Acoustic Node Localization

SSPressing-Colist sub-project (TEC2015-67387-C4)

Roberto Gil Pita
University of Alcalá

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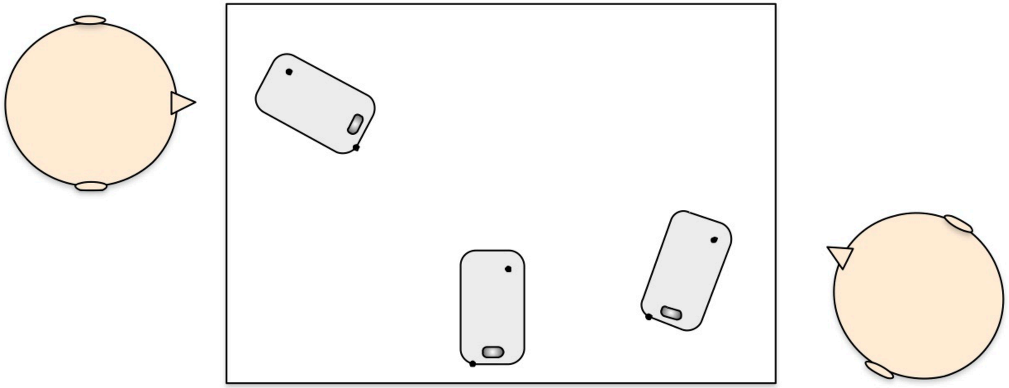
Outline

- Introduction and scope
- Maximum Likelihood localization
- Managing uncertainties
- Experiments and results
- Conclusions

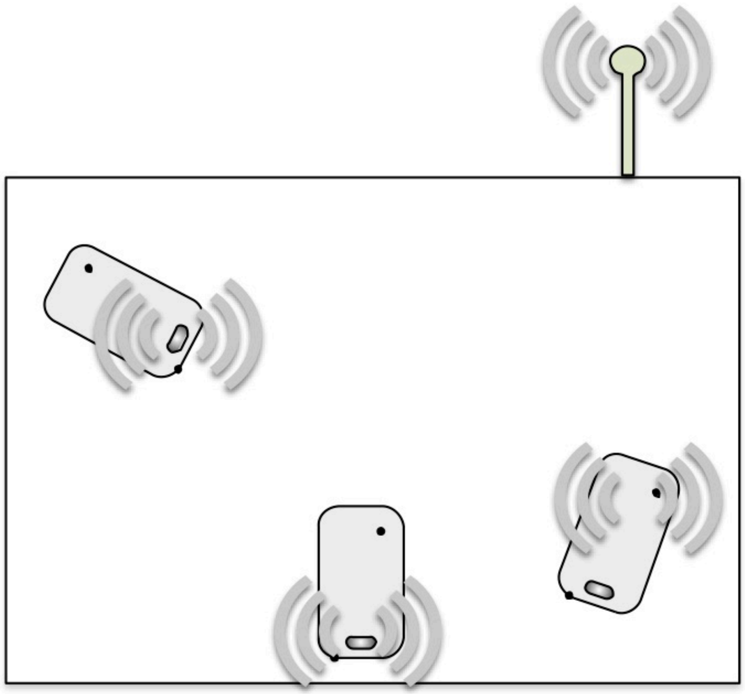
Introduction

- Wireless Sensor Networks (WSNs)
  - Sensor node locations often unavailable
  - Sensor's location gives meaning to the data
- WSNs composed of smartphones have many trending applications:
  - Acoustic WSN (AWSN)
  - Indoor positioning systems
  - Surveillance
  - Health monitoring



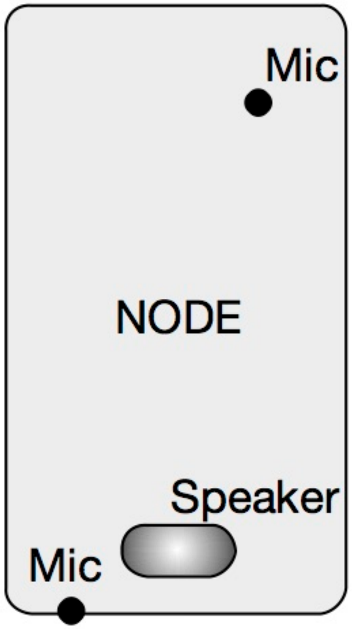
Introduction

- Indoor applications: GPS not available
  - RF, acoustic and infrared signals used for node localization
  - Common measurements: TOA, DOA, RSS
- Problems:
  - Random measurements (time-varying and static errors)
- Lack of synchronization



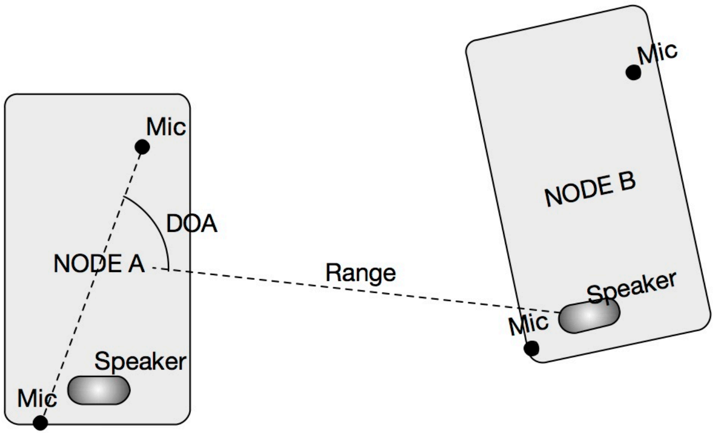
Scope

- Proposed approach
  - Blind node localization (no reference sensors)
  - Each node is a state-of-the art smartphone with two microphones
  - Nodes are localized and orientated combining the information from different sensors:
  - Microphones, Loudspeaker, Accelerometer, Magnetometer
- Distributed localization: cooperation



Active localization, oriented nodes

- J nodes fully interconected, each node estimates its own orientation (magnetometer)
- Distributed schema, no precise clock synchronization.
- Node k transmits an acoustic chirp 5-10 kHz (0.1 s)
- The remaining nodes (J-1) estimate de position of node k
- DOA+range: estimation of node k position
  - Each node estimates acoustic DOA
  - DOA, RSS, and other acoustic parameters are used to estimate the range of the node => Neural network

