Time-based Location Techniques Using Inexpensive, Unsynchronized Clocks in 802.11 Wireless Cards

PinPoint Location System

Matthew Mah
Ashok Agrawala

University of Maryland, College Park

March 25, 2010

Goals for PinPoint Location System

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Meter-level location accuracy for mobile devices
  - 1 μs $\approx$ 300m
  - 1 ns $\approx$ 0.3m (1 ft.)
- Locate both system participants and nonparticipants
- Use inexpensive, off-the-shelf hardware
- Require no synchronization infrastructure

Location Methods For Wireless Signals

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

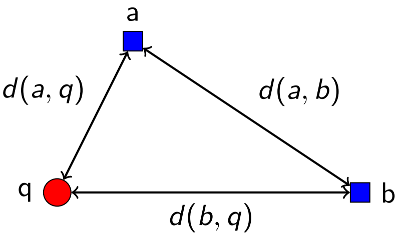
Data Source	Process
Angle	Triangulation
Signal Strength	Radio Map
Time	Trilateration, Hyperbolic Location

- Hybrid systems combine data sources
- Measuring angle of arrival requires special antennas
- Radio maps require extensive calibration

Timing Location: TOA, TDOA

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Measure time accurately
- Convert times to distance: $D = c * \Delta t$. To simplify notation, use time version of distance $d = D/c$
  - Time of Arrival (TOA): $d(a,b), d(a,q), d(b,q)$
  - Time Difference of Arrival (TDOA): $d(b,q) - d(a,q)$



Distances for PinPoint TOA, TDOA

- Solve optimization problem for location

Time Notation

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Distinguish between idealized global time and measured local times

t	global time
τ	local clock time

- Describe send and receive times for network messages

$t^s(i)$	Send time of message i sent by s
$t^s_r(i)$	Receive time of message i sent by s and received at r
$\tau^s(i)$	Send time measured at s of message i sent by s
$\tau^s_r(i)$	Receive time measured at r of message i sent by s and received at r

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

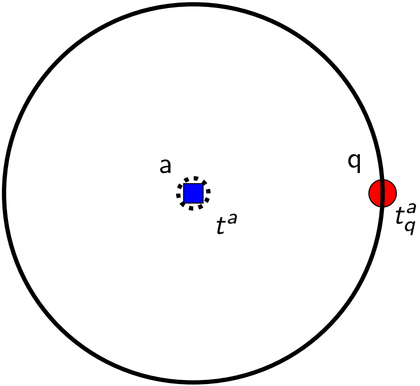
Time of Arrival (TOA)

1. Timestamped message sent from *a*

Time of Arrival (TOA)

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

1. Timestamped message sent from a
2. Reception is timestamped at q:
3. $d(a, q) = t_q^a - t^a$ Location is ambiguous within sphere solution set



Trilateration

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

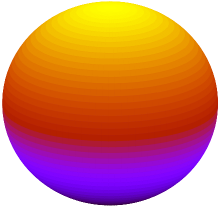
Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

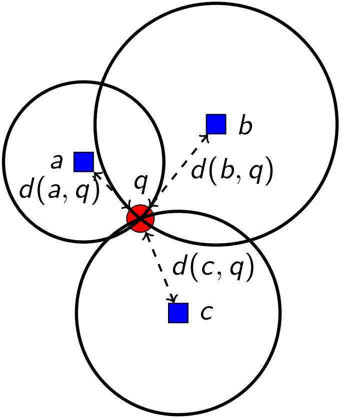
Future Work

Questions?



