

A Multi-Carrier Technique for Precision Geolocation for Indoor/Multipath Environments

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Motivation

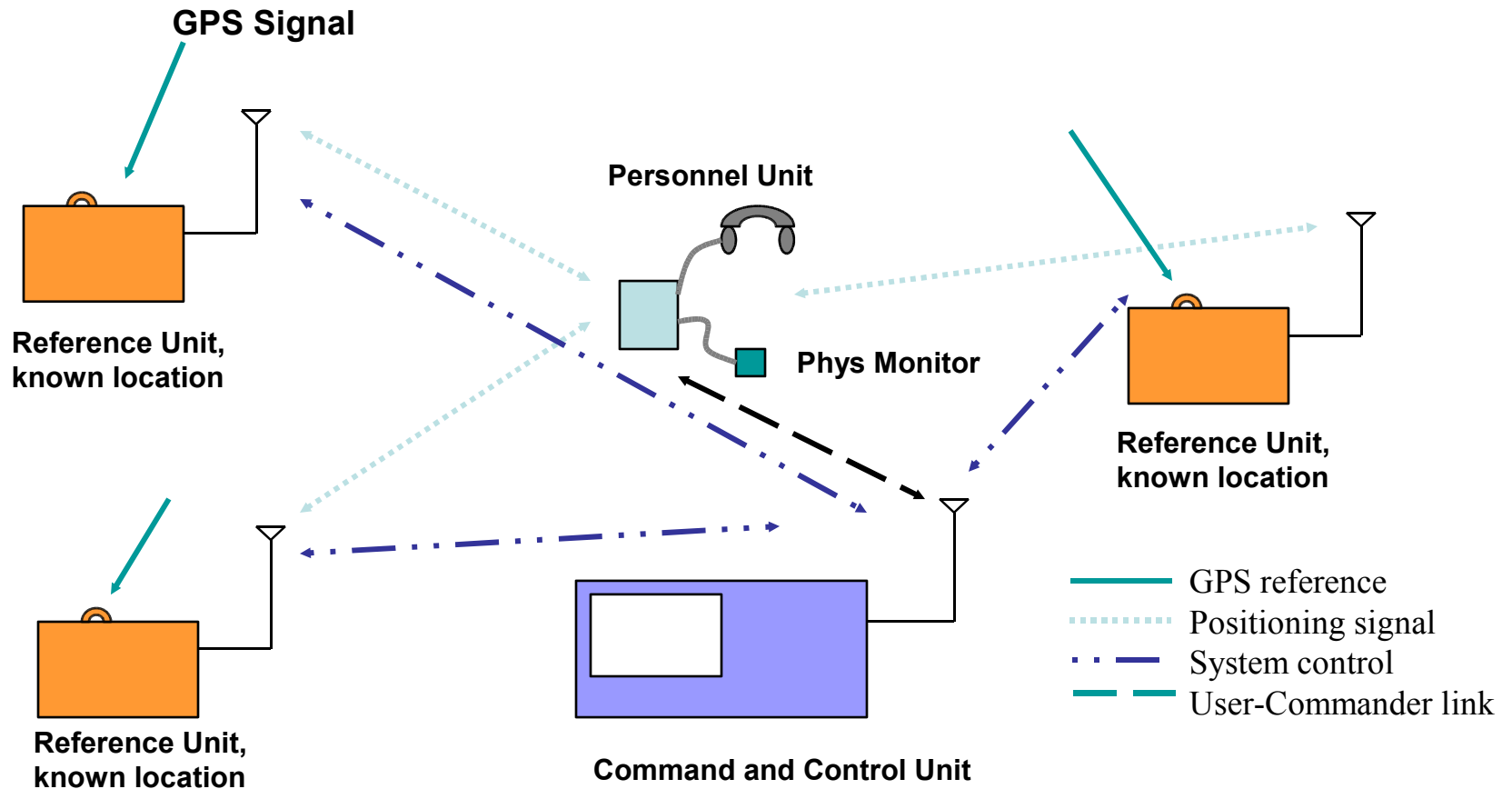
- ↑ 12/3/99: On that day, six firefighters lost their lives in a tragic cold storage warehouse fire in Worcester, MA. Two fire fighters initially got lost and then two search teams became lost in the maze due to zero visibility from the dense smoke. Six people died literally within 100 feet of safety.
- ↑ 9/11/01: A disaster of far greater magnitude, with some deaths in circumstances similar to the Worcester warehouse fire
- ↑ Current firefighter escape technology: raised arrows on the hoses pointing toward the exit.