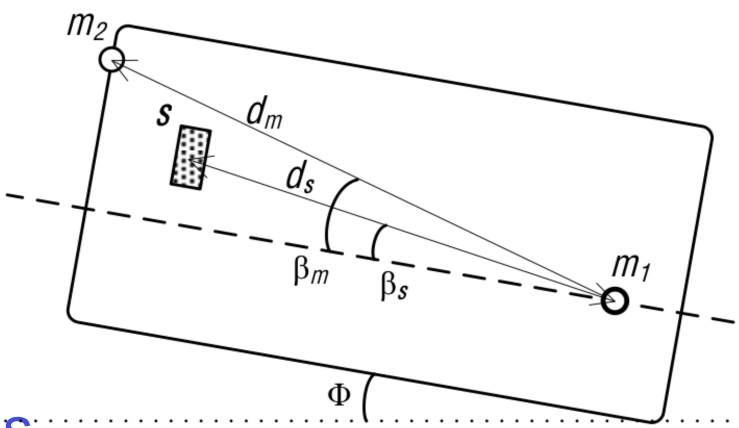


Problem formulation

- Assume an ad hoc fully connected network with J nodes (smartphones). Signals in node j:

$$s_j(t)$$

$$m_{1j}(t),\ m_{2j}(t)$$



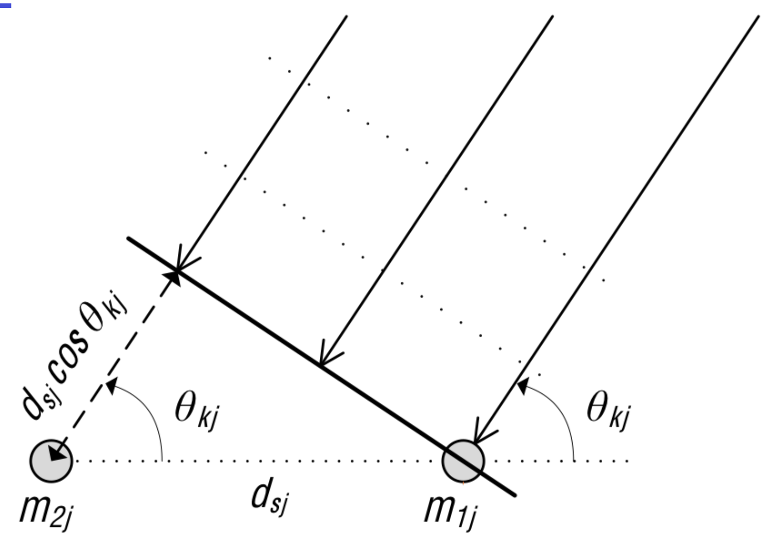
- Goal: localize and orientate J nodes (2D)
- Localize m1+orientation ϕ

DOA estimation

- DOA estimation (acoustic) $\tau_j = d_{sj} \cos\theta_{kj}/c$
- DOA estimated from TDOA between 2 mics

$$\hat{\tau}_1 = \arg\max_t((m_{1j} * s_k)(t))$$
$$\hat{\tau}_2 = \arg\max_t((m_{2j} * s_k)(t))$$
$$\hat{\tau}_j = \hat{\tau}_2 - \hat{\tau}_1$$

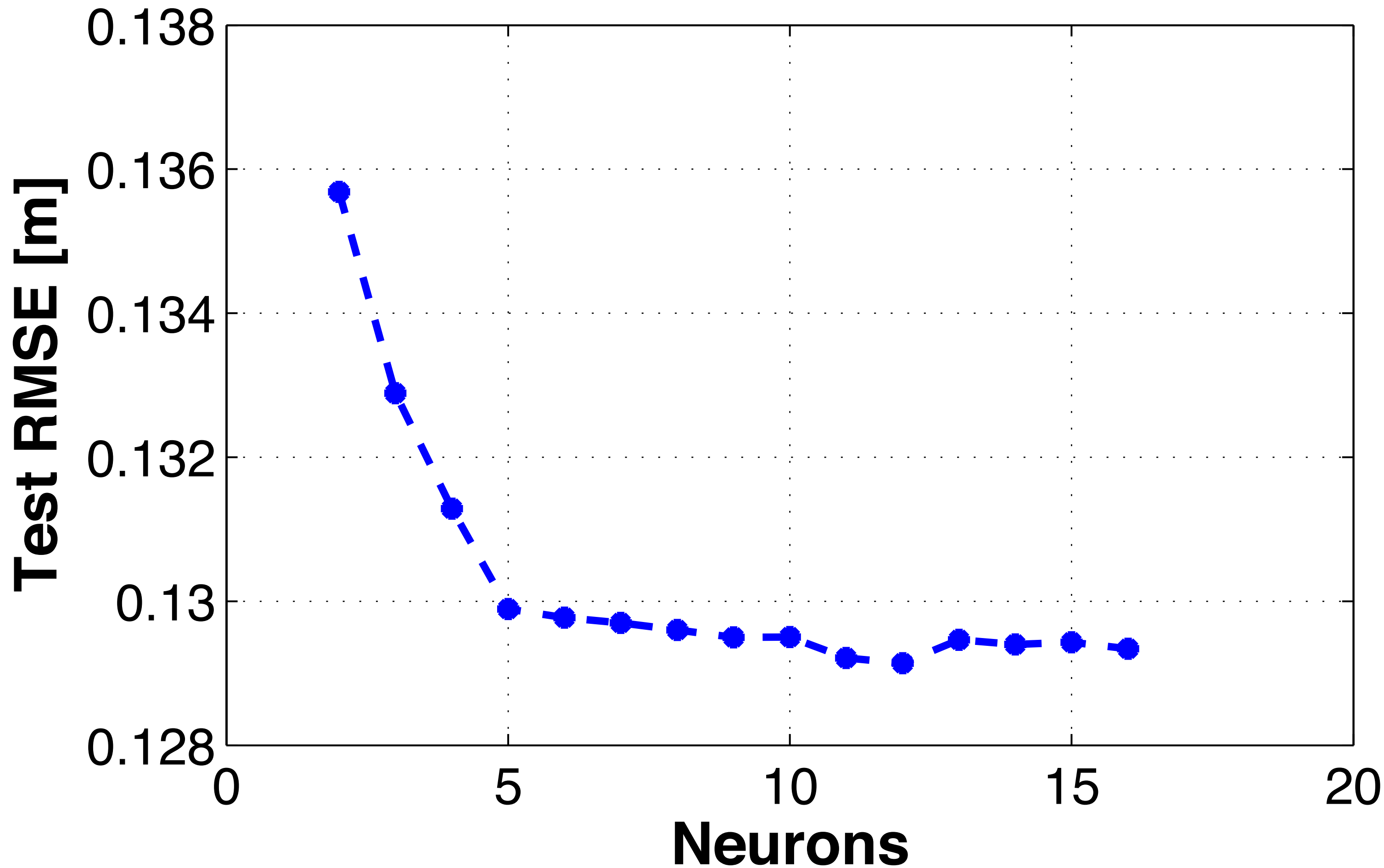
- Since we know the transmitted signal TDOA is calculated from TOA in each mic



