# Secure Location Verification with Hidden and Mobile Base Stations

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## Outline

- Introduction
- Model
- Infrastructure Centric Localization
- Node Centric Localization
- Sensor Networks with Mobile Base Stations
- Mobile Ad Hoc Networks
- Analysis
- Conclusion

## Overview

- Determining node location and ranging is used to implement location based routing and location related functions including access control
- Techniques rely on measurement of radio time of flight (RF ToF), ultrasound time of flight (US ToF), measurement of received strength of radio signals (RF RSS)
- Techniques are vulnerable to attacks

Introduction - Overview

## Approach

- Proposed methods do not require fast processing at the prover and works with use of any kind of ranging
- Approach relies on Covert Base Stations (CBS) – location unknown to attacker when localization is performed. CBS is typically passive
- Goal – prevent a node from lying about position

Introduction - Approach

## System Model

- Localization infrastructure consists of set of CBSs and Public Base Stations (PBS)
- Assumptions:
  -Attacker can not tamper with CBS location or compromise a CBS
  -Every node shares a secret key with each PBS or each PBS holds authentic public key of node
  -CBS can measure signal strength and perform ranging
  -Communication between CBS and PBS is through channel that preserves location privacy (e.g. wired or infrared)
  -Nodes have a limited number of attempts to prove location

Model - System Model

## Attacker Model

- Two types of attacks:
  -Internal - Dishonest or compromised node provides a false location
  -External – External attacker is able to spoof an honest node's position
- Two types of localization systems:
  -Node centric – Node computes its own location
  -Infrastructure centric – Infrastructure computes location of nodes

Model - Attacker Model

## Infrastructure Centric Localization w/ CBS

- System based on utilizing time difference of arrival (TDOA) and CBSs

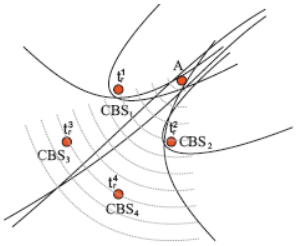



Fig. 1. An example of positioning with Time Difference Of Arrival. The base stations $CBS$ measure the differences of signal arrival times, and compute the position of node $A$.

**TDOA with hidden base stations**

1 $PBS(t_s) \rightarrow A: N$
2 $A \rightarrow *:$ m $= \{A, N, \text{sig}_{K_A}(A, N)\}$
3 $CBS_n$ : receive m at $t_r^n$
: with $t_r^1, \ldots, t_r^n$, compute $p$ with TDOA
: if $\sum_{i>j}(|t_r^i - t_r^j| - h(p,i,j))^2 \leq \Delta$ and $\max_i(t_r^i - t_s) \leq T$
then $p_A = p$; else reject $p$

$$p = \arg\min_{p^*} \sum_{i>j} (|t_r^i - t_r^j| - h(p^*, i, j))^2$$

Infrastructure Centric Localization-Model

## Infrastructure Centric Localization w/ CBS

- To cheat attacker needs to know, or correctly guess, location of CBSs
- Precision of $\Delta$ is key
- Wormhole attacks are partially mitigated through use of nonce and time period in which response is expected
- Node location privacy is not preserved as PBS is not authenticated

Infrastructure Centric Localization-Security Analysis

## Node Centric Localization - Model

- Node computes its own position, reports it to infrastructure through radio and ultrasonic messages, infrastructure verifies.

**Position verification with hidden base stations**

1 $PBS(t_s) \rightarrow A: N$

2 $A \rightarrow$ (rf)$*$ : $m_{rf} = p_F, \text{sig}_{K_A}(\text{rf}, p_F, N)$

(us) : $m_{us} = p_F, \text{sig}_{K_A}(\text{us}, p_F, N)$

3 $CBS$ : receive $m_{rf}$ at $t_{rf}$ and $m_{us}$ at $t_{us}$

: $d_F^e = d(p_F, p_{CBS})$

: $d_F^m = (t_{us} - t_{rf})s$

: if $|d_F^e - d_F^m| \leq \Delta$ and $(t_{rf} - t_s) \leq T$ then $p_A = p_F$; else reject $p_A$

