Software-Defined Radio System for Tracking Application

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Background

Proposed solution

Used signal processing

Simulation in GNU Radio

Measurement Results

Conclusion and Outlooks
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STC group in charge of telemetry and bi-directional links with flying projectiles
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Work developed within a PhD funded by ISL, supervised by ISL and XLIM

XLIM: A multidisciplinary Research Institute located on several geographical sites, mainly in Limoges but also in Poitiers
Background

Many Software Defined Radio (SDR) tracking applications in research focus on tracking mobile phones, vehicles, satellites, etc [1-2] with various difficulties to overcome (indoor localization, multi-path).

[1]: V. Nambiar et al., "SDR based indoor localization using ambient WiFi and GSM signals," 2017 ICNC.
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Many Software Defined Radio (SDR) tracking applications in research focus on tracking mobile phones, vehicles, satellites, etc [1-2] with various difficulties to overcome (indoor localization, multi-path).

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Our project:

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Our project:

**develop a passive high-speed projectile tracking system based on commercial SDR and antenna arrays**

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Proposed solution
Proposed solution

Steered antenna array electronically follows projectile (no mechanical displacement)
Proposed solution

Steered antenna array electronically follows projectile (no mechanical displacement)

Direction of the projectile computed from received signals (DOA)
Steered antenna array electronically follows projectile (no mechanical displacement)

Direction of the projectile computed from received signals (DOA)

Array main lobe steered towards estimated direction of the transmitter
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Used signal processing

Equi-phase wavefront

Transmitter
Used signal processing

Equi-phase wavefront

Transmitted signal:

$$s_{TX} = e^{j\omega t}$$
Used signal processing

Transmitted signal:

\[ s_{TX} = e^{j\omega t} \]

Received signals:

\[ s_1 = e^{j(\omega t + \varphi_1)} \]
\[ s_2 = e^{j(\omega t + \varphi_2)} \]
\[ s_3 = e^{j(\omega t + \varphi_3)} \]
Used signal processing

By influencing on the phase shifts between signals:

favor constructive interference for chosen particular $\theta$ (DOA).
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focus reception/transmission energy in wanted direction while limiting it in others
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By influencing on the phase shifts between signals:

- favor constructive interference for chosen particular $\theta$ (DOA).
- focus reception/transmission energy in wanted direction while limiting it in others

For a Uniform Linear Array (ULA), phase shifts between adjoining elements $\varphi$:

$$\varphi = \frac{2\pi}{\lambda} d \sin \theta$$

$\lambda$: wavelength
$d$: inter-element spacing
Used signal processing

Equi-phase wavefront

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\[ s_3 = e^{j(\omega t + \varphi_3)} \]

\( \varphi_1, \varphi_2 \) and \( \varphi_3 \) are used to estimate \( \theta \) (DOA)
Used signal processing

DOA computed using conventional beamformer algorithm (Bartlett)

- Only one transmitting source
Used signal processing

The DOA is computed using the conventional beamformer algorithm (Bartlett)

- Only one transmitting source
- Easy and fast to implement
Used signal processing

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- Less computationally demanding than MUSIC
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\[
\begin{align*}
S &= \begin{pmatrix} S_1 \\ \vdots \\ S_N \end{pmatrix} \\
w &= \begin{pmatrix} w_1 \\ \vdots \\ w_N \end{pmatrix}
\end{align*}
\]
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S &= \begin{pmatrix} S_1 \\ \vdots \\ S_N \end{pmatrix} \\
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S_{BF}^T &= w_1^* s_1 + \cdots + w_N^* s_N = w^H s
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Optimize \( w \) in order to maximize \( S_{BF}^T \)
Used signal processing

Work presented here focuses on reception mode.

Commercial UBX-160 & Octoclock

- frequency and sampling time synchronization between channels
- NO phase synchronization between channels
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- Initialization position referred as “ $\theta = 0^\circ$ ” position.
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**Simulation in GNU Radio**

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Simulation in GNU Radio

Aimed application: passive solution for projectile following
Simulation in GNU Radio

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Estimated DOA used to steer array main lobe in projectile direction in real-time
Simulation in GNU Radio

Aimed application: passive solution for projectile following

Estimated DOA used to steer array main lobe in projectile direction in real-time

θ values were generated from a previous firing to run simulations in GNU Radio
Simulation in GNU Radio

Expected performance for a particular setup
Simulation in GNU Radio

Expected performance for a particular setup

$\theta$ values simulate sampling for projectiles of different speeds and for different sampling rates
Simulation in GNU Radio

Expected performance for a particular setup

θ values simulate sampling for projectiles of different speeds and for different sampling rates

DOA estimation performance can be adjusted by setting DOA search angular resolution and number of samples per estimation.
Simulation in GNU Radio