Range estimation

- Range estimation (acoustic + RF)
  - Estimation based on an Artificial Neural Network (ANN).
  - FF network with 3 hidden layers.
- Input features for estimation:
  - Received acoustic power (RMS) of the 2 channels
  - Estimated DOA
  - Direct-to-Reverberant Ratio (DRR) $DRR = E_D/(E_T - E_D)$
  - ED estimated from the output of a DS beamformer steered towards the estimated DOA
  - RT20 : Time required for reflections of a direct sound to decay 20 dB. Estimated from the cross-correlation function of

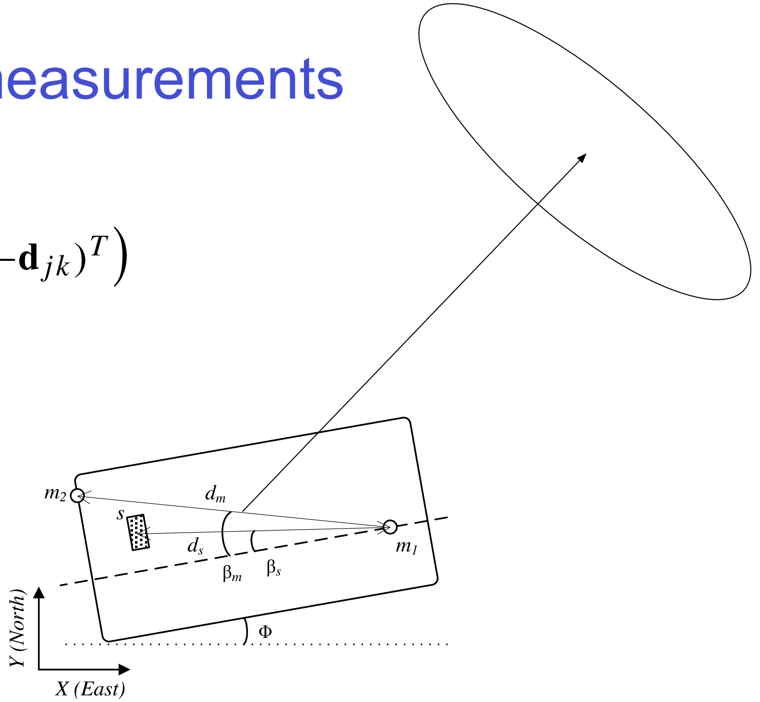
Range estimation



ML estimation of the position

- Probability density function of the measurements

$$f_{jk}(\mathbf{P}) = \frac{1}{2\pi\,|\mathbf{C}_{jk}|^{\frac{1}{2}}} e^{\left(-\frac{1}{2}(\mathbf{p}_j-\mathbf{p}_k-\mathbf{d}_{jk})\mathbf{C}_{jk}^{-1}(\mathbf{p}_j-\mathbf{p}_k-\mathbf{d}_{jk})^T\right)}$$



- Log-Likelihood

$$L = \sum_{j=1}^{J} \sum_{\substack{k=1 \\ k\neq j}}^{J} \log(f_{jk}(\mathbf{P})).$$

$$L = b - \frac{1}{2}\sum_{j=1}^{J}\sum_{k=1}^{J}(\mathbf{p}_j-\mathbf{p}_k-\mathbf{d}_{jk})\mathbf{D}_{jk}(\mathbf{p}_j-\mathbf{p}_k-\mathbf{d}_{jk})^T \qquad \mathbf{D}_{jk} = \begin{pmatrix} \rho_{xx}(j,k) & \rho_{xy}(j,k) \\ \rho_{yx}(j,k) & \rho_{yy}(j,k) \end{pmatrix}$$

ML estimation of the position

- Maximizing the Log-Likelihood

$$\begin{pmatrix} \mathrm{diag}(\mathbf{R}_{xx}\mathbf{j}) - \mathbf{R}_{xx} & \mathrm{diag}(\mathbf{R}_{xy}\mathbf{j}) - \mathbf{R}_{xy} \\ \mathrm{diag}(\mathbf{R}_{yx}\mathbf{j}) - \mathbf{R}_{yx} & \mathrm{diag}(\mathbf{R}_{yy}\mathbf{j}) - \mathbf{R}_{yy} \end{pmatrix} \cdot \mathbf{p} = \mathbf{S}$$