Sphere

- TOA measurements
- Solution is intersection of spheres
- Non-linear optimization problem to minimize

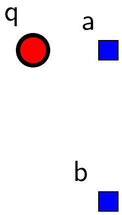


Trilateration

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Time Difference of Arrival (TDOA)

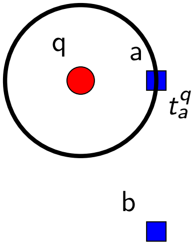
1. Message sent by q



Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

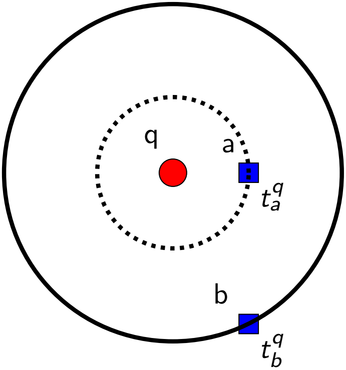
Time Difference of Arrival (TDOA)

1. Message sent by q
2. Message received by a at t_a^q



Time Difference of Arrival (TDOA)

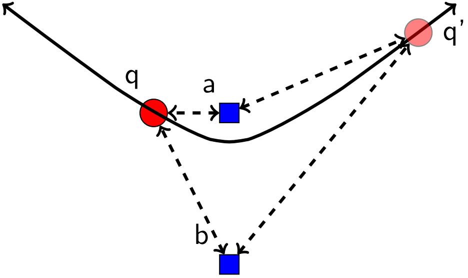
1. Message sent by q
2. Message received by a at t_a^q
3. Message received by b at t_b^q



Time Difference of Arrival (TDOA)

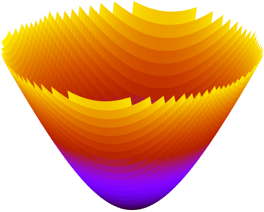
Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

1. Message sent by q
2. Message received by a at t_a^q
3. Message received by b at t_b^q
4. Solution set is hyperboloid with foci at A, B satisfying $d(b, q) - d(a, q) = t_b^q - t_a^q$

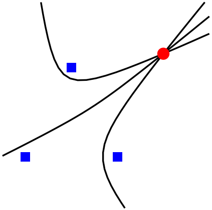


Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Hyperbolic Location



Hyperboloid Branch



Hyperbolic Location

- TDOA measurements
- Solution is intersection of hyperboloids
- Non-linear optimization problem to minimize difference of differences of distances

Challenges

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Must measure time very precisely and accurately: 1 ns $\approx$ 0.3m (1 ft.)
- Times from multiple clocks must be translated to common frame of reference
- Clocks drift at variable relative rates
- For 802.11, clocks are typically accurate to 10 ppm. Manufacturing specification is 100 ppm.

Existing Location Systems

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

Future Work

Questions?

	Mobile Unit Mode	
	Active	Passive
TOA	PinPoint TOA Goodtry Pseudolite	E-OTD GPS D-GPS A-GPS
TDOA	GSM UL-TOA PinPoint TDOA	E-OTD LORAN

Location System Classification

- For user privacy, passive mobile units are preferred.
- Nonparticipant targets must be active

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

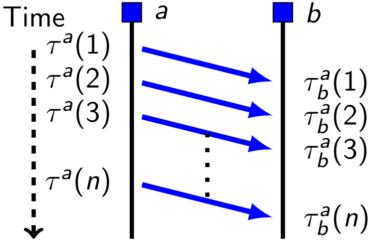
Clock Model

$$\tau_a^q = \beta_a(t^q + \alpha_a) + r + e_a^q \qquad \text{receive}$$
$$\tau^a = \beta_a(t^a + \alpha_a) + s + e^a \qquad \text{send}$$

- Each clock runs independently at separate rate β
- Each clock started at different time (α)
- Real time t is not directly measureable
- Time measured with receive delay r or send delay s in local time

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Pairwise Clock Drift



$$\frac{\beta_b}{\beta_a} = \frac{\tau^a_b(i) - \tau^a_b(i-k)}{\tau^a(i) - \tau^a(i-k)}$$

- From 802.11 standard, drift < 100ppm
- Apply exponential filter to repeated measurements to reduce error

Average Clock Drift: Fully Connected

Goals

Location Methods
TOA
TDOA

Challenges

Existing Location Systems

Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior

PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering

Experimental Results

Future Work

Questions?

