Enabling Large-Scale Urban Air Quality Monitoring with Mobile Sensor Nodes

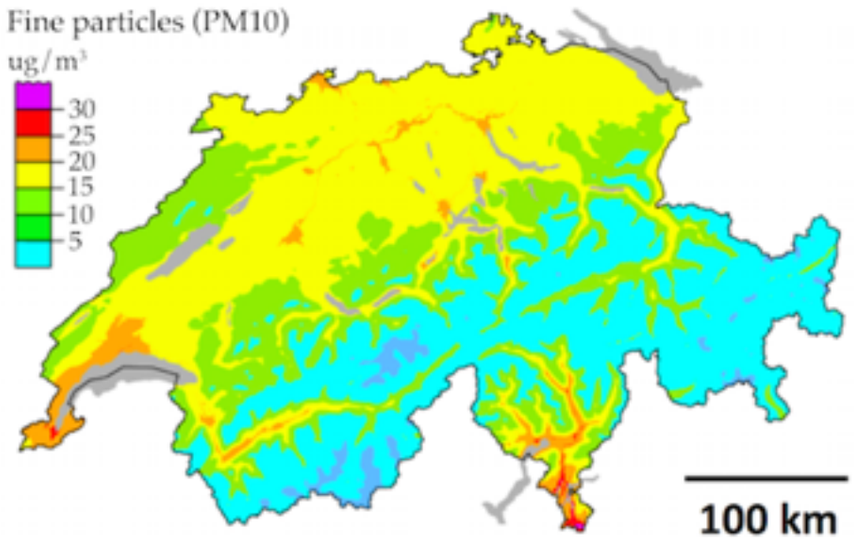
David Hasenfratz

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

nano-tera.ch

Air Pollution Monitoring: Current Approach

Static measurement network



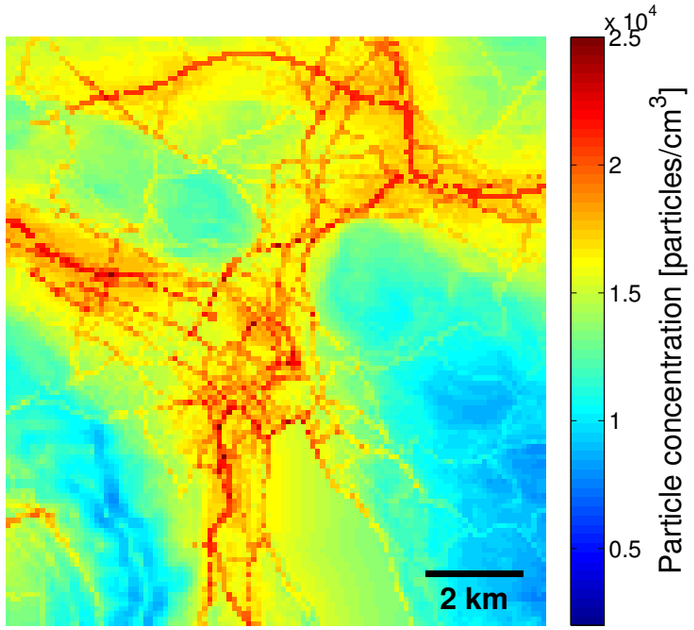
Pollution map at regional scale

- Static networks operated by national authorities
- Highly reliable and accurate measurements
- High acquisition and maintenance costs