$$\mathbf{R}_{xy} = \mathbf{H}_{xy} + \mathbf{H}_{xy}^T$$

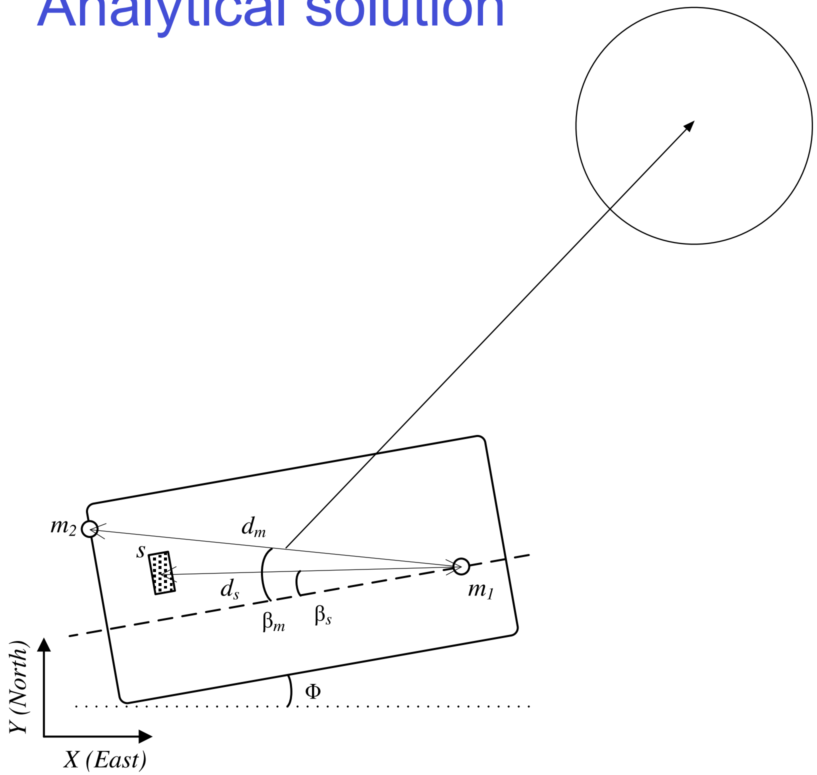
$$\mathbf{H}_{xy} = \begin{pmatrix} 0 & \rho_{xy}(1,2) & \dots & \rho_{xy}(1,J) \\ \rho_{xy}(2,1) & 0 & \dots & \rho_{xy}(2,J) \\ \vdots & \vdots & & \vdots \\ \rho_{xy}(J,1) & \rho_{xy}(J,2) & \dots & 0 \end{pmatrix}$$

$$\mathbf{S} = \begin{pmatrix} \sum_{j=1}^{J} \rho_{xx}(1,j)v_{1j} - \rho_{xx}(j,1)v_{j1} \\ + \cdots + \rho_{xy}(1,j)w_{1j} - \rho_{xy}(j,1)w_{j1} \\ \vdots \\ \sum_{j=1}^{J} \rho_{xx}(J,j)v_{Jj} - \rho_{xx}(j,J)v_{jJ} \\ + \cdots + \rho_{xy}(J,j)w_{Jj} - \rho_{xy}(j,J)w_{jJ} \\ \sum_{j=1}^{J} \rho_{yx}(1,j)v_{1j} - \rho_{yx}(j,1)v_{j1} \\ + \cdots + \rho_{yy}(1,j)w_{1j} - \rho_{xy}(j,1)w_{j1} \\ \vdots \\ \sum_{j=1}^{J} \rho_{yx}(J,j)v_{Jj} - \rho_{yx}(j,J)v_{jJ} \\ + \cdots + \rho_{yy}(J,j)w_{Jj} - \rho_{xy}(j,J)w_{jJ} \end{pmatrix}$$

- Rank: $2J - 2$ $\qquad \sum_{j=1}^{J} x_j = 0$
- Two more equations: $\sum_{j=1}^{J} y_j = 0$

Case 1: Naive Covariance Matrix Estimation (NCME)

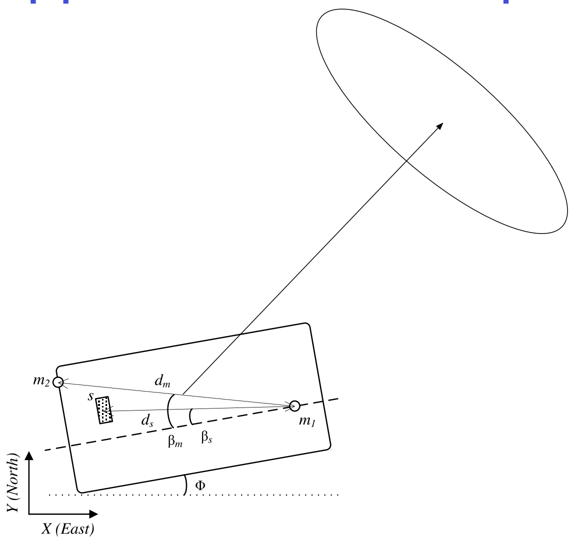
- Diagonal and identical covariance matrixes $\mathbf{D}_{jk} = \rho \mathbf{I}$
- Analytical solution



$$\mathbf{p} = \begin{pmatrix} \frac{1}{2J}\sum_{j=1}^{J} \upsilon_{1j} - \upsilon_{j1} \\ \vdots \\ \frac{1}{2J}\sum_{j=1}^{J} \upsilon_{Jj} - \upsilon_{jJ} \\ \frac{1}{2J}\sum_{j=1}^{J} \omega_{1j} - \omega_{j1} \\ \vdots \\ \frac{1}{2J}\sum_{j=1}^{J} \omega_{Jj} - \omega_{jJ} \end{pmatrix}$$

Case 2: Full Covariance Matrix Estimation (NCME)

- Approximated from polar coordinates



$$\mathbf{C}_{jk} \simeq \mathbf{R}_{jk} \cdot \begin{pmatrix} \sigma_r^2 & 0 \\ 0 & \sigma_a^2 (r_{jk}^2 + \sigma_r^2) \end{pmatrix} \cdot \mathbf{R}_{jk}^T$$

$$\mathbf{R}_{jk} = \begin{pmatrix} \cos(\gamma_{jk}) & -\sin(\gamma_{jk}) \\ \sin(\gamma_{jk}) & \cos(\gamma_{jk}) \end{pmatrix}$$

