Accuracy Enhancements for TDOA Estimation on Highly Resource Constrained Mobile Platforms

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Overview

- Introduction
- Motivation
- Challenges
- Solutions
- Results
- Demo

- Supported by DARPA / IXO
Introduction

- Increase in location aware systems and services, E911
- Need for close range monitoring
  - urban and hostile environments
- Need for intelligence in hazardous areas
- Availability of enabling technology
  - Low-cost, low-power DSP
  - RF networks
  - Positioning services (GPS)
Existing systems

- Large form factors
- Large stand off / fixed locations
- High cost
  - Cell phone base station
    ~$10,000
  - Military units (~$50,000-100,000)
- High precision, networked systems
- Urban clutter
- “Theater” level vs. field level

Image: courtesy Southwest Research Institute (SwRI ®)
Challenges

- Effective in urban areas
  - Uniform high precision in all scenarios
- Mobile = Small and low weight
- Longevity = low power
- Stealth = limited bandwidth
- Spatially separated = No global clock
- Low cost = No high precision sampling clock
- Varying environmental conditions
  - Differing radio characteristics
Solutions

- Local processing
  - Matched filtering with template
  - Stealth, low power, Low bandwidth
- GPS for global clock
  - Jitter correction, introspection
  - Lack of common global clock
- Doppler and time-shift correction
  - Using GPS clock for local clock calibration
  - Varying sample rates
  - Low precision clock
TOA electronics package

- DSP Module
- Analog Front-End
- A/D Converter (2MHz)
- Power Supply
- GPS, RF Modem

Weight: under 1 lb
Size: 4”x5”x6”
FRS Radio Modifications for IF

Benefits:
- Ability to use any radio
- Cheap
- Flexible

Challenges:
- Phase Linearity
- Poor Demod Perf.
- Poor Baseband Perf.
- Near Field Effects
- Limited Range

Diagram:
- 450 KHz IF (goes to A/D)
- Sharp IF Filter
- Frequency Synthesizer
- LNA
- Antenna
- High-“Q” Filter
- Quad Demod and Mixer
- 465MHz
- 20MHz
- Compander
- Audio AMP and speaker output
Signal processing system architecture

- Slow drift
  - GPS 1PPS
  - Local Osc Count

- LMS 1 PPS Estimator
- LMS Frequency estimator
- Corrected GPS

- Software Radio
  - Narrow-Band Filter 420-480K
  - Phase Locked Loop (Demod)

- Gross Signal Location
- Sample Rate Correct

- Generalized Cross Correlation
- Peak Estimation/Interpolation
- Global Clock Correction

TOA Est

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Effect of different sampling frequencies

\[ g(t) = f(s(t - \tau)) \]

\[ G(\omega) = s^{-1} F(\omega / s) e^{-j\omega \tau} \]
Approximating frequency scaling as shifting

- Doppler shift explanation
  - Taylor series approximation
- Let \( s = 1 - a \), then

\[
G(\omega) = 1/(1 - a)F(\omega/(1 - a))e^{-j\omega(1-a)\tau}
\]

If \( a << 1 \), we have

\[
G(\omega) = (1 + a)F(\omega(1 + a))e^{-j\omega(1-a)\tau}
\]

(Typically, \( a = 20-200 \) ppm)
For narrow band signals,

\[ F(\omega_0 + \delta \omega) = 0, \left| \delta \omega \right| > \frac{\omega_b}{2} \]

\[ F(s \omega) = F(s \omega_0 + \delta \omega) = 0, \delta \omega = \omega - \omega_0 \]

\[ G(\omega) \approx (1 + a)F(\omega + a\omega_0))e^{-j\omega \tau} \]

\[ g(t) \approx f(t - \tau)e^{-j\omega_d(t-\tau)} \]

where \( \omega_d = a \omega_0 = (1-s) \omega_0 \)
Disadvantages of Doppler shifting

- Input signals modulated by complex exponential before Fourier domain correlation

\[
\tau = \arg \max \left[ \int_{-\infty}^{\infty} f(u)g^*(u + t)e^{-j\omega t} du \right]
\]