Node Centric Localization-Model

## Node Centric Localization - Attacks

- Internal attack –
  False position report - CBS checks accuracy of reported distance
- External attack – Include spoofing, jamming, replay – Partially prevented through the use of time limit on responses
- Cloning attack not addressed, and again location privacy is not preserved (but could be)

Node Centric Localization-Attacks

# Sensor Networks with MBSs

- Method for secure localization using MBSs
- Sensors compute their location on their own
- An MBS securely knows its own location
- Each MBS shares a secret key with each sensor



# Model

- An MBS sends a verification request to a node from a location and then waits for a response at a different location

**Position verification with mobile base stations**

1 ($t_1$) $MBS \rightarrow A$ : MBS, $N, T_R$
2 ($t_2$) S $\rightarrow *$ (rf) : $p$, $\text{MAC}_K(\text{rf}, p, \text{MBS}, N)$
(us) : $p$, $\text{MAC}_K(\text{us}, p, \text{MBS}, N)$
3 $MBS$ : receive (rf) at $t_{rf}$ and (us) at $t_{us}$
: $d_S^e = d(p, p_{MBS})$
: $d_S^m = (t_{us} - t_{rf})s$
: if $|d_1^e - d_1^m| \leq \Delta$ and $(t_{rf} - t_1) \leq T_R$
: then $p_S = p$; else reject $p_S$

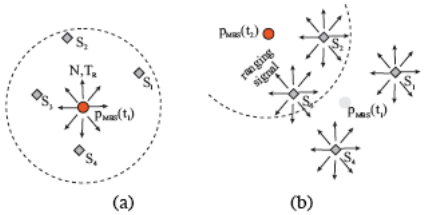
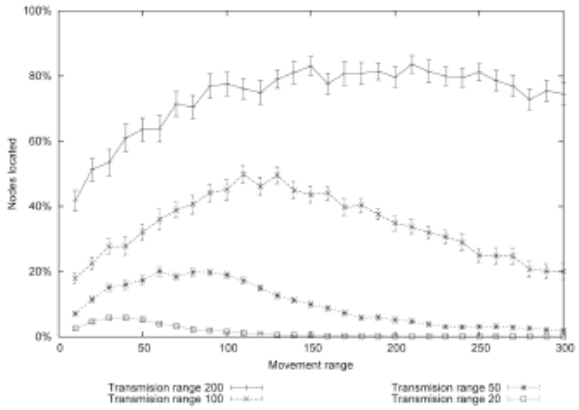



Fig. 4. Position verification in sensor networks. A mobile base station (MBS) verifies positions of nodes; (a) at time $t_1$ MBS challenges sensor nodes; (b) at time $t_2 > t_1$ the sensors reply to the challenge and their positions are verified by MBS.

# Coverage and Simulation

- If sensors are uniformly distributed and at each motion step the MBS moves within the circle defined by its power range it will hear at least 39% of the sensors in its power range at previous time interval





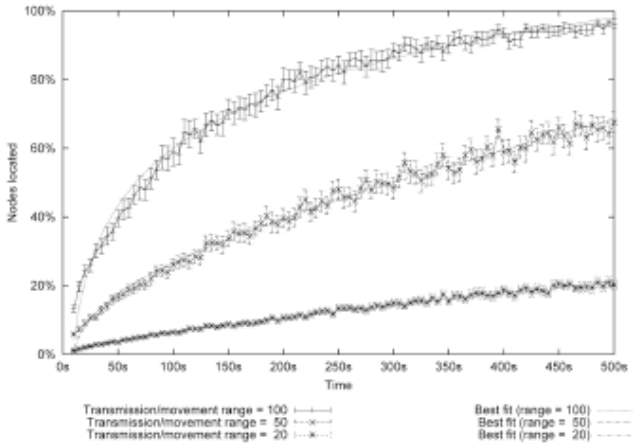




Fig. 10. MBS coverage as a function of time. Every point on the graph is the average result of 50 simulations, whereas the vertical bars indicate the 95 percent confidence interval.