Today's pollution maps have limited spatial resolution

Air Pollution Monitoring: Our Approach

Mobile sensor node on top of a streetcar

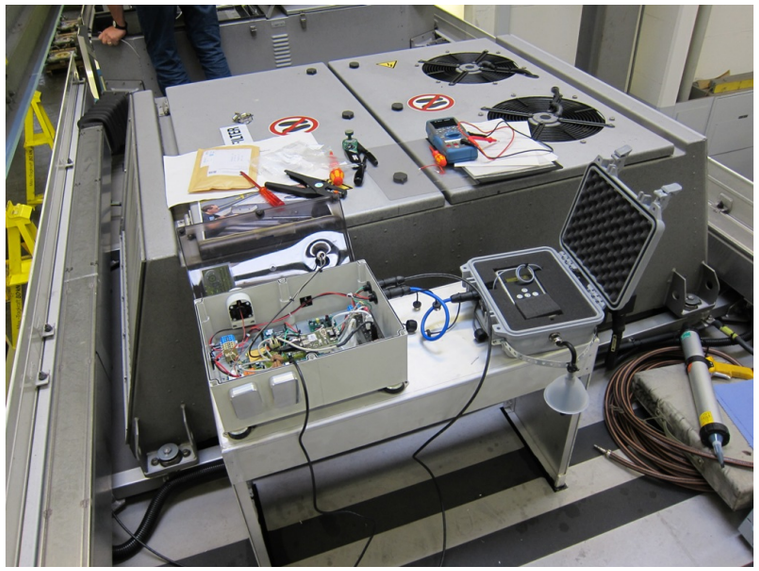


Fine-grained pollution map

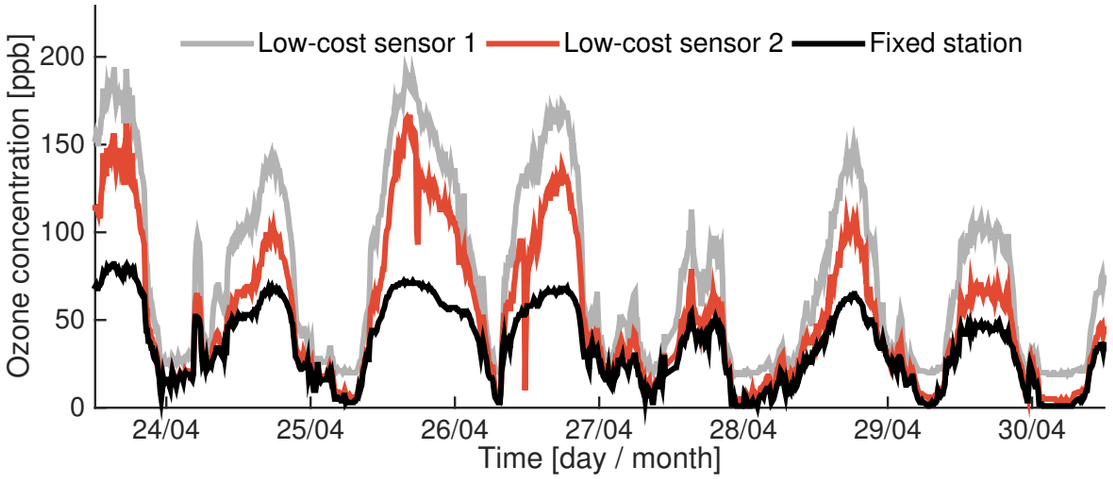
- Mobile sensor nodes with low-cost sensors
- Lower accuracy but much higher spatial coverage

Enables pollution maps with unprecedented spatial and temporal resolution facilitating novel applications

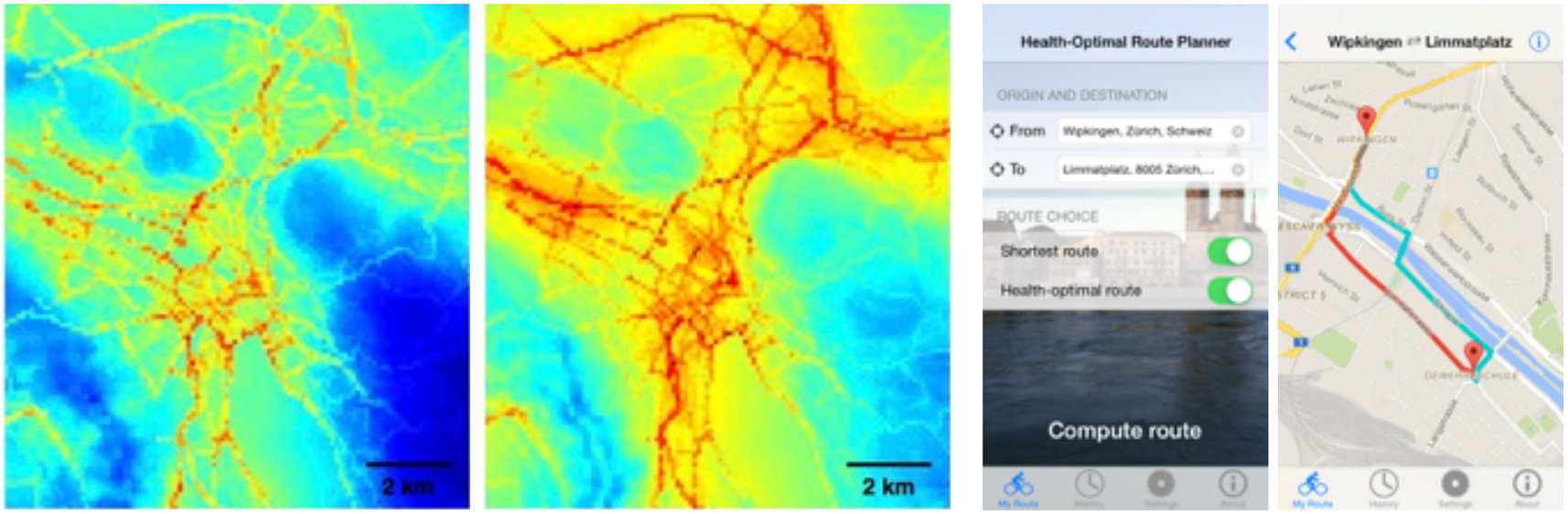
Challenges of Mobile Air Quality Monitoring