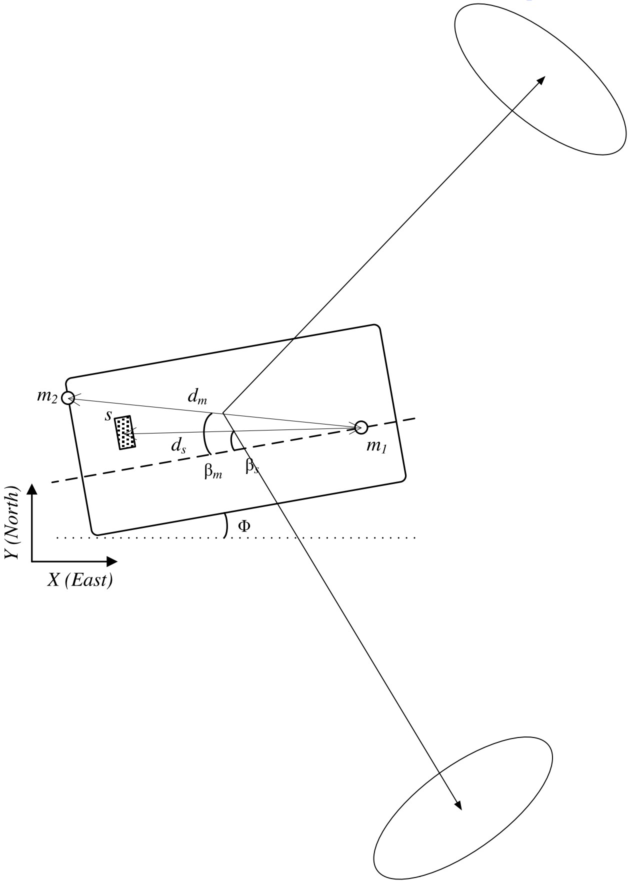
$$\mathbf{D}_{jk} = \mathbf{C}_{jk}^{-1} \simeq \mathbf{R}_{jk}^T \cdot \begin{pmatrix} \frac{1}{\sigma_r^2} & 0 \\ 0 & \frac{1}{\sigma_\gamma^2 (r_{jk}^2 + \sigma_r^2)} \end{pmatrix} \cdot \mathbf{R}_{jk}$$

Comparing NMCE and FMCE

	$NCME$				$FCME$			
J	Mean	Std	Trimean	O^2	Mean	Std	Trimean	O^2
3	0.344	0.547	0.155	2,919	0.311	0.452	0.160	3,372
4	0.272	0.336	0.160	5,828	0.261	0.356	0.136	6,794
5	0.228	0.270	0.136	9,705	0.197	0.254	0.113	11,472
6	0.193	0.194	0.128	14,550	0.158	0.177	0.101	17,470
7	0.191	0.170	0.133	20,363	0.153	0.168	0.097	24,852
8	0.176	0.149	0.128	27,144	0.129	0.128	0.090	33,682
9	0.179	0.155	0.129	34,893	0.134	0.126	0.094	44,024
10	0.179	0.143	0.132	43,610	0.129	0.101	0.097	55,942

DOA uncertainty

- With two microphones we have uncertainty in the angle



- We consider a JxJ matrix U that contains the sign of the uncertainty
- We must optimize this matrix => Genetic Algorithm

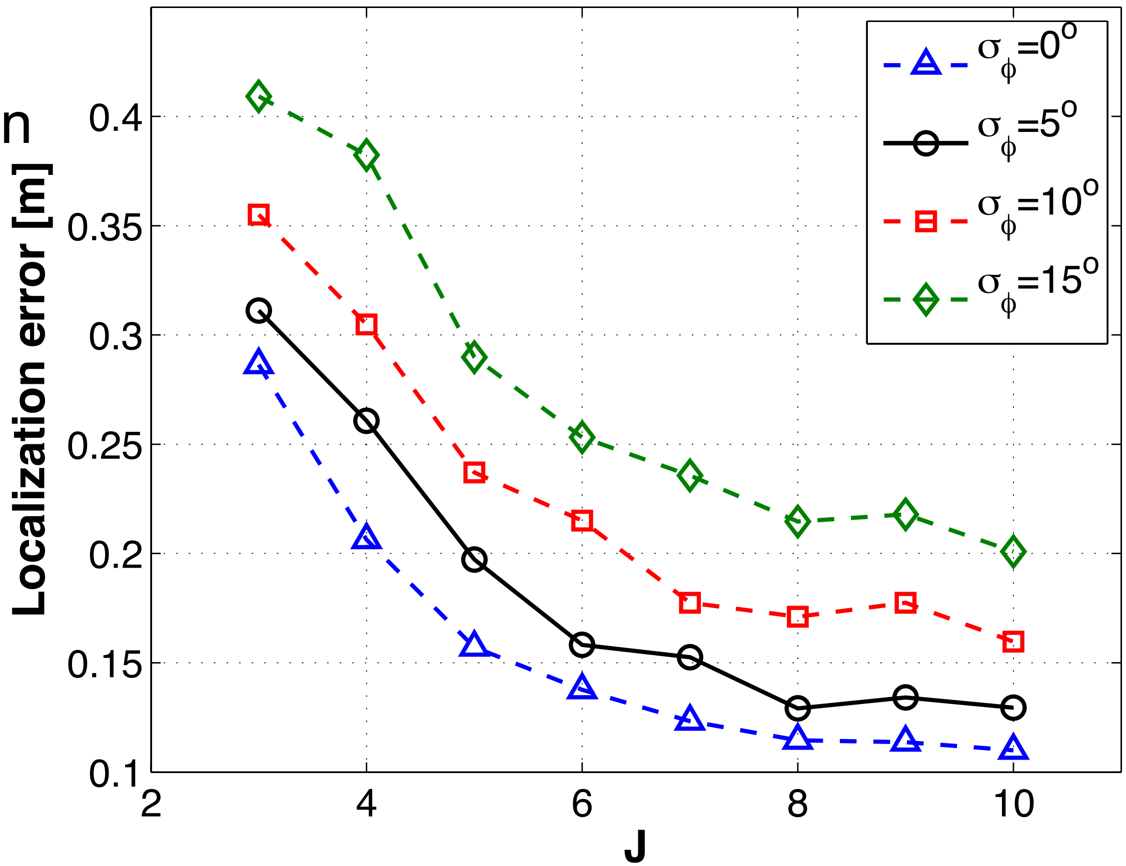
$$L_N(\mathbf{U}) = b - \frac{1}{2}\sum_{j=1}^{J}\sum_{k=1}^{J}(x_j - x_k - v_{jk})^2 + (y_j - y_k - w_{jk})^2$$

$$\max\{L_N(\mathbf{U})\} = b - \frac{1}{2}\left(\sum_{j=1}^{J}\sum_{k=1}^{J} r_{jk}^2\right) + J\left(\sum_{j=1}^{J} x_j^2 + y_j^2\right)$$