# Node Centric Location Verification in Mobile Ad Hoc Networks

- No dedicated MBSs rather nodes obtain their own positions and rely on neighbors for verification
- Each node has public/private key pair and shares a secret key with location database server



# Protocol

$$
\begin{array}{l}
A: \text{pick } N \leftarrow \{0,1\}^k \\
A \overset{*}{\rightsquigarrow} *: A, P_A, T_A, N, \text{sign}_{K_A}\{A, P_A, T_A, N\} \\
\\
\quad B: d_A^c \leftarrow \text{dist}(P_A, P_B) \\
\quad\quad d_A^m \leftarrow (t_{us} - t_{rf}) \cdot v_s \\
\quad\quad \textbf{if } |d_A^c - d_A^m| \leq \Delta \\
\quad\quad \textbf{then } m \leftarrow \text{enc}_{K_{BS}}(B, A, T_B, P_A, ok) \\
\quad\quad \textbf{else } m \leftarrow \text{enc}_{K_{BS}}(B, A, T_B, P_A, nok) \\
\quad\quad stat_B \leftarrow m, \text{sign}_{K_B}\{m, N\} \\
\\
B \longrightarrow A: stat_B \\
A \longrightarrow S: m
\end{array}
$$

Fig. 12. Node $B$ issues a witness location statement, attesting if $A$ was at location $P_A$ at time $T_B$. Note that $A$ does not know if $B$'s witness statement is positive *ok* or negative *nok*. $A$ forwards this statement to the server $S$ (in a private message and possibly over multiple hops). $A$'s location $P_A$ is therefore disclosed only to its surrounding nodes (for location verification) and to the location server $S$ and is not disclosed to other network nodes.

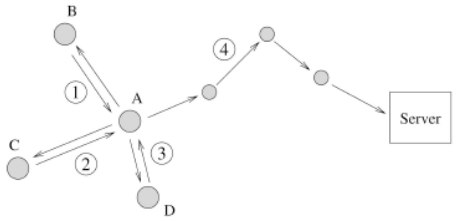



Fig. 11. Node $A$ gathers signed witness statements about its location in order to update a central location database (residing on the server $S$). Each using the protocol in Fig. 12, nodes $B$, $C$, and $D$ first verify the location of $A$ (steps 1, 2, and 3) and then send (to $A$) signed statements about their locations. $A$ then sends its position, along with the collected witness statements (positive and negative), in a confidential message to the server (step 4).

## Analysis

- Authors analyze probability that an internal attacker is able to cheat the proposed methods by guessing location of or distance to CBSs
- Success for attacker is when a false location is reported and the CBS calculates a reported position within the confidence interval that verifies the reported position

$$|d_F^c - d_F^m| \leq \Delta \qquad Pr(|d_F^c - d_F^m| \leq \Delta | p_F \neq p_A)$$

Analysis

## Analysis

- Assume localization occurs on a disk (2D) or sphere (3D) to reflect power ranges of devices
- Assume position of base station is uniformly chosen

Analysis

## Attacker Average Success Probability

- If attacker and hidden base station are placed uniformly on disk/sphere
- Authors show that the more precise $\Delta$ is and the larger the area of the disk/sphere the more secure the position verification becomes.
- An attacker's chance for success can also be reduced by using multiple CBSs for position verification



## Attacker Maximum Success Probability

- Which position on the disk/sphere will yield highest probability for success?
- Authors show that highest probability of success is when position is chosen at center of disk/ sphere and false measured distance is

$$d_F^m = R$$

# Analysis of Time Difference of Arrival

- When TDOA is used attacker must also guess direction where directional antenna should be pointed to send delayed message to correct base station
- Attacker desires to hit correct CBS and not hit any of the other CBSs
- Maximum probability of success occurs when angle chosen is 1/n where n is the number of base stations which is the max of

$$P_{hit} = \frac{\theta}{\theta_{max}} = \theta_{rel}, \qquad P_{intr} = (1 - \theta_{rel})^{n-1}.$$

