Non-Regenerative Relaying for Network Localization

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Research Overview

1. **Topic**: Enhanced Localization Coverage using UWB non-regenerative relaying techniques.
2. **Research Motivation.**
   - Adoption of UWB technology
     $\rightarrow$ high localization accuracy
   - Harsh propagation environments and UWB power emission constraints
     $\rightarrow$ poor localization coverage
3. **Proposal.** The idea is to add low complexity non-regenerative UWB relays to improve the performance in terms of coverage and accuracy.

Problems & Solutions: Exploring the Technology

- Challenges:
  - How to provide reliable and **high-accuracy** localization while maintaining **low power consumption** and **costs**?
  - How to extend the area coverage for localization in **harsh propagation environments** and in NLOS conditions?
- Proposed Solutions:
  - **UWB** technology: high-accuracy ranging, low power consumption, robustness to multipath, low detection probability, coexistence capability with spectrum sharing.
  - Non-regenerative **Relaying** techniques
    - ⋆ Other Solutions:
      - increasing anchors's number → high infrastructure cost
      - cooperation between tags → high complexity tags
      - virtual anchors based on reflections → e.m. knowledge needed

Non-regenerative UWB Relay for Localization

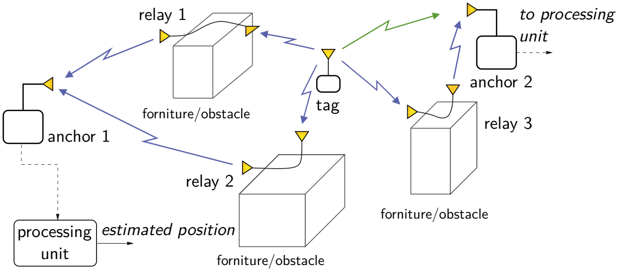
Main Idea

Non-regenerative relay-based system is here considered localization-oriented (not communication-oriented).

- Regenerative vs Non-Regenerative Relays
  - Regenerative Relays: Decode & Forward Technique
    - regeneration of the signal by fully decoding and re-encoding the signals prior the retransmission
    - similar complexity of anchors
    - depends on signal format
- Non-Regenerative Relays: Amplify & Forward and Just Forward Technique
  - JF (Just Forward): Fully passive $\rightarrow$ no power supply required
  - AF (Amplify & Forward): Amplifier needed $\rightarrow$ but no signal regeneration
  - Low cost, Deployment flexibility, No tight synchronization issues

Localization Scenario Employing Non-regenerative UWB Relay

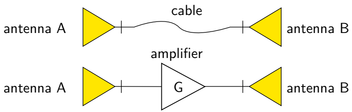
Network localization is typically based on an infrastructure including tags attached to objects (*agents*) and reference nodes (*anchors*) placed in known position.



$\mathbf{p}_m^{(A)}$ $m = 1 \dots N_A$ synchronized anchors

$\mathbf{p}_l^{(R)}$ $l = 1 \dots N_R$ relays

$\mathbf{p}$ tag position



Signalling with non-regenerative UWB relay

- Signal Received at *m*th anchor

$$r_m(t) = s_m(t) + \sum_{l=0}^{N_R} n_{m,l}(t)$$

- Useful Component

$$s_m(t) = \sum_{l=0}^{N_R} a_{l,m} g_{l,m}(t - \tau_{l,m})$$

where

$$a_{l,m} = \begin{cases} \sqrt{E_{\mathrm{T}}}\, \omega(\mathbf{p}, \mathbf{p}_m^{(\mathrm{A})}) & l = 0\,, \\ \sqrt{E_{\mathrm{T}}}\, \omega(\mathbf{p}, \mathbf{p}_l^{(\mathrm{R})})\, \sqrt{G_l}\, \omega(\mathbf{p}_l^{(\mathrm{R})}, \mathbf{p}_m^{(\mathrm{A})}) & l = 1, 2, \ldots, N_R \end{cases}$$

$$\tau_{l,m} = \begin{cases} \tau(\mathbf{p}, \mathbf{p}_m^{(\mathrm{A})}) + t_0 & l = 0\,, \\ \tau(\mathbf{p}, \mathbf{p}_l^{(\mathrm{R})}) + \delta_l + \tau(\mathbf{p}_l^{(\mathrm{R})}, \mathbf{p}_m^{(\mathrm{A})}) + t_0 & l = 1, 2, \ldots, N_R \end{cases}$$