Orientation uncertainty

Magnetic compases

- Low precision
- Require calibration
- Not reliable



Orientation uncertainty

- Solution: include the estimation of the orientation

$$u_{jk}\alpha_{jk} + \phi_j - u_{kj}\alpha_{kj} - \phi_k \simeq \begin{cases} \pm\pi, & \text{if } j \neq k \\ 0, & \text{if } j = k. \end{cases}$$

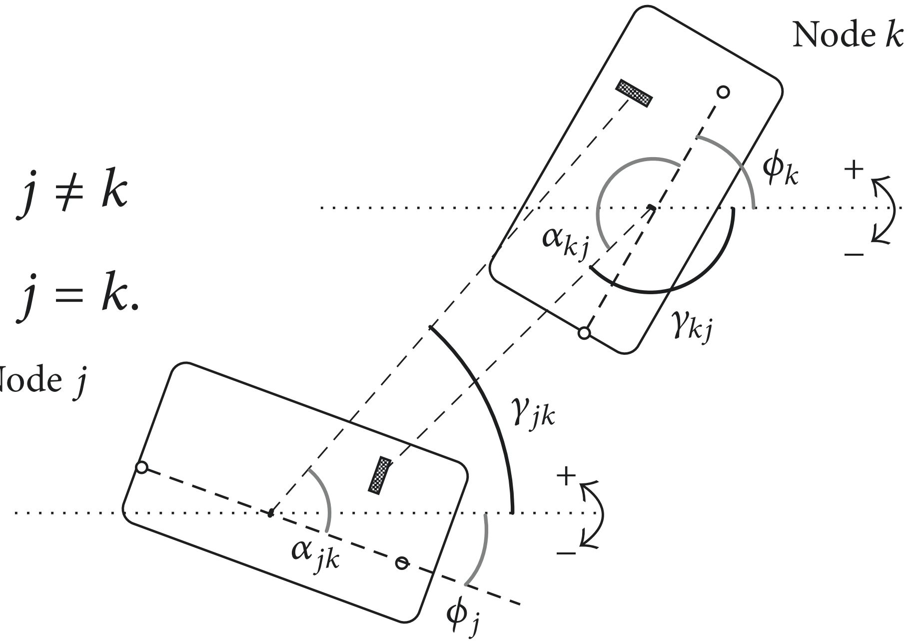


FIGURE 3: Angular relations between node pairs.

Orientation uncertainty

- In complex representation

$$e^{i(\phi_k-\phi_j)} \simeq \begin{cases} e^{i(\mu_{jk}-\mu_{kj}-\pi)}, & \text{if } j \neq k \\ 1, & \text{if } k = j. \end{cases}$$

- We must asume one orientation $\hat{\phi}_1 = 0$

$$e^{i\phi_k} \simeq \begin{cases} e^{i(\mu_{jk}-\mu_{kj}-\mu_{j1}+\mu_{1j})}, & \text{if } j \neq k,\ j \neq 1 \\ e^{i(\mu_{1k}+\mu_{k1}-\pi)}, & \text{if } j = 1,\ k \neq 1 \\ e^{i(\mu_{1k}+\mu_{k1}-\pi)}, & \text{if } j = k,\ k \neq 1 \\ 1, & \text{if } k = 1. \end{cases}$$

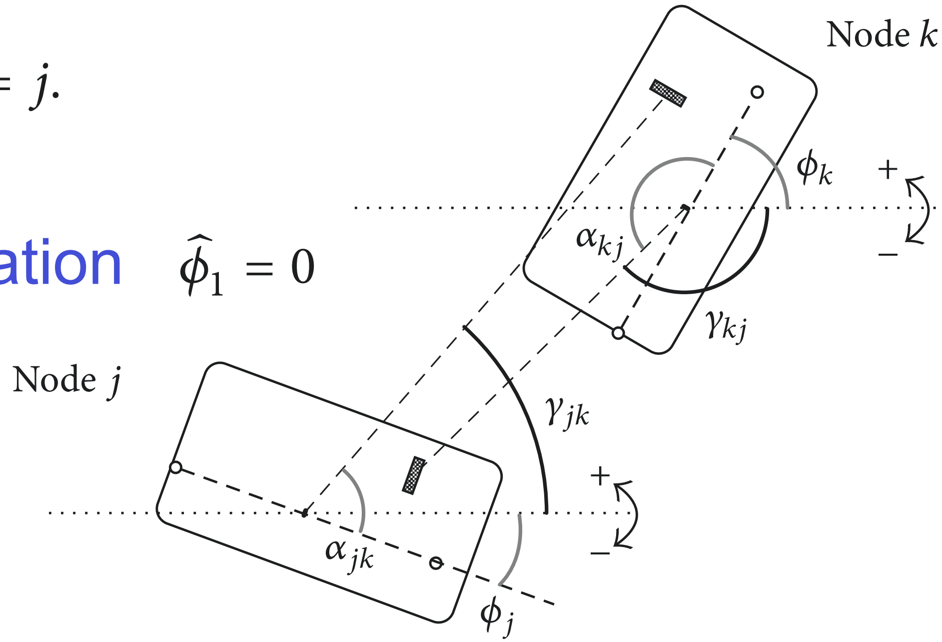


FIGURE 3: Angular relations between node pairs.