- Pairwise clock drift estimated from set $\Omega = \{a, b, \ldots\}$
- Define $\beta_* = \frac{1}{|\Omega|} \sum_{\omega \in \Omega} \beta_\omega$
- For the matrix

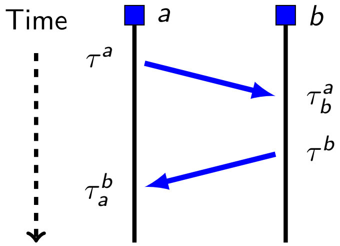
$$B = \frac{1}{|\Omega|} \begin{bmatrix} 1 & \frac{\beta_b}{\beta_a} & \frac{\beta_c}{\beta_a} & \cdots \\ \frac{\beta_a}{\beta_b} & 1 & \frac{\beta_c}{\beta_b} & \cdots \\ \frac{\beta_a}{\beta_c} & \frac{\beta_b}{\beta_c} & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

- Eigenvector for the greatest eigenvalue ($\lambda = 1$) contains conversions from local clocks to virtual global clock

$$\begin{bmatrix} \frac{\beta_*}{\beta_a} \\ \frac{\beta_*}{\beta_b} \\ \frac{\beta_*}{\beta_c} \\ \vdots \end{bmatrix}$$

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Round Trip Time and Clock Offset



Timestamped Messages

- Timestamped messages passed between two nodes to determine round trip time and clock offset as in SNTP
- Round trip time δ:

$$\delta = [(\tau_a^b - \tau^a) - (\tau^b - \tau_b^a)]$$

- Clock offset $\theta_{a \mapsto b}$:

$$\theta_{a \mapsto b} = \frac{1}{2}(\tau^b - \tau_a^b + \tau_b^a - \tau^a)$$

Nonlinear Behavior of $\theta_{a \mapsto b}$

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

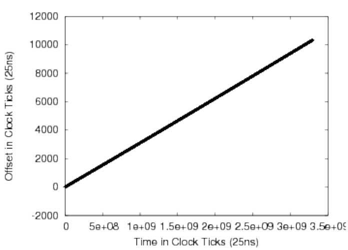
Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

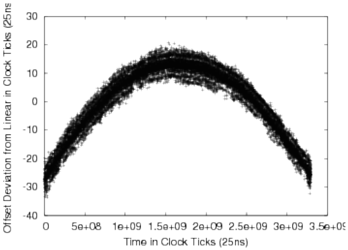
Experimental Results

Future Work

Questions?



$\theta_{a \mapsto b}$ over a 80 second interval



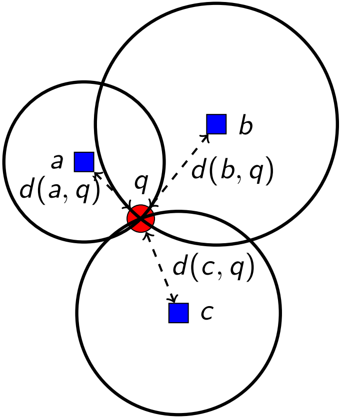
$\theta_{a \mapsto b}$ Deviation from Linear over 80 second interval

- Clocks behave nonlinearly even over short 80 second time periods
- Nonlinear behavior of approximately 0.01 ppm is within specified precision of 100 ppm
- Must model time to handle nonlinear behavior

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

PinPoint Variants

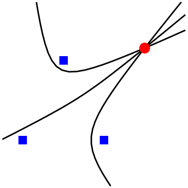
TOA



Trilateration

TDOA

1. Active Target
2. No Send Times
3. Low Traffic

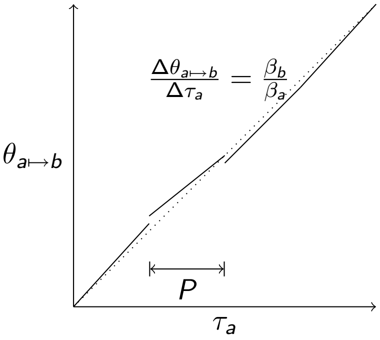


Hyperbolic Location

PinPoint Approach

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Frequently exchange messages to implicitly track nonlinearity of clock offset $\theta_{a \mapsto b}(\tau)$ with period P
- Assume piecewise linear model
- Filter and combine many samples to statistically improve distance estimate
- Solve nonlinear optimization problem to find location