Mobile measurement system

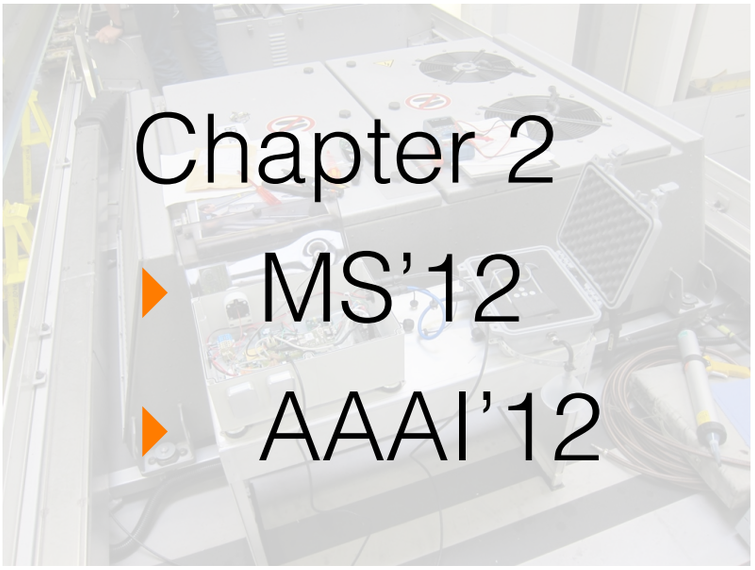


Data quality assurance



High-resolution air quality models and its applicability

Thesis Contributions



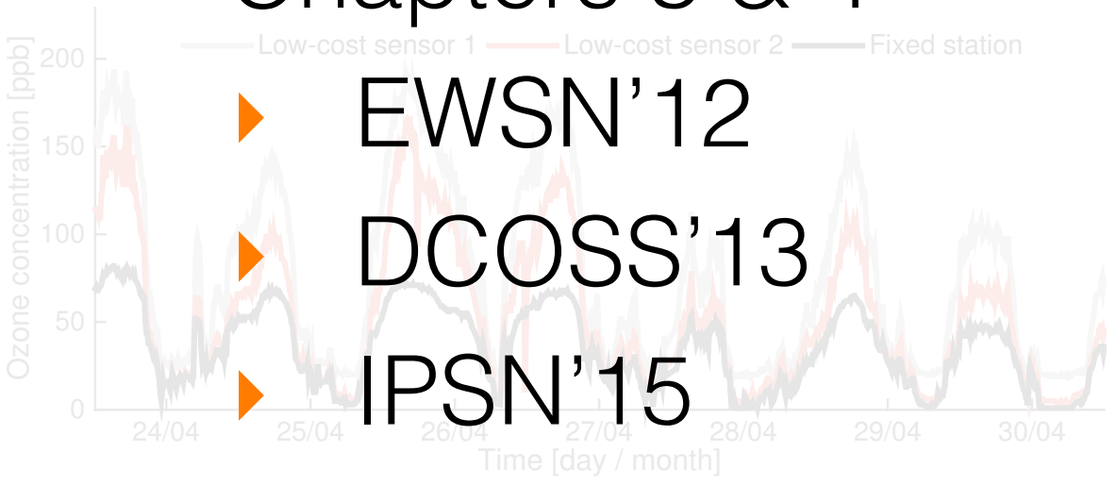
Chapter 2

- MS'12
- AAAI'12

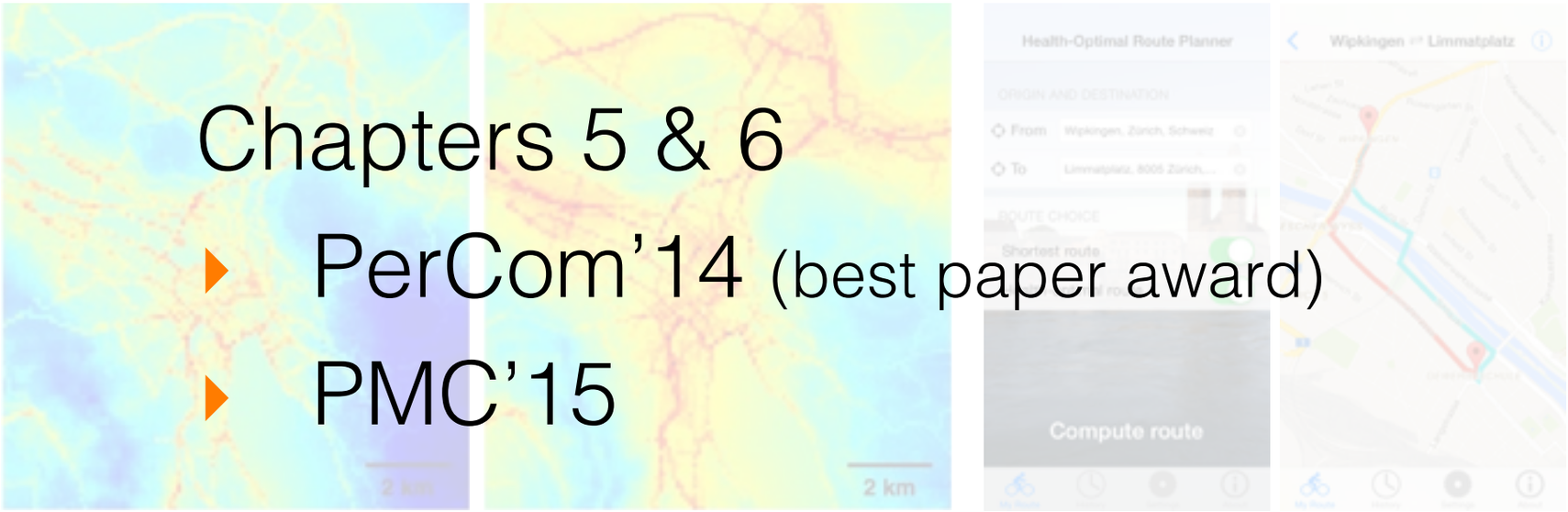
Mobile measurement system

