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Single Frequency Surveillance Radar Network using an adapted ℓ_1 Minimization Approach for Extended Targets

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Motivation

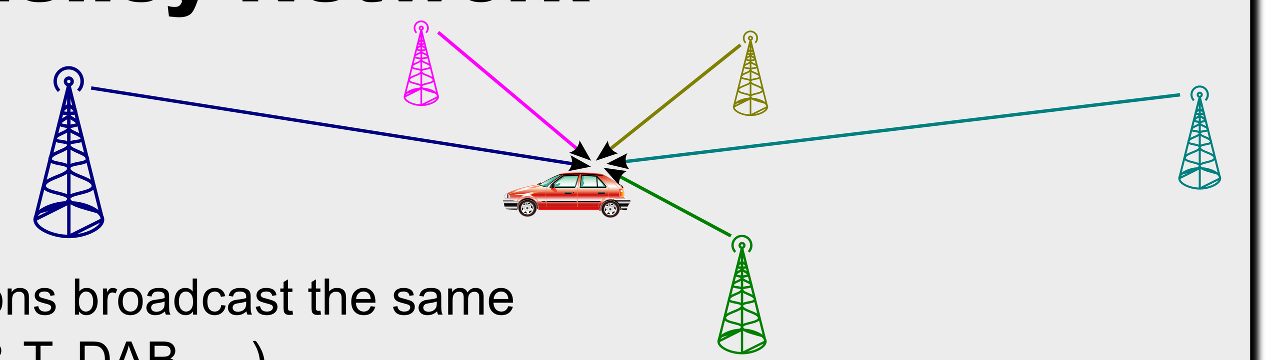
Passive Radar:

- There exists hundreds of electromagnetic source (GSM, TV, FM, WiFi, ...)
  - ⇒ No transmitter ⇒ lower cost of operation and maintenance, smaller size
- Covert operation ⇒ increased electronic protective measures (EPM) capabilities
  - ⇒ No hassle with frequency licence
  - ⇒ Reduced impact on environment and electromagnetic pollution
- Communication signals with spread spectrum modulation techniques are ideal for passive surveillance radars.

Radar Networks:

- Higher spatial and angle resolution
- Improved Doppler processing through diversity of look angles
- Joint estimation enhances target detection, location, recognition, and tracking
- Enhanced processing with multiple targets

Single Frequency Network



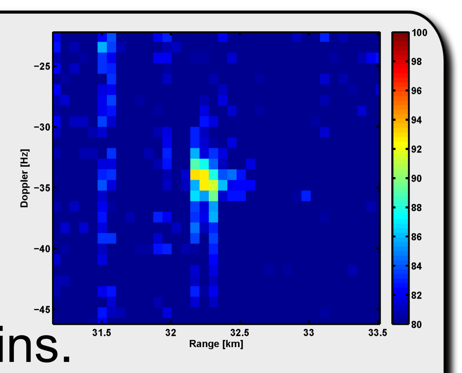
- In a SFN all TX stations broadcast the same signal coherent (DVB-T, DAB, ...).
  - ⇒ Interference-free reconstruction possible if delay of multi-path signals < Guard Interval relative to nearest transmitter
  - ⇒ Received signal is a composition of static direct and multipath signals, echos from moving targets, and noise

$$y(t) = \sum_{m=1}^{M} \alpha_{m0}\, x(t-\tau_{m0}) + \sum_{m=1}^{M}\sum_{k=1}^{K} \alpha_{mk}\, x(t-\tau_{mk})\, e^{-j2\pi(f_{D_{mk}}+f_c)\tau_{mk}} + n(t)$$

$$\tau_{mk} = \frac{\|\mathbf{p_k}-\mathbf{p_{tm}}\| + \|\mathbf{p_r}-\mathbf{p_k}\|}{c} \qquad f_{D_{mk}} = \frac{f_c}{c_0}\left(\mathbf{v}_k\cdot\mathbf{u}_{k_{tm}} + \mathbf{v}_k\cdot\mathbf{u}_{k_r}\right)$$

$\mathbf{p}_{tm,r,k}$: the position vector, $\mathbf{v}_k$: the velocity vector of target p, and
$\mathbf{u}_{k_{tm},r}$: the direction vector pointing from target k to TX_m or RX, respectively.velocity vector of target p, and

Extended Target



- In real scenarios targets are **no** point scatterers.
- Complex Objects are composed of multiple scattering centers distributed over their surface.
  - ⇒ target echo outstretches over several range/Doppler-bins.
  - ⇒ Especially for high-resolution radars!
- Further spreading due to long integration time to achieve high SNR.
- Solution: cluster database which contains a link between connected detections and their related range/Doppler-bins
- Assumption: echoes from two targets do not commingle in the range/Doppler

$\tilde{y}$ holds all connected *range/Doppler-bins* of an extended target

$$\boldsymbol{y} = \sum_{l=1}^{L} \tilde{\boldsymbol{y}}_l$$

For the optimal case $L = mK$. Real scenarios: $L < mK$ due to shadowing effects and Doppler zero constellations.

