Accurate Distance Measurement using Narrowband Bluetooth Devices

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Outline

• Introduction
• Principle of the Phase Based Ranging
• Impact Multipath on Phase Based Ranging
• Proof of Concept
• Conclusion
Accurate Distance Measurement using Narrowband Bluetooth Devices

INTRODUCTION
Introduction

- Bluetooth is a one of the dominating radio technologies on the market,
- It is already providing distance and location services.
- At 43% CAGR, location services is the fastest growing Bluetooth solution area.
Introduction

- Overview of Radio Localization Technologies

<table>
<thead>
<tr>
<th>System</th>
<th>Target area</th>
<th>Active power usage</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS and similar satellite based</td>
<td>Outdoor</td>
<td>50-200mW</td>
<td>3-15m[1]</td>
</tr>
<tr>
<td>Cellular proximity</td>
<td>Both</td>
<td>50mW</td>
<td>300-3500m</td>
</tr>
<tr>
<td>802.11 Fingerprinting</td>
<td>Indoor</td>
<td>50-300mW</td>
<td>3-10m[8]</td>
</tr>
<tr>
<td>802.11 Time differential lateration</td>
<td>Indoor</td>
<td>50-300mW</td>
<td>30cm</td>
</tr>
<tr>
<td>UWB Time differential lateration</td>
<td>Indoor</td>
<td>50-60mW</td>
<td>30cm</td>
</tr>
<tr>
<td>BLE proximity</td>
<td>Indoor</td>
<td>&lt;10mW</td>
<td>10-50m</td>
</tr>
<tr>
<td>Bluetooth RSSI</td>
<td>Indoor</td>
<td>&lt;40mW</td>
<td>5-10m</td>
</tr>
<tr>
<td>Bluetooth Fingerprinting</td>
<td>Indoor</td>
<td>&lt;40mW</td>
<td>3-10m</td>
</tr>
</tbody>
</table>

- BLE is not that accurate... Imagine if it would be!

Introduction

- What is determining the accuracy of ranging?
  - Cramer Rao Lower Bound (for Rectangular Spectrum):

\[
var(\hat{d}^2) \geq \frac{3c_0^2}{2\pi^2 \frac{E}{N_0} B^2}
\]

- Accuracy depends on product of Bandwidth and SNR
- SNR is good for BLE, but how to increase its bandwidth?
  - Answer; phase-based ranging
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PRINCIPLE OF THE PHASE BASED RANGING
Phase Difference approach

- Simple LOS scenario

Initiator (A)  
\[ r \text{ (Distance between A&B)} \]

Reflector (B)  
\[ \phi(f, r) = 2\pi fr \mod 2\pi \]

- Phase rotation introduced by radio channel for a frequency \( f \) and distance \( r \)
Phase Difference approach

- Active reflector principle allows for half duplex operation and increases max. distance
- Conducting phase/IQ measurements at both sides (A&B) (No LO locking to incoming signal)
- Only course time-synchronization needed, time-offset falls out
- PLL/LO must remain active when switching TX <-> RX (continuous LO generation)

[source] 15-09-0613-00-004f-ranging-with-ieee-802-15-4-narrow-band-phy.ppt
Phase Difference approach

• Both, initiator (A) and reflector (B) device, have their own clock references which are only coarsely synchronized

\[ \phi_{AB}(f, r) = 2\pi f \left( \frac{r}{c_0} - \theta \right) \mod 2\pi \]
\[ \phi_{BA}(f, r) = 2\pi f \left( \frac{r}{c_0} + \theta \right) \mod 2\pi \]

• Phase difference between both clock references results in a distance error. Hence,

  – Device B measures phase of receives signal relative to its own LO signal phase
  – Phase correction term is transferred to device A used as correction factor.

\[ \phi_{2W}(f, r) = \phi_{AB} + \phi_{BA} = 4\pi f \frac{r}{c_0} \mod 2\pi \]

