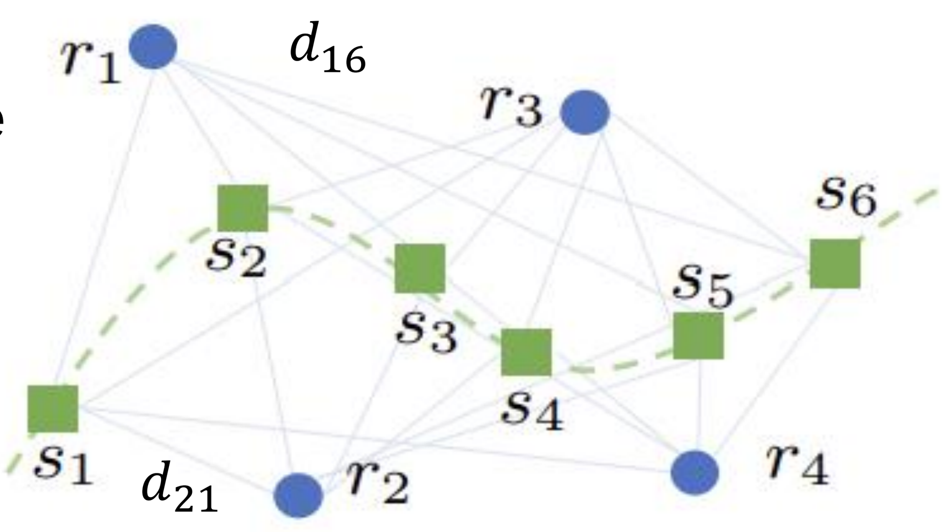
A Roomful of Distances

Malte Larsson - Lund University, Combain
Centre for Mathematical Sciences - CVML

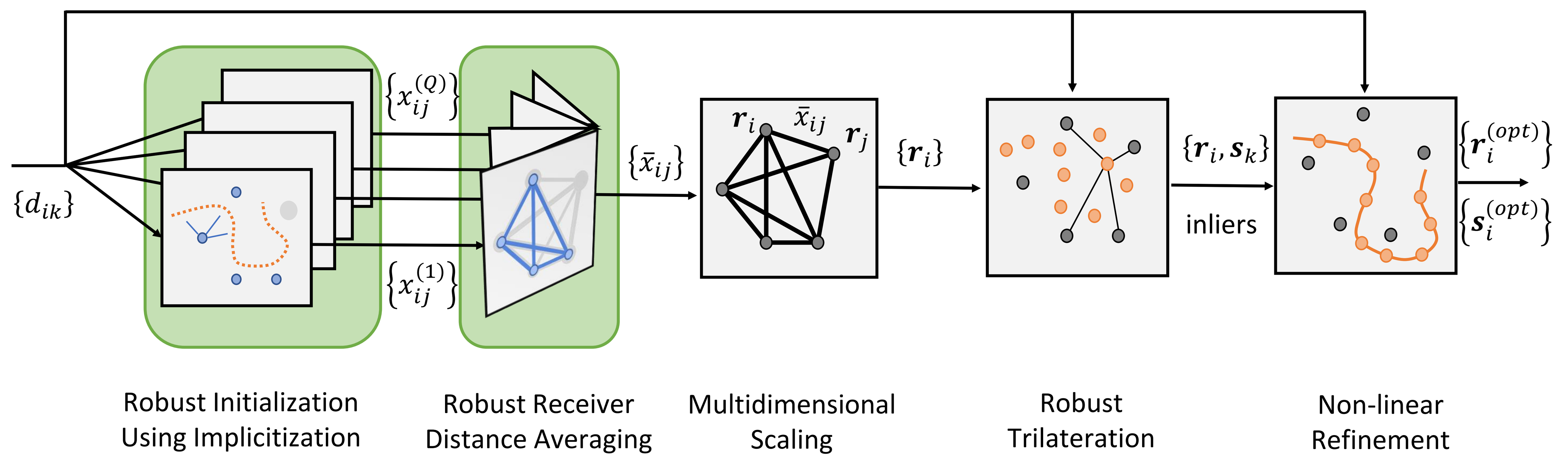
Time-of-Arrival Self-Calibration

We look at the Time-of-Arrival self-calibration problem. There are m **receivers** r_i and n **senders** s_j (imagine microphones and loudspeakers) in **unknown positions**. We assume $m \gg n$. This could be the case for a moving sound source. Given **distance measurements** between receivers and senders (for example from the time it takes for sound to travel from the loudspeaker to the microphone), we want to **find the positions** of everything, matching the given distances.



