EFFICIENT: BackscattEr FabrIC For MultidImensional SpEctrum SituatioNal AwarEness and ProTection

RUTGERS WINLAB | Wireless Information Network Laboratory

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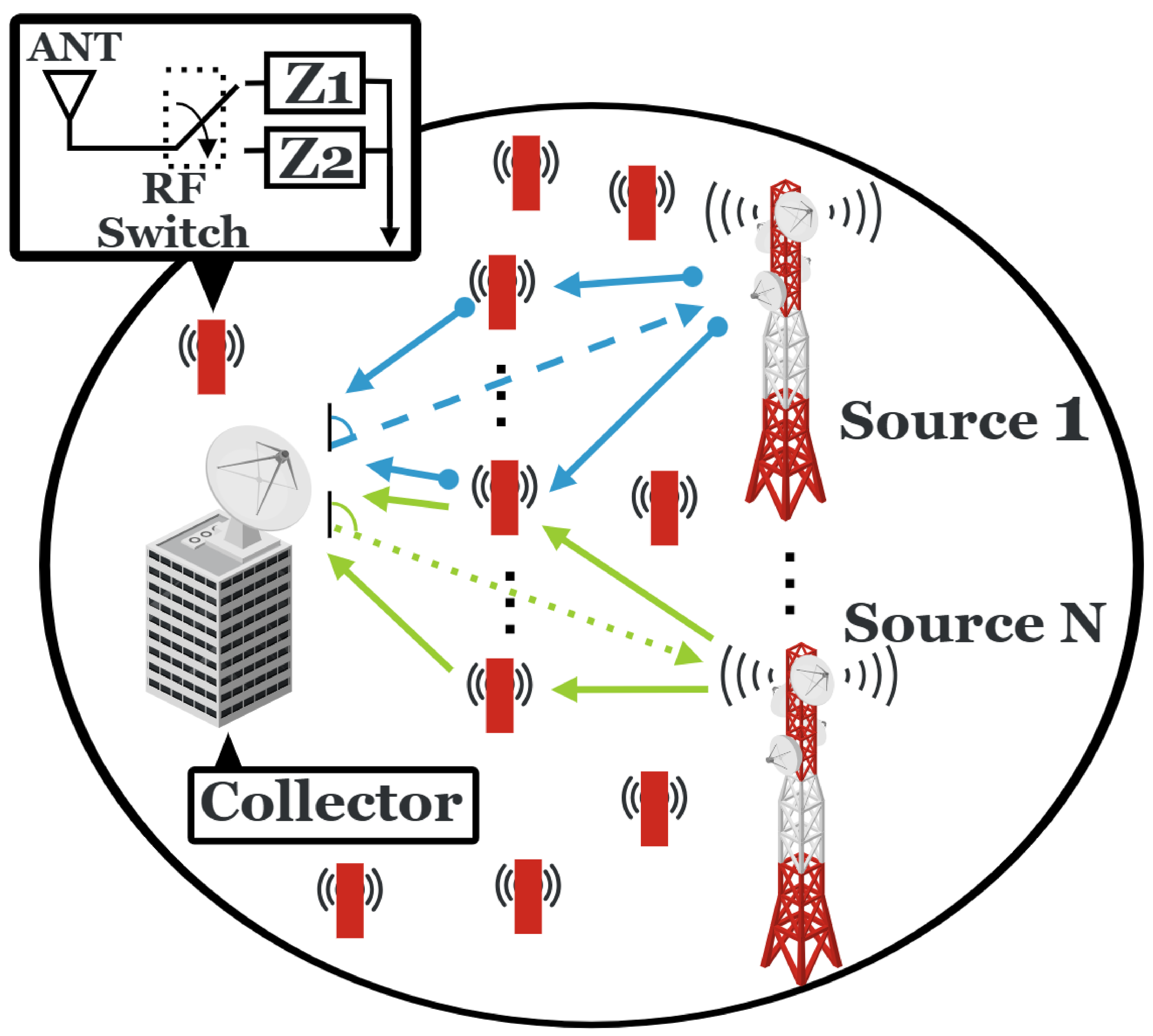
Goal