Orientation uncertainty

- J estimates of each orientation
  - 70% triggered mean

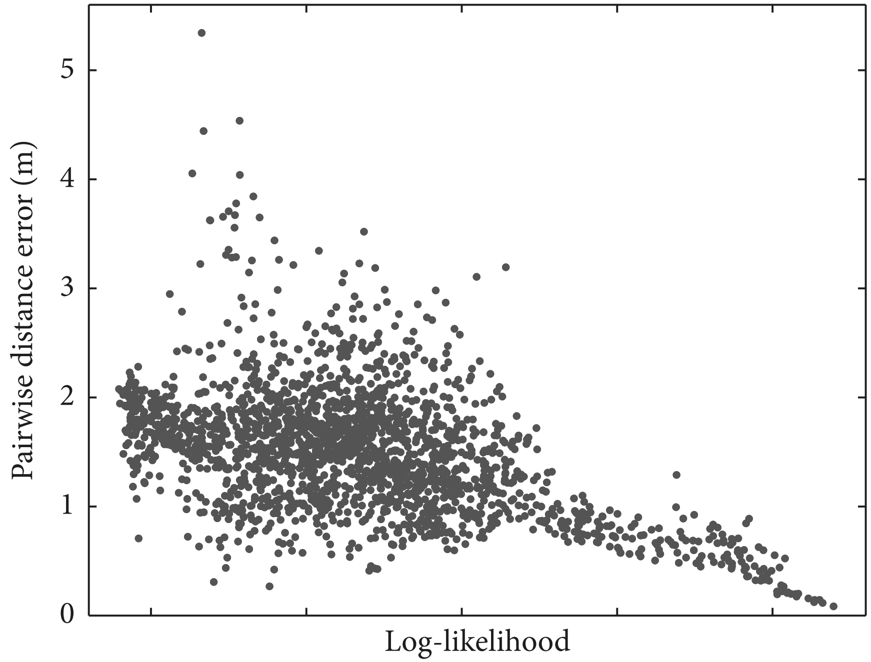


FIGURE 4: Relation between the log-likelihood and the pairwise distance error for all possible values of **U** with $J = 4$.

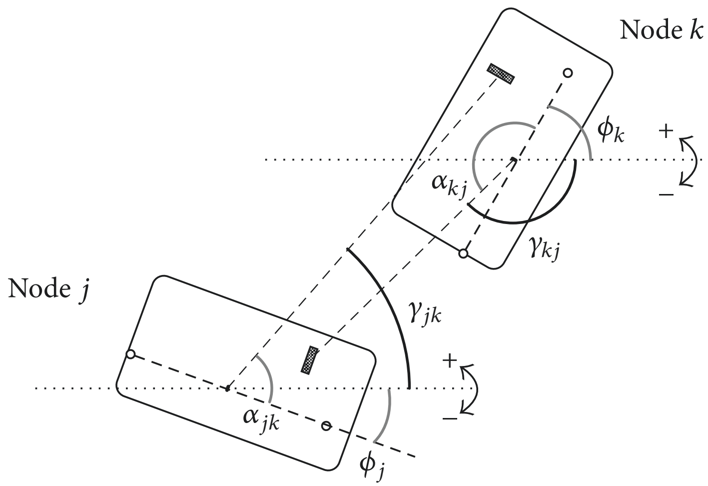


FIGURE 3: Angular relations between node pairs.

Optimization process

- U matrix => Elimination tournament of genetic algorithms
  - Easy to distribute
- Position: NCME solution (analytical)
  - Very fast
- Orientation: 70% triggered mean of J estimations
- Once finish: FCME solution
  - Precise

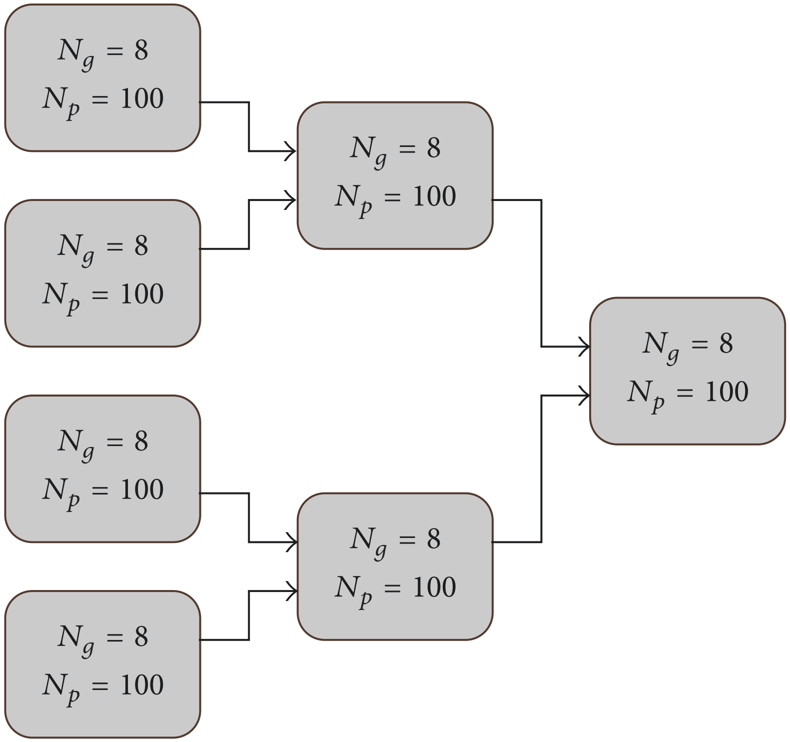


FIGURE 5: Example of elimination tournament with $N_r = 3$ rounds, $N_g = 8$ generations per round, and $N_p = 100$ individuals per stage of the tournament.

Experiments

- Room: from 6x2m to 12x3m, reflex: 0-0.5
- SNR 5-20dB
- 5x2m room table
- Minimum distance between nodes: 15cm
- Transmitted signal: band-limited 9.29ms noise
  - 500Hz-16kHz
- Sampling rate 44.1 kHz
- Number of nodes: from 3 to 10
- 300 scenarios

Results

- Localization (cm)

J	Proposed With uncertainty Mean	Std.	Trim
3	8.3	8.0	7.4
4	8.8	11.5	7.4
5	8.1	8.1	7.2
6	8.0	9.3	6.8
7	8.9	11.7	6.9
8	9.3	14.3	6.7
9	10.0	15.7	6.7
10	10.9	16.6	6.9

Angle (°)

Proposed With uncertainty Mean	Std.	Trim
4.6°	11.2°	2.0°
2.6°	7.0°	1.7°
2.2°	6.2°	1.5°
2.2°	6.3°	1.3°
2.9°	8.6°	1.3°
3.0°	8.6°	1.2°
4.2°	12.3°	1.2°
6.0°	13.4°	1.6°