Chapters 3 & 4

- EWSN'12
- DCOSS'13
- IPSN'15



Data quality assurance

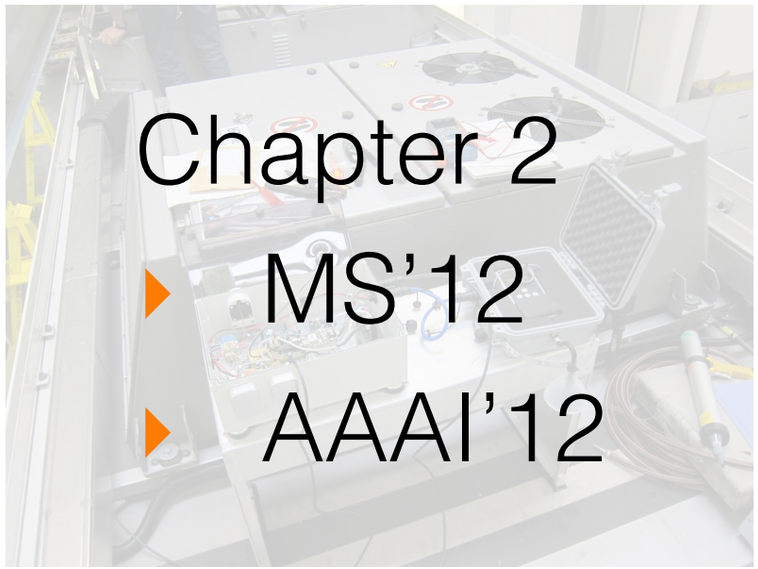


Chapters 5 & 6

- PerCom'14 (best paper award)
- PMC'15

High-resolution air quality models and its applicability

Thesis Contributions

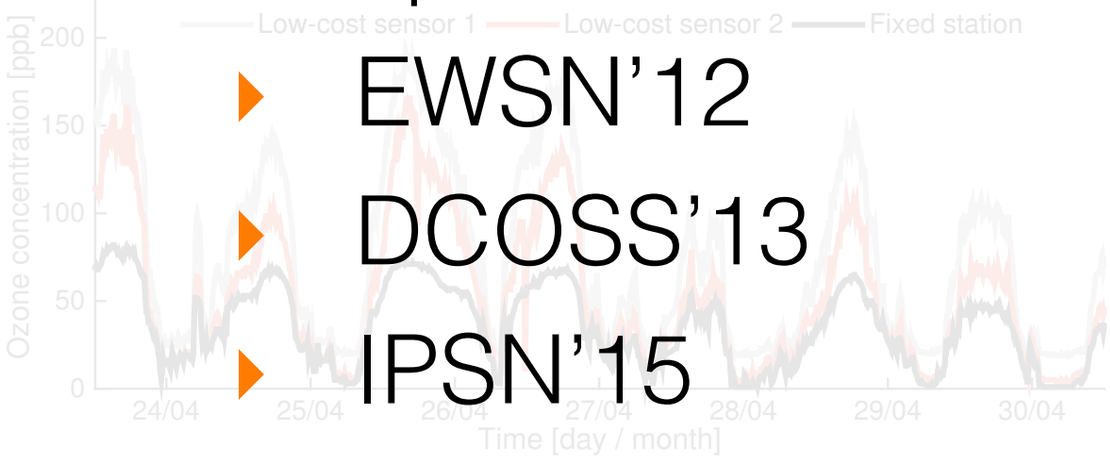


Chapter 2