- Direction of arrival (DoA) estimation using low-cost passive backscatter radio tags and a single antenna receiver



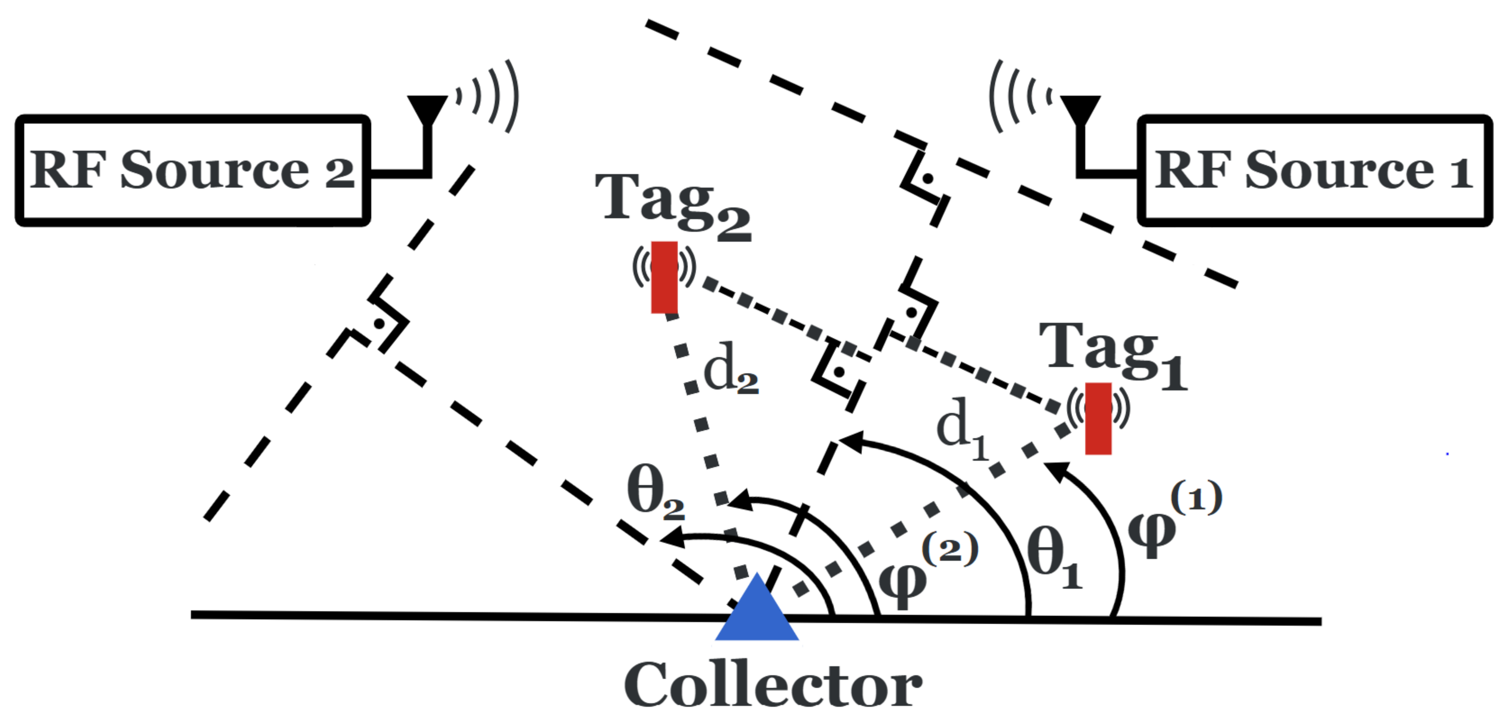
Prior Art – Single Source

- Passive backscatter tags emulate a spatially distributed antenna array
- The source signal is modulated onto different frequency bands
- No CSI or centralized coordination is required