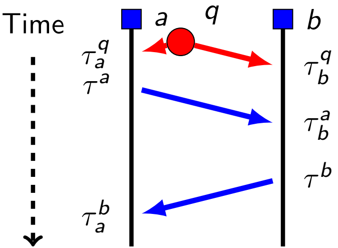
Piecewise Linear Approach

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

PinPoint Reference Equations

- Use messages passed between anchors to translate times
- Assume locally linear behavior

$$\tau^a = \beta_a(t^a + \alpha_a) + s_a + e^a$$
$$\tau_b^a = \beta_b(t^a + \alpha_b + d(a, b)) + r_b + e_b^a$$
$$\tau^b = \beta_b(t^b + \alpha_b) + s_b + e^b$$
$$\tau_a^b = \beta_a(t^b + \alpha_a + d(a, b)) + r_a + e_a^b$$
$$\tau_a^q = \beta_a(t^q + \alpha_a + d(a, q)) + r_a + e_a^q$$
$$\tau_b^q = \beta_b(t^q + \alpha_b + d(b, q)) + r_b + e_b^q$$



PinPoint TDOA Messages

Goals

Location Methods
TOA
TDOA

Challenges

Existing Location Systems

Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior

PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering

Experimental Results

Future Work

Questions?

PinPoint Variants Qualitative Comparison

No Send Times Some drivers support receive timestamps but not than send timestamps. A protocol without send times supports more platforms.

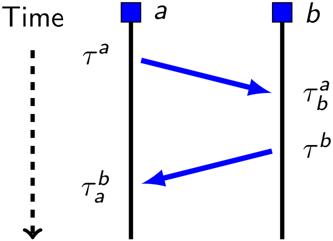
Participant Target node must timestamp

Active Target node must send messages frequently

Variant	*No Send Times*	*Participant*	*Active*
TOA		$\surd$	$\surd$
TDOA			$\surd$
TDOA No Send Times	$\surd$		$\surd$
TDOA Participant		$\surd$	

PinPoint TOA

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?



$$\beta_* d(a,b) = \frac{1}{2}\left[\frac{\beta_*}{\beta_a}\left[\left(\tau_a^b - \tau^a\right) - (r_a - s_a)\right] - \frac{\beta_*}{\beta_b}\left[\left(\tau^b - \tau_b^a\right) - (s_b - r_b)\right]\right]$$

PinPoint TDOA: Active Target

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

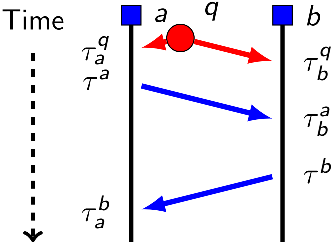
Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

Future Work

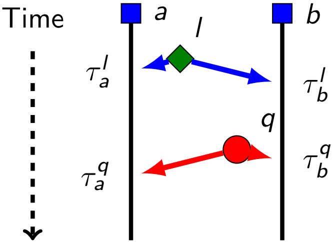
Questions?



$$\beta_*(d(b,q)-d(a,q)) = \frac{\beta_*}{\beta_b}\left(\tau_b^q - \frac{1}{2}(\tau^b+\tau_b^a)-(r_b-s_b)\right) - \frac{\beta_*}{\beta_a}\left(\tau_a^q - \frac{1}{2}(\tau^a+\tau_a^b)-(r_a-s_a)\right)$$

PinPoint TDOA: No Send Times

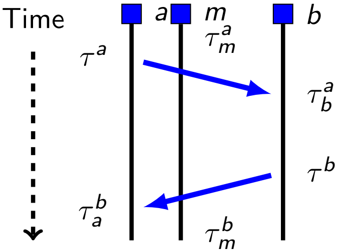
Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?



- Requires geometry for a, b, l, which may be known beforehand or computed with TOA.

$$\beta_* \left[d(b,q) - d(a,q)\right] = \beta_* \left[d(b,l) - d(a,l)\right] + \frac{\beta_*}{\beta_b}\left(\tau_b^q - \tau_b^l\right) - \frac{\beta_*}{\beta_a}\left(\tau_a^q - \tau_a^l\right)$$

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?



