Multi-Carrier Technology for Precision Personnel Location

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Overview

- Project motivation
- System requirements
- Present precision technologies
- Origin of the MC-UWB concept
- Technological roots of MC-UWB
- Technology Demonstrators
- Status of the project
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 involving Firemen, Police, EMTs, etc., in which personnel location would have provided fast answers, vital command and control data and greatly enhanced search and rescue.
Project Goal

- The lives of First Responders, Corrections Staff and other Public Safety Personnel can depend upon precise location information.

- Our Goal: **Create a system which will track the location of emergency responders in 3-D space without requiring any pre-installed infrastructure**
Initial Focus Area

- Precision, ad hoc, positioning and associated exchange of data for situational awareness and command/control for
  - Firefighters
  - Law enforcement officers
  - First-responders
  - Corrections officers
  - Military
**System Concept**

- **Personnel Unit**
- **Communications (Optional)**
- **Positioning signal**
- **System control**
- **Phys Monitor (Optional)**
- **Reference Unit, known location**
- **Command and Control Unit**
- **User-Commander link**

Reference Unit, known location

Reference Unit, known location

Reference Unit, known location

Command and Control Unit
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.
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.
Fundamental capabilities:
- 3-D location of each user relative to a chosen reference point
- Relative locations among users
- Graphical display at command/control station
- Graphical path information on all users
- Self rescue information to users (audio)

Accuracy: +/- 1 ft

Maximum range: 2000 ft

Max number of simultaneous users: 100

Enhancements:
- Physiologic information telemetry
- Integration with stored databases: geographic and structural
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.
  - The most significant problem is reference initialization (site self-calibration).

- **Size, cost, power**: personnel devices must be small, very low cost and operate without interruption for widespread deployment
In Summary:

- How do we achieve transportable (no infrastructure) precision location on the order of 1 foot accuracy indoors?
Possible Approaches

- GPS
- Impulse Ultra-Wideband (UWB)
- Inertial Nav
- RFID
- Direction Finding (angle of arrival)
- Dead reckoning (Pedometer/Compass)
Significant Limitations:

- **Inertial Nav**: Cost/size/performance issues
- **RFID**: Requires existing infrastructure, insufficient precision
- **Direction Finding**: Multipath limited
- **Dead reckoning (Pedometer/Compass)**: Performance/usability issues
Remaining Possible Approaches

- **GPS?**
  - Insufficient resolution
  - Insufficient signal strength inside buildings
  - Multipath degraded
  - Significantly different requirements/uses
Differences from GPS

- Small operational area (< ~1km$^2$)
- Absolute geographic reference may not be needed
- User devices may be active
- Overall system cost must be kept low – especially the numerous user devices
- Entire system must be self-initializing, self-monitoring, self-repairing
Impulse UWB

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

- Extremely narrow pulses imply large signal acquisition times, difficult tracking, huge bandwidth
- Pulse generation and time-windowing at receiver may require exotic, costly, 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
True benefit of I-UWB?

- **Marketing!**
  - The approach is immediately appealing because of the vivid transparency of its operation
  - Its short pulses on direct path transmission arrive before any reflections and hence allow multipath elimination and precise location.

- **The reality is:**
  - This compelling picture obscures the fact that short pulses are not needed for precision location.
Multi-Carrier Ultra-Wideband

Solution found within two recent innovations:

- Super-resolution SAR/ISAR Radar
  - Enhances Radar resolution to centimeters
- Orthogonal Frequency Division Multiplexing
  - A data communications innovation which allows high speed data to be transmitted over low-quality telephone wires (DSL service) or via wireless
Conventional vs. Super Resolution Radar

High Bandwidth

Low Bandwidth

Super-Resolution
The OFDM Concept

Channels spaced $\Delta f$

Pulses transmitted at rate $1/\Delta f$

Interferer

Constellation and bit rate and power chosen per channel

Distortion

Noise
MC-UWB Summary

- Precision location (cm accuracy)
- Operation in multi-path environment
- Compatibility with existing communications services
- Combined location and high bandwidth communication capability
Position determination

- MC-UWB method provides time differences between roving transmitter and reference receivers
- Sophisticated signal processing techniques are applied
- Numerical solution method determines distances and then positions while rejecting multipath signals
Prototype Architecture