Topologies

- Linear: Inter-element spacing $d_0 = {}^{\lambda}/_{2}$
- Linear-2: ULA with nominal spacing $d_0 = 2\lambda$ perturbed as $\sim \mathcal{N}(\mathrm{x_{tag}}, {}^{d_0}/_{4} I_2)$
- Random-Grid: Regular grid with nominal spacing $d_0 = 12.5\lambda$ perturbed as $\sim \mathcal{N}(\mathrm{x_{tag}}, {}^{d_0}/_{4} I_2)$
- Random: Tag angles and distances from the receiver drawn from $\mathcal{U}(0,\pi)$ and $\mathcal{U}(1{,}20)\ m$, respectively

Generalization – Multiple Sources



- Tag-to-collector delay

$$\tau_m^{(n)} = \tau_R^{(n)} - \Delta\tau_m^{(n)},\ \Delta\tau_m^{(n)} = \frac{d_m \cos\left(\phi^{(m)} - \theta_n\right)}{c}$$

- Complex baseband equivalent signal at the tag

$$\tilde{c}_m(t) = \sum_{n=1}^{N} a_m^{(n)} \mathrm{m}_n\left(t - \tau_m^{(n)}\right)$$

- Tag's switching signal

$$x_{\text{tag}}^{(m)}(t) \approx m_{\text{dc}}^{(m)} e^{j\theta_{\text{dc}}^{(m)}} + m_{\text{tag}}^{(m)} e^{j\theta_{\text{tag}}^{(m)}} \cos\left(2\pi F_{\text{sw}}^{(m)} t + \varphi_m\right)$$

- Tag-reflected signal at the collector

$$y_m(t) = \tilde{c}_m(t)\, x_{\text{tag}}^{(m)}\left(t - \tau_{\text{TR}}^{(m)}\right) s_m\, h_{\text{TR}}^{(m)}\, e^{-j2\pi\Delta F t}$$

- Received signal at the collector

$$y(t) = \sum_{n=1}^{N} a_{\text{CR}}^{(n)} e^{-j\phi_{\text{CR}}^{(n)}} \mathrm{m}_n(t) e^{-j2\pi\Delta F t} + \sum_{m=1}^{M} y_m(t) + n(t).$$

- Correlation-based tag signal extraction

$$r_m^{\pm} = \sum_{k=0}^{L-1} y[k] \left(e^{\pm j2\pi F_{\text{sw}}^{(m)} k T_s}\right)^{*}.$$

  - $F_{\text{sw}}^{(m)} \gg \mathrm{BW}(\mathrm{m}_n(t)),$
  - $\left|F_{\text{sw}}^{(i)} - F_{\text{sw}}^{(j)}\right| \gg \mathrm{BW}(\mathrm{m}_n(t)),\ i \neq j, \quad i,j \in \{1,\ldots,M\}$

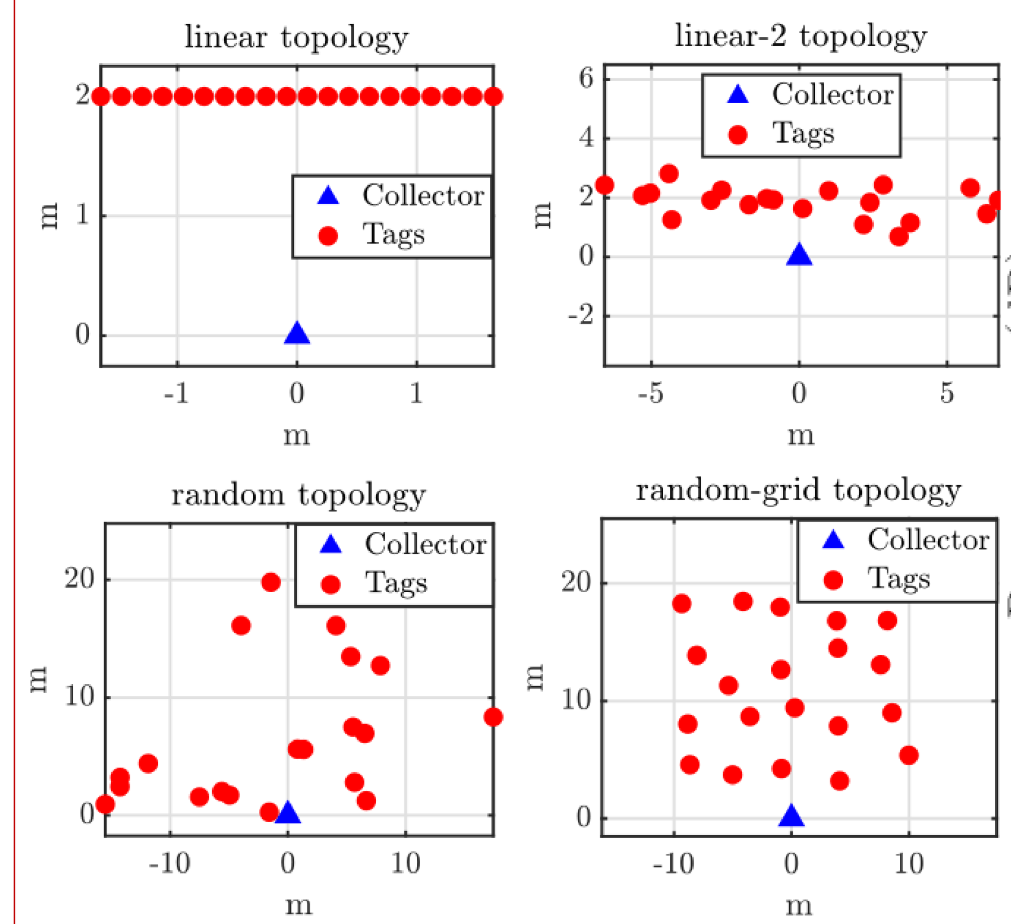
- Statistics from the correlators' outputs