This can be formulated as wanting to find the positions that minimize $\varepsilon_{ML}(\boldsymbol{r},\boldsymbol{s}) = \sum_{i,j}\left(\|\boldsymbol{r}_i - \boldsymbol{s}_j\| - d_{ij}\right)^2$. The data typically contains **outliers** making it important to find **good initializations**.

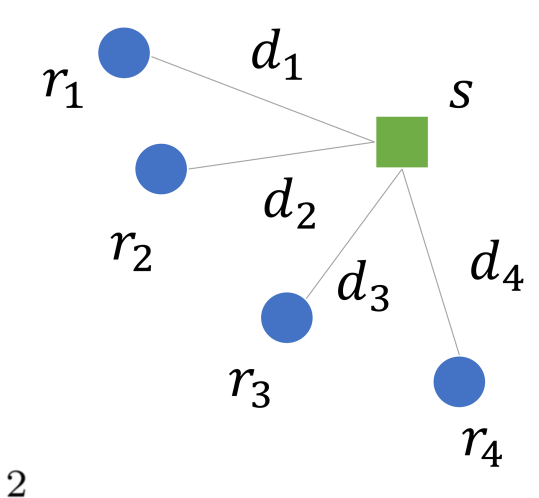
System overview:



Solving 4-systems

We solve systems consisting of **4 receivers and many senders**. We use a **RANSAC** scheme to deal with outliers. We sample distances to 6 senders and use minimal solvers to construct possible receiver configurations. In order to improve speed, we construct an error measure that allows us to not compute all sender positions.

If we consider the distances $\boldsymbol{d}$ from four receivers $\boldsymbol{r}$ to one sender, these must fulfil a polynomial constraint $p(\boldsymbol{r},\boldsymbol{d}) = 0$.



For fixed receiver positions, a single sender contributes to the ML-error with:

$$\mathcal{E}_{ML}(\mathbf{r}) = \min_{\mathbf{s}\in\mathbb{R}^3} \sum_{i=1}^{4} \left(\|\mathbf{r}_i - \mathbf{s}\| - d_i\right)^2$$

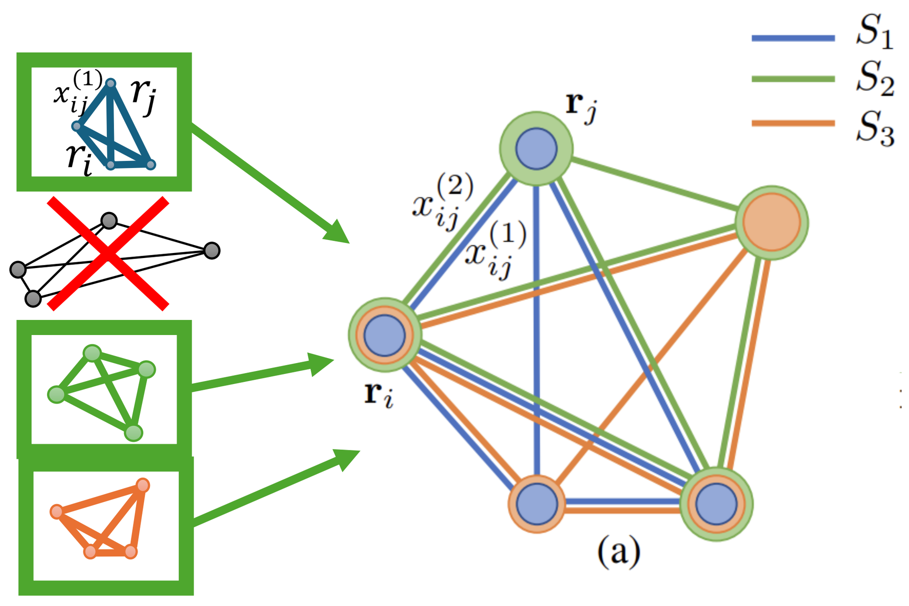
$$\hat{\mathbf{d}} \text{ s.t. } p(\mathbf{r},\hat{\mathbf{d}}) = 0$$

Linearizing the constraint around **d** and simplifying gives us

$$\mathcal{E}_{QS}(\mathbf{r}) = \frac{p(\mathbf{r},\mathbf{d})^2}{\|\nabla_{\mathbf{d}} p\|^2}$$

This value holds geometrical meaning and can be used to evaluate and refine receiver positions.

Combining 4-systems



If we have more than four receivers, we can choose to solve the problem for many choices of only four receivers. This gives us a lot of small solutions that we want to combine. We need to handle that some 4-solutions will be completely wrong.

