Performance Limits and Field Tests of a Precision Indoor Positioning System using a Multi-Carrier Approach

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Project Focus

Precision, ad hoc, indoor/outdoor positioning and associated exchange of data for situational awareness and command/control for

- Firefighters
- Law enforcement officers
- Military
- First-responders
- Corrections officers
System Overview

Personnel Unit

Reference units

Commander Display

Intra-Reference Unit Communication: 802.11
3-D Escape Routing
New Results and Context

- **ION-GPS 03**: System Architecture and Principles of Operation, Proof of Concept Demonstration
- **ION-NTM 04**: RF Performance Bounds (no Multipath)
- **ION-AM 04**: Geometric Performance Bounds
- **ION-NTM 05**: Multipath Performance
System Components

- GPS Signal
- Reference Unit, known location
- Personnel Unit
- Phys Monitor
- Reference Unit, known location
- Command and Control Unit
- User-Commander link
System Requirements

- Number of dimensions: 3
- Accuracy: +/- 1 ft
- Maximum range: 2000 ft
- Max number of simultaneous users: 100

Fundamental capabilities:
- 3-D location of each user relative to a chosen reference point
- Relative locations among users
- Graphical display at base station
- Graphical path information on all users
- Self rescue information to users (audio)

Enhancements:
- Physiologic information telemetry
- Integration with stored databases: geographic and structural
Functional Differences from GPS

- Small operational area (< ~1km²)
- Major focus is *indoors*
- Absolute geo reference may not be needed
- User devices may be active
- Overall system cost must be kept low
- Entire system must be self-initializing, self-monitoring
Technical Challenges

- Multipath
  - The indoor radio environment is much more problematic than outdoor
  - Signal reflections pose a fundamental issue with respect to precision of location.

- Portability and quick set-up
  - Response vehicles must be ready to go with the geolocation system immediately on arrival.
  - Automated reference initialization (site self-calibration).

- Size, cost, power
  - Personnel devices must be small, very low cost and operate without interruption for widespread deployment
Basic Concept

- Sharply defined energy pulses are unnecessary for precise location
  - Avoids problems of wide and flat bandwidth antenna, receiver, and transmitter design
- Multiple continuous carriers that sample frequency space can be utilized
  - Spectrally friendly, near 0 bandwidth components
- Superresolution techniques can trade SNR for increased precision at fixed bandwidth
  - Also provides means for multipath resolution
The OFDM Concept
Transmitted Signal

\[ s(t) = \sum_{m=0}^{M-1} A e^{j[2\pi(f_0 + m\Delta f)t + \phi_m]} \]

M carriers
Carrier spacing = \( \Delta f \)
Each carrier has arbitrary phase \( \phi_m \)
Example Result for 1 Path

“Freq Index” corresponds to carrier frequencies in the transmitted signal “comb.”
As path length changes…
Functional Diagram

- Generate sine comb
- RF up-convert
- Range TDOA Est.
- State Space Freq Est.
- A/D
- RF down-convert

Multiple paths

Reference Positions

Position Determin.
Sinusoidal Frequency Estimation

- Estimation of the frequencies of sinusoids in noise (not necessarily harmonically related) is an old/fertile field.

- We use the state space approach:
  - Exact solution (without noise) for $P$ frequencies given $M > 2P$ Fourier samples (comb frequencies)
  - Direct solution, good noise performance
  - Model-based ($P$ must be estimated a priori)
Ranges from Frequencies

- Given the frequencies, TDOAs of all paths immediately follow.
- Can reject multipath TDOAs based on inconsistency with a single source (computation-intensive).
- Given time synchronization with transmitter, TDOA becomes TOA and direct paths can be identified directly.
- Or, make the system unambiguous range cell larger than the maximum physical operations area, and order solutions to identify shortest path.
System Prototype Development

Two RF systems:

- Narrowband (5 MHz) system at 2.4 GHz (completed)
  - Tone modulation of existing off-the-shelf radios
  - Rapid prototype
- Wideband (50 MHz) system at 400 MHz
  - Actual build-out of the OFDM transmitter and receiver
Performance Validation

- Detailed system analysis
- Simulations
  - Standard transmit signal synthesis
  - Standard range determination algorithm
  - No RF
  - Numerical signal delay and noise addition
- Cable tests
  - No RF
- RF tests
Narrowband Range Tests

4 MHz BW, 2.4 GHz carrier
Ranging Performance, Outdoors

Direct Path est. distance (of 4 reflections)
Outdoors, calibration at 2m, move to 5, 8, 16, 24 meters, 2004-09-03 14:28:04

\[
\begin{align*}
\mu_{2m} &= 1.62m \\
\sigma_{2m} &= 0.25m \\
\mu_{5m} &= 5.03m \\
\sigma_{5m} &= 0.29m \\
\mu_{8m} &= 8.20m \\
\sigma_{8m} &= 0.41m \\
\mu_{16m} &= 15.75m \\
\sigma_{16m} &= 0.27m \\
\mu_{24m} &= 23.04m \\
\sigma_{24m} &= 0.71m
\end{align*}
\]
Ranging Performance, Indoors
Ranging Performance, Synthetic Data

Direct path estimate given a 0.50 amplitude added reflection
4MHz Bandwidth, 10-70dB SNR, 500 Monte Carlo Tests

Sample Mean of Direct Path estimate, meters

Path length difference, meters

8m
A=1

(8+\Delta)m
A_r=0.5
Effect of Reflected Path Amplitude

Direct path estimate given a 1.00 amplitude reflection, 4MHz Bandwidth, 500 Monte Carlo Tests

Sample Mean of Direct Path estimate, meters

Path length difference, meters

\( A_r = 1.0 \)

\( A_r = 0.5 \)
Minimum Resolvable Path Length Difference
Cable Data

- Need data
Next: Wideband RF using Custom Hardware
Conclusions

- This analysis provides encouraging results on system performance
- Continuing work will tighten the performance bounds and remove the simplifying assumptions
- Implementation of an RF proof-of-concept system is underway