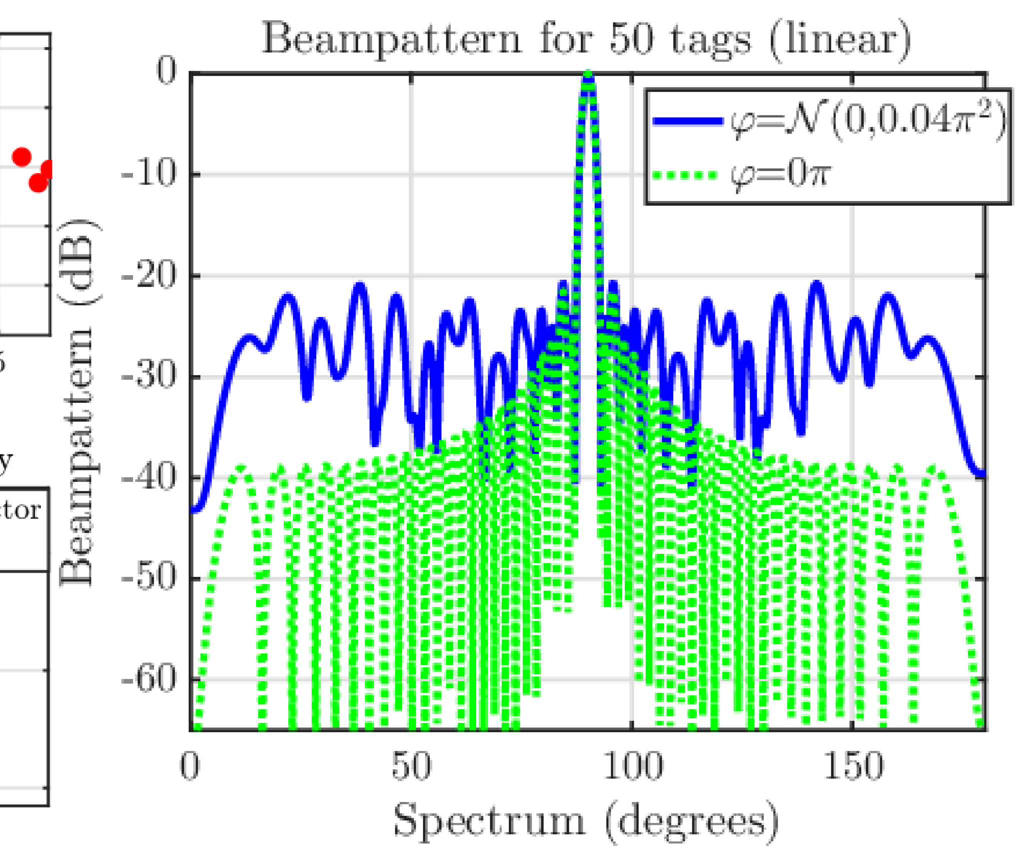
$$\mathbf{r}_q = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_M \end{bmatrix}_q = \sum_{n=1}^{N} \mathbf{h}_p(\theta_n)\mu_{c,n}^{(q)} + \mathbf{n}_q = \mathbf{A}(\boldsymbol{\theta})\,\boldsymbol{\mu} + \mathbf{n}_q,$$

