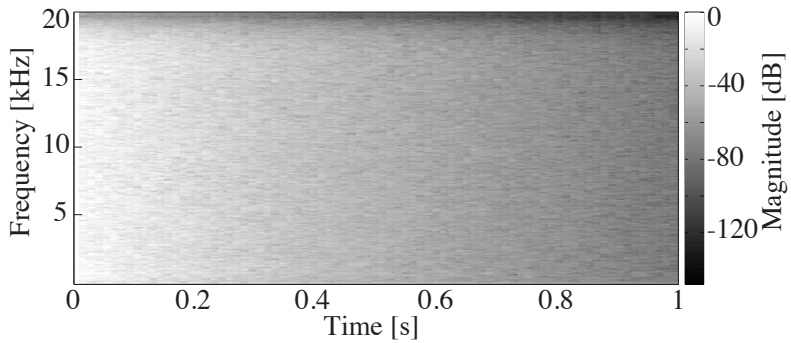
- Choose non-regular setup, e.g. random, or...

Randomized Image Method

- Small random displacement of images
- Uniform in ± 8 cm sufficient to remove completely
- Same complexity of rectangular image method



RIR: play REV: play

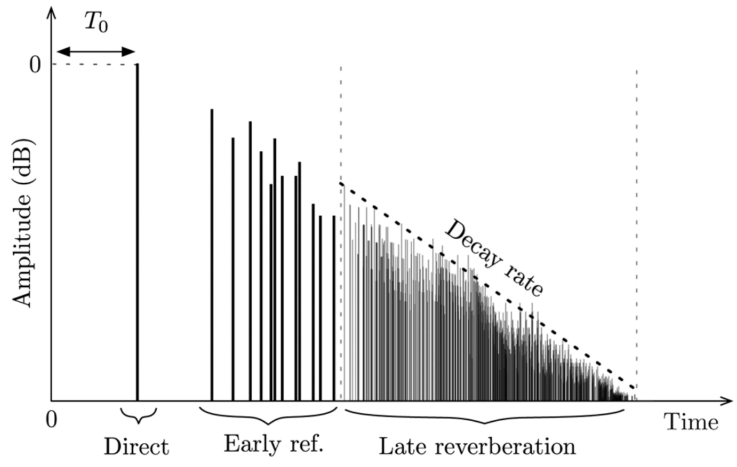


RIR: play REV: play

Rendering of dynamic scenes with geometric models

- Even then, we still need to
  1. recalculate RIR when moving source/observer
  2. run a convolution (computationally expensive for real-time applications)
- If physical accuracy not needed, perceptual methods provide better option

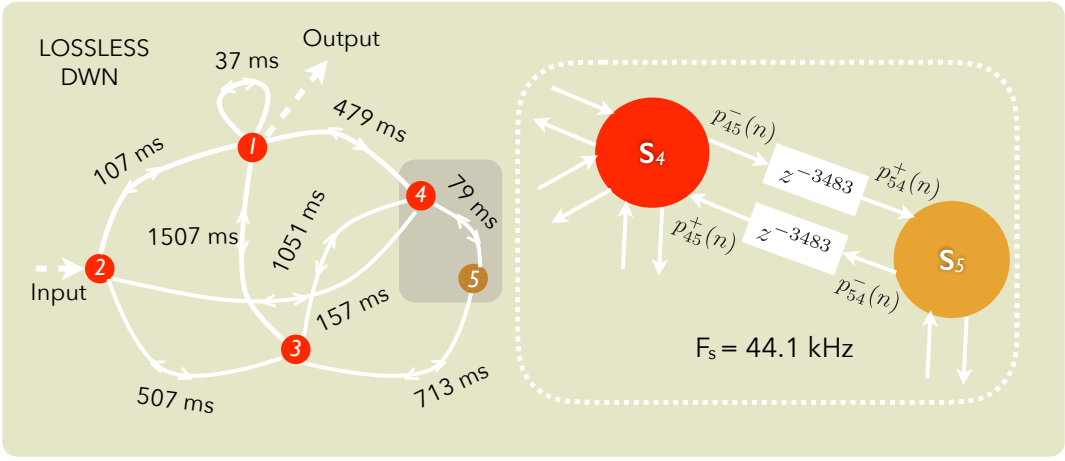
Room acoustics perception



RIR components:

- Direct line-of-sight
- Early reflections: important for perception of size and shape
- Late reverberation: important for envelopment and perception of size; we are not sensitive to exact structure
- Echo density has to be high enough for perceived texture
- Mode density high enough so that it is not metallic

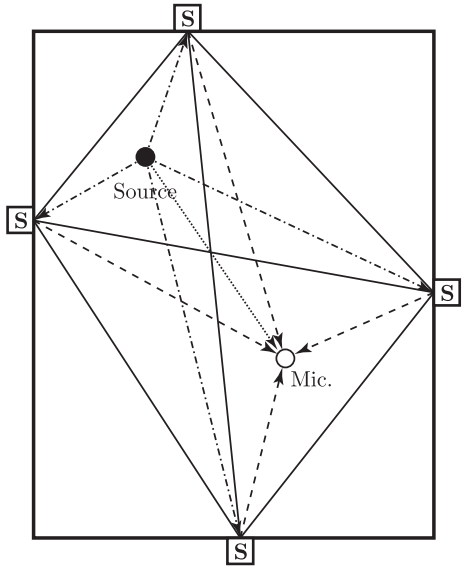
Digital waveguide networks (DWN)



- Network of bi-directional delay lines connected at scattering junctions [Smith, 1985]
- Can be interpreted as network of acoustic tubes
- **Question:** How to set parameters (delay line lengths, network connections, scattering matrix..)?

Scattering delay network (SDN) [De Sena et al., 2015]

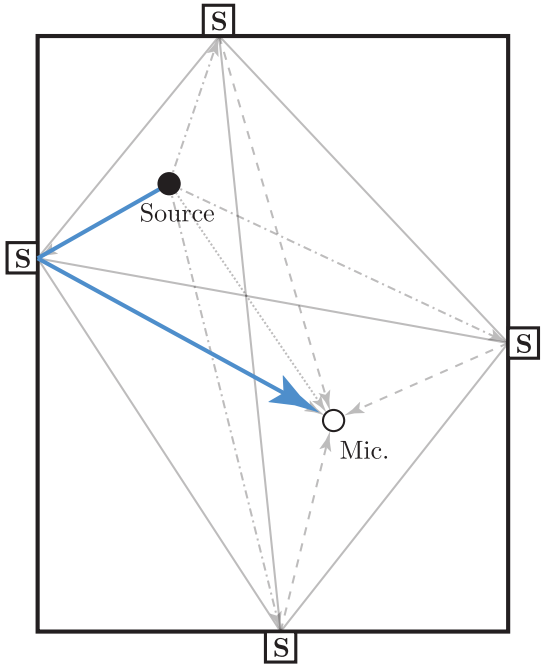
- Design DWN based on characteristics of a physical room



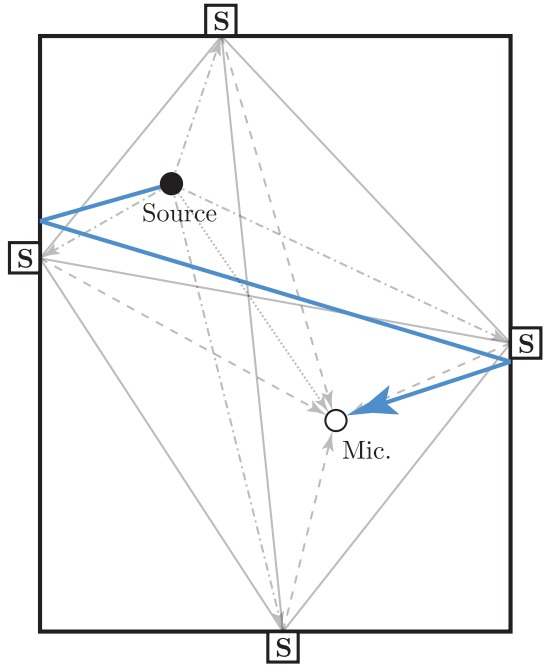
- Position nodes at first-order reflection points
- Fully connected DWN network
- Mono-directional lines for source-junction and junction-mic