Still a range ambiguity ½ wavelength

[source] 15-09-0613-00-004f-ranging-with-ieee-802-15-4-narrow-band-phy.ppt
Phase Difference approach

- Resolve ambiguity by measuring at 2 frequencies \( (f_0 \text{ and } f_1 \text{ with } \Delta_f = f_1 - f_0) \)

\[
\Delta \phi = \phi_{2W}(f_1, r) - \phi_{2W}(f_0, r) = 4\pi \Delta_f \frac{r}{c_0} \mod 2\pi
\]

such that

\[
r = \frac{c_0}{4\pi \Delta_f} \Delta \phi \mod \frac{c_0}{2\Delta_f}
\]

- Can be extend to \( K_f \) tones, every time the frequency increment is \( \Delta_f \)

\[\text{BW} = (K_f - 1)\Delta_f\]

\[
\Delta \phi = \frac{1}{K_f - 1} \sum_{k=1}^{K_f-1} \Delta \phi[k]
\]

- Multi Frequency step -> better accuracy without reduction of unambiguous range

range ambiguity = \( \frac{1}{2} \) difference in wavelength
\[
\Delta_f = 1\text{MHz} \Rightarrow 150 \text{ meter unambiguous range}
\]
Phase Difference approach

<table>
<thead>
<tr>
<th>Ranging Request</th>
<th>Ranging Ack</th>
<th>N Phase Measurements ( (N = (F_{\text{max}} - F_{\text{min}}) / Df) )</th>
<th>Phase Meas. Results</th>
<th>Distance Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B TX</td>
<td>RX</td>
<td>TX</td>
<td>TX</td>
<td>TX</td>
</tr>
<tr>
<td>Device</td>
<td>TX</td>
<td>TX</td>
<td>TX</td>
<td>TX</td>
</tr>
<tr>
<td>A RX</td>
<td>TX</td>
<td>RX</td>
<td>RX</td>
<td>RX</td>
</tr>
</tbody>
</table>

Time [µs]

TX Frequency
Dev. A [MHz]

Network Channel

\[ F_{\text{min}} \]
\[ \Delta f \]
\[ F_{\text{max}} \]

SFD \( T_{\text{start B}} \)
200 µs
PLL settling to \( \Delta f \) step

Instant. BW is small
Overall BW much larger

[Source] 15-09-0613-00-004f-ranging-with-ieee-802-15-4-narrow-band-phy.ppt
Phase Difference allows for indirect measurement of the propagation delay/distance

- Instantaneous BW is small, overall BW scalable
  - No additional requirement on ADC sampling rate
- Only coarse synchronization needed
- TX signal is constant-envelope (Power-efficient and avoid AM2PM)
- Half-duplex by nature
- Device to Device power/gain variations (TX power, LNA)
- Insensitive to constant phase-offsets:
  - AGC freeze; to ensure the delays/phase-shift in the baseband do not change and has a negative impact.
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IMPACT MULTIPATH ON PHASE BASED RANGING
Impact Multipath on NRB ranging

- LOS contains information on distance (and has smallest delay)
- Each ray has constant magnitude and linear phase shift with frequency
- Measured tone is sum of all rays (dotted-lines)
  - Phase & Magnitude change with frequency
  - Both contain information!

Simple LOS with reflections scenario

sum of complex exponentials
Impact Multipath on NRB ranging

Uniform Linear Array

Freq domain multipath channel with uniform frequency steps

\[ N = \# \text{signals} \quad z_n = \exp(j \, 2\pi \sin(\theta_n) d/\lambda) \]

\[ N = \# \text{rays} \quad z_n = \exp(j 2\pi \Delta_f \tau_n) \]

- Lots of work done in area of super-resolution signal separation for antenna arrays
  - (root)-MUSIC, Matrix-Pencil, Esprit, ...
  - Provide temporal resolution beyond $1/BW \implies$ Improved separation of LOS and NLOS
Superresolution