Initial Focus Area

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

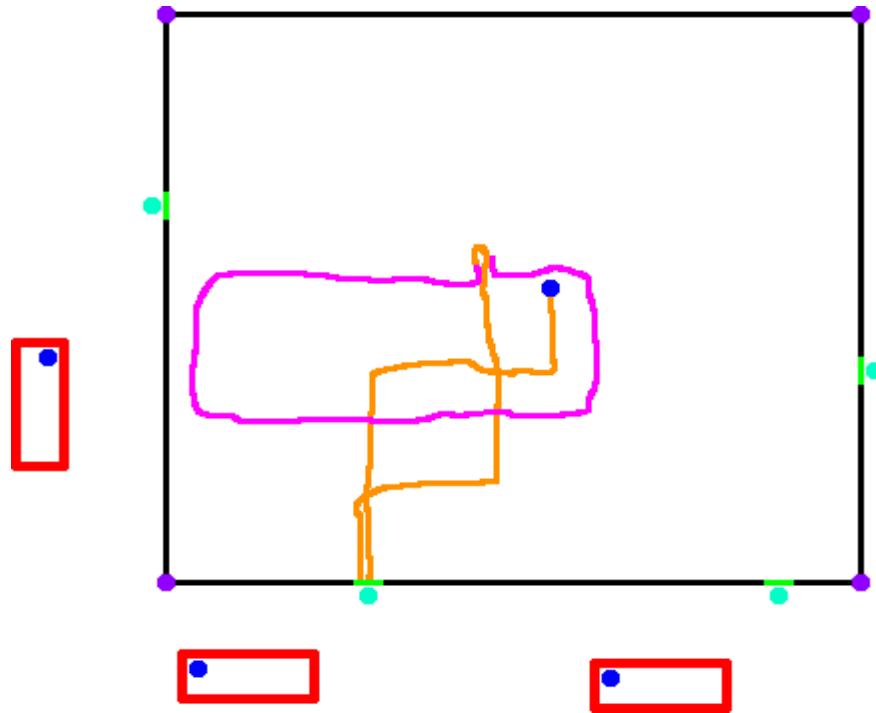
- ★ Firefighters
- ★ Law enforcement officers
- ★ Military
- ★ First-responders
- ★ Corrections officers

System Overview



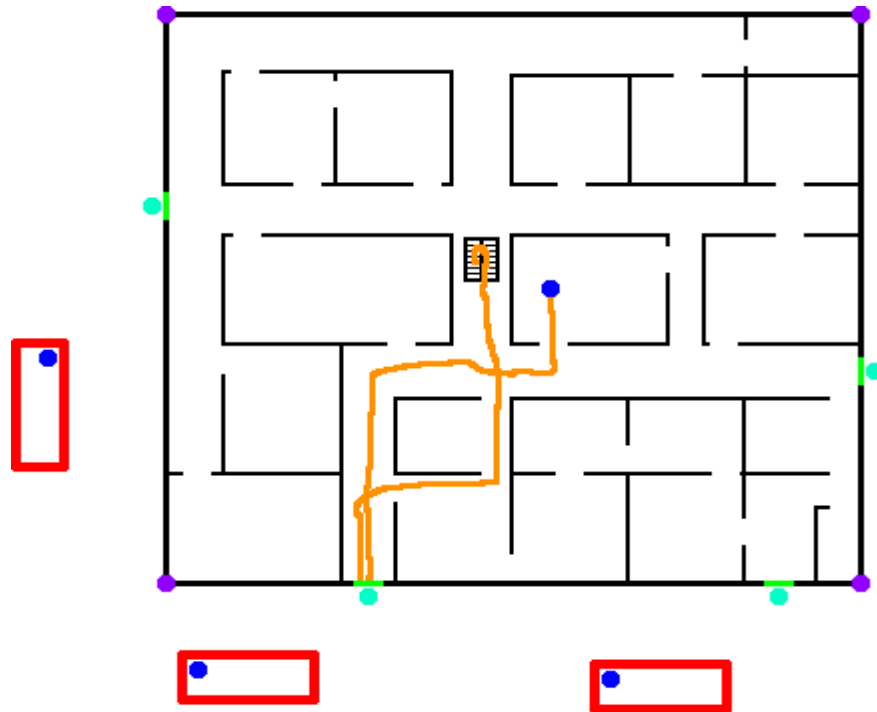
Real-Time Deployable Personnel Geolocation

Vehicles (red)
drive
up to a building
and
use reference units
(blue) to locate and
display tracks of
fire fighters. Exits
and other key
building features
may be “marked”
on the fly.