Results

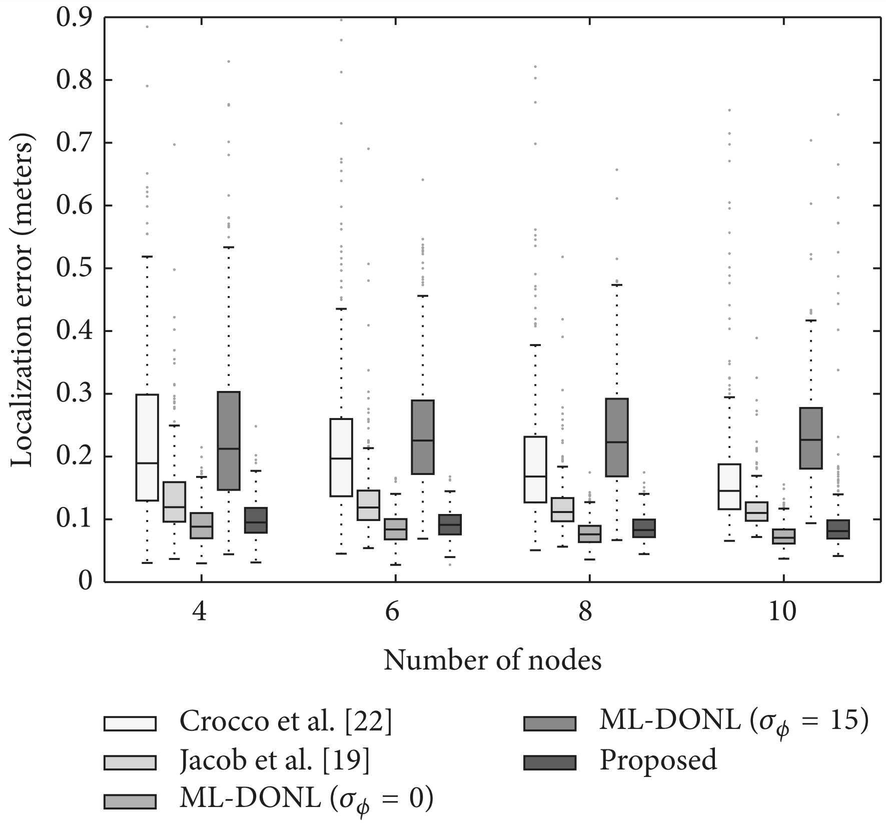
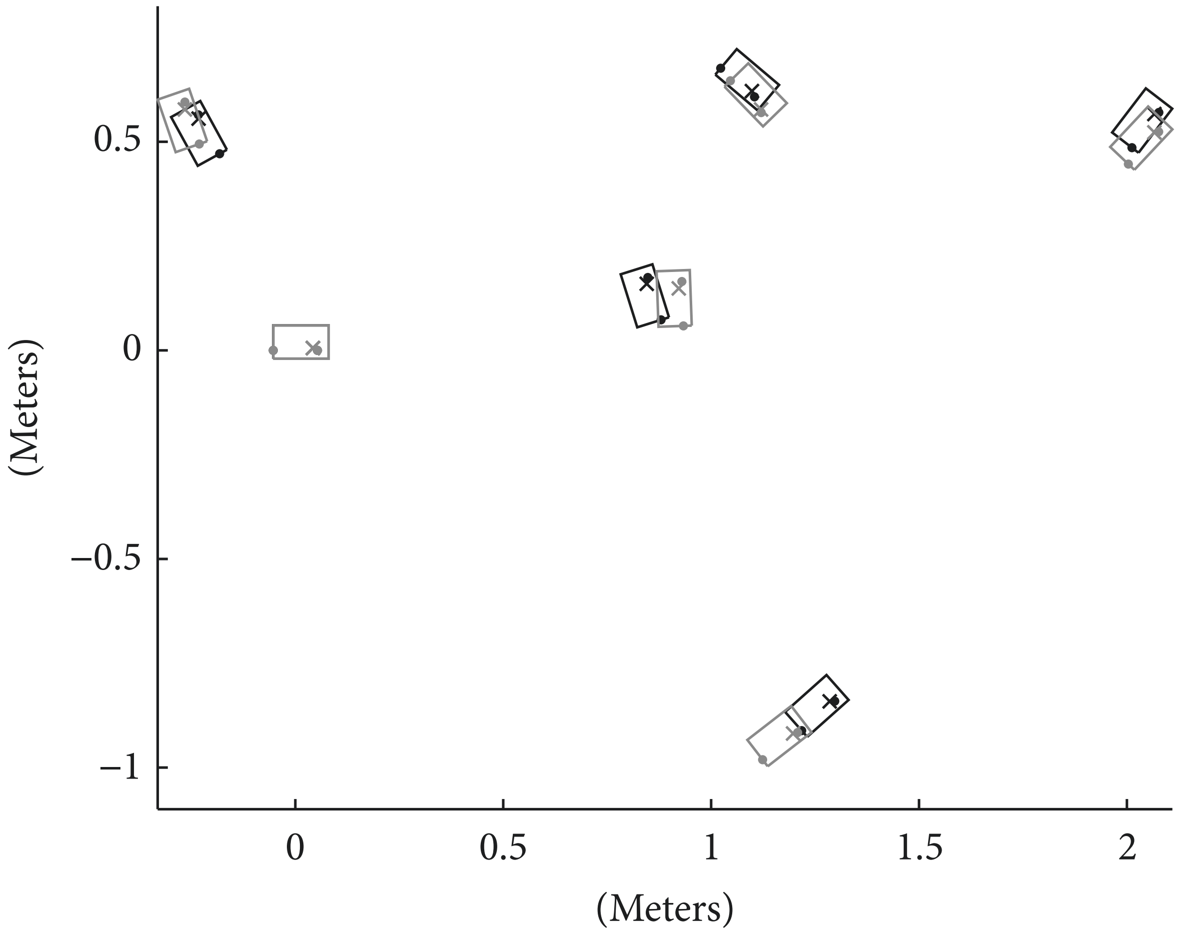


Figure 7: Box plot of the localization results for the tested algorithms with different number of nodes and $\sigma_r = 0.2$.

Results



Conclusions

- Self-localization algorithm for acoustic wireless sensor networks
- No need to synchronize the nodes with a high precision
- 2 microphones per node, errors lower than other methods, even in the case of unknown oritentation

Thank you!

Sound Source Localization

SSPressing-Colist sub-project (TEC2015-67387-C4)

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