Background on Network Localization

2-Step Localization Process

Received signal measurements (ex. TOA / TDOA / AOA) + Localization Algorithm (ex. LS, ML etc.)

1-Step (Direct) Localization Process

The position is directly inferred from the signal (ex. direct ML)

Direct ML position estimator

- ML estimator with perfect CSI
  - perfect CSI: perfect knowledge of $g_{l,m}(t)$ and $\omega(\cdot,\cdot)$.
- ML estimator with partial CSI
  - unknown amplitudes of the received signal replicas $\rightarrow$ TOA-based with known signal (estimator B1)
  - unknown NCRs $g_{l,m}(t)$ with known amplitudes $\rightarrow$ joint RSSI-TOA based ML estimator with unknown signal (estimator B2)
  - blind estimator (unknown NCRs $g_{l,m}(t)$ and unknown amplitudes) $\rightarrow$ TOA based with unknown signal (estimator B3)

ML Estimator with Perfect CSI (Estimator A)

ML tag's position estimator

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p}, t_0) \in (\mathcal{P}, \mathcal{T})}{\operatorname{argmax}} \; l(\mathbf{p}, t_0)$$

where

$$l(\mathbf{p}, t_0) = \sum_{m=1}^{N_A} \left\{ \frac{2}{N_m} \left[\sum_{l=0}^{N_R} a_{l,m} \, \chi_{l,m} \left(\tau_{l,m} \right) \right] - \frac{E_m}{N_m} \right\}$$

with the correlation term

$$\chi_{l,m}(\xi) \triangleq \int_{T_{\text{ob}}} r_m(t) \, g_{l,m}(t - \xi) \, dt$$

- correlation term $\rightarrow$ implementation via a bank of filters matched to $g_{l,m}(t)$
- alternatively: a bank of filters matched to $s(t)$

TOA-based with known signal (Estimator B1)

Received signal in vector notation

$$\mathbf{r}^{(m)} = \mathbf{s}^{(m)} + \mathbf{n}^{(m)} = \mathbf{W}_m \, \mathbf{a}^{(m)} + \mathbf{n}^{(m)}$$

the vector $\mathbf{a}^{(m)}$ unknown deterministic $\rightarrow$ substitute with its ML estimate $\hat{\mathbf{a}}^{(m)}$

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p}, t_0) \in (\mathcal{P}, \mathcal{T})}{\operatorname{argmax}} \; \ell \left(\mathbf{p}, t_0; \{\mathbf{a}^{(m)}\} = \{\hat{\mathbf{a}}^{(m)}\} \right)$$

Non overlapped Assumption

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p}, t_0) \in (\mathcal{P}, \mathcal{T})}{\operatorname{argmax}} \left\{ \sum_{m=1}^{N_\mathrm{A}} \frac{1}{N_m} \sum_{l=0}^{N_\mathrm{R}} \frac{1}{E_{l,m}} \chi^2_{l,m}(\tau_{l,m}) \right\}$$

Joint RSSI-TOA-based with unknown signal (Estimator B2)

Received signal in vector notation

$$\mathbf{r}^{(m)} = \mathbf{H}_m \, \mathbf{g} + \mathbf{n}^{(m)}$$

$\mathbf{g}$ is unknown (non-coherent position estimator) $\rightarrow$ substitute $\mathbf{g}$ with its ML estimate $\hat{\mathbf{g}}$

