Breaking the Range Limit of RFID Localization: Phase-based Positioning with Tunneling Tags

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Location tracking systems (LTS)

- Taxonomy of location tracking systems and techniques used by RFID location tracking systems.
Accuracy and range of state-of-art LTS

Most techniques are bounded by the range-accuracy limitation with poor accuracy at longer distance.
What limit the accuracy and range?

- Operating Frequency
- Path Loss/Distance
- Reader Sensitivity
- Reader/Tag Antenna
- Multipath
- Shadowing
- Technique
- Algorithm
## Typical frequency bands

*Wavelength and range limits*

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Band</th>
<th>Wavelength</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>125/134 KHz</td>
<td>LF</td>
<td>2.2 km - 2.4 km</td>
<td>&lt;1 m</td>
</tr>
<tr>
<td>13.56 MHz</td>
<td>HF</td>
<td>20 m - 22 m</td>
<td>&lt;10 m</td>
</tr>
<tr>
<td>433 MHz</td>
<td>UHF</td>
<td>0.68 m - 0.69 m</td>
<td>&lt;30 m</td>
</tr>
<tr>
<td>860 - 960 MHz</td>
<td>UHF</td>
<td>0.31 m - 0.34 m</td>
<td>&lt;100 m</td>
</tr>
<tr>
<td>2.4 - 2.45 GHz</td>
<td>UHF</td>
<td>0.12 m - 0.125 m</td>
<td>&lt;10 m</td>
</tr>
<tr>
<td>5.8 GHz</td>
<td>Microwave</td>
<td>5.11 cm - 5.24 cm</td>
<td>&lt;5 m</td>
</tr>
<tr>
<td>&gt;24 GHz</td>
<td>mm-Wave</td>
<td>1.23 cm - 1.25 cm</td>
<td>&lt;1 m</td>
</tr>
</tbody>
</table>
What do you get from a backscatter link?

*Amplitude and Phase*

$$RSSI = \frac{I_{rx}^2 + Q_{rx}^2}{Z_0}$$

$$\varphi_{rx} = \arctan \left( \frac{Q_{rx}}{I_{rx}} \right)$$
Conventional RF Link Budget

\[ P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2} \]

- \( P_t \): Power Received by the Tag Antenna (Watts)
- \( P_T \): Power Transmitted by the RFID Reader (Watts)
- \( G_T \): Reader TX Antenna Gain
- \( G_t \): Tag Antenna Gain
- \( \lambda \): Wavelength (m)
- \( r \): Reader-Tag separation distance (m)
Quantum Tunnel Tags

*Break the Range Limitation*

- Tunnel diode at end of antenna
- Bias in neg-resistance region makes amplifier
- Very low power consumption (10s of microWatts)
Quantum Tunnel Tags

*Break the Range Limitation*

1200m Range Through Midtown Atlanta at 5.8 GHz

Why use phase-based ranging?

*Limitation brought by quantum tunneling tags*

\[
P_t = \frac{P_T G_T G_t \lambda^2}{(4\pi r)^2} \cdot G_{TT}
\]

- Backscatter Gain (Not Uniform)

\[
\varphi_{ps} = -\frac{2\pi f_c d}{c}
\]

- Propagation phase shift

\[
\varphi_{rx} = \varphi_{ps} + \varphi_{multipath} + \varphi_0
\]

- Phase shift caused by Tunnel diode

- Phase shift caused by multipath
RFID reader design
What do you get from a backscatter link?

*Amplitude and Phase*

\[ \varphi_{ps} = -\frac{2\pi f_c d}{c} \]
Three ranging techniques that utilize phase

And their drawbacks

- Reader/tag has to move
- Expensive Implementation
- Need a broader bandwidth

# Measurement setup

<table>
<thead>
<tr>
<th>Indoor</th>
<th>Outdoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>ST</td>
</tr>
<tr>
<td>$G_t$ (dBi)</td>
<td>1</td>
</tr>
<tr>
<td>$d$ (m)</td>
<td>3, 15</td>
</tr>
<tr>
<td>$P_T$ (dBm)</td>
<td>3</td>
</tr>
<tr>
<td>$G_{tx}$ (dBi)</td>
<td>7.5</td>
</tr>
<tr>
<td>$G_{rx}$ (dBi)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

TT: Tunneling Tag; ST: Semi-passive Tag.