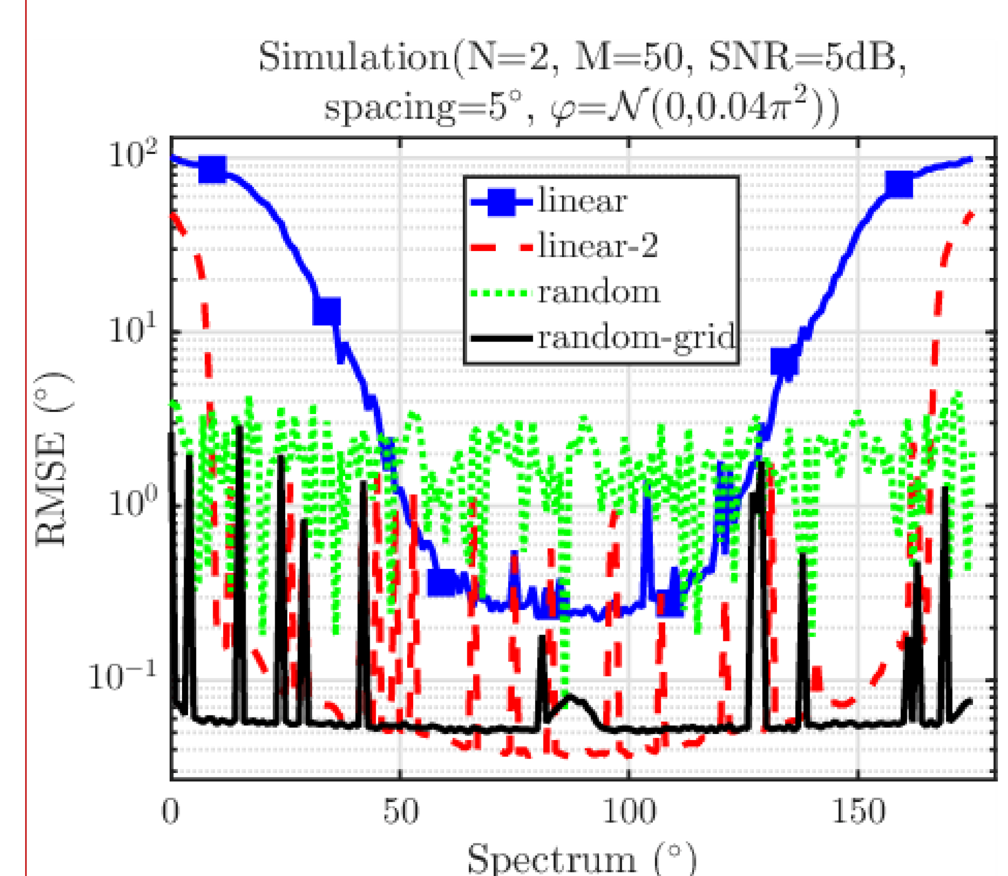
where $\mathbf{A}(\boldsymbol{\theta}) = \left[\mathbf{h}_p(\theta_1),\ \mathbf{h}_p(\theta_2),\ \ldots,\ \mathbf{h}_p(\theta_N)\right]$, $\mathbf{h}_p(\theta) \triangleq (\mathbf{h}(\theta) \odot \mathbf{g})$, $\mathbf{h}(\theta) \triangleq [h_1(\theta),\ldots,h_M(\theta)]^{\mathrm{T}}$, $\mathbf{g} \triangleq [\gamma_1\cos(\Phi_1),\ldots,\gamma_M\cos(\Phi_M)]^{\mathrm{T}}$, $q \in \{0,\ldots,N_s-1\}$, $\boldsymbol{\mu} = \left[\mu_{c,1}^{(q)},\ \mu_{c,2}^{(q)},\ \ldots,\ \mu_{c,N}^{(q)}\right]^{\mathrm{T}}$, $\mathbf{n}_q \sim \mathcal{CN}(0, 2\sigma_n^2 \mathbb{I}_M)$