Reference Unit, fixed location
Reference Unit, fixed location
Reference Unit, fixed location
Reference Unit, fixed location
Mobile Unit
Command and Control Unit, fixed location
Reference Unit, fixed location
Reference Unit, fixed location
Reference Unit, fixed location

MC-UWB signal
802.11 System control

Reference units emit MC-UWB signals during initialization phase
Proof of Concept Demonstration

- Used audio, not RF - greatly eased prototyping
- Top audio freq. has wavelength in air of 4.5"
- 1:1 scale behavior with RF BW 2.625 GHz
- Demo of real-time location with laptop PC
- Off the shelf microphone/speaker components could be used thanks to the OFDM like signal
- Displays true location solution and multipath solutions
Proof-of-Concept Demonstrator
Demonstration
System Analysis and Design

- To move from concept to implementation:
  - Complete analysis of performance
    - Mathematical performance modeling
    - System Engineering criteria
    - Simulation of end-to-end system

- Prototype Construction/Evaluation
  - Troubleshooting/Feedback/Re-analysis

- Development of encompassing technology
  - Auto-calibration, data exchange, …
System Engineering Tools

Contour lines of Period Energy (from bottom right: 1E-15, 2E-15, 5E-15, 1E-14, ... [J])

Array Length [m]

Fractional Bandwidth

CTC/WPI Requirements Assessment Focus Group
Position Solution Simulation

• The MC-UWB concept only provides the node-to-node distances.

• An optimized position solver was needed.

• Using this simulator many approaches were evaluated.
Sensor Placement/System Criteria

Performance is affected by external factors such as placement of sensors.

Simulation again played a large engineering role.
Automatic Calibration Problem

By exchanging signals, each RN can determine its distance from each other RN.

The geometry of the configuration must be found from these internodal distances.

This is known as the multi-dimensional scaling (MDS) problem.
Prototypes Galore

Every concept, analysis and algorithm was confirmed along the way with a prototype and lab test.
Demonstrator Target Systems

- Goal: construct demonstration systems that allow evaluation of MC-UWB approach

- Two RF based “Software Radio” demonstration systems being constructed
  - Wideband (50 MHz) system at 400 MHz
  - Narrowband (6 MHz) system at 2.4 GHz

Let’s take a closer look at the engineering of the wideband system implementation…
RF and Software Radio Design

- RF Electronics for 440 MHz Software Radio

Phase 1:
- 6 MHz bandwidth
- 50 MSamples/sec

Phase 2:
- 50 MHz bandwidth
- 200 MSamples/sec
Receiver RF Chain

- Antenna
- Mixer
- A/D
- FPGA (PC interface)
Digital/RF Testing
Embedded System Design

- Transmitter requirements
  - Continuously transmits the OFDM signal
  - Must be small, lightweight, and have low power consumption (battery powered)

- Receiver requirements
  - Self configuring
  - Continuously receives transmitter signals to determine position in 3-dimension
  - Complex signal processing
Example System Implementations

- Use high density integrated circuits
  - Very versatile, code can be upgraded
  - Microcontrollers
    - Like PC but much smaller and more reliable!
  - Field Programmable Gate Arrays (FPGAs)
    - Devices with >1,000,000 gates
    - Need special programming languages
      - VHDL
        » VHSIC HDL
        » Very High Speed Integrated Circuit
Designing receiver and transmitter boards
Designing the new chips - pins!
Inside the integrated circuits
Simulating the Receiver and Transmitter
Status

- DOJ/NIJ Support: $996,497
- Analytic, simulation and proof-of-concept, system optimization, performance analysis completed
- Selection/optimization of TDOA position solver and evaluation of geometric effects completed
- Five reference node 3D location demonstrated
- Two RF based demonstration systems (narrowband and wideband) at 400 MHz and 2.4 GHz under construction based on Software Radio Design
- Wideband and narrowband concept tests successful
  - 1 foot in 12000 km resolution with 100 KHz wide signal!
Next Steps

- Complete construction and troubleshooting of the two RF demonstrators
  - Narrowband demo: Q3-Q4, 2004
  - Wideband demo: Q1, 2005
- Introduce all-encompassing software and hardware systems: Q2, 2005
- Complete Precision Indoor Location System Demonstration: Q3, 2005
- Commercialization follows