NEXUS
Collaborative Research Center 627

Scalable Management of Trajectories and Context Model Descriptions

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Motivation

Context-awareness and **context-aware computing**

> "… the ability of a mobile user's applications to discover and react to changes in the environment they are situated in."
>
> (Schilit and Theimer, 1994)

Examples:

- Adapt ring volume to ambient noise
- Navigation of blind persons

➔ Advancements are closely connected to **miniaturization** of sensing, computing, and communication hardware

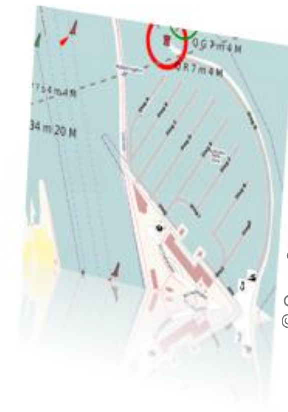
Motivation (2)

Proliferation of **sensing** technologies

- Cameras, satellites, weather stations, WSNs, GPS receivers, RFID readers, **smartphones**, …

Comprehensive **models** of physical environment

- Differ in geographic extent, aspect, granularity, dynamism, …
- Variety of commercial and non-commercial providers
  - Examples: TeleAtlas, Google, OpenStreetMap, CWOP



➔ Huge **potential** for context-aware applications

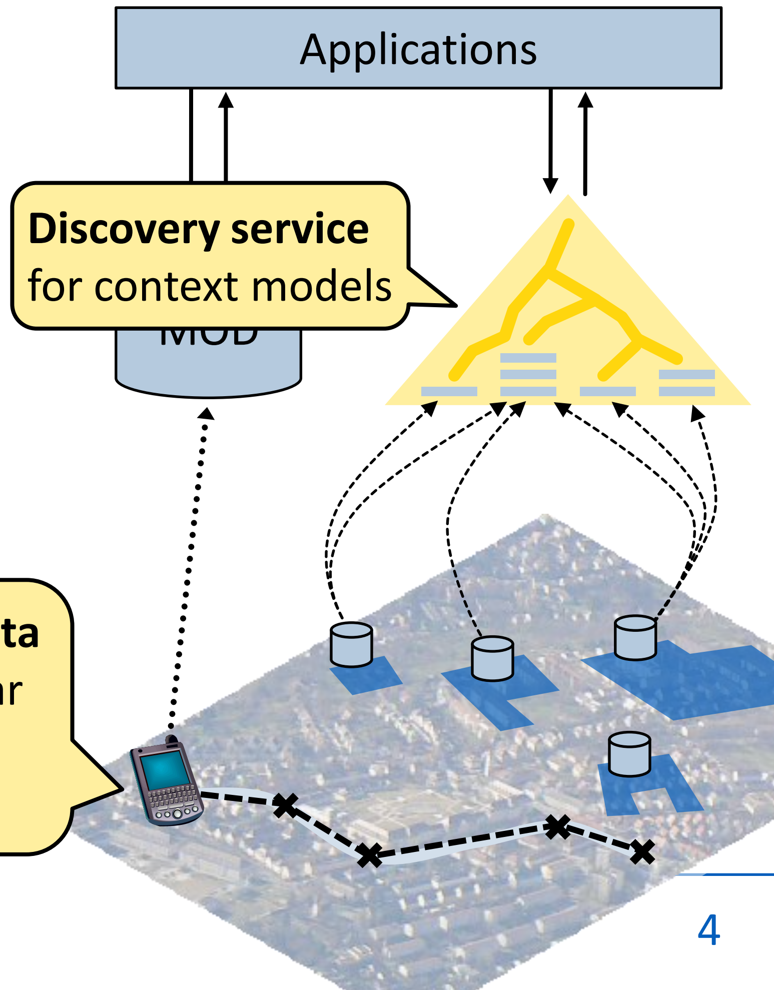
- Ability to select context information from different providers
- Trend: Millions of **context models** shared by large number of applications

Problem Statement

How to provide efficient access to the immense amounts of distributed dynamic context information **?**

1. Formal describing of context models
2. Indexing of context model descriptions
3. Efficient real
4. Distributed i
   space-partiti

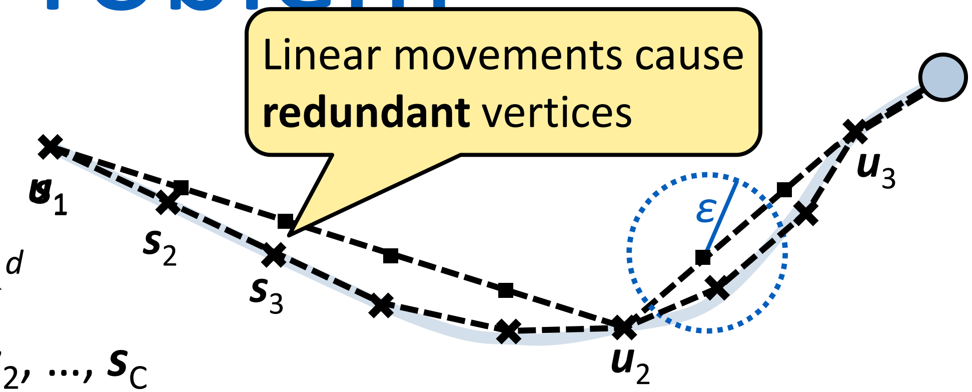
Large amounts of **trajectory data**
- E.g. $3 \cdot 10^7$ GPS records per year
- High communication cost
- Huge storage consumption



Overview

- Motivation and problem statement
- Efficient real-time trajectory tracking
    - Formal problem description
    - Related work
    - Connection-Preserving Dead Reckoning (CDR)
    - Generic Remote Trajectory Simplification (GRTS)
    - Evaluation and conclusion
- Distributed indexing of space-partitioned trajectories
- Summary

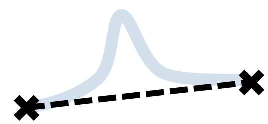
Tracking: Formal Problem



Actual trajectory $\boldsymbol{a}(t)$ is function $\mathbb{R} \rightarrow \mathbb{R}^d$

Sensed trajectory $\boldsymbol{s}(t)$ with vertices $\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_C$