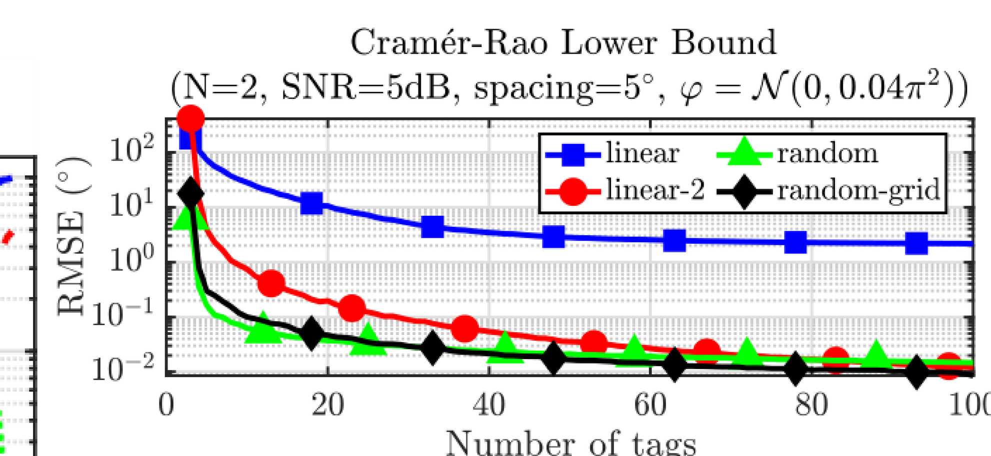
$$h_m(\theta_n) \triangleq e^{j2\pi \frac{d_m \cos\left(\phi^{(m)} - \theta_n\right)}{\lambda}}$$

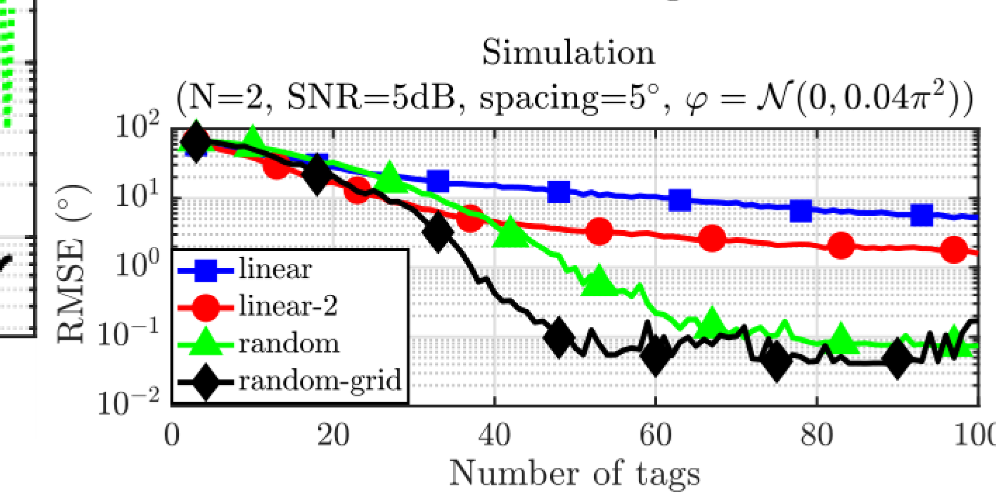
Analytical and Simulation Results











- The synchronization mismatch disrupts the array beampattern
- Tag position randomization eliminates sparse array ambiguities
- The random-grid array offers better coverage than the linear ones
- The random-grid array attains accuracy closer to CRB than the linear arrays

Conclusion

- Extended the single-source method to multiple signal sources
- Tag position randomization improves DoA estimation

Acknowledgments

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