Using Shift-invariance property, the rank can be increased and enables use of covariance-based, super-resolution algorithms on single snapshot. Results is decorrelation of ‘correlated’ multipath.

\[
\begin{bmatrix}
    h_0 \\
    h_1 \\
    \vdots \\
    h_{K_f-1}
\end{bmatrix} = \begin{bmatrix}
    1 & 1 & \cdots & 1 \\
    z_0 & z_1 & \cdots & z_{N-1} \\
    z_0^2 & z_1^2 & \cdots & z_{N-1}^2 \\
    \vdots & \vdots & \ddots & \vdots \\
    z_0^{K_f-L-1} & z_1^{K_f-L-1} & \cdots & z_{N-1}^{K_f-L-1}
\end{bmatrix} \begin{bmatrix}
    \tilde{a}_0 \\
    \tilde{a}_1 \\
    \vdots \\
    \tilde{a}_{N-1}
\end{bmatrix}
\]

\[
\text{Rank} = 1
\]

\[
\begin{bmatrix}
    h_0 \\
    h_1 \\
    \vdots \\
    h_{K_f-1}
\end{bmatrix} = \begin{bmatrix}
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
    \vdots \\
\end{bmatrix}
\]

Using Shift-invariance property, the rank can be increased and enables use of covariance-based, super-resolution algorithms on single snapshot. Results is decorrelation of ‘correlated’ multipath.

\[
H = \begin{bmatrix}
    h_0 & h_1 & \cdots & h_L \\
    h_1 & h_2 & \cdots & h_{L+1} \\
    \vdots & \vdots & \ddots & \vdots \\
    h_{K_f-L-1} & h_{K_f-L} & \cdots & h_{K_f-1}
\end{bmatrix} = [Za \ Z\Lambda(z)^1a \ \cdots \ Z\Lambda(z)^{L-1}a]
\]

Superresolution: e.g. MUSIC

1. Apply SVD / EVD: \( H = U \Lambda(s) V^H / \quad c = H^H H = V \Lambda(s)^2 V^H \)

2. Divide vector space \( V \) in signal(\( V_S \))-and noise subspace \( V_n \)

3. Process the Pseudo-spectrum
   a) Generate steering–vector (hypothesis on \( \tau \))
      \[
      e(\tau) = \begin{bmatrix} 1 & \exp(-j2\pi\Delta_f \tau) & \exp(-j2\pi2\Delta_f \tau) & \ldots & \exp(-j2\pi(K_f - 1)\Delta_f \tau) \end{bmatrix}^T
      \]
   b) Find first significant peak Pseudo-spectrum is:
      \[
      \hat{P}_{MU}(\tau) = \frac{1}{e(\tau)^H V_n V_n^H e(\tau)}
      \]

4. In ranging context: find first significant peak!

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PROOF OF CONCEPT
Ranging platforms

Zigbee
- Zigbee transceiver; Atmel ATREB2015-XPRO
- uC board; Atmel ATSAM4E-XPRO
- Dual, polarized antennae
- RF-Switch
- IQ-to-distance algorithm running on uC

Bluetooth
- Automotive Qualified Bluetooth®5 Wireless MCUs based on Arm® Cortex®-M0+
- Development Kit for Kinetis® KW36/35 MCUs
Ranging platforms

• evaluation in Indoor multipath environment

At short distances (2 meter) multipath is also significant!

2.4 GHz ISM-BAND
Ranging platforms

- Localization
ranging platform

• Performance in multipath environment

Ranging accuracy
No compensation for bias/offset

2-D single-shot localization/No tracking with polarization diversity

RMS error 0.49 [m]
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CONCLUSIONS
Conclusion

• Sub meter accurate ranging using NRB radios is possible
• Polarization Diversity increases accuracy and robustness against outliers
  • But not a must for low-cost implementations
• Careful front-end design important
  • Requirements and implementation aspects for radio have design been identified
  • No show-stoppers for low-power radio design found
• Concept has been proven using COTS radios