... with GIS (Geographic Info. Sys.) overlays.

If GIS information such as complete floor plans are available, they can be integrated with the track display to assist route planning and other time-critical decisions.



System Requirements Draft

- ↑ 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



Differences from GPS

- ↑ Small operational area ($< \sim 1\text{km}^2$)
- ↑ 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

Possible Approaches

↑ How do we achieve transportable (no infrastructure) precision geolocation on the order of 20 cm accuracy indoors?

↑ GPS ?

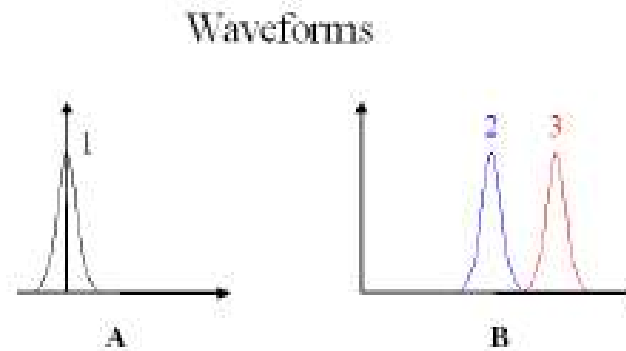
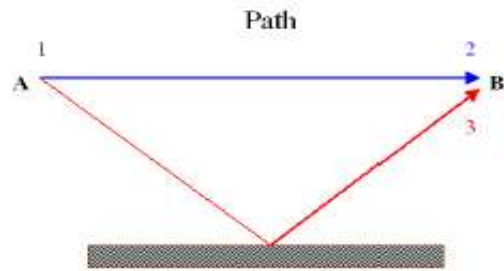
- ★ Insufficient resolution

- ★ Insufficient signal strength inside buildings

- ★ Multi-path degraded

↑ What about Impulse Ultra-Wideband (UWB)?

Impulse UWB



Ultra-narrow pulses enable simple isolation of direct paths from reflected paths

I-UWB Problems

- ⤴ Extremely narrow pulses imply large signal acquisition times and difficult tracking!
- ⤴ Pulse generation and time-windowing at receiver may require exotic circuitry
- ⤴ Maintenance of pulse characteristics requires low distortion transmitter and receiver antennas over huge bandwidths

UWB Problems cont.