0 dBm Output Power

![Diagram of measurement setup](image)

**a)**

**b)**

**c)**
IQ constellation

for both the semi-passive and the Tunneling tags measured indoor at a distance of 3 m

The IQ constellation points in the 5.8 GHz band (5.840 to 5.858 GHz) for both the semi-passive and the Tunneling tags measured indoor at a distance of 3 m from the reader.

As expected, the Tunneling Tag provides a higher level of backscattered power.
How to get range estimation from phase?

\[
\hat{D} = \frac{c}{4\pi N} \sum_{n=1}^{N-1} \left| \frac{\varphi_{r+x_n} - \varphi_{r+x_{n+1}}}{f_n - f_{n+1}} \right|, \\
\Delta f = f_{n+1} - f_n \quad \lambda_e = \frac{c}{\Delta f} \\
\hat{D} = \frac{\lambda_e}{4\pi N} \sum_{n=1}^{N-1} \left| \varphi_{r+x_n} - \varphi_{r+x_{n+1}} \right| = \frac{\lambda_e}{4\pi} \Delta \varphi,
\]

- Maximum Range: \( \hat{D}_m = \frac{\lambda_e}{2} \), 150m for 1MHz Frequency Step.
IQ constellation

for both the semi-passive and the Tunneling tags measured indoor at a distance of 3 m.

The IQ constellation points in the 5.8 GHz band (5.840 to 5.858 GHz) for both the semi-passive and the Tunneling tags measured indoor at a distance of 3 m from the reader.

As expected, the Tunneling Tag provides a higher level of backscattered power.
When multipath comes to play

Multipath measurements

- IFFT of S21 response
- CLEAN Algorithm to reduce the noise level
When multipath comes to play

Calibration

\[ \varphi_{rx} = \varphi_{ps} + \varphi_{multipath} + \varphi_0 \]

\[ \tilde{R}(\tau) = \sum_n A_n(\tau) \approx R_o \exp (-j \Delta \bar{\varphi}) \exp (-j 2\pi f \tau) \]

\[ \Delta \bar{\varphi} = \frac{2\pi c \bar{\tau}}{\lambda} \quad \Rightarrow \quad \bar{\tau} = \frac{\int_0^\infty \tau A(\tau)}{\int_0^\infty A(\tau)} \]
Phase measurements

a) Phases and b) phase differences between ten adjacent channels measured indoor at 3 meters away from the reader with both the semi-passive and the Tunneling tags.
Phase measurements

The c) indoor and d) outdoor IQ constellation points in the 5.8 GHz band measured from the same distance.
Phase measurements

Tunneling Tag indoor and outdoor a) phases and b) phase differences between fifty adjacent channels measured at 15 meters from the reader.
### Summary

*Localization accuracy for different tag in different scenarios*

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Semi-passive Tag</th>
<th>Tunneling Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor 3m Uncalibrated</td>
<td>3.598 m (19.9%)</td>
<td>3.643 m (21.5%)</td>
</tr>
<tr>
<td>Indoor 3m Calibrated</td>
<td>3.0129 m (0.43%)</td>
<td>3.0582 m (1.94%)</td>
</tr>
<tr>
<td>Indoor 15m Uncalibrated</td>
<td>N/A</td>
<td>16.35 m (9.00%)</td>
</tr>
<tr>
<td>Outdoor 15m Uncalibrated</td>
<td>N/A</td>
<td>15.91 m (6.07%)</td>
</tr>
</tbody>
</table>
**Contribution**

- outlined a distance estimation algorithm based on received signal phase using a custom frequency-hopping RFID system operating at the 5.8 GHz ISM band (from 5.725 GHz to 5.975 GHz);
- used a 5.8 GHz RFID system with a Tunneling Tag extending the communication range of a conventional RFID tag and applied the phase-based positioning algorithm;
- ran indoor preliminary experiments to estimate the delay errors due to multipath;
- demonstrate how a long-range LoS localization is possible with Tunneling Tags.
Next step

- Extend Phase-Based Tracking to 2D By Using Trilateration
- Investigate Phase-Based Tracking in NLOS Environments
Q&A

Thank you

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