# Direct Methods for Geolocation over Multipath Channels

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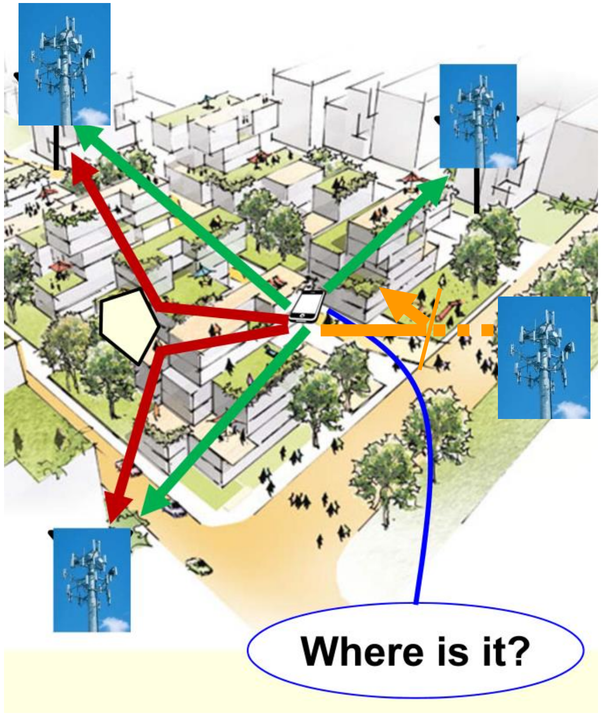
# At a Glance

- Goal: Localization (geolocation) of RF emitters in multipath environments

- Challenges:
  - Line-of-sight (LOS) paths
  - Non-line-of-sight (NLOS) paths
  - Blocked LOS paths (e.g. indoor)




- Applications:
  - Cellular map services
  - Defense applications
  - Location based services
  - E911

# Problem Statement



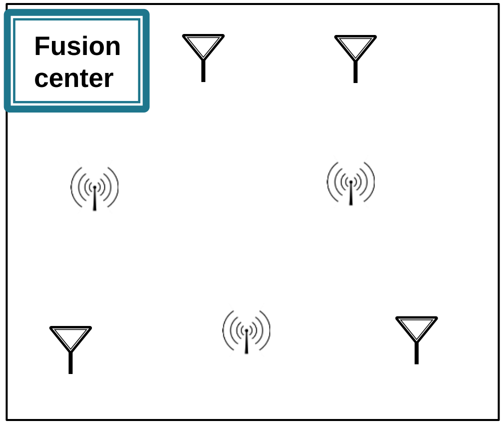
## Goal

- Estimate emitters locations

## Assumptions

- Network of distributed sensors with fixed, known locations
- Sensors have ideal communication with fusion center
- Emitters' waveforms and their timing are known
- Synchronization
  - Time synchronization between sensors and emitters
  - No phase synchronization
- Observation time << channel coherence time

  ☞ Time-invariant multipath channel
- No prior information on multipath channel



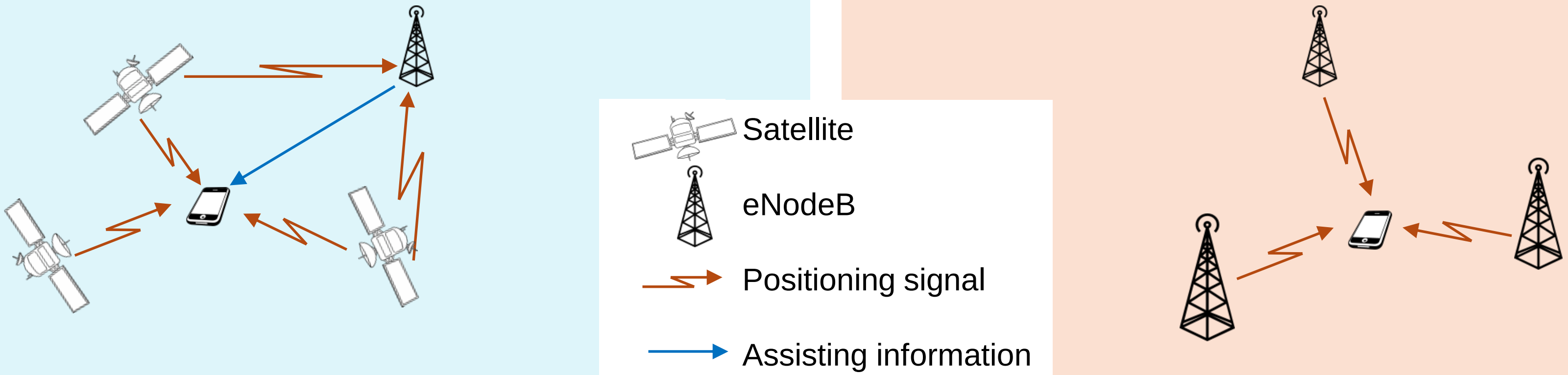
# Context - LTE Positioning Methods (I)

## Assisted Global Navigation Satellite System (A-GNSS) Positioning

- Relies on TOA's
- ✓ The eNodeB assists the UE so it can synchronize with the GNSS signals faster.
- ✗ Not more accurate than GNSS
- ✗ Challenged in dense urban and indoor situations