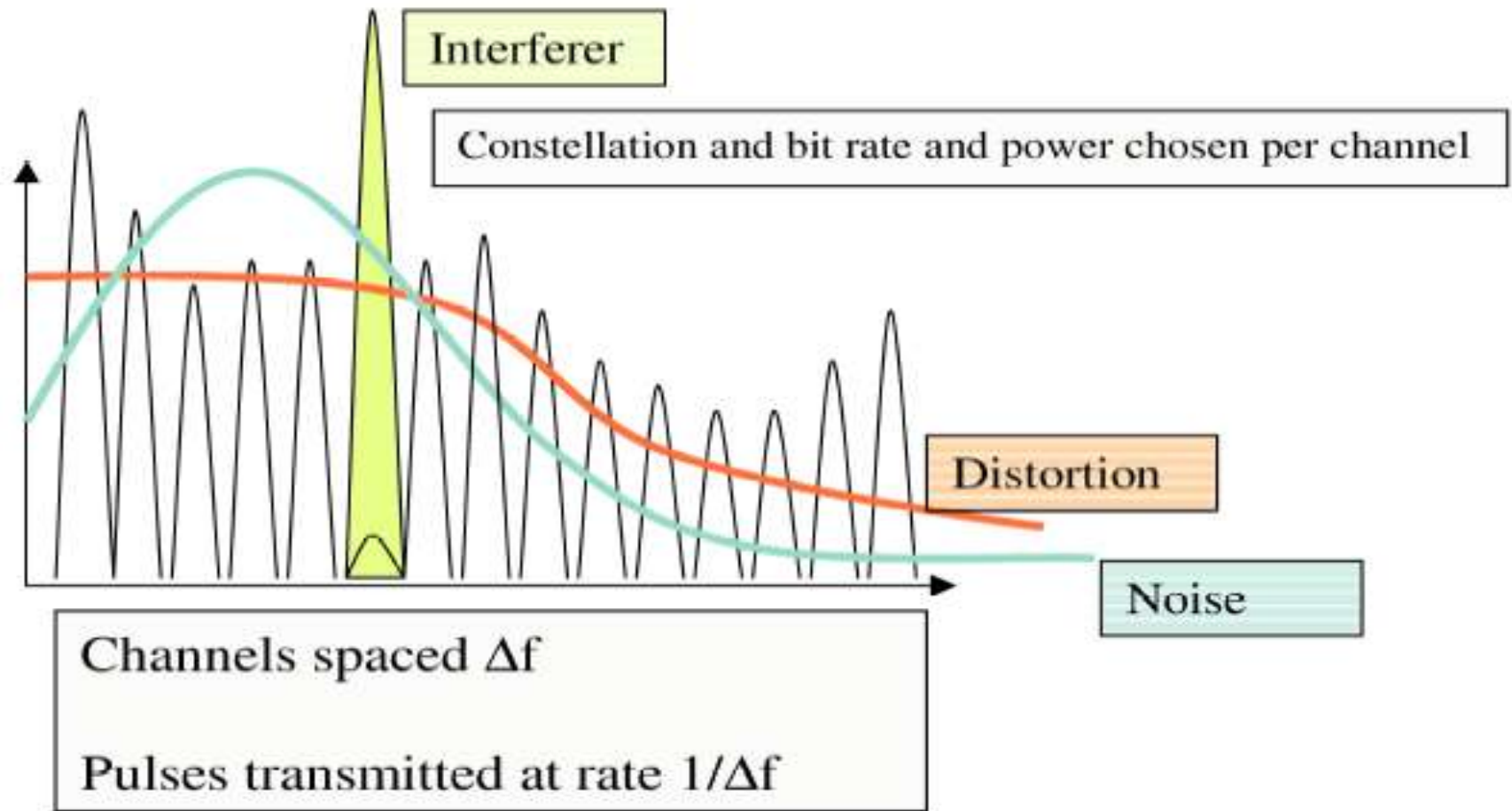
↶ Conflict with regulators:

- ★ UWB industry claims no spectral allocation needed
- ★ Other services and regulators worry about protecting existing services

↶ Conflicting claims by UWB industry:

- ★ High penetration capability enabled by low frequency components
- ★ High precision ranging enabled by high frequency components

The OFDM Concept



Lessons Learned from OFDM

High data rate transmission via multicarrier modulation does not require a single wide band channel with:

- ⤴ Low distortion (in amplitude and/or phase response)
- ⤴ Narrow pulses
- ⤴ Uniform noise
- ⤴ Absence of interferers
- ⤴ Precise synchronization

I-UWB vs. MC-UWB

⤴ Wide (ultra-wide) bandwidth *is* needed for multipath rejection, but ultra-narrow time pulses *are not* needed.

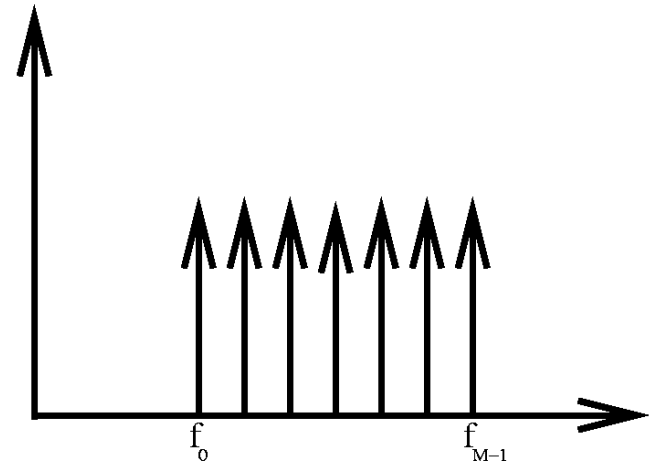
Transmitted Signal

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

M carriers

Carrier spacing = Δf

Each carrier has arbitrary phase ϕ_m



Received Signal

$$s_k(t) = \sum_{m=0}^{M-1} A_k e^{j[2\pi(f_0 + m\Delta f)(t + t_0 - \tau_{k0}) + \phi_m]}$$

t_0 : user clock offset; τ_{k0} : path delay

In the simple (no multipath) case, any 2 of the M carriers may be used to identify a phase difference and hence a time and distance difference between two receiver sites.