Sensor Fusion

- Target echo for a given range/Doppler-bin depend on: $s_k = [x, y, v_x, v_y]^T$
- Due to extended targets and imprecise measurements response is best specified by a probability function.
- Assuming a Gaussian distribution the multivariate distribution function is:

$$f(s_k) = \frac{1}{\sqrt{(2\,\pi)^4\,|\Sigma|}} \exp\left(-\frac{(s_k-\mu)^T}{2}\,\Sigma^{-1}(s_k-\mu)\right)$$

with $|\Sigma|$ the determinate of the covariance matrix Σ

- Assumption: estimated precisions for position and Doppler are independent.
- Then accuracy of targets location can be determined in general by solving the linear equation set ⇒ linearisation around the actual target position

$$\boldsymbol{\delta}_{mk} = \begin{bmatrix}\delta_{px}\\ \delta_{py}\end{bmatrix} \quad \boldsymbol{\delta}_x = \begin{bmatrix}\delta_x\\ \delta_y\end{bmatrix} \qquad \boldsymbol{\delta}_{mk} = \boldsymbol{H}\,\boldsymbol{\delta}_x \qquad \boldsymbol{\delta}_x = \boldsymbol{H}^{-1}\,\boldsymbol{\delta}_{mk}\,,$$

$$\boldsymbol{\Sigma}(\delta_x) = \begin{bmatrix}\delta_{px} & 0\\ 0 & \delta_{py}\end{bmatrix} = \begin{bmatrix}\sigma^2_{UERE} & 0\\ 0 & \sigma^2_{UERE}\end{bmatrix} = \boldsymbol{I}_{2\times 2}\,\sigma^2_{UERE}$$

$$\boldsymbol{\Sigma}(\delta_x) = E\{\boldsymbol{\delta}_x\,\boldsymbol{\delta}_x^T\} = E\{\boldsymbol{H}^{-1}\,\boldsymbol{\delta}_{mk}\,\boldsymbol{\delta}_{mk}^T\,\boldsymbol{H}^{T^{-1}}\} = \boldsymbol{H}^{-1}\,\boldsymbol{\Sigma}(\boldsymbol{\delta}_{mk})\,\boldsymbol{H}^{T^{-1}} = \left(\boldsymbol{H}^T\,\boldsymbol{H}\right)^{-1}\sigma^2_{UERE}$$

Group Sparsity

For a SFN network consisting of several transmitters (Tx: *1, ..., m*) and one receiver received signal can be expressed by:

$$y = \sum_{l=1}^{L} \tilde{y}_l = \sum_{m=1}^{M} A_m\, s_m$$

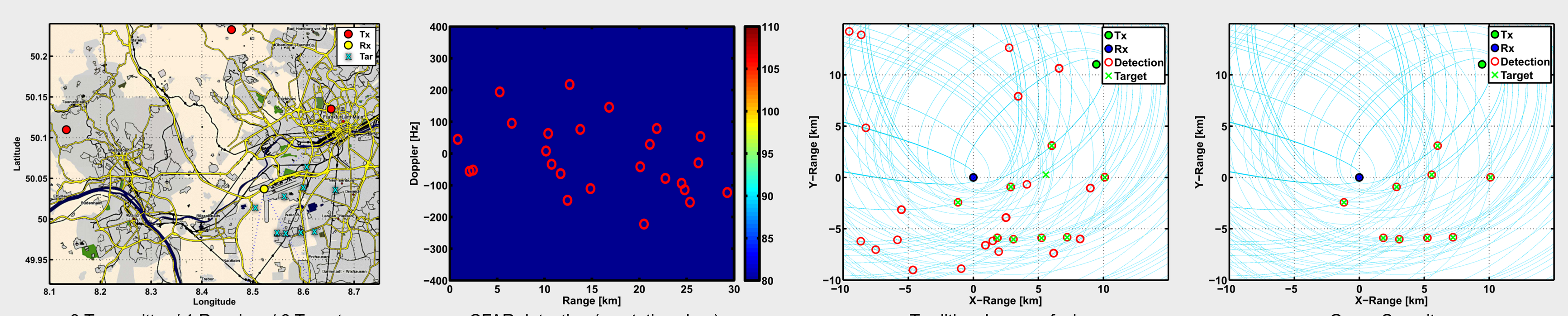
with $\tilde{\boldsymbol{y}}_l$: cluster database, $\boldsymbol{A}_m$: sensing matrix and the target state vektor $\boldsymbol{s}_m$ = $[\boldsymbol{s}_{m1}, ..., \boldsymbol{s}_{mP}]^T$ affiliated to the *m*-th transmitter.