## Observed Time Difference of Arrivals (OTDOA)

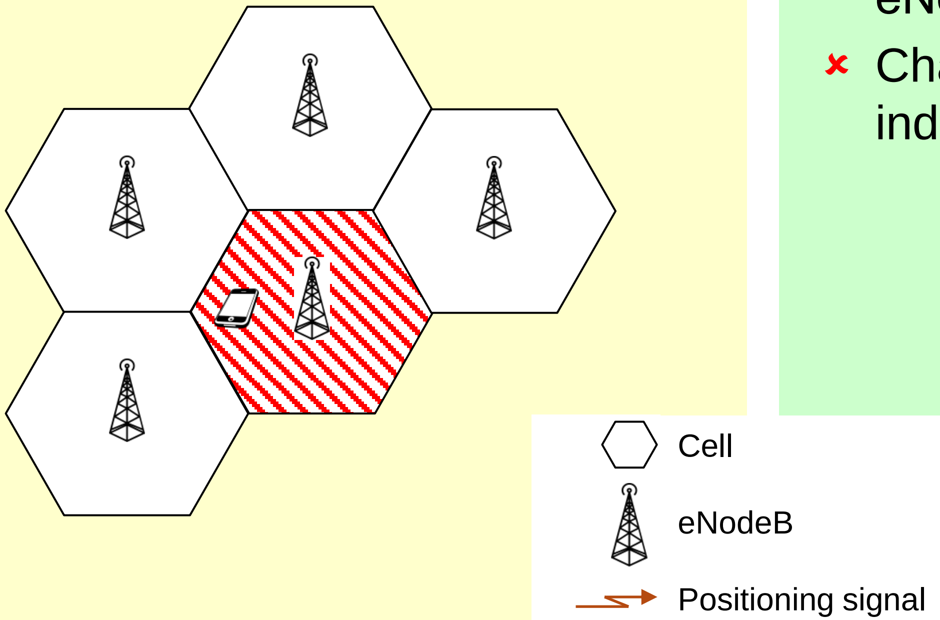
- Relies on TDOA's
- ✓ Faster than A-GNSS
- ✗ Requires synchronization among base stations.
- ✗ Requires signals from at least 3 eNodeB
- ✗ Challenged in dense urban and indoor situations



# LTE Positioning Methods (II)

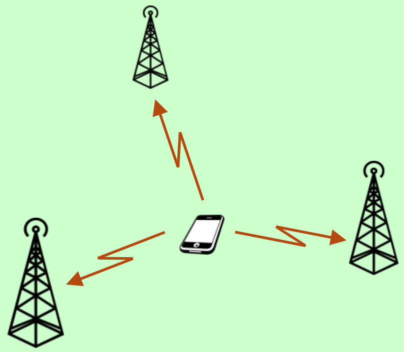
## Cell-ID-based Positioning

- ✓ Connection needed to only a signle eNodeB
- ✗ Very coarse accuracy




## Uplink TDOA (RAN)

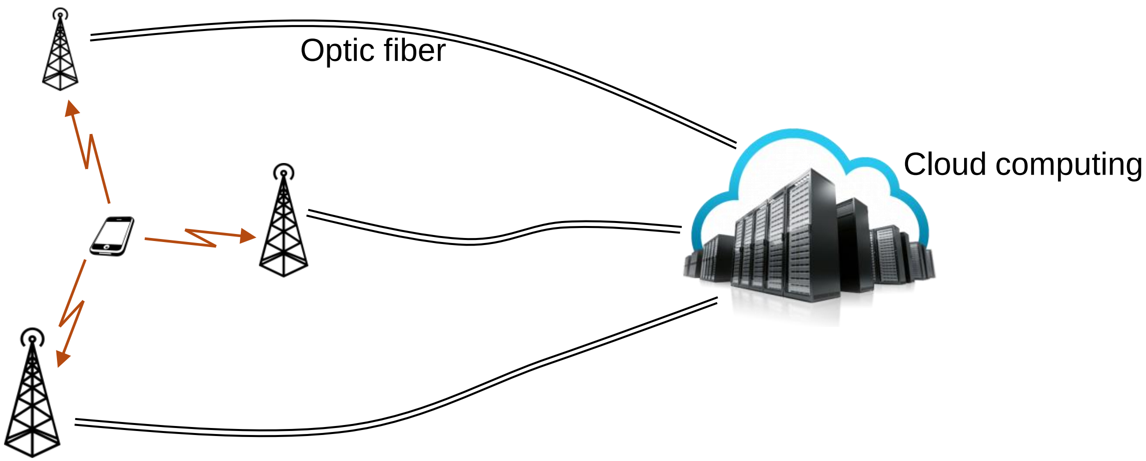
- Relies on TDOA's
- Uses uplink signals
- ✓ Computation done in the eNodeB's instead of the UE.
- ✗ Requires synchronization among eNodeB's
- ✗ Challenged in dense urban and indoor situations



# Cloud-RAN Positioning



- Future LTE releases may include Cloud Radio Access Network (Cloud-RAN or C-RAN)
  - Centralized processing architecture for cellular networks.
  - Base stations downconvert signals and relay them to a fusion center.
  - ✓ **Improved uplink positioning accuracy compared to RAN?**

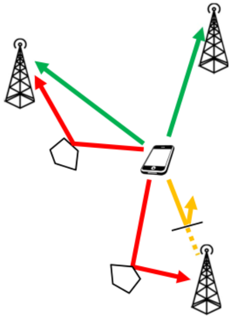



- Localization over multipath channels still an open problem!

# Signal Model

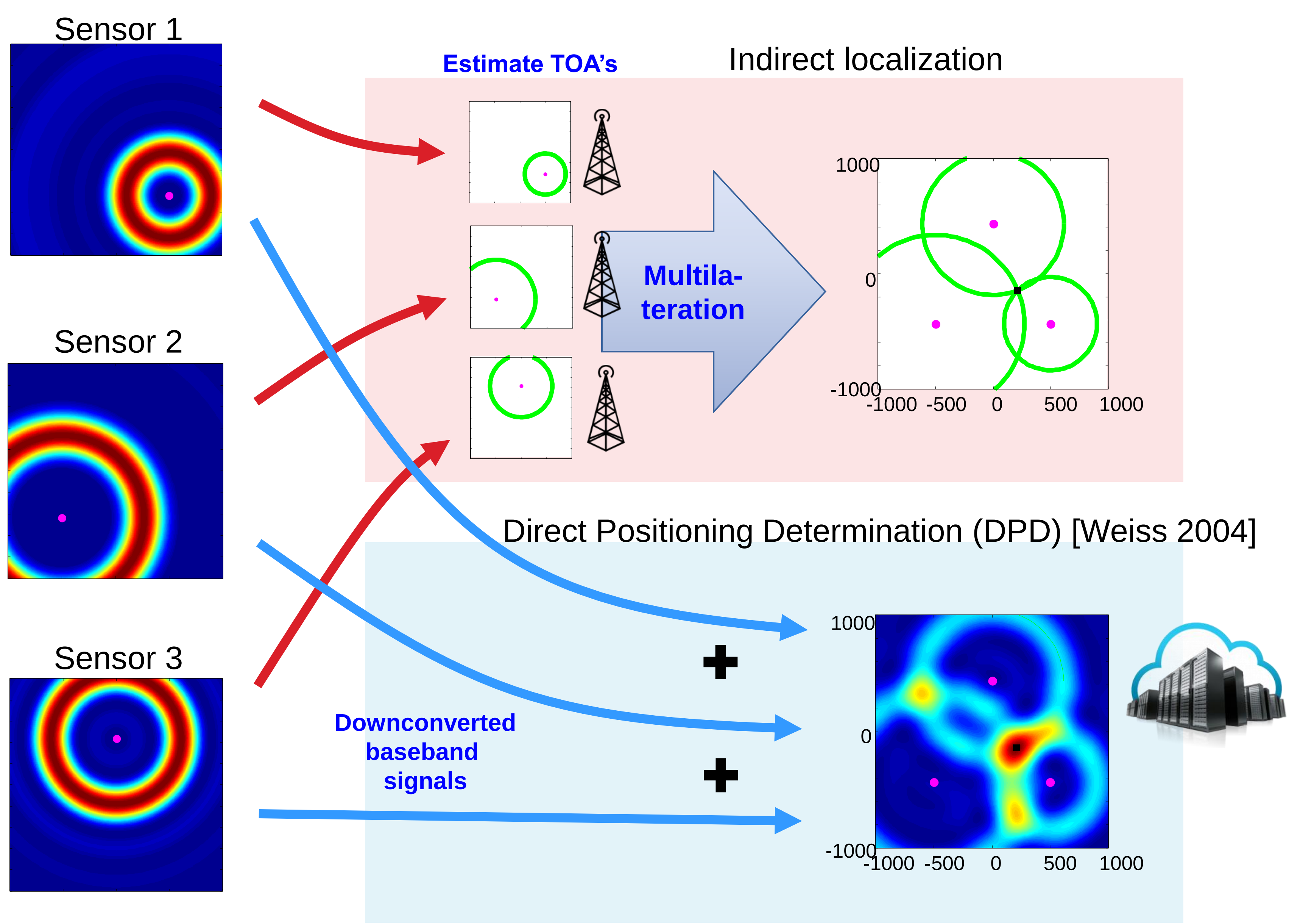
Signal at the $l$-th sensor:

$$r_l(n) = \sum_{q=1}^{Q} b_{lq} s_q\left(t - \tau_l(\mathbf{p}_q)\right) + \sum_{q=1}^{Q} \sum_{m=1}^{M_{lq}} b_{lq}^{(m)} s_q\left(t - \tau_{lq}^{(m)}\right) + n_l(t)$$



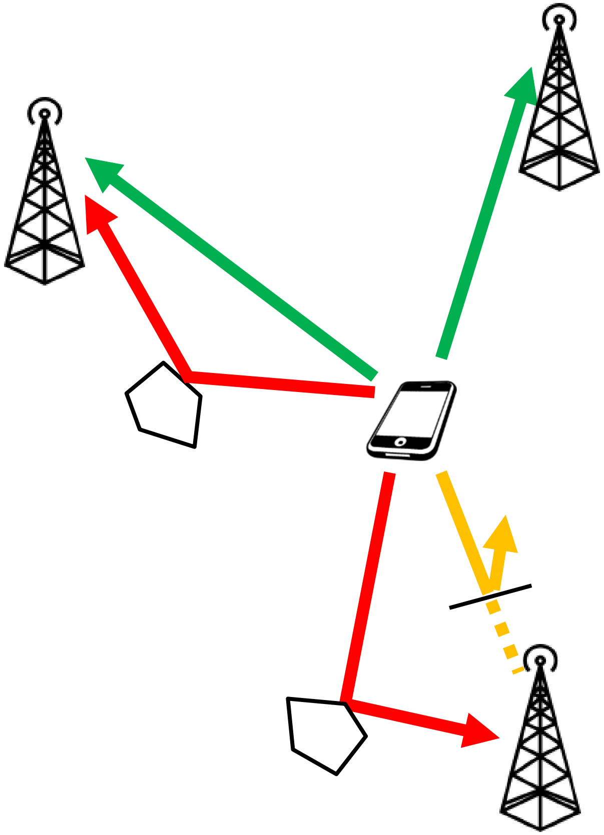
- $Q$ emitters and $L$ sensors
- $s_q(t)$: the signal of the $q$-th emitter
- LOS parameters:
  - $b_{lq}$: complex amplitude of the LOS path between emitter *q* and sensor $l$
  - $\tau_l(\mathbf{p}_q)$: propagation time from location $\mathbf{p}_q$ to sensor $l$
- NLOS parameters
  - $b_{lq}^{(m)}$: complex amplitude of the $m$-th NLOS path between emitter *q* and sensor $l$
  - $\tau_{lq}^{(m)}$: propagation time from location $\mathbf{p}_q$ to sensor $l$

# Indirect and Direct Localization



# Multipath: the Challenge

- Direct positioning determination (DPD) is asymptotically optimal in the maximum likelihood sense for ideal LOS channels
- DPD performs better than multilateration at low SNR
- DPD does not address localization in multipath:
  - Non-line-of-sight (NLOS) paths
  - Blocked LOS paths

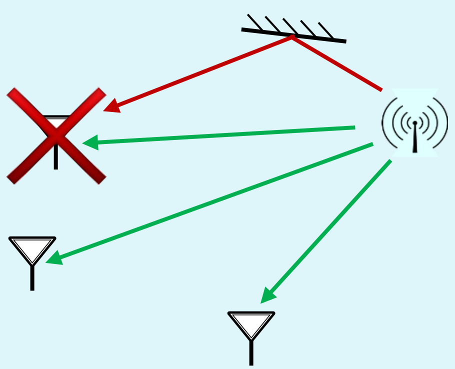


# Ad-Hoc Multipath Mitigation Methods



**Mitigate/reject contribution from sensors with strong NLOS (Chen 1999)**

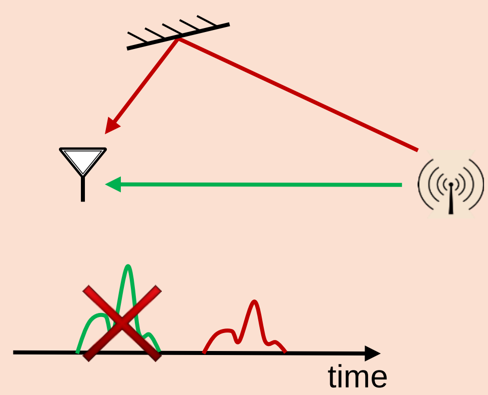
- Various metrics were suggested



**Measure TOA of 1st arrival (Lee 2002)**

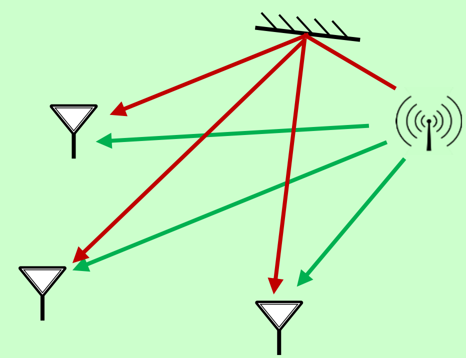
- Works only for discrete mp contributions
- If LOS is blocked

  ☞ error




**Single-bounce geometric model (Liberti,Rappaport 1996)**

- NLOS signals bounce only once
- Known number of reflectors
- Joint estimation of reflectors and emitters locations.



ML estimation in white Gaussian noise

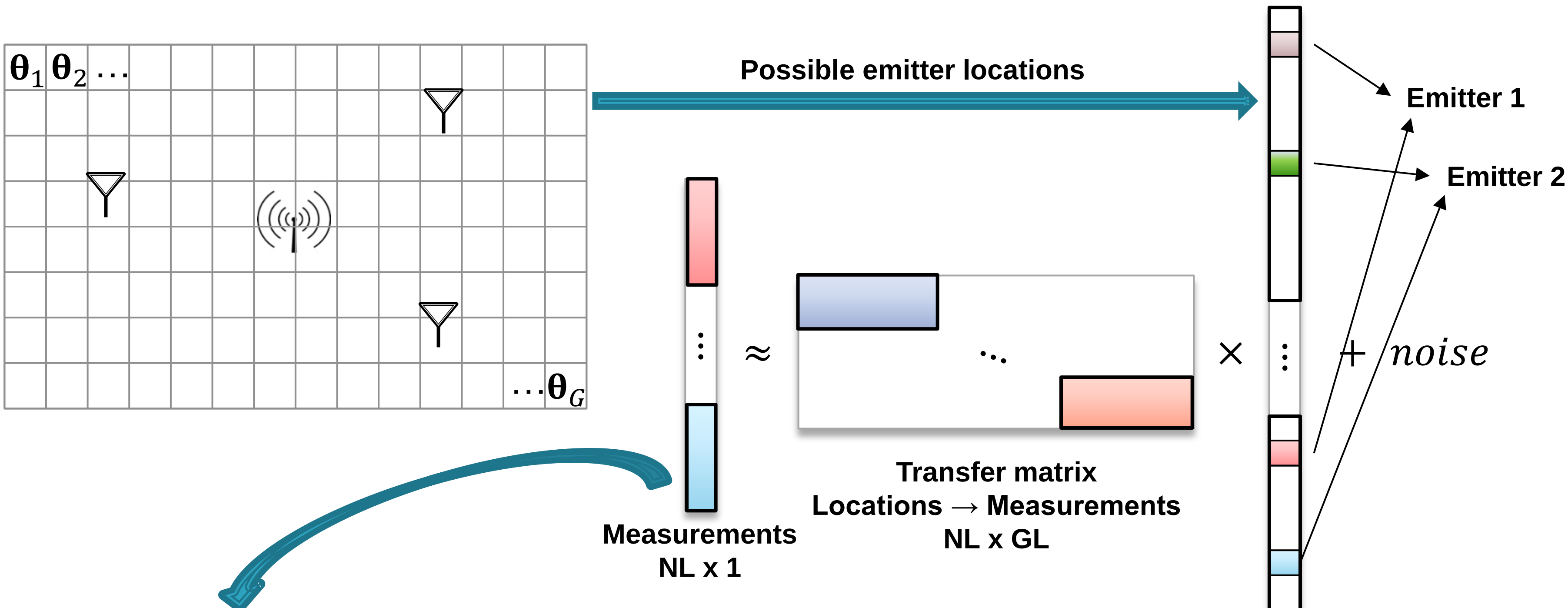
- Measurements
- Unknown parameters related to LOS paths
- Unknown parameters related to NLOS paths

$$\min_{\substack{\mathbf{p}_1,\ldots,\mathbf{p}_Q \\ b_{11},\ldots,b_{LQ} \\ M_{11},\ldots,M_{LQ} \\ \mathbf{i}_{11}^{1},\ldots,\mathbf{i}_{LQ}^{M_{LQ}} \\ b_{11}^{1},\ldots,b_{LQ}^{M_{LQ}}}} \sum_{l=1}^{L} \left\| r_l(n) - \sum_{q=1}^{Q} b_{lq} s_q\left(n - \tau_l(\mathbf{p}_q)\right) - \sum_{q=1}^{Q} \sum_{m=1}^{M_{lq}} b_{lq}^{(m)} s_q\left(n - \tau_{lq}^{(m)}\right) \right\|^2$$

- ✗ Large unknown parameters pool
- ✗ Infeasible complexity
- ✗ Overfitted solution even if problem could be solved

# Additional Information not Captured by ML

1. A relatively small number of sensors L
2. Possible multiple, but a small number of emitters that need to be localized, Q < L
3. A large number of possible locations for the emitters G >> Q




- Highly underdetermined system
- Unique solution under sparsity assumption
- Efficient algorithms – highly active area of research

# Proposed Approach

| Goal | Phase 1 (local)<br>**Multipath mitigation** | Phase 2 (global)<br>**Estimate emitter locations** |
|---|---|---|
| **Key info** | • LOS path is **first** arrival<br>• MP paths are **sparse** | • Emitters are **sparse**<br>• LOS paths originate from **common** location<br>• Multipath is **local** |
| **Procedure** | • Estimate **TOA's** :<br>$\hat{\tau}_1 < \hat{\tau}_2 \ldots < \hat{\tau}_T$<br>and their amplitudes<br>$\hat{a}_1, \hat{a}_2, \ldots, \hat{a}_T$<br>at each sensor.<br>• Exploit **sparsity**<br>• **Remove** 2nd and later estimated arrivals from signals<br>$\hat{r}_l(t) = r_l(t) - \sum_{i=2}^{T} \hat{a}_i s(t - \hat{\tau}_i)$ | • **Direct** approach relies directly on observations<br>• **Cloud**-based<br>• Formulate and solve a **convex optimization** problem<br>• **Least number** of sources and NLOS that describe the measured signals |

# Summary of Proposed Approach

## Multipath mitigation

- Sparse framework and convex optimization

## Localization

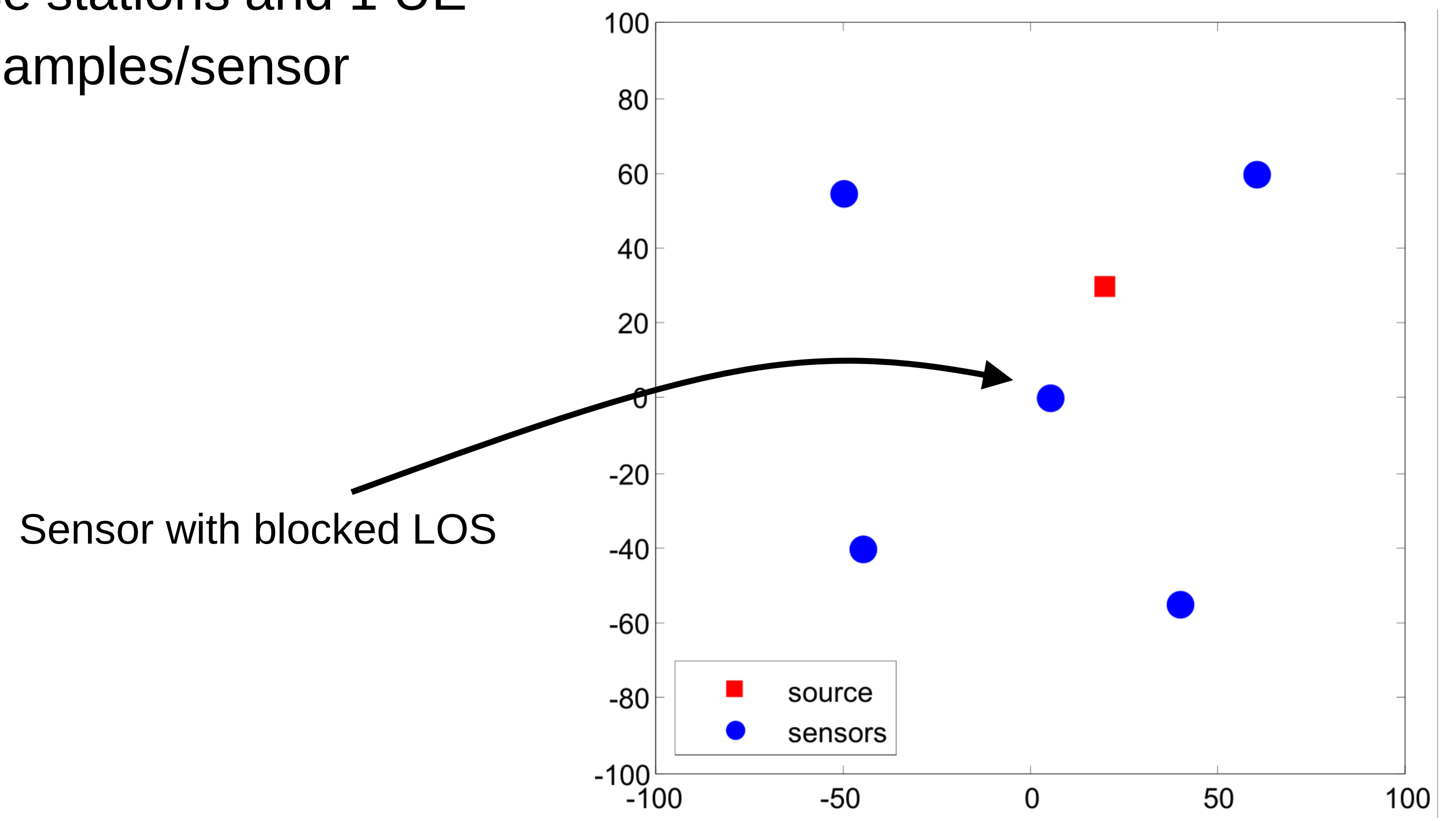
- Sources locations found by solving **a convex optimization** problem with the least number of sources and NLOS path that *describe* the received signals

$$\begin{cases} \text{minimize:} & (\text{\# of sources}) + (\text{\# of NLOS paths}) \\ \text{subject to:} & \text{Error}\left(\text{Observed signals} - \text{estimated signals}\right) \leq \epsilon \end{cases}$$

- $\epsilon$ is chosen according to the noise level

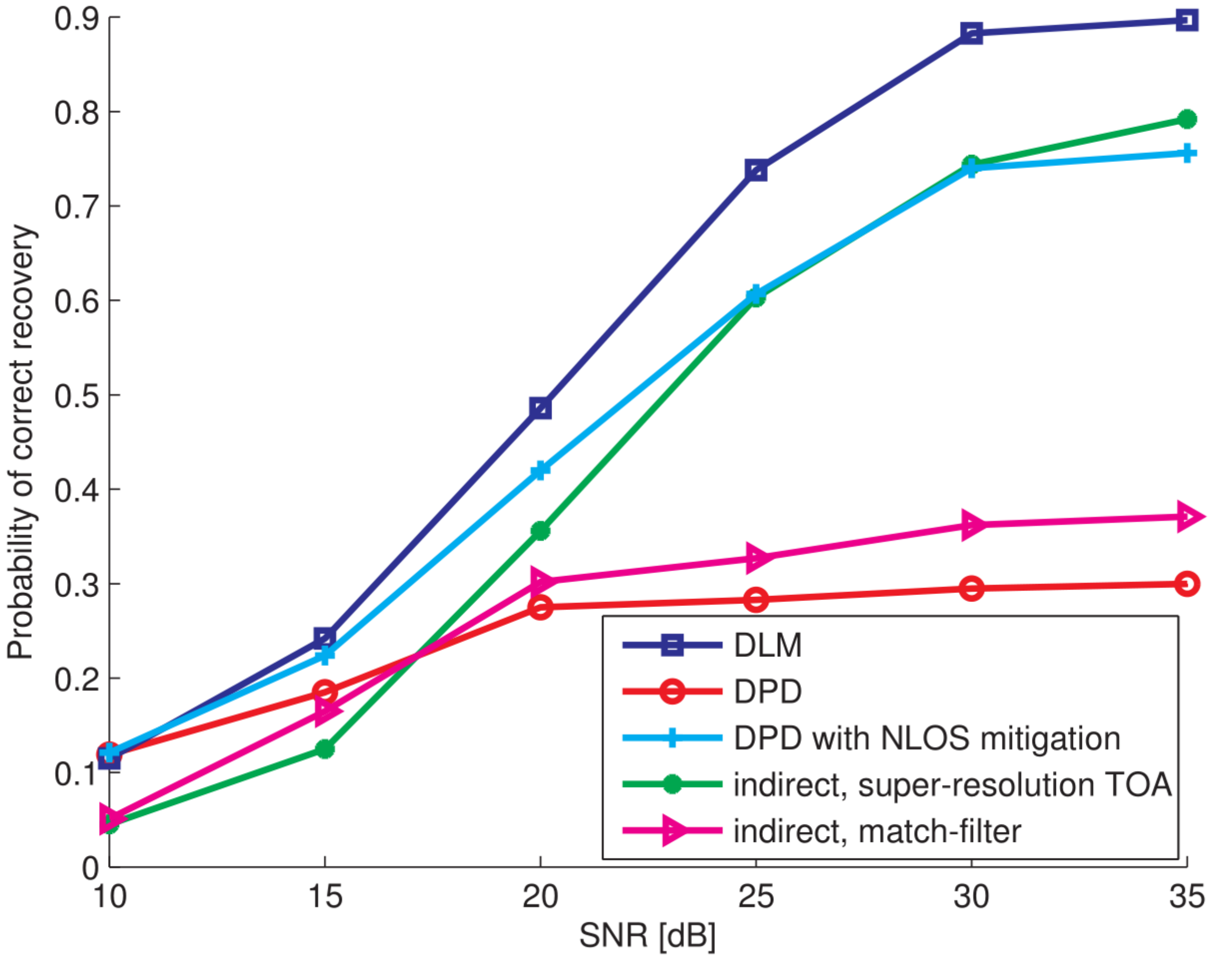
# Simulation Scenario

- 10 MHz emitter (30 m ranging resolution)
- Multipath channel RMS delay spread is 500 ns (exponential profile, Poisson arrivals)
- Search area: 200 x 200 m
- 5 base stations and 1 UE
- 100 samples/sensor



# Probability of Correct Recovery vs. SNR

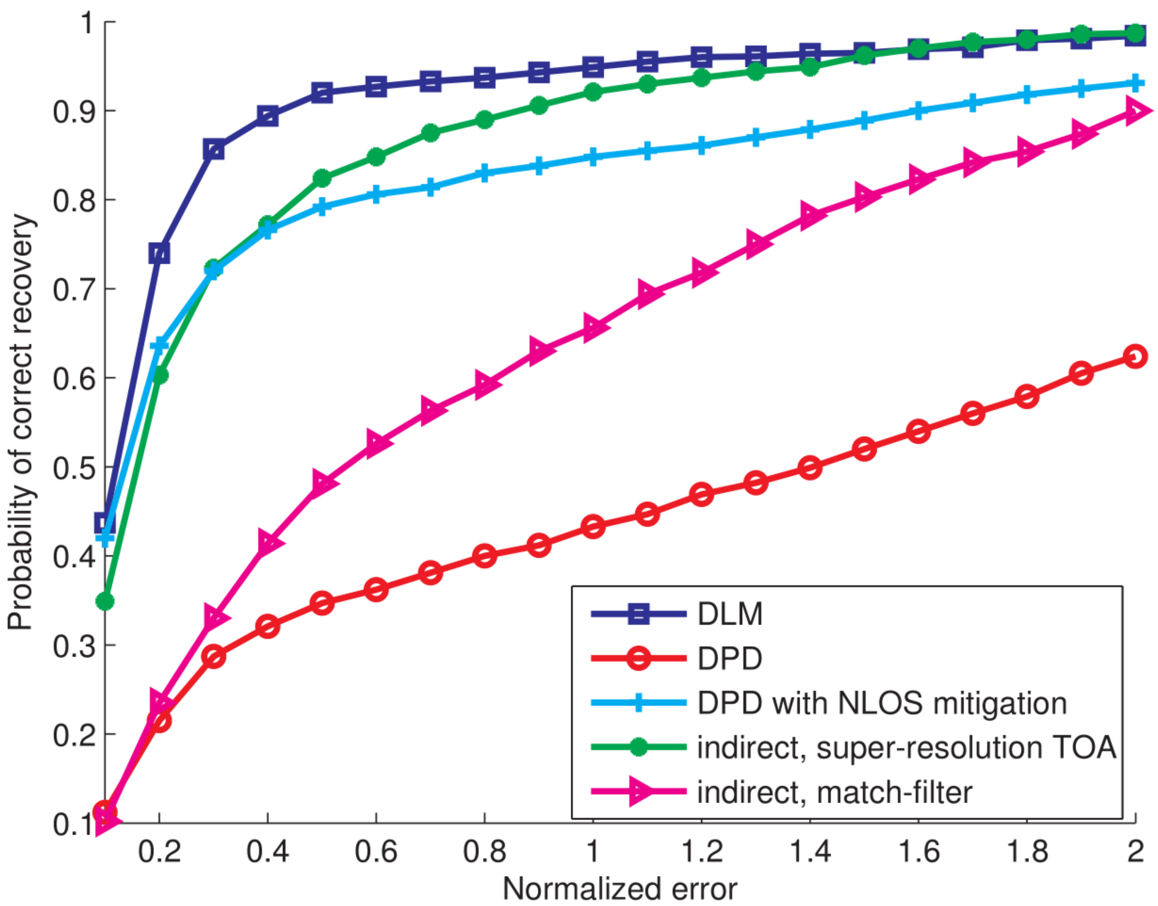
- Correct recovery if error smaller than 10 m



# Probability of Correct Recovery vs. Error

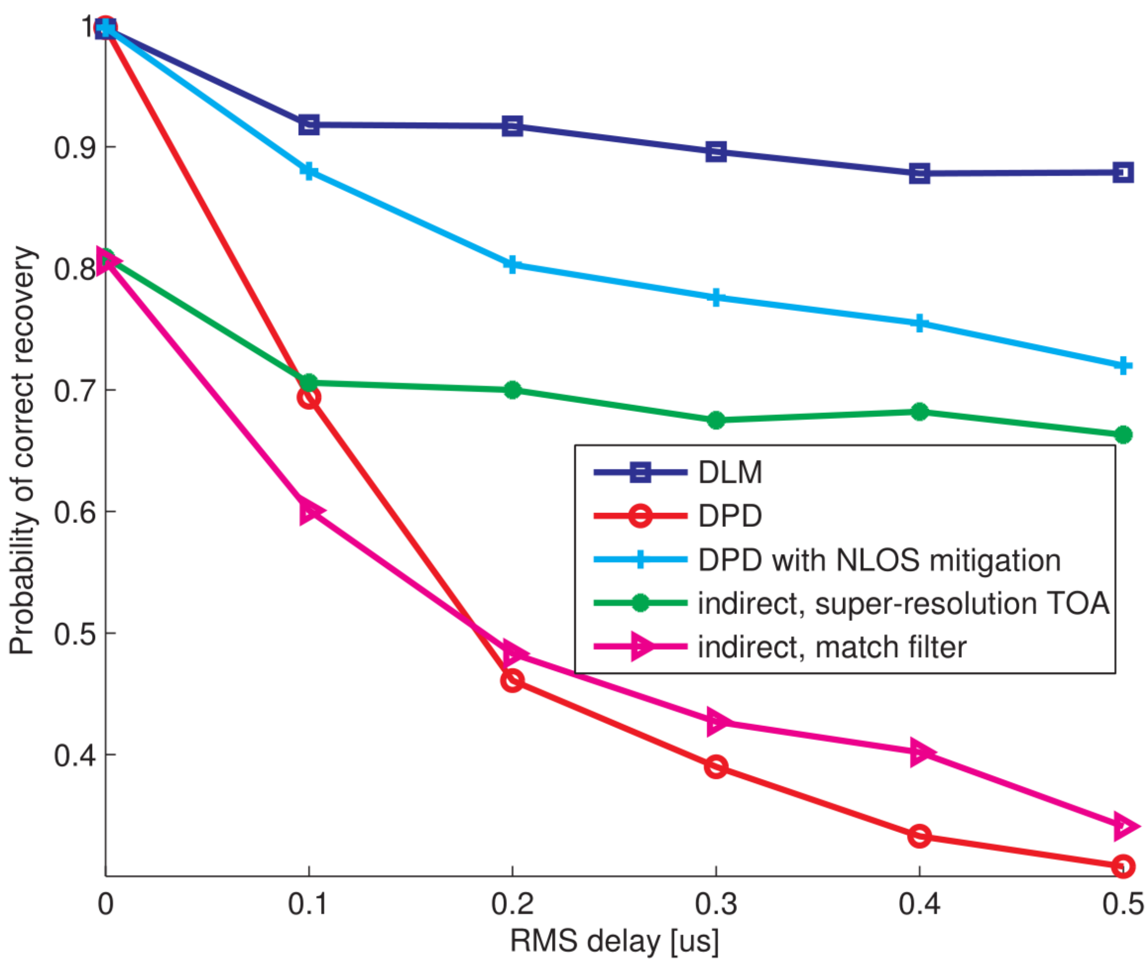


- Error normalized to 30 m
- SNR $=$ 30 dB per observation window (100 samples and 5 sensors)



# Prob. of Correct Recovery vs. Delay Spread

- SNR = 30 dB per observation window



# Summary



- ✓ A **novel approach** for localization of emitters in multipath featuring:
- ✓ **Direct localization** outperforms classical TOA indirect localization
- ✓ An approximation of **ML** formulation
- ✓ + proposed framework captures **additional information**
  - ✓ **Sparse** multipath
  - ✓ LOS are **first arrivals**
  - ✓ **Sparse** emitters
  - ✓ LOS signals originate from a **common** emitter location
  - ✓ Multipath is **local**
- ✓ **Does not require channel state information**, such as power delay profile
- ✓ **Cloud**-based
- ✗ **Computationally more expensive** than indirect techniques.