There is phase and hence distance ambiguity, with ambiguity distance of $c/\Delta f$ where c is the velocity of the wave. For our situation, Δf may be chosen sufficiently small to eliminate the ambiguity.

Frequency Sampling of Received Signal

The m th Fourier coefficient of the k th reference receiver:

$$S_{km} = A_k e^{j[-2\pi (f_0 + m\Delta f)\tau_{k0} + \phi_m + \psi_m]}$$

where the clock offset is $\psi_m = 2\pi (f_0 + m\Delta f)t_0$

multiplied by

$$S_m = A_k e^{j[\phi_m]}$$

results in

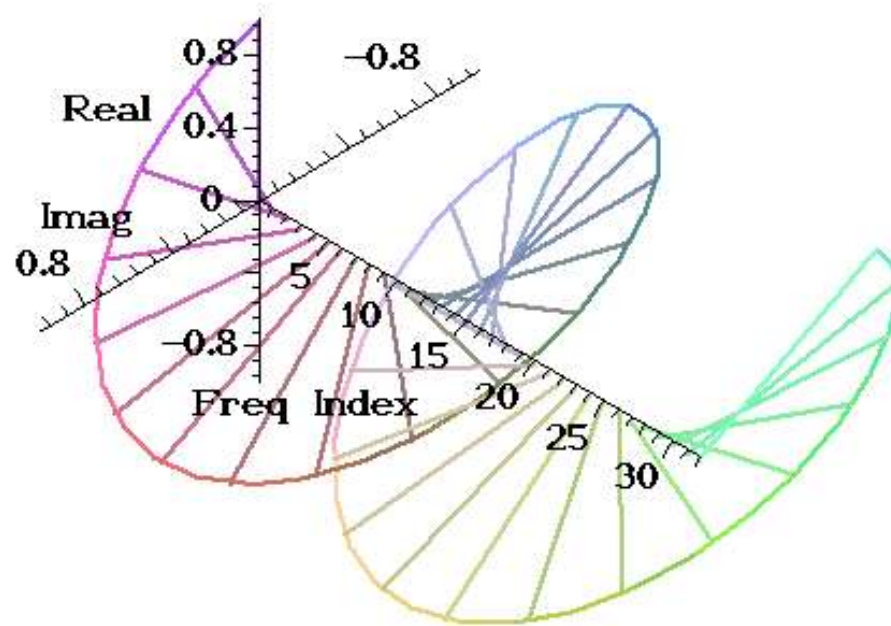
$$\begin{aligned}
S_{km} S_m^* &= A_k A^* e^{jm(-2\pi\Delta f\tau_{k0}) + \psi_m} \\
&= A_k A^* e^{jm[2\pi(\Delta f t_0 - \Delta f\tau_{k0})] + j2\pi f_0 t_0} \\
&= B_k e^{j\Omega_k m},
\end{aligned}$$

where

$$\Omega_k = 2\pi\Delta f(t_0 - \tau_{k0})$$

Which represents samples of a sinusoid with sampling index m and frequency $2\pi\Delta f(t_0 - \tau_{k0})$. Hence, given Δf , the time difference can be found.

Sample Result for 1 Signal



“Freq Index” corresponds to carrier frequencies in the transmitted signal “comb.”