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p}, t_0) \in (\mathcal{P}, \mathcal{T})}{\operatorname{argmax}} \; \ell \left(\mathbf{p}, t_0; \{\mathbf{g}\} = \{\hat{\mathbf{g}}\} \right).$$

Non overlapped Assumption

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p}, t_0) \in (\mathcal{P}, \mathcal{T})}{\operatorname{argmax}} \left\{ \sum_{m=1}^{N_\mathrm{A}} \frac{2E_m}{N_m} \left(\sqrt{\frac{1}{E_m} \int_{\mathcal{D}^{(m)}} r_m^2(t) \, dt} - \frac{1}{2} \right) \right\}$$

- very simple implementation $\rightarrow$ energy measurements in particular time intervals.

TOA-based with unknown signal (Estimator B3)

Received signal in vector notation

$$\mathbf{r}^{(m)} = \mathbf{s}^{(m)} + \mathbf{n}^{(m)}$$

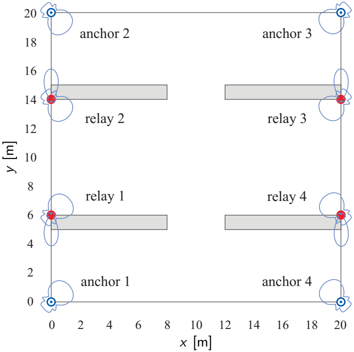
$\mathbf{s}^{(m)}$ is unknown (non-coherent position estimator) $\rightarrow$ substitute $\mathbf{s}^{(m)}$ with its ML estimate $\hat{\mathbf{s}}^{(m)}$

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p},t_0)\in(\mathcal{P},\mathcal{T})}{\operatorname{argmax}} \ \ell\left(\mathbf{p}, t_0; \{\mathbf{s}^{(m)}\} = \{\hat{\mathbf{s}}^{(m)}\}\right)$$

Continuous Time Version

$$(\hat{\mathbf{p}}, \hat{t}_0) = \underset{(\mathbf{p},t_0)\in(\mathcal{P},\mathcal{T})}{\operatorname{argmax}} \left\{ \sum_{m=1}^{N_\mathrm{A}} \frac{1}{N_m} \int_{\mathcal{D}^{(m)}} r_m^2(t)\, dt \right\} . \tag{1}$$

Case Study: Scenario and Performance Metrics



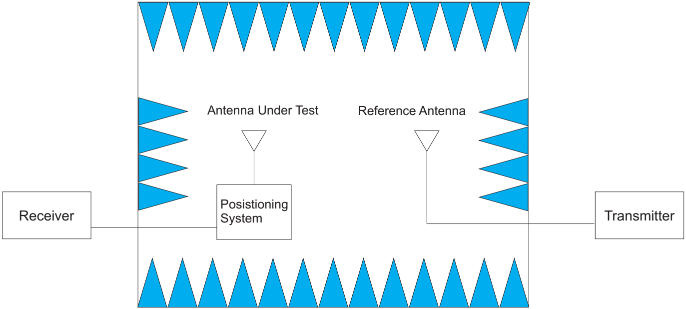
$$e_{n,m} = \|\hat{\mathbf{p}}_{n,m} - \mathbf{p}_n\|$$

$$\mathrm{CDF}(e_{\mathrm{th}}) = \frac{1}{N_{\mathrm{p}} M_{\mathrm{c}}} \sum_{n=1}^{N_{\mathrm{p}}} \sum_{m=1}^{M_{\mathrm{c}}} \mathbf{1}(e_{\mathrm{th}} - e_{n,m})$$

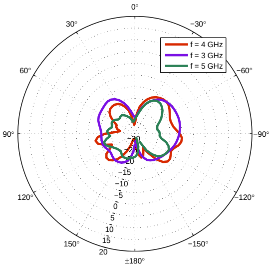
$$e_{\mathrm{RMS}}\left(\mathbf{p}_n\right) = \sqrt{\frac{1}{M_{\mathrm{c}}} \sum_{m=1}^{M_{\mathrm{c}}} e_{n,m}^2} \,.$$

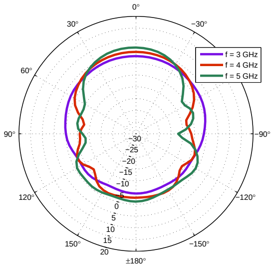
Antenna Characterization in Anechoic Chamber.