We look at the distances between receivers in the 4-solutions. We consider solutions to be good if the distances between the same receivers in several solutions agree with each other. We formulate this as on optimization problem where S_q represent the quality of a solution and $x_{ij}^{(q)}$ the distances between receivers in a solution:

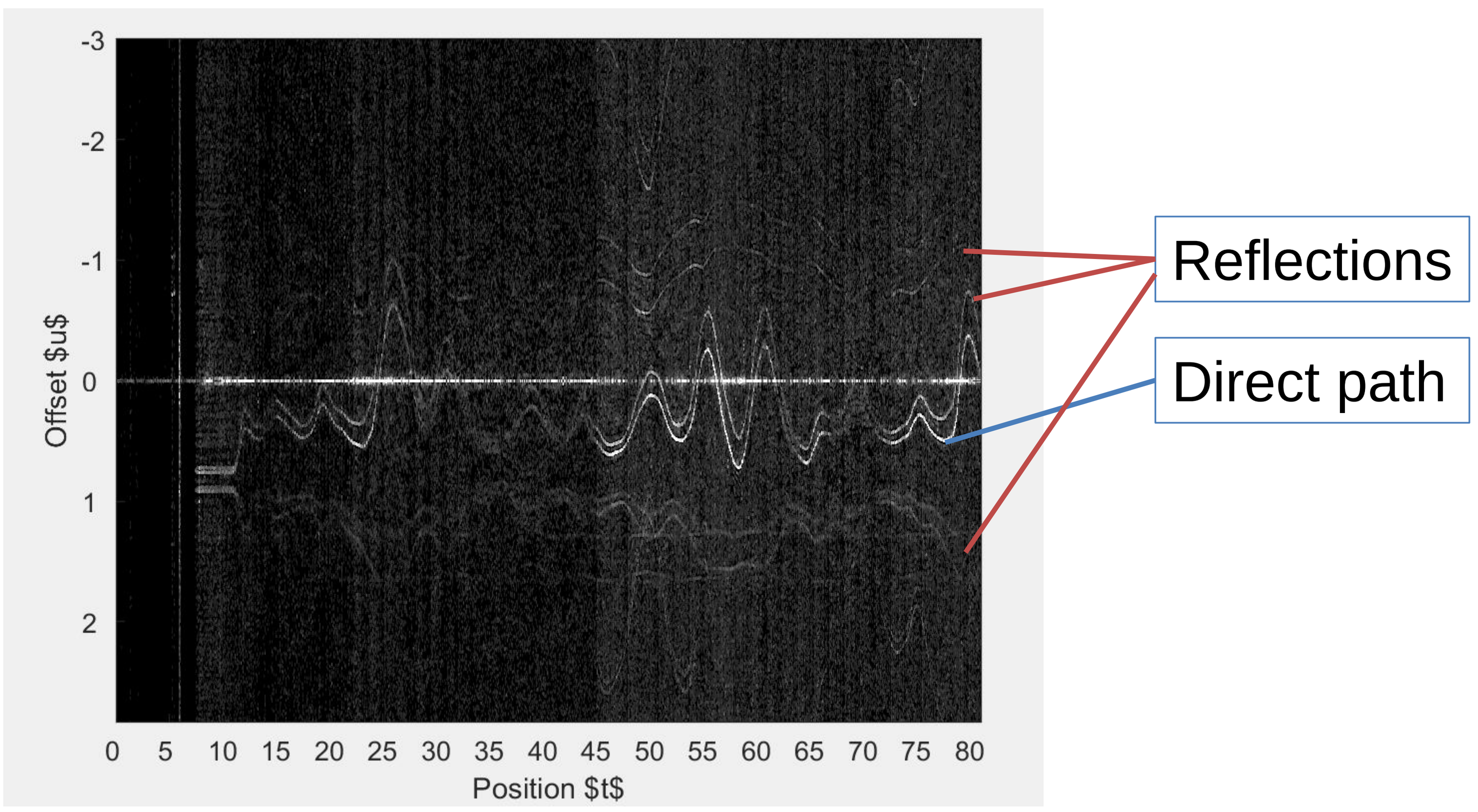
$$\min_{S_q\in[0,1]} -\lambda \sum S_q + \sum S_q\left(\bar{x}_{ij} - x_{ij}^{(q)}\right)^2$$

$$\bar{x}_{ij} = \frac{\sum S_q \cdot x_{ij}^{(q)}}{\sum S_q}$$

Current research: Room Geometry estimation using echoes

A microphone can pick up echoes of sound as well. This opens the possibility to find where the walls are in a room. With known microphones and speaker positions, three distances corresponding to a reflection in the same wall is enough to estimate the position of that wall. Using RANSAC techniques we try to find walls matching much of the data.

This plot shows which time delays gives large correlation between the received sounds of two microphones using gcc-phat.



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