With Multipath

With N multipaths:

$$\begin{aligned} S_{km} S_m^* &= \sum_{n=0}^N A_{kn} A^* e^{2\pi j(-m\Delta f\tau_{kn}) + \psi_m} \\ &= \sum_{n=0}^N B_k e^{jm\Omega_{kn}}. \end{aligned}$$

Now N sinusoidal frequencies must be estimated

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)

Positions from Frequencies

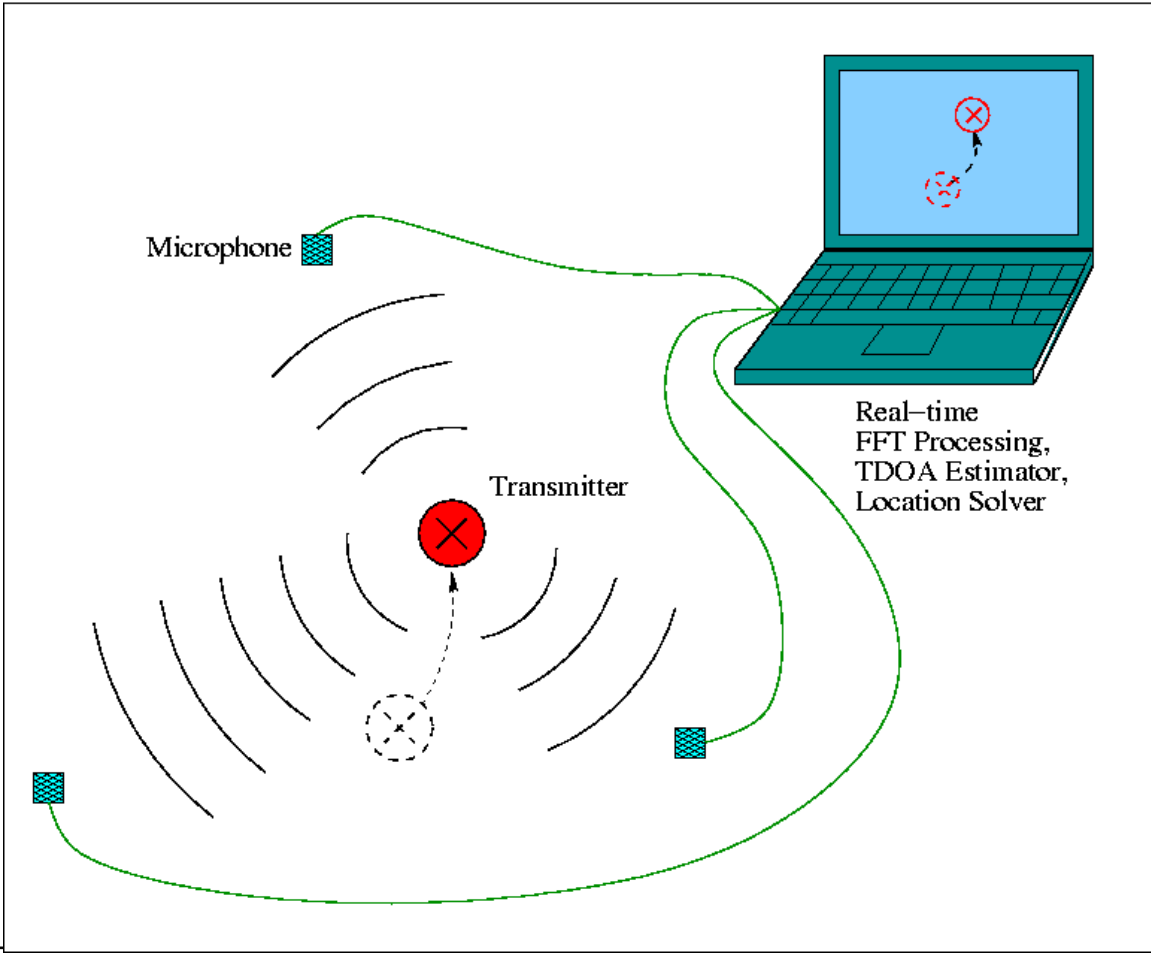
- ↑ Given the frequencies, TDOAs of all paths immediately follow
- ↑ Can reject multipath TDOAs based on inconsistency with a single source (computation-intensive)
- ↑ Given time synchronization with transmitter, TDOA becomes TOA and direct paths can be identified directly
- ↑ Or, make the system unambiguous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

Proof of Concept Demonstration

- ↑ Uses audio, not RF - greatly eased troubleshooting
- ↑ Top audio frequency has wavelength in air of 4.5 in
- ↑ 1:1 scale behavior with an RF bandwidth of 2.625 GHz
- ↑ Implements real-time location system using MATLAB
- ↑ Off the shelf microphone/speaker components can be used thanks to the OFDM like channelization
- ↑ Displays true location solution as well as multipath solutions