SDN: approximation of geometric acoustics

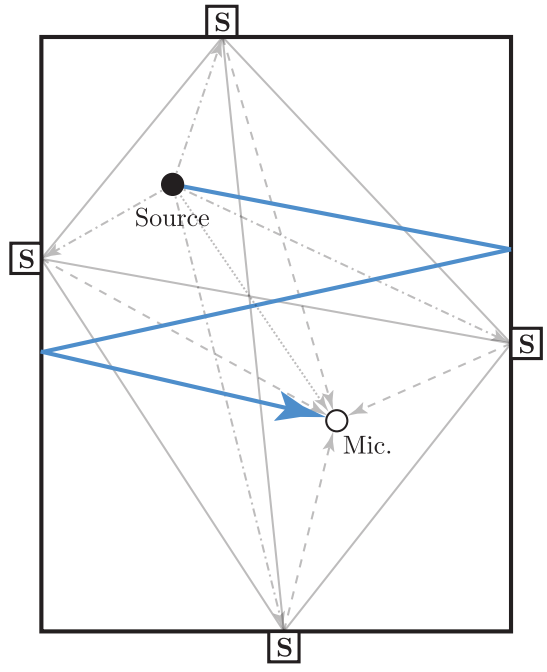
- Correct rendering of LOS and first-order reflections in time, amplitude and direction
- Approximation of second and higher-order reflections, less important perceptually



I-order reflection



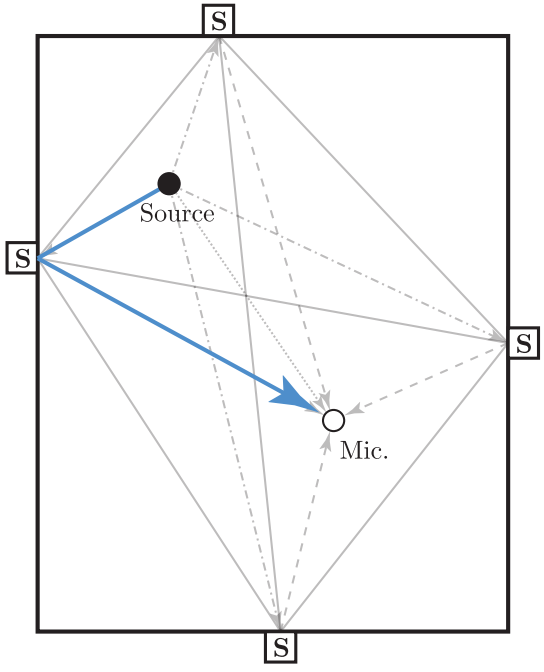
II-order reflection



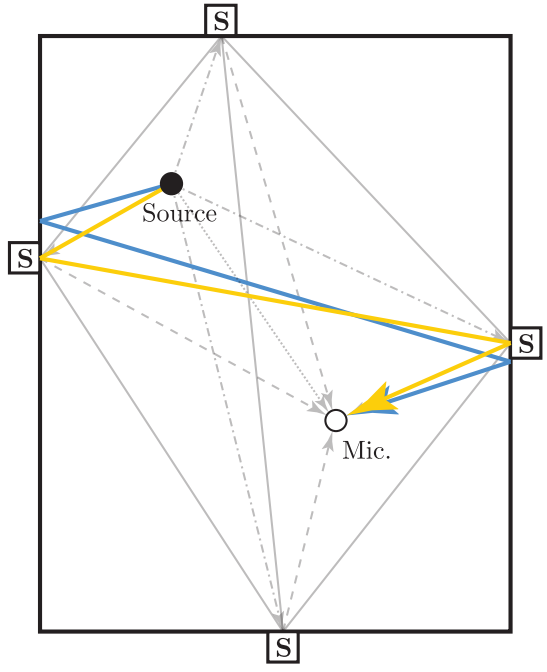
Another II-order reflection

SDN: approximation of geometric acoustics

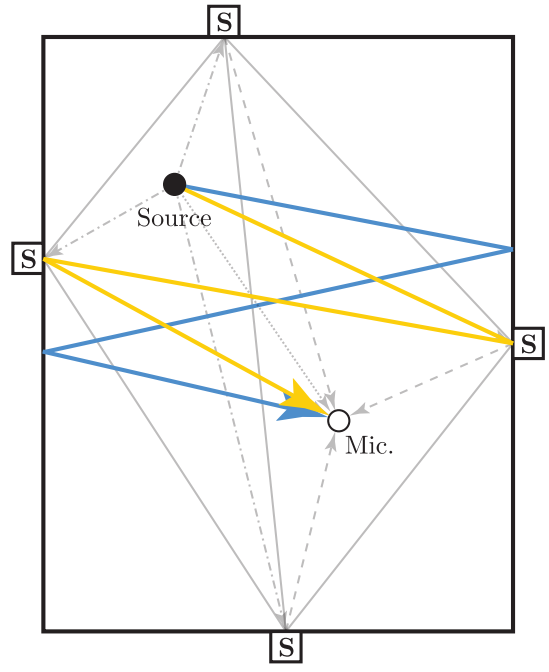
- Correct rendering of LOS and first-order reflections in time, amplitude and direction
- Approximation of second and higher-order reflections, less important perceptually