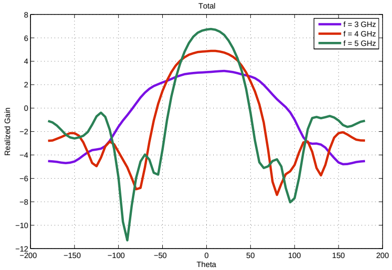
- Main goal of the measurement process
  - measurement of the radiation pattern and of the gain of the antenna under test
  - association of each UWB measured antenna with a specific role in the localization contest
- The measurement process takes place in an anechoic chamber which stops reflections thanks to the radiation absorbent materials of which it is made up.



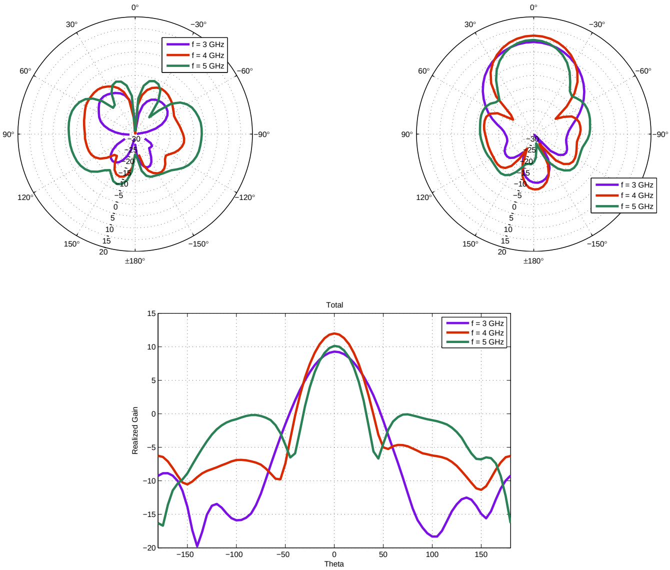
Anchors's and Relays to Tag Antenna Characterization. (Vivaldi)







Relays to Anchors's Antenna Characterization. (4-Patch)



Simulation Parameters

Parameters	Symbol	Value
RRC pulses		
Central Frequency	f_0	4 GHz
Pulse Width Parameter	τ	1 ns
Roll-off Factor	η	0.6
Ranging Packet		
Processing Gain	N_s	512
Pulse Repetition Period	T_f	120 ns
UWB Antenna		
Anchors's Antenna Gain	G_A	5 dBi
Anchors's Antenna HPBW		101°
Relays's Antenna to Anchor Gain	G_R	12 dBi
Relays's Antenna to Anchor HPBW		45°

Numerical Results (1/3)