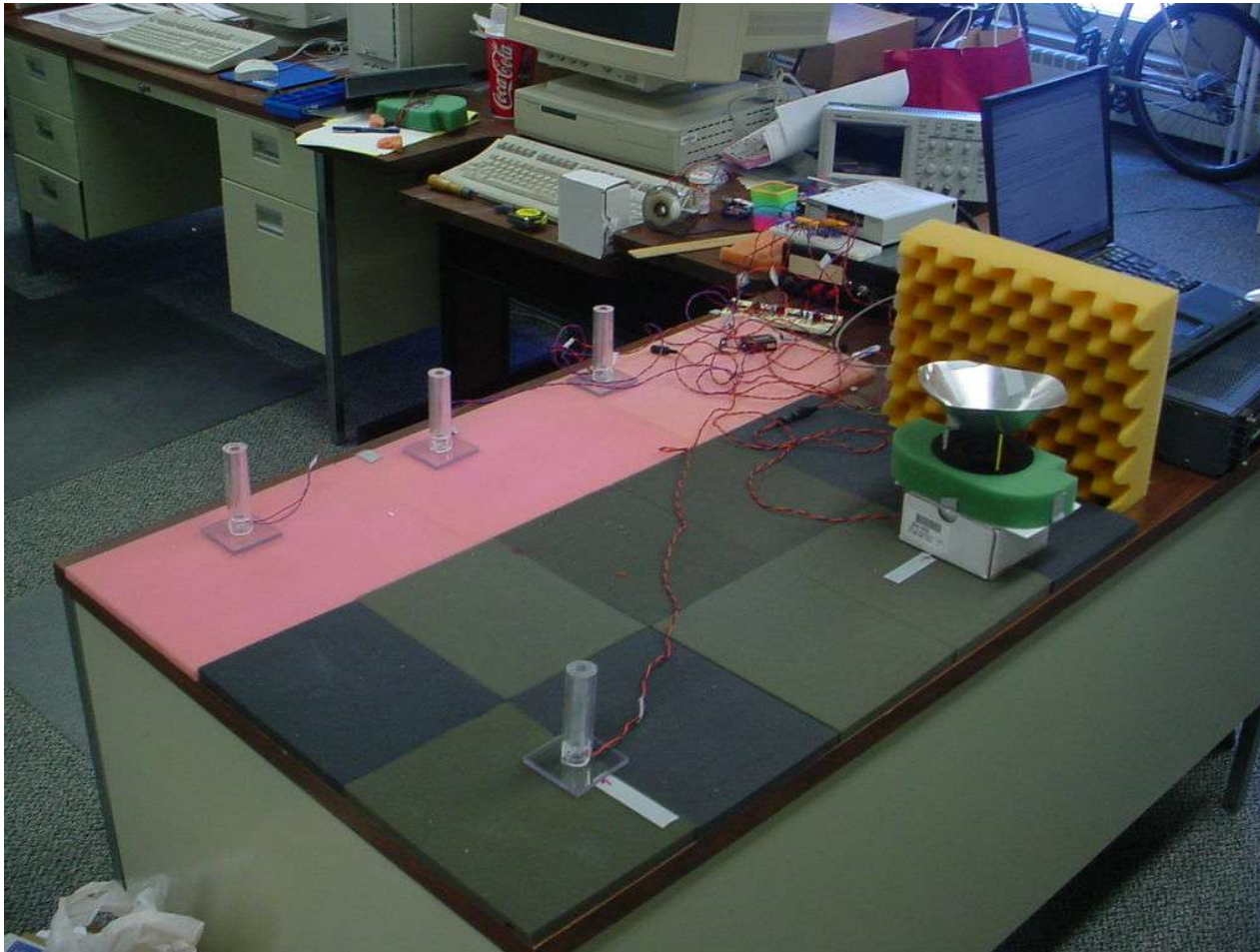
Proof-of-Concept Demonstrator



Video of Demonstration



Current Demo Setup



Conclusions

- ⤴ MC-UWB signal structure and solution techniques appear well-suited to the indoor positioning problem
- ⤴ Initial analytic and proof-of-concept experimental work have been accomplished
- ⤴ Performance analysis and RF demonstration system design/construction are now underway.