Expected performance for a particular setup

Signal amplitudes normalized to unit
Simulation in GNU Radio

Expected performance for a particular setup

Signal amplitudes normalized to unit

Program ability to maintain phase alignment between channels assessed by computing $|s_{BF}^T|^2$
Simulation in GNU Radio

\[ \text{Sum signal}(\theta, \theta_{DOA}) = \sum_{n=1}^{4} e^{j(n-1) \frac{2\pi}{\lambda} d(\sin\theta - \sin\theta_{DOA})} \]
Simulation in GNU Radio

\[
\text{Sum signal}(\theta, \theta_{\text{DOA}}) = \sum_{n=1}^{4} e^{j(n-1)\frac{2\pi}{\lambda} d(\sin\theta - \sin\theta_{\text{DOA}})}
\]

\[
G_{\text{reception simulation}}(\theta, \theta_{\text{DOA}}) = \left| \sum_{n=1}^{4} e^{j(n-1)\frac{2\pi}{\lambda} d(\sin\theta - \sin\theta_{\text{DOA}})} \right|^2
\]
Simulation in GNU Radio

Presented simulation is for a projectile flying at Mach 4.9 (≈ 1670 m/s)

Sampling rate 1MS/s, DOA search 1° precise with 128 samples per DOA estimation
Simulation in GNU Radio

Simulation shows the program can accurately follow the projectile at Mach 4.9 (faster than real fired projectiles)
Simulation in GNU Radio

Reception gain variations below $10^{-2} \text{dB}$
Simulation in GNU Radio

Reception gain variations below $10^{-2} \, dB$

- successfully maintained constant over projectile trajectory by accurately steering array main lobe in projectile direction.
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Measurement results

Fired projectiles
Measurement results

Fired projectiles

Embedded electronics
Projectiles fired at Mach 1.3 in June

Transmitter onboard projectile GFSK 2Mbits/s @ 2,369 GHz

Projectile directly visible by antenna array in the [-60°; +50°] angular range

Conventional beamformer (Bartlett) algorithm

1MS/s sampling rate

128 samples per DOA estimation with 1° of angular resolution
Measurement results

Compensation of phase-shifts created by hardware and antennas

\[
G_{\text{reception measurement}}(\theta, \theta_{\text{DOA}}) = \left| \sum_{n=1}^{4} e^{j(\varphi_{\text{ant}} n(\theta) - \varphi_{\text{ant}} n(\theta=0^\circ))} e^{j(n-1)\frac{2\pi}{\lambda}(\sin\theta - \sin\theta_{\text{DOA}})} \right|^2
\]
Measurement results

1st projectile

Projectile visible by array when in [-60°; +50°]

Measurements outside [-60°; +50°] irrelevant
Measurement results

1st projectile

Accurate DOA acquisition in $[-30^\circ; +30^\circ]$ 

Noise peaks between 0.5 and 0.6s, and between 1.1 and 1.2s.
Measurement results

2nd projectile

Estimated DOA vs true angle (conventional Bearformer with verification of DOA by 50°)

- Estimated DOA
- True angle

Projectile visible by array

Irrelevant
DOA acquisition noisier than with the 1st projectile

Noise peaks between 0.5 and 0.6s, and between 0.8 and 0.9s
Measurement results

3rd projectile

Estimated DOA vs true angle (conventional Bearformer with verification of DOA by 30°)

- *estimated DOA*
- *true angle*

**Projectile visible by array**

**Irrelevant**
Measurement results

3rd projectile

DOA verification loop blocked DOA at -90° between 0.7 and 0.8s

wrong estimates over 0.05s
Measurement results

1st projectile

Normalized reception gain (conventional beamformer with DOA verification by 50°)

- Projectile visible by array
- Some points indicate gain losses

Irrelevant
Measurement results

1\textsuperscript{st} projectile

3 point averaging

Gain losses represent a minority of points

Besides noise peaks, reception gain is constant within 5dB
Measurement results

1st projectile

Gain losses represent a minority of points.

Besides noise peaks, reception gain is constant within 5dB.
Measurement results

2nd projectile

Normalized reception gain (conventional beamformer with DOA verification by 50°)

Projectile visible by array

Noise peaks on DOA estimations induce more gain losses
Measurement results

2\textsuperscript{nd} projectile

Noise peaks on DOA estimations induce more gain losses
Measurement results

2nd projectile

Majority of points remain above -5dB when correct DOA estimation

Irrelevant
Measurement results

2\textsuperscript{nd} projectile

10 point averaging

Majority of points remain above -5dB when correct DOA estimation

Normalized reception gain (conventional beamformer with DOA verification by 50°)

DOA noise peaks

Irrelevant
Measurement results

3rd projectile

DOA verification loop blocked DOA at -90° between 0.7 and 0.8s

Wrong estimates over 0.05s
Measurement results

3rd projectile

DOA errors aside, the averaged reception gain remains over -5dB over the projectile trajectory
Measurement results

3\textsuperscript{rd} projectile

DOA errors aside, the averaged reception gain remains over -5dB over the projectile trajectory
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A passive solution for high-speed projectile tracking using commercial UBX-160 and GNU Radio is proposed
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First measurements have been performed with real projectiles and have demonstrated the system ability to follow projectiles in real conditions.

Errors in DOA have been found, but the reception gain has been shown to remain constant within 5dB for the projectile trajectory with accurate estimation.
Outlooks

Measurements using other DOA algorithms (Capon)
Outlooks

Measurements using other DOA algorithms (Capon)

Hardware update for remote measurement triggering
Outlooks

Measurements using other DOA algorithms (Capon)

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Increase of the sampling rate to 25MS/s to run while performing telemetry reception measurements
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Research on embedding SDR components in gyrostabilized projectiles