- Input signals become complex
- Memory requirement doubles
  - Greater memory access times
  - Lower through put
  - More power consumption
  - More memory / faster memory = greater cost
Can we shift in time instead of frequency?
- Accomplished by multiplication by complex exponential in frequency domain
- Performed during frequency domain correlation operations

Time and frequency are duals
Shifting and approximating in time = shifting and approximating in freq
Time domain effects of different sampling rates

- Faster sampling rate “delays” features in the sampled domain
- Compensate by advancing delayed signal

\[ \tilde{F}(\omega) = F(\omega)e^{j\tau_d\omega} \]

\[ \tilde{f}(t) = f(t + \tau_d) = f(t + (s-1)\frac{T_2 - T_1}{2} - s\tau) \]

Effect of differing sample rates on cross-correlation

\[ f(t) = \cos(20t + \pi/6) \]

- \( F_s = 500 \) Hz
- \( F_s = 1000 \) Hz
Comparing the two

- Trade-off between accuracy and performance
  - **Doppler**
    - Affords greater accuracy
    - Requires more memory / computation
    - Modulates entire signal with complex cosine before xcorr
  - **Time-shifting**
    - Provides acceptable accuracy
    - Uses lesser memory (input signal stays real)
    - Applies only to few significant frequency bins
    - Faster throughput

- Approximations are easy to apply

\[
\exp(j \omega_d t) = 1 + j(\omega_d t)
\]
Results – Evaluating correction techniques

- Corrected error is within allocated error budget for the signals of interest
  - Signal of interest (1Khz – 3kHz) PRN
  - Oscillator clock drift: ±100 ppm
  - Delay in uncompensated case: ~1-10 µ-sec
  - Duration of signal of interest (template): 0.2 sec
  - Nominal sampling freq: 2 MHz
Testing Results
Time-of-arrival Consistency

Delta
2m
103m
190m
127m
170m
1243m

Measured TOA vs Actual

Actual Distance
0.00 200.00 400.00 600.00 800.00 1000.00 1200.00 1400.00

Measured TOF
0.00 200.00 400.00 600.00 800.00 1000.00 1200.00 1400.00
Conclusion

- Developed a new TDOA system
  - Highly constrained
  - Solved several problems due to distributed clocks
  - Developed algos
  - Tested in field
Questions/ Applause?
Road Map

- Overview
  - Present all the different topics we are going to talk about
- Introduction
  - Increase in location aware systems and services, E911
  - Need for close range monitoring – urban and hostile environments
  - Need for intelligence in hazardous areas
- Motivation
  - Cost – compare cell phone/ E911
  - Large stand off
  - Urban clutter
  - Theater level vs. field level
- Challenges
  - Spatially separated - Lack of global clock
  - Stealth + low-power - Lack of bandwidth for communication
  - Cost - No high precision common sampling clock
  - Varying environmental conditions – changing sample rates
- **Solutions**
  - Local processing – matched filtering with template
  - GPS for global clock – jitter correction, introspection
  - Doppler and time-shift correction – varying sample rates
- **Signal processing system architecture**
  - Insert picture here
- **Effect of different sampling frequencies**
  - Show picture of how things scale with changing sampling freq
  - Show equation
- **Approximating scaling with frequency shifts**
  - Doppler shift explanation – Taylor series approximation
  - Include figure from Sonar signal analysis
- **Disadvantages of Doppler shifting**
  - Input signals modulated by complex exponential
  - Input signals become complex
  - memory requirement doubles -> greater memory access times
Alternative correction
  - Time shifting
  - Time and frequency are duals
    - Insert picture for gate function and sinc function
  - Shifting and approximating in time = shifting and approximating in freq
  - Include relevant equations here

Advantages
  - Reduces memory requirements
  - Reduces access times
  - Approximation is easy to apply
    - Add equation for $1 + jw$
  - Trade-off between accuracy and performance

Results
  - Simulation results
  - Field results

Demo