- m must timestamp and estimate clock drift, but is not required to send messages for each distance estimate

$$\beta_* \left(d(b,m) - d(a,m)\right) = \frac{\beta_*}{\beta_m}\left(\tau_m^b - \tau_m^a\right) - \frac{1}{2}\frac{\beta_*}{\beta_b}\left(\left(\tau^b - \tau_b^a\right) - (r_b - s_b)\right) + \frac{1}{2}\frac{\beta_*}{\beta_a}\left(\left(\tau^a - \tau_a^b\right) - (r_a - s_a)\right)$$

Card Delay Equations

Goals

Location Methods
TOA
TDOA

Challenges

Existing Location Systems

Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior

PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering

Experimental Results

Future Work

Questions?

- Times reported by wireless cards are consistently biased.
- Anecdotally stable for 20+ minutes
- Measured with anchor nodes colocated such that $d(a,b) = d(b,q) - d(a,q)$.
- Requires 3 nodes to measure

$$r_b - s_b = \tau_b^q - \tau^b + \frac{\beta_b}{\beta_a}\left(\tau_a^b - \tau_a^q\right)$$

$$r_a - s_a = \frac{\beta_a}{\beta_b}(-\tau_b^q + \tau_b^a) + \tau_a^q - \tau^a$$

Card Delay Results

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Beacon Interval (k ticks)	Clock Speed (MHz)	Sample Size	$r-s$ clock ticks 5213A	2414
100	20	48000	22422.65	-54377.87
500	20	11000	22423.20	-361577.38
1000	20	6000	22423.02	-745577.91
1000	40	8000	45230.69	-722771.39

Card Delays

- Delays vary with card, beacon interval and clock speed
- Send delays appear to increase linearly with beacon interval
- Error from neglecting $r-s$ is $(\frac{\beta_b}{\beta_a}-1)*(r-s)$. For $(\frac{\beta_b}{\beta_a}-1) = 10*10^{-6}$ and $r-s = 45000$, this is 0.45 clock ticks, or roughly 4 m at 40 MHz clock speed.

Error for PinPoint TOA and TDOA

- Assumptions
  1. Anchor messages send periodically roughly every P clock ticks
  2. Send and receive errors are independent with standard deviation σ
  3. $r - s$ can be determined accurately using prior data
  4. There is a value of $\frac{\beta_\omega}{\beta_*}$ within ϵ of real clock drift values for entire time period
  5. We can estimate $\frac{\beta_\omega}{\beta_*}$ within ϵ

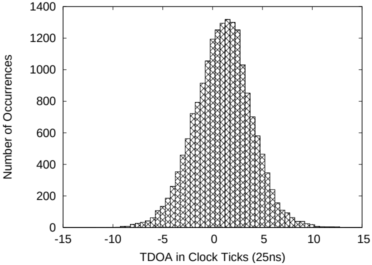
Algorithm	Std Dev	Bias
TOA	σ	$\epsilon[(r_a - s_a) + (r_b - s_b) + P]$
Active Target	$\sqrt{3}\sigma$	$\epsilon[\frac{1}{2}((r_b - s_b) + (r_a - s_a)) + 2P]$
No Send Times	2σ	$2\epsilon P$
Low Traffic	$\sqrt{3}\sigma$	$\epsilon[\frac{1}{2}((r_b - s_b) + (r_a - s_a)) + 2P)$

Expected Error for PinPoint Variants

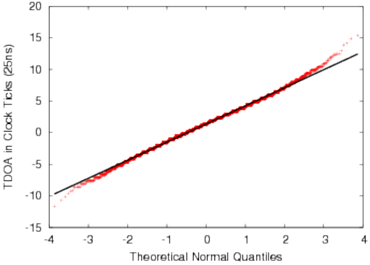
TDOA Filtering

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

- Filter out all outliers outside $[\text{median} - 10, \text{median} + 10]$
- Standard deviation 2.83 clock ticks