I-order reflection



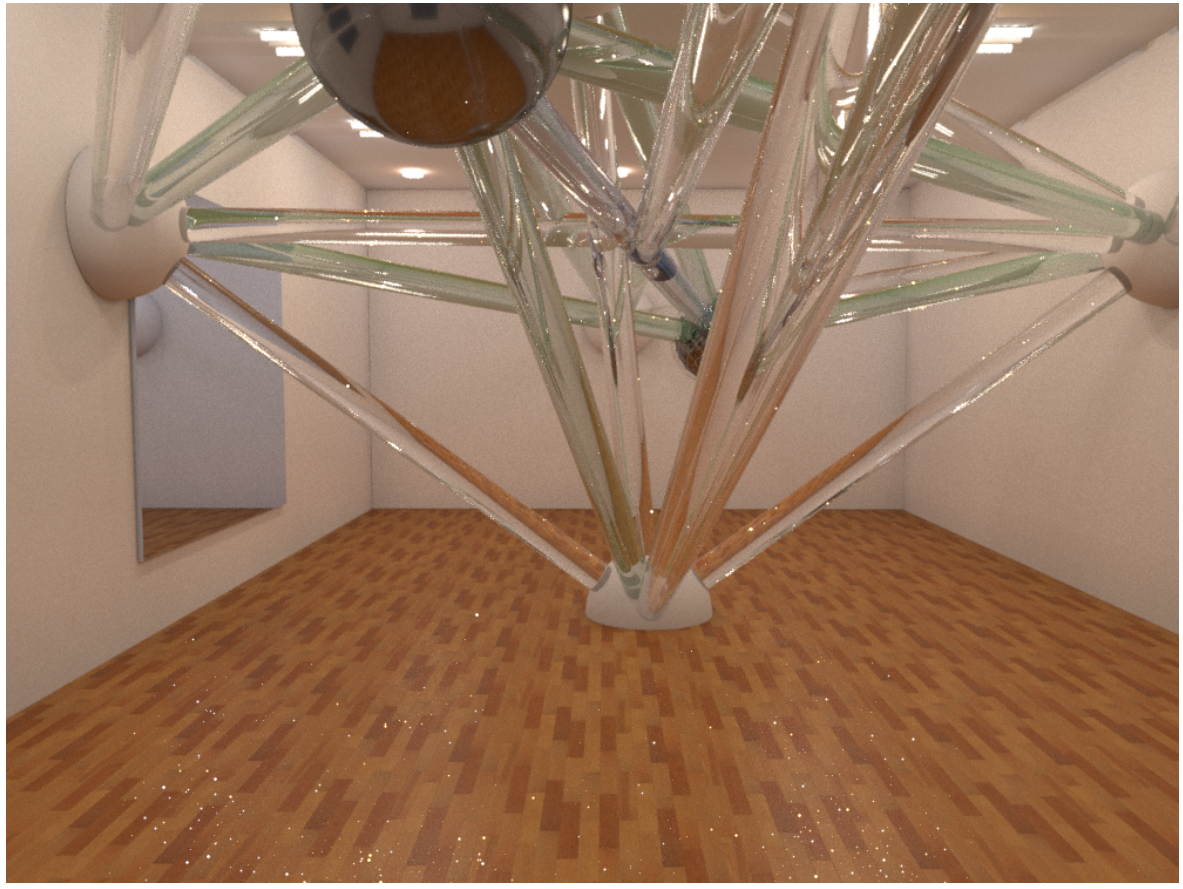
II-order reflection



Another II-order reflection

SDN: alternative interpretation

- Can also be interpreted as model of network of acoustic tubes

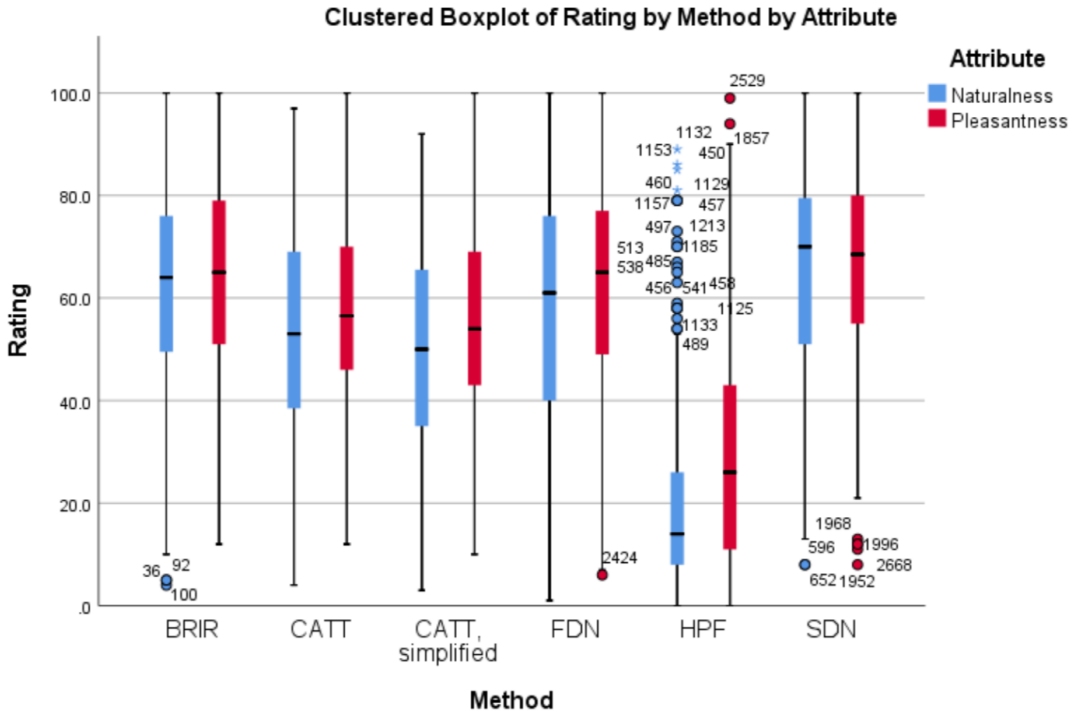


Advantages

- Also, not shown here:
  - similar frequency-dependent RT60 to full-scale models
  - similar echo density to full-scale models
  - sufficient modal density
  - axial resonant modes of room well approximated
- Orders of magnitude faster than FFT convolution (alone!)
- All parameters of model derived from physical properties

Perceptual evaluation [Djordjevic, 2019]

- Headphone-based (binaural) comparison (28 subjects)
- Higher pleasantness ($p < 0.001$) and naturalness ($p < 0.001$) than comparable delay-network based method

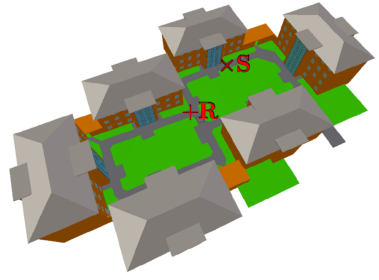


Comparison of SDN-IM-FDTD

See https://youtu.be/1hdhhrM4juQ

Recent advancements in SDN

- Stevens et al. (2017):
  - Extension to exact second-order reflections
  - Implementation of direction-dependent scattering (e.g. modelling of trees)
  - Modelling of outdoor scenes (sky absorbing nodes)
- Schlecht and Habets (2017):
  - Showed scattering matrix is "unilossless"



- SCReAM (SCalable Room Acoustics Modelling): £407k EPSRC project, hiring 3-year postdoc (deadline 16 Nov)

Outline

Contributions

Recording and reproduction

- Consistent ICLD/ICTD pairs $\Rightarrow$ sources easier to localise
- Small ICTDs $\Rightarrow$ larger sweet spot by delaying occurrence of inconsistent ICLD/ICTD pairs
- Beamforming used to bypass need for explicit DOA estimation

Room Acoustics Simulation

- When using image method, beware of sweeping echoes
- SDN is simple/fast network of delay lines that renders accurately what is more important perceptually
- Orders of magnitude faster than convolution (alone!)

- That's all folks! :) Questions?

Further Reading

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