- Probability of aiming N directional antennas at N CBSs without hitting any wrong CBSs $\prod_{n=1}^{N} \frac{1}{n}\left(1 - \frac{1}{n}\right)^{n-1}$
- Best case probability to cheat with 4 CBSs is 9.6 * 10^-9
- Attacker's probability of success can also be decreased by placing CBSs around the localization areas

Analysis

# Sensitivity

- Desire to set $\Delta$ such that it minimizes false negatives and false positives
- Two sources of error – error in reported position and error in distance measurement
- Assuming errors are normally distributed total error $|d_F^c - d_F^m|$ is $error \sim N(0, \sigma^2 = \sigma_P^2 + \sigma_R^2)$
- Let $\Delta = k\sigma$ and $(\sigma = \sqrt{\sigma_P + \sigma_R})$
- $s$ is defined as $1/k$ and is a measure of sensitivity

Analysis

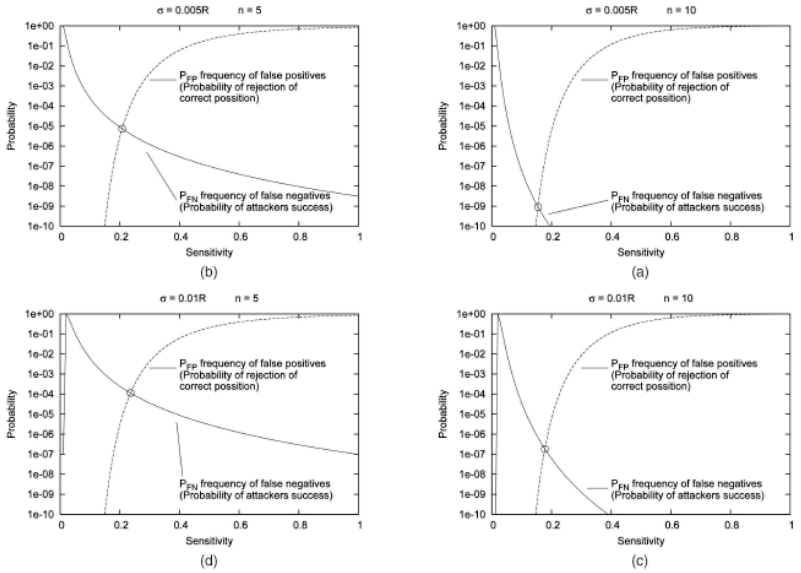



Fig. 17. The frequency of false positives and false negatives, and a crossover error rate for (a) $\sigma = 0.005R$ and $n = 5$, (b) $\sigma = 0.005R$ and $n = 10$, (c) $\sigma = 0.01R$ and $n = 5$, (d) $\sigma = 0.01R$ and $n = 10$. $s = 1/k$ is the sensitivity. $\Delta = k\sigma$ is the tolerated localization and ranging error. $\sigma$ is the standard deviation of the localization and ranging error. Note that the probability axis is logarithmic.

# Further Improvement

- If frequency of false positives is set to 1%

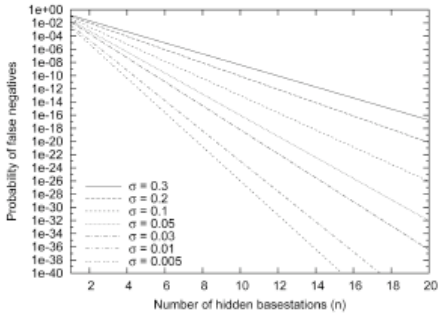



Fig. 18. The frequency of false negatives (the probability of the attacker's success) if the frequency of false positives is set to 1 percent.

Analysis

## Conclusion

- Approach proposes secure localization using CBSs in infrastructure centric and node centric scenarios
- Secure localization is also presented for secure localization in sensor networks with mobile base stations and for location verification in mobile ad hoc networks
- Future work will focus on implementation and will look into privacy