- Attribute $\boldsymbol{s}_i.\boldsymbol{p}$ denotes position at time $\boldsymbol{s}_i.t$
- Differs from $\boldsymbol{a}(t)$ due to δ_{sense} and movement during T_{sense}



$$\frac{1}{2} a_{\max} \left(\frac{T_{\text{sense}}}{2} \right)^2$$

Simplified trajectory $\boldsymbol{u}(t)$ with vertices $\boldsymbol{u}_1, \boldsymbol{u}_2, \ldots$

Definition: **Efficient real-time trajectory tracking**

- Goals: Minimize $|(\boldsymbol{u}_1, \boldsymbol{u}_2, \ldots)|$ and communication cost
- Simplification constraint: $|\ \boldsymbol{u}(t) - \boldsymbol{a}(t)\ | \leq \varepsilon \ \ \forall\ t$
- Real-time constraint: $\boldsymbol{u}(t)$ is available $\ \forall\ t \in [\boldsymbol{s}_1.t, t_C]$

Tracking: Related Work

Line simplification algorithms

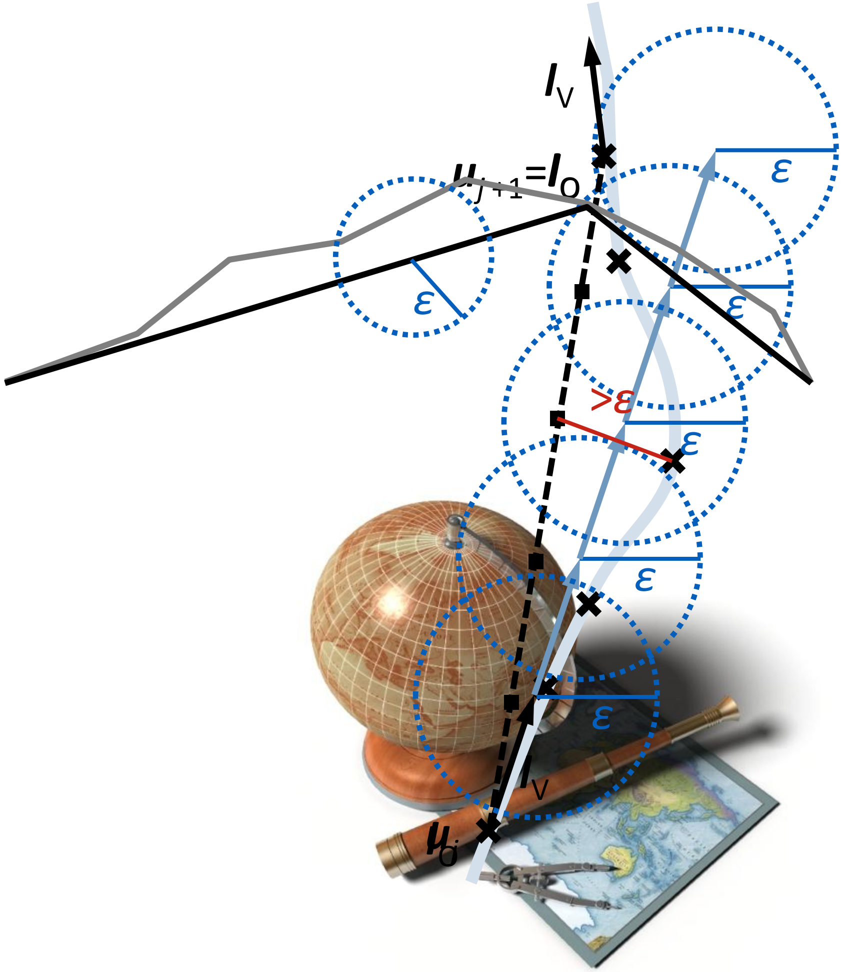
- E.g. Douglas-Peucker heuristic

➔ High communication cost, no real-time behavior

Position tracking protocols

- Best mechanism: Dead Reckoning (DR)

➔ Linear DR with ½ε allows for trajectory tracking [Trajcevski et al. 2006]



Tracking: CDR

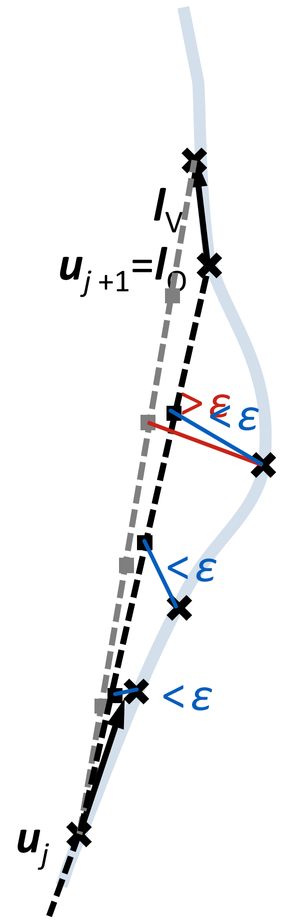
Connection-preserving DR extends linear DR

- Object manages $\boldsymbol{l}_{\mathrm{O}}$, $\boldsymbol{l}_{\mathrm{V}}$, and **sensing history** $\mathbb{S}$
- Second update condition:

  $\exists\ s_i \in \mathbb{S}$ with $|\overline{\boldsymbol{l}_{\mathrm{O}}\boldsymbol{s}_{\mathrm{C}}}(\boldsymbol{s}_{\mathrm{i}}.t) - \boldsymbol{s}_{\mathrm{i}}.\boldsymbol{p}| > \varepsilon$
- New prediction starts at **last** sensed position