Over all transmit-receive combinations we can form groups α_i consisting of identical target states: $\alpha_1 = [s_1(1), s_2(1), s_3(1)] \quad \alpha_2 = [s_1(2), s_2(2), s_3(2)], \quad \ldots$
Estimation of the target state vector $\boldsymbol{s}$ is performed by an enhanced Basis Pursuit Denoising (BPDN) algorithm which takes into account the interlaced groups, the clustering, and the probabilistic accuracy:

$$\min \sum_i \|s_{\alpha_i}\|_2 \quad \text{subject to} \quad \left\|\sum_{m=1}^{M} A_m\, s_m - y\right\|_2 \le \epsilon$$

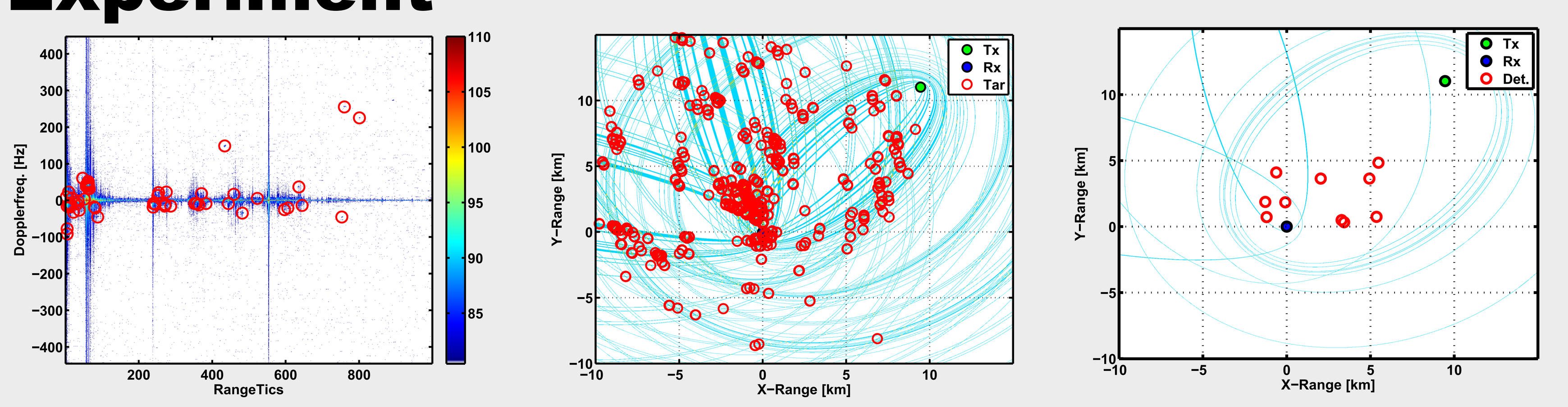
ε is a threshold parameter determined by the present noise.

Simulation



3 Transmitter / 1 Receiver / 6 Targets — CFAR detection (no static echos) — Traditional sensor fusion — Group Sparsity

Experiment



CFAR detection (no static echos) — Traditional sensor fusion — Group Sparsity

Conclusion

SFN surveillance radar network with 3 DVB-T stations and 1 receiver
⇒ OFDM: signal bandwidth independent of information content.
⇒ Reference signal generated from surveillance channel
Real targets with low RCS compete with strong direct and static clutter signals:
⇒ High dynamic range receiver with high IP3!
⇒ High signal processing gain (integration time)!
⇒ Real targets provoke smeared echoes over several Range/Doppler cells!
⇒ Extended CS algorithm with cluster database and enhanced probability description.

Outlook

Enhance robustness of CS
⇒ Timing/detection error (not aligned on the correct range tics!)
Improve processing speed of extended CS group estimation.
Implement two modes: surveillance (low range resolution) and tracking (only local high range resolution)
Extend CS so neighbouring DVB-T channels are taking into account ⇒ increased range resolution