- MS'12
- AAAI'12

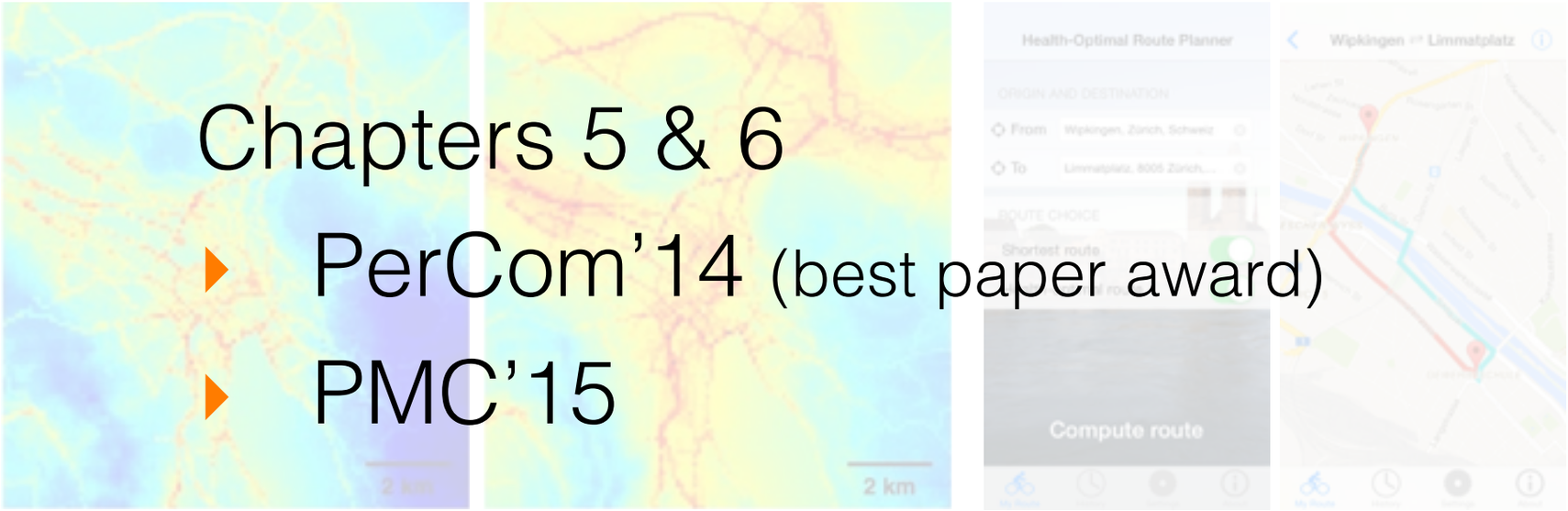
Mobile measurement system

Chapters 3 & 4



- EWSN'12
- DCOSS'13
- IPSN'15

Data quality assurance

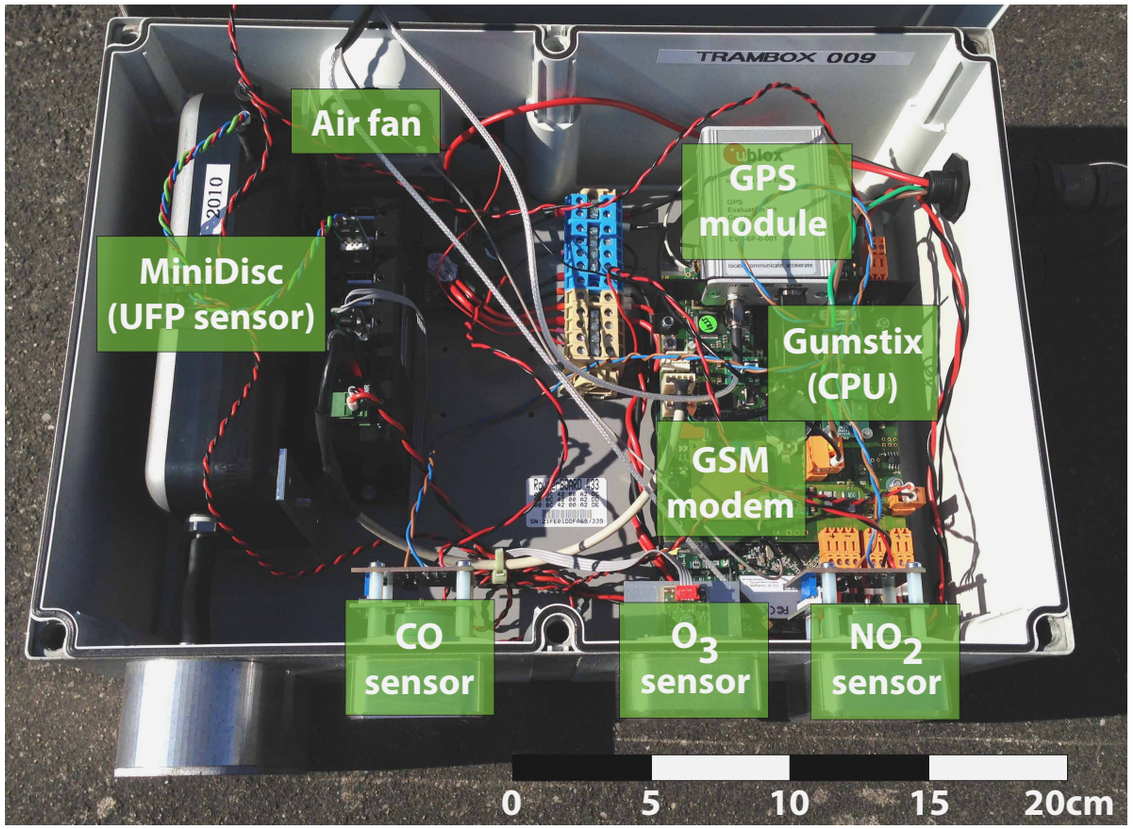


Chapters 5 & 6

- PerCom'14 (best paper award)
- PMC'15

High-resolution air quality models and its applicability