Histogram of TDOA readings for 15.24 m



QQ Plot shows TDOA distribution has long tails

PinPoint TDOA Test Setup

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

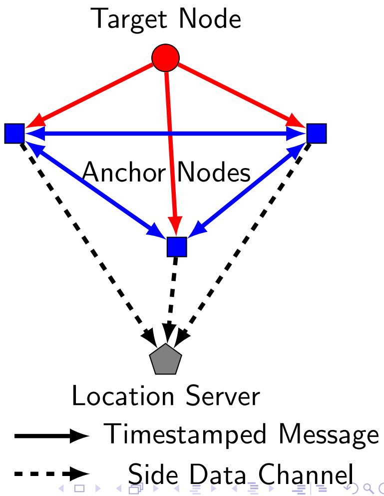
PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

Future Work

Questions?

- 3 Anchor laptops arranged in indoor corridor environment
- Anchors attached using secondary network card to wireless router
- Separate display unit
- All anchor nodes operate with 40 MHz reference clocks and beacon interval of 1000
- All nodes are operating on the same channel



PinPoint TDOA End-to-End Results

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

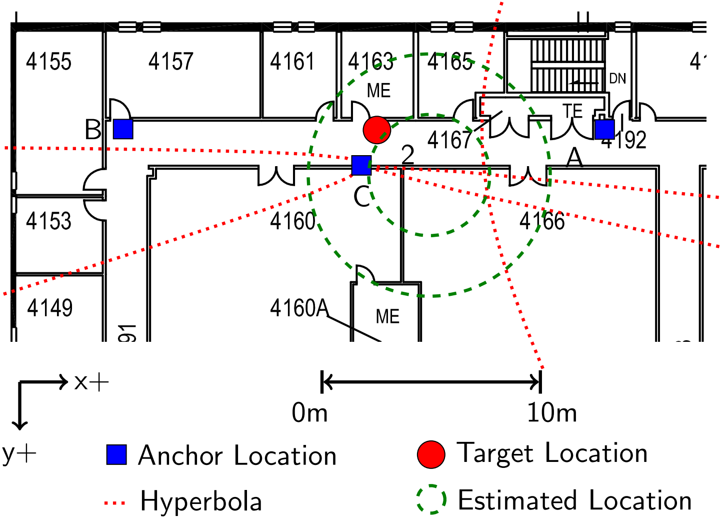
Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

Future Work

Questions?



Localization Example

PinPoint TDOA Location Error

Goals

Location Methods
- TOA
- TDOA

Challenges

Existing Location Systems

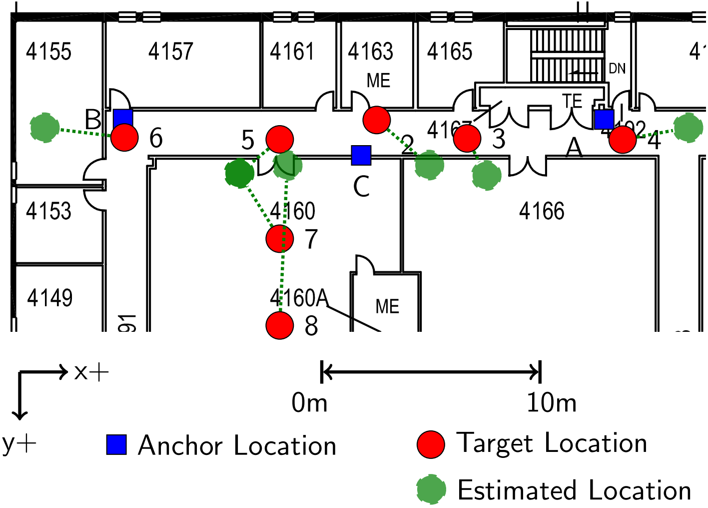
Clocks
- Clock Drift
- Round Trip Time and Clock Offset
- Nonlinear Clock Behavior

PinPoint
- TOA
- TDOA Variants
- Card Delays
- Error Analysis
- Filtering

Experimental Results

Future Work

Questions?