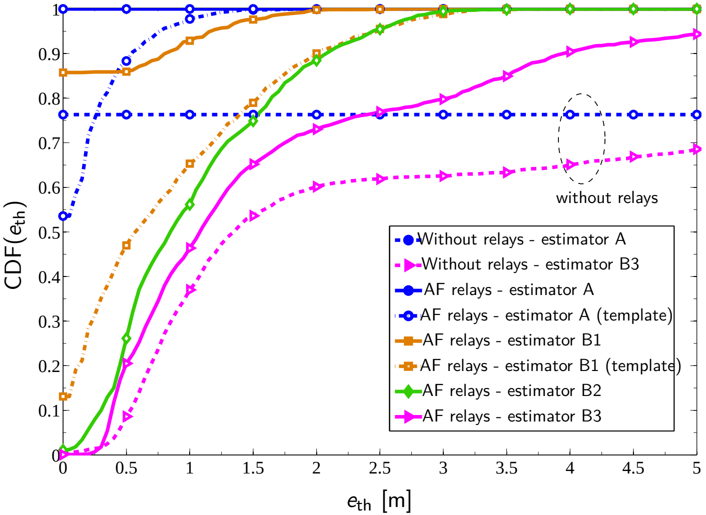


Figure: Estimated CDF using the TDL channel model for AF relays with $G = 10\,\text{dB}$.

Numerical Results (2/3)

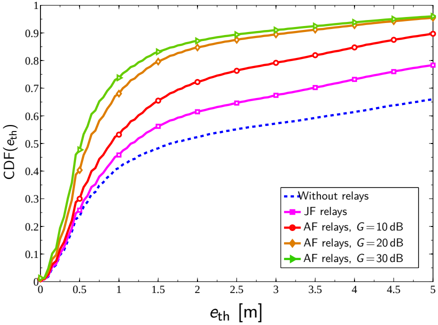


Figure: Estimated CDF for the IEEE 802.15.4a CM7 for different relays gain.

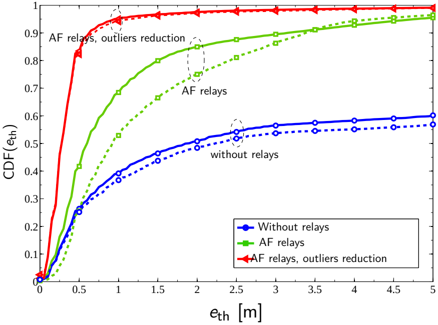


Figure: Estimated CDF for the IEEE 802.15.4a CM7 (continuous lines) and CM3 (dashed lines) for AF relays with $G = 20\,$dB.

Numerical Results (3/3)

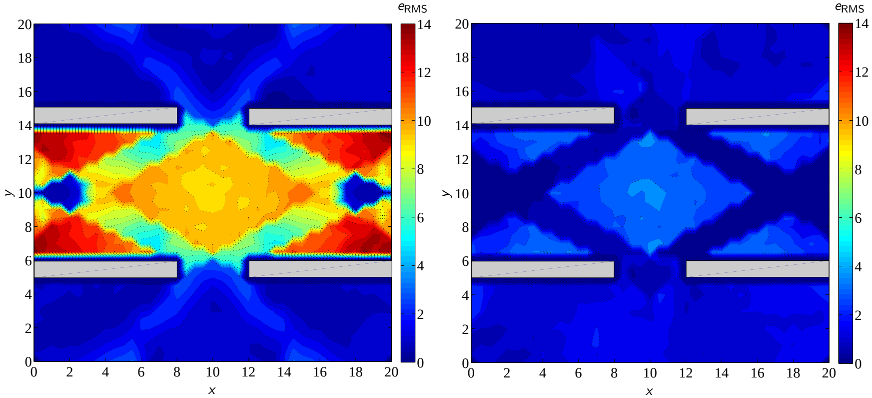


Figure: RMSE contour map in the 2D environment for the IEEE 802.15.4a CM7.

Conclusions

- Non-regenerative relaying $\rightarrow$ low complexity approach to increase the service coverage in localization systems operating in severe NLOS propagation conditions;
- Increment of the number of received signal components improving the localization capability in shadowed areas thanks to the adoption of UWB JF or AF relays;
- Derivation of different ML position estimators, accounting for the knowledge of relays' position and complete or partial CSI;
- Performance improvement using simple passive JF relays, with respect the absence of relays;
- Reduction of the number of anchors $\rightarrow$ reduction of the network infrastructure cost and complexity.

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Thank you for your attention

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