Mobile Measurement System

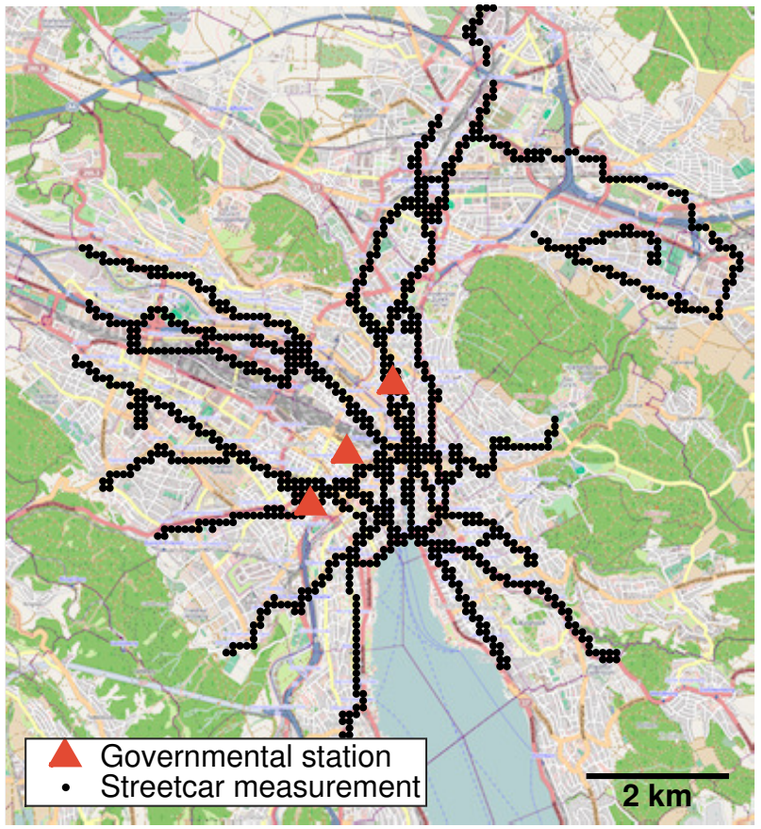


Air quality sensor node equipped with UFP, CO, O_3, and NO_2 sensors

- Based on existing hardware and software infrastructure
- Air quality sensor nodes monitor main pollutants
- Measurements sent in real-time to backend server