Location estimated within 3.5m for line-of-sight arrangements

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

Future Work

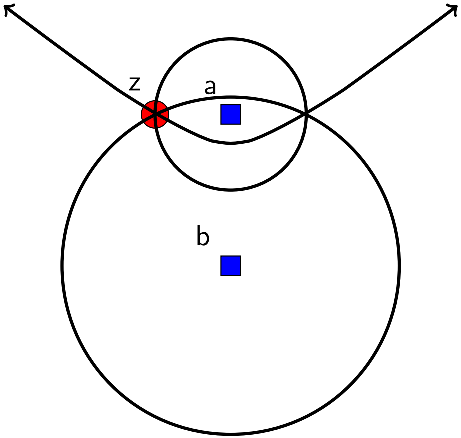
1. Fusion of TOA and TDOA data
2. Improvement of TOA and TDOA accuracy
3. Semi-definite programming for TOA optimization
4. Implementation for embedded devices
5. Applications for MyeVyu, etc.

Questions?

Goals
Location Methods
TOA
TDOA
Challenges
Existing Location Systems
Clocks
Clock Drift
Round Trip Time and Clock Offset
Nonlinear Clock Behavior
PinPoint
TOA
TDOA Variants
Card Delays
Error Analysis
Filtering
Experimental Results
Future Work
Questions?

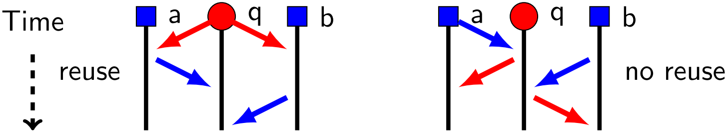
Hybrid TOA-TDOA Problem

- Fusion of TOA and TDOA data
- Related work approaches are for simulated data and do not consider use of timestamps for both TOA and TDOA



Hybrid $d(b, q) - d(a, q)$

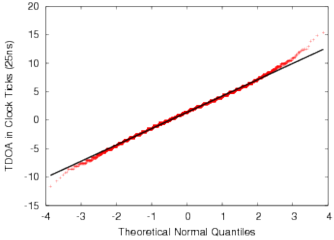
- Examine basic hybrid computation
- Two basic ways to compute $d(b, q) - d(a, q)$
  1. TDOA(a, b, q)
  2. TOA(b, q) − TOA(a, q)
- Also two ways to compute TOA(b, q) − TOA(a, q) based on whether messages are reused across nodes



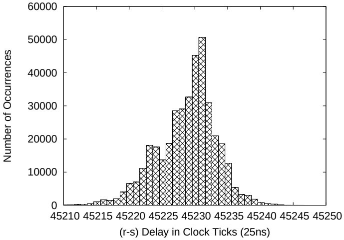
- Minimize variance of difference for PinPoint computations $k\text{TDOA}(a, b, q) + (1 - k)(\text{TOA}(b, q) - \text{TOA}(a, q))$

	Optimal k	Best Hybrid Solution
TOA w/ reuse	0	TOA only
TOA w/o reuse	0.25	TOA and TDOA

TOA and TDOA Accuracy



QQ Plot shows TDOA distribution is non-normal

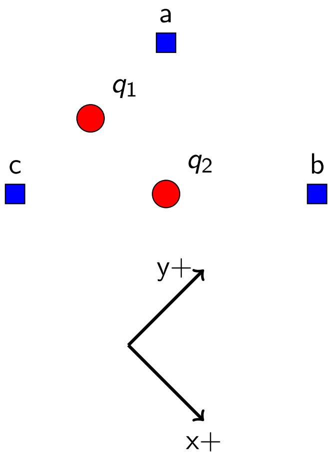


Histogram of Card Delays

- Error model required to explain non-normal TDOA behavior
- Card delay histogram is unexpectedly asymmetric
- Multipath issues may also need to be explored

Local Coordinate System Integration

- Solved problem in sensor network field, solutions need to be integrated
- Coordinates are relative to PinPoint nodes
- No anchor nodes with known position are required
- Nodes discover their own coordinates
- Combine capability to compute location of stranger nodes



Goodtry

- 802.11 TOA trilateration system
- Exploit fixed interframe spacing between RTS, CTS, data, and ACK frames
- data traffic between nodes a and b allows all nodes to measure $d(a, b)$
- $O(n^2)$ algorithm to find all pairwise distances