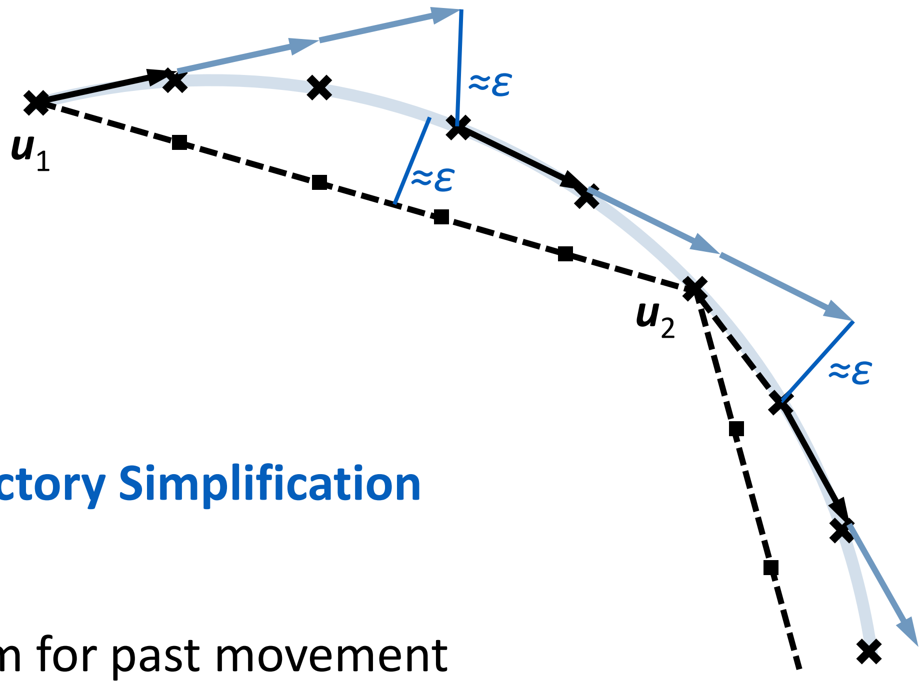
CDR$_{\mathrm{m}}$ limits computational cost by $|\mathbb{S}| \leq m$

- Compression approach to prevent periodic updates



Tracking: GRTS

Tracking and simplification
are **different concerns**

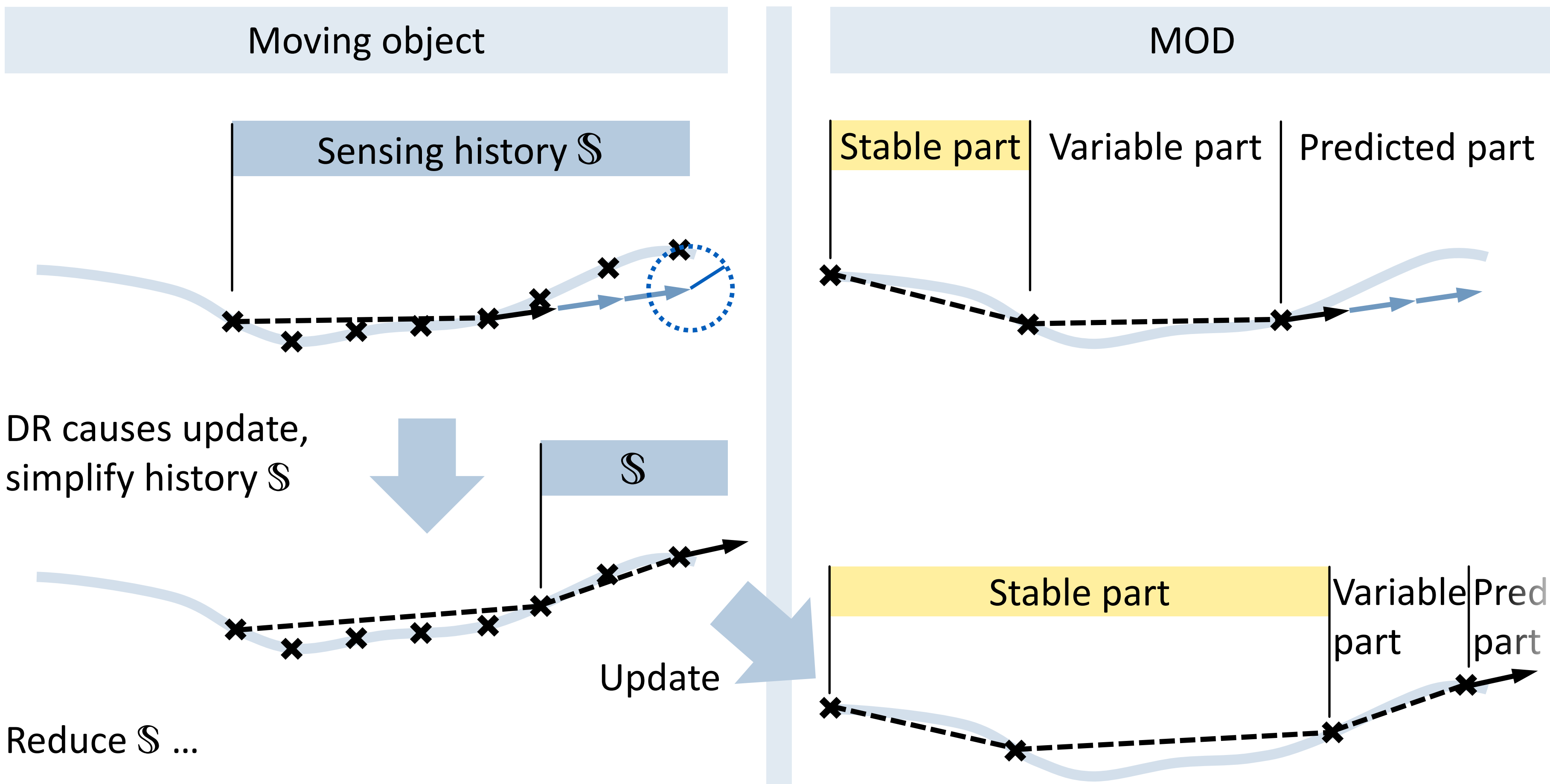


Basic approach of **Generic Remote Trajectory Simplification**

- DR to report latest movement
- Arbitrary line simplification algorithm for past movement
  - Computational cost ↔ reduction efficiency

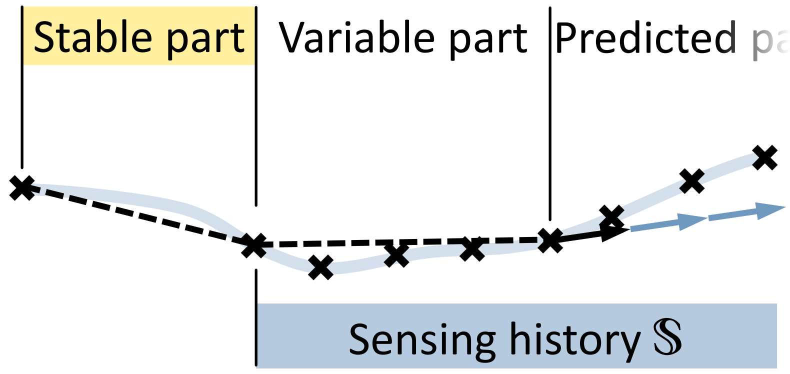
→ Tracking and simplification must be synchronized!

Tracking: GRTS Protocol



Tracking: GRTS k/m Variants

So far, not defined how to reduce $\mathbb{S}$ …



GRTS$_k$ limits variable part to *k* line sections

- Unlimited computational costs

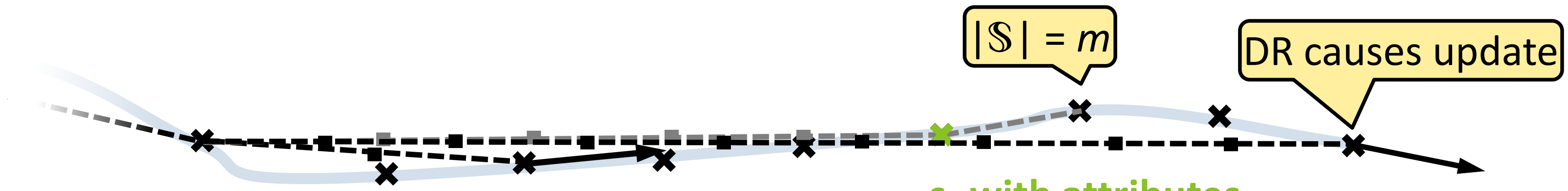
➔ Only of theoretical interest

GRTS$_m$ limits $|\mathbb{S}|$ to *m*

- Limits computational costs – essential for real-time behavior
- Adds vertex to $\boldsymbol{u}(t)$ at least every *m* sensing operations

➔ Compress $\mathbb{S}$ if its size exceeds *m*

Tracking: GRTS mc Variant



s_2 with attributes
p = (48.42°,9.01°)
t = 2009-12-15 14:25:17.3
δ = 7m

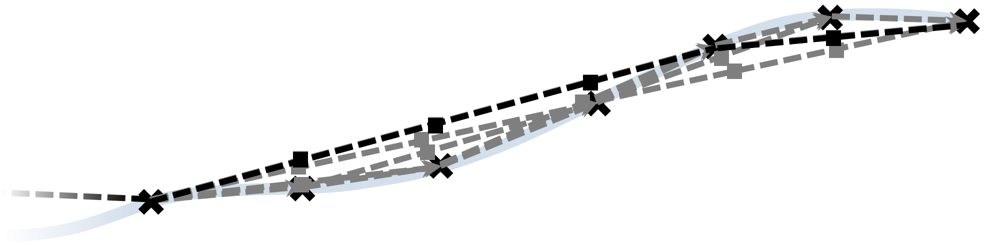
GRTS$_{mc}$

- $\boldsymbol{s}_i.\delta$ gives **maximum deviation** along line section from $\boldsymbol{s}_{i\text{-}1}$ to $\boldsymbol{s}_i$
- Number of compressed positions should be small (c = 1 or 2)
- With uncompressed positions, $\boldsymbol{s}_i.\delta$ may represent varying δ_{sense}

Tracking: $GRTS_*^{Sec}$ and $GRTS_*^{Opt}$

$GRTS_*^{Opt}$ – with optimal simplification algorithm [Imai and Iri 1988]

- Reduces simplification to shortest-path problem



- Segmentation by *k* or *m* influences reduction efficiency

$GRTS_*^{Sec}$ – with Section Heuristic [e.g. Meratnia and de By 2004]

- Online algorithm enables per-sense simplification
- Proposed improved version, optimizing $|\mathbb{S}|$

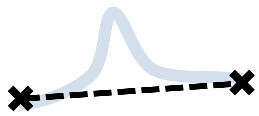
Tracking: Evaluation Setup

Comparing CDR variants and GRTS$_*$ realizations to …

- Linear DR with ½ε (LDRH)
- Optimal offline simplification (Ref$^{\text{Opt}}$)
- Douglas-Peucker algorithm (Ref$^{\text{DP}}$)

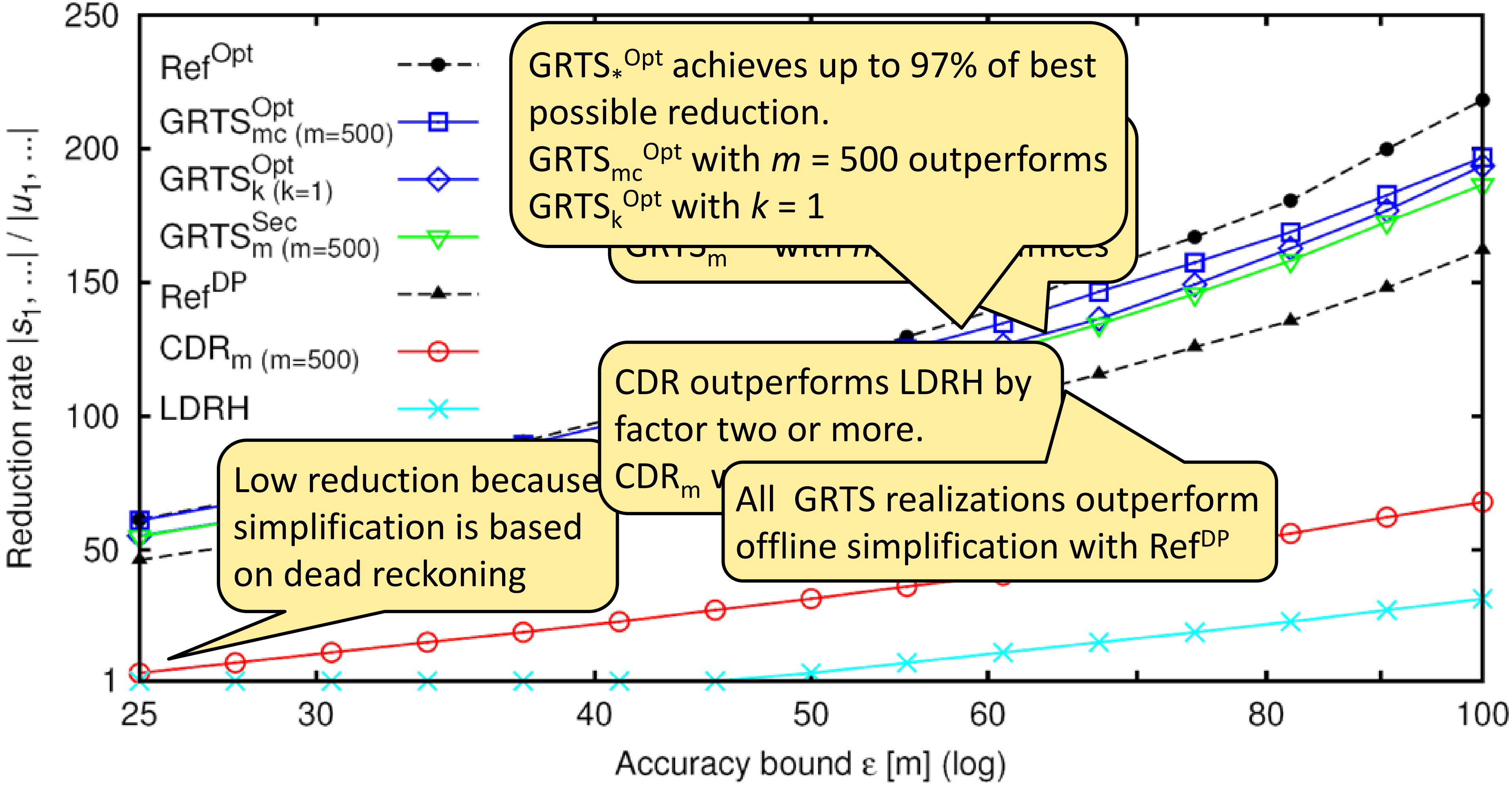
Simulated with **real** GPS traces from OpenStreetMap

- **> 1.2 million** sensed positions, i.e. **> 330 h** of data
- Sensor inaccuracy of δ_{sense} = 7.8 m
- Sensing period T_{sense} = 1 s
- Maximum acceleration $a_{\max}$ = 10 m/s²

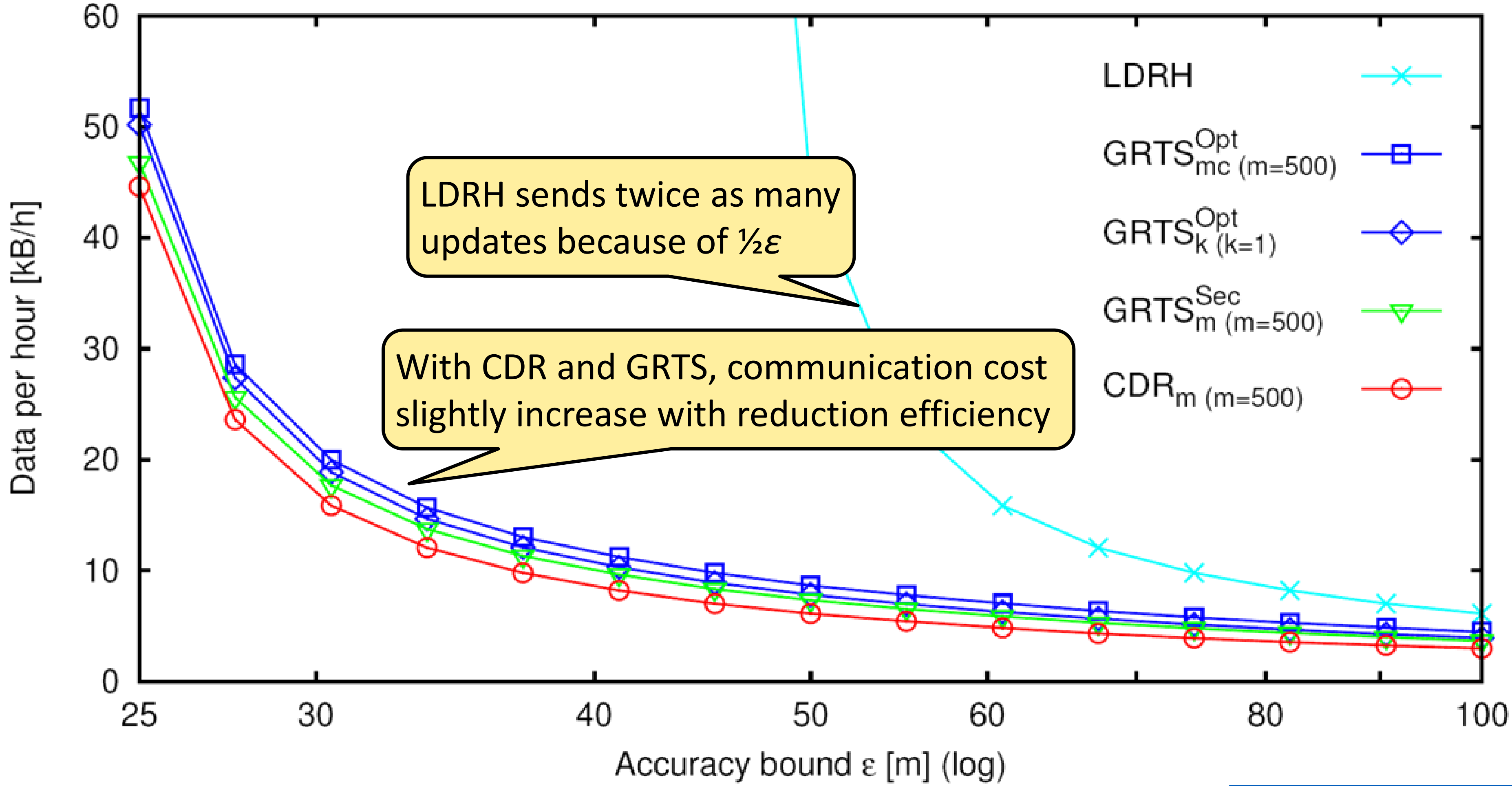


$$\delta_{\text{sense}} + \frac{1}{2} a_{\max} \left(\frac{T_{\text{sense}}}{2} \right)^2 = 9.1\,\text{m}$$

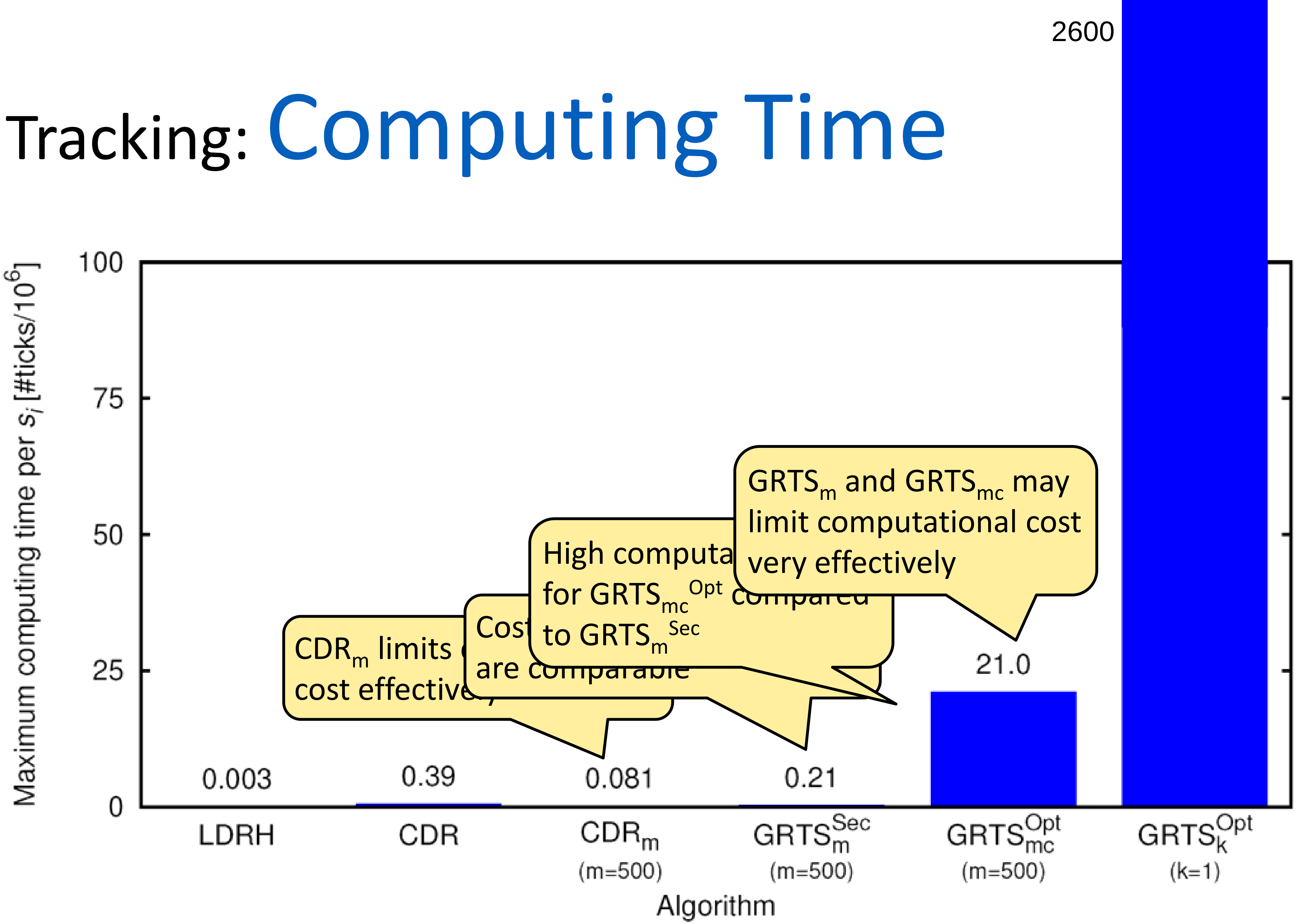
Tracking: Reduction Efficiency



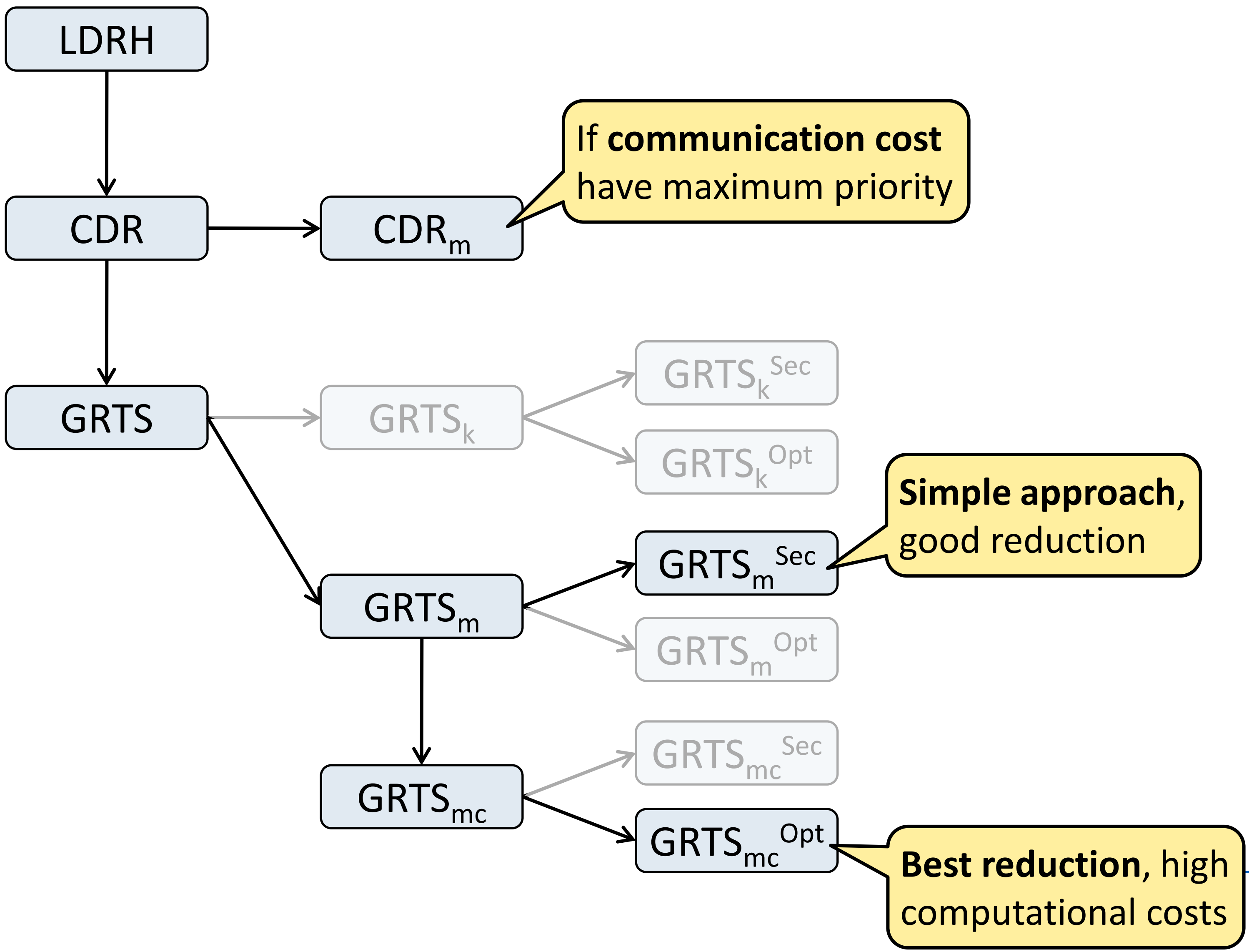
Tracking: Communication



Tracking: Computing Time

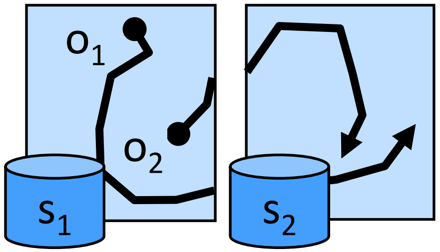


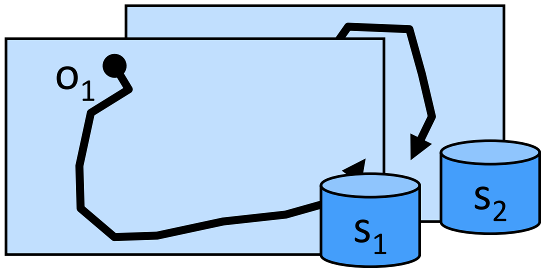
Tracking: Conclusion



Distributed Indexing of Trajectories

Managing large number of mobile objects
requires **distributed** MOD





	Spatial partitioning	**Object-based partitioning**
Coordinate-based queries	✓	–
Trajectory-based queries	?	✓
Update-aware distribution	✓	

How to determine and route to relevant servers efficiently?

- **Coordinate-based** query: “Which objects were located in R during $[t_1,t_2]$?”
- **Trajectory-based** query: “What distance covered object o_2 during $[t_3,t_4]$?”

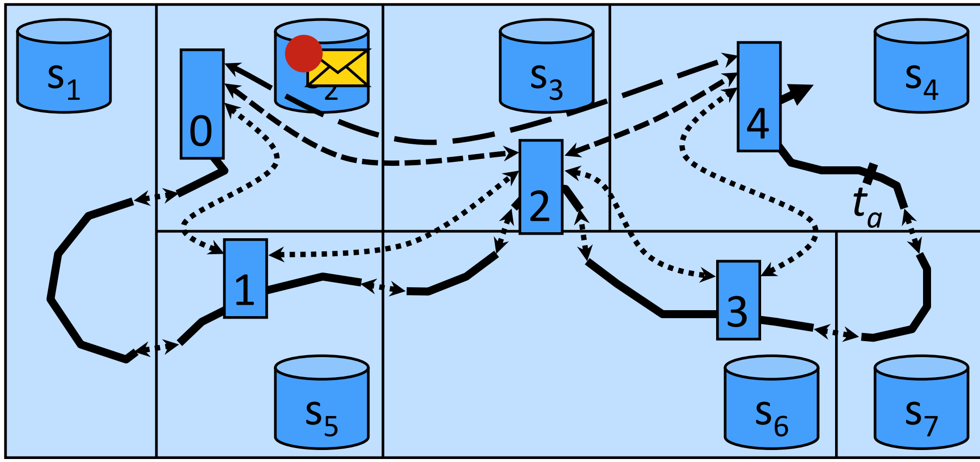
Distributed Indexing of Trajectories (2)

Trajectory-based routing along queried trajectory can take many hops

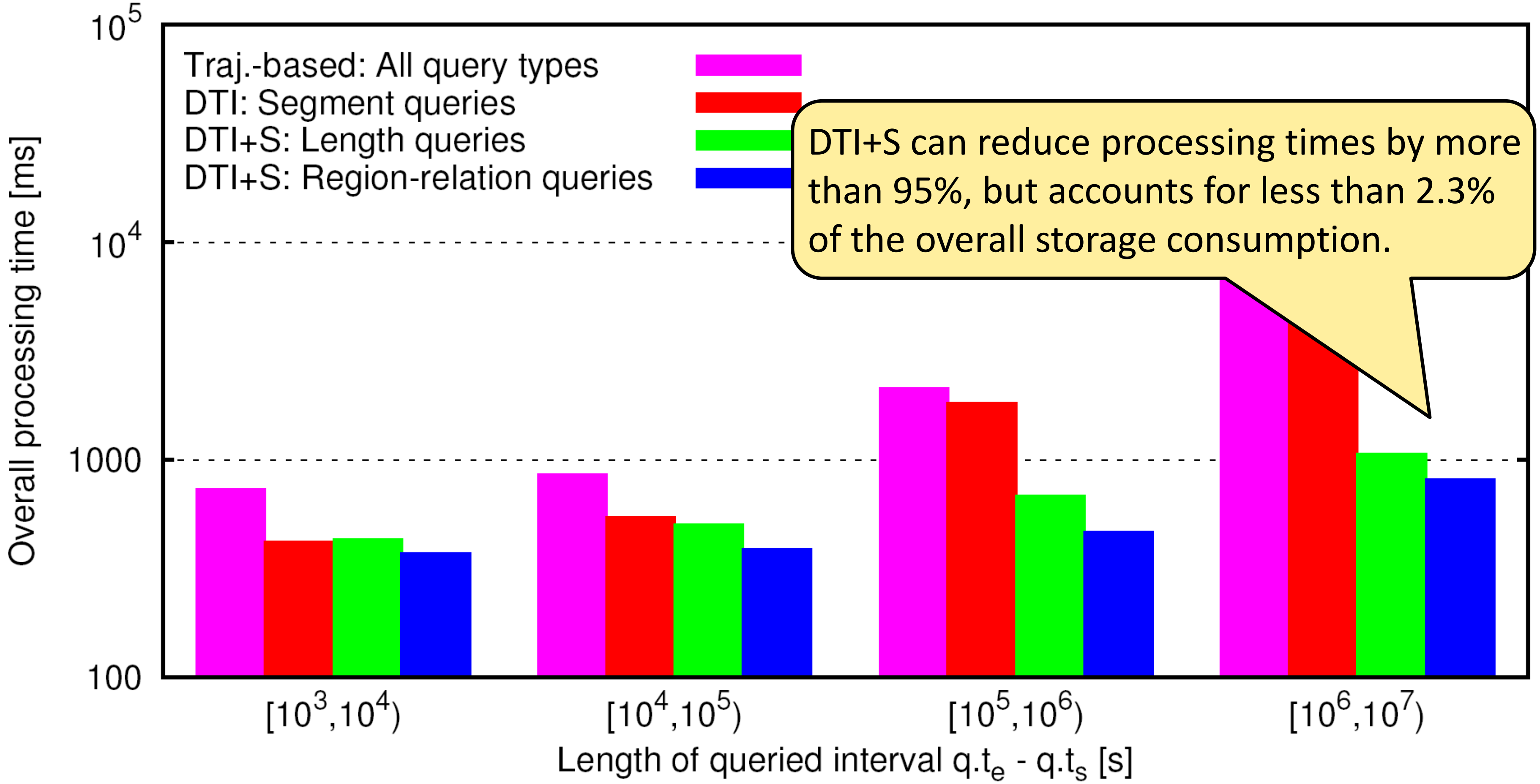
- Depends on queried time span and trajectory route

Solution: **Distributed Trajectory Index** (DTI)

- DTI scheme creates independent index (overlay) for each trajectory
- Enables efficient routing by pointers to temporally distant positions
- **DTI+S** also stores **summaries** (speed, MBR, …) on segments
- Linear storage consumption



Distributed Indexing of Trajectories (3)

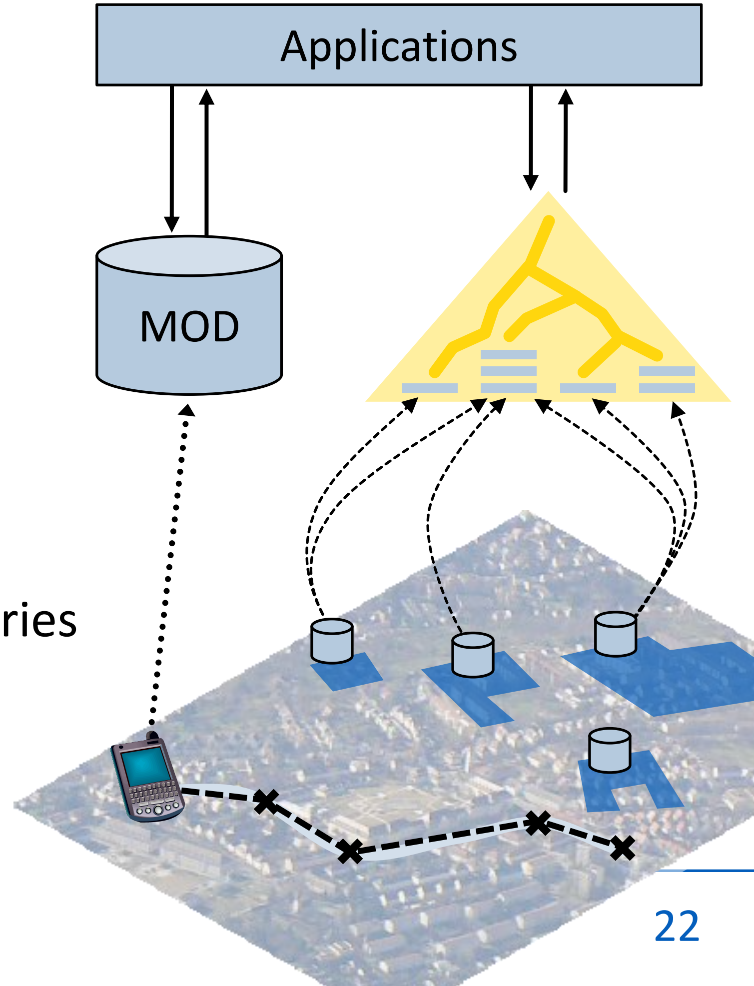


Summary

Proliferation of sensing technologies constitutes huge potential for context-aware applications

How to provide efficient access to the immense amounts of distributed dynamic context information ?

1. CDR and GRTS for real-time trajectory tracking
2. DTI for scalable distributed indexing of trajectories
3. Formalism and SDC-Tree for describing and indexing of context models *(see thesis)*



Thank you

for your attention!

Selected Publications:

- Ralph Lange, Frank Dürr, Kurt Rothermel: "Indexing Source Descriptions based on Defined Classes". In: *Proc. of 14th IDEAS*. Montreal, QC, Canada. Aug 2010.
- Ralph Lange, Frank Dürr, Kurt Rothermel : "Efficient Tracking of Moving Objects using Generic Remote Trajectory Simplification". In: *Proc. of 8th PerCom Workshops*. Mannheim, Germany. Mar 2010.
- Ralph Lange, Harald Weinschrott, Lars Geiger, André Blessing, Frank Dürr, Kurt Rothermel, Hinrich Schütze: "On a Generic Uncertainty Model for Position Information". In: *Proc. of 1st QuaCon*. Stuttgart, Germany. Jun 2009.
- Ralph Lange, Tobias Farrell, Frank Dürr, Kurt Rothermel: "Remote Real-Time Trajectory Simplification". In: *Proc. of 7th PerCom*. Galveston, TX, USA. Mar 2009.
- Ralph Lange, Frank Dürr, Kurt Rothermel: "Scalable Processing of Trajectory-Based Queries in Space-Partitioned Moving Objects Databases". In: *Proc. of 16th ACM GIS*. Irvine, CA, USA. Nov 2008.
- Ralph Lange, Frank Dürr, Kurt Rothermel: "Online Trajectory Data Reduction using Connection-preserving Dead Reckoning". In: *Proc. of 5th MobiQuitous*. Dublin, Ireland. Jul 2008.
- Tobias Farrell, Ralph Lange, Kurt Rothermel: "Energy-efficient Tracking of Mobile Objects with Early Distance-based Reporting". In: *Proc. of 4th MobiQuitous* . Philadelphia, PA, USA. Aug 2007.

➔ See www.lange-ralph.de for complete list