Streetcar Measurement Network

Sensor node on top of a streetcar



Measurement coverage

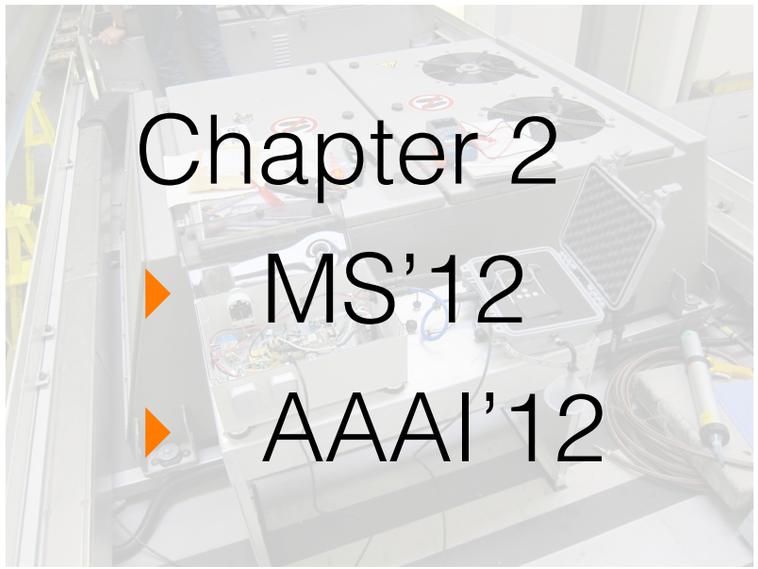
- Ten sensor nodes are installed on top of streetcars

Collected largest data set of spatially resolved air pollution measurements with over 100 million data points

Mobile Sensor Networks: Related Work

- Mobile air pollution measurements
  - Standard instruments, e.g.,
    - Wallace et al., Mobile monitoring of air pollution in cities: the case of Hamilton, Ontario, Canada, Environmental Monitoring, 2009
    - Hudda et al., Emissions from an international airport increase particle number concentrations 4-fold at 10 km downwind, Environmental Science & Technology, 2014
  - Low-cost gas sensor node prototypes, e.g.,
    - Dutta et al., Common sense: participatory urban sensing using a network of handheld air quality monitors, SenSys, 2009
    - Zwack et al., Characterizing local traffic contributions to particulate air pollution in street canyons using mobile monitoring techniques, Atmospheric Environment, 2011
    - Elen et al., The aeroflex: a bicycle for mobile air quality measurements, Sensors, 2013
- Sensor networks based on existing infrastructure, e.g.,
  - Chen et al., B-Planner: Night bus route planning using large-scale taxi GPS traces, PerCom, 2013
  - Shang et al., Inferring gas consumption and pollution emission of vehicles throughout a city, SIGKDD, 2014

Thesis Contributions



Chapter 2

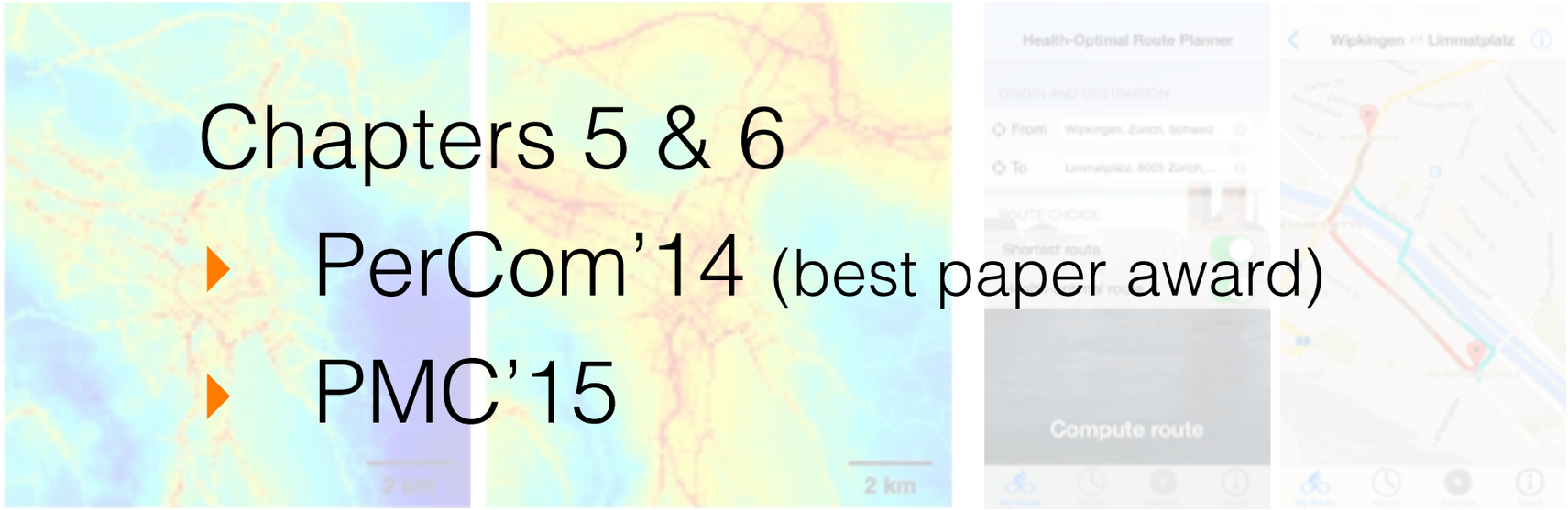
- MS'12
- AAAI'12

Mobile measurement system

Chapters 3 & 4

- EWSN'12
- DCOSS'13
- IPSN'15

Data quality assurance



Chapters 5 & 6

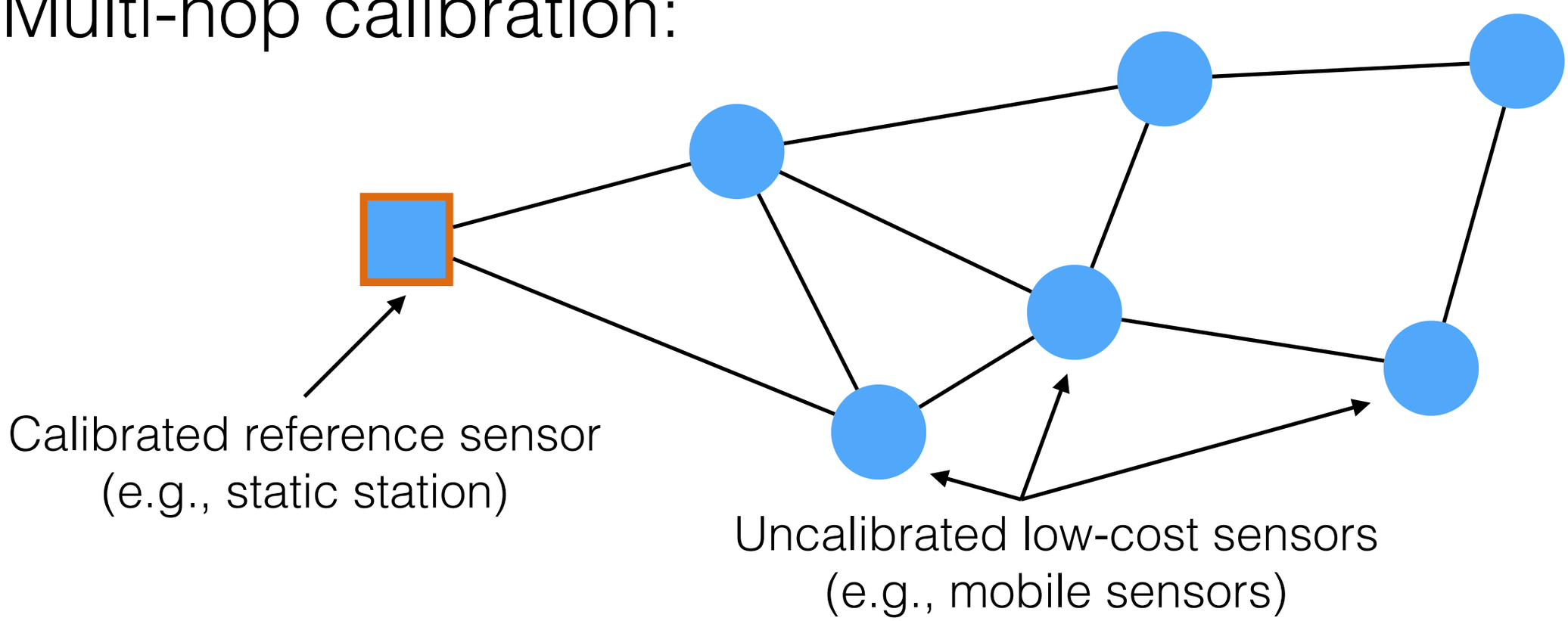
- PerCom'14 (best paper award)
- PMC'15

High-resolution air quality models and its applicability

Calibration of Mobile Sensor Networks

- Use meeting points between low-cost sensors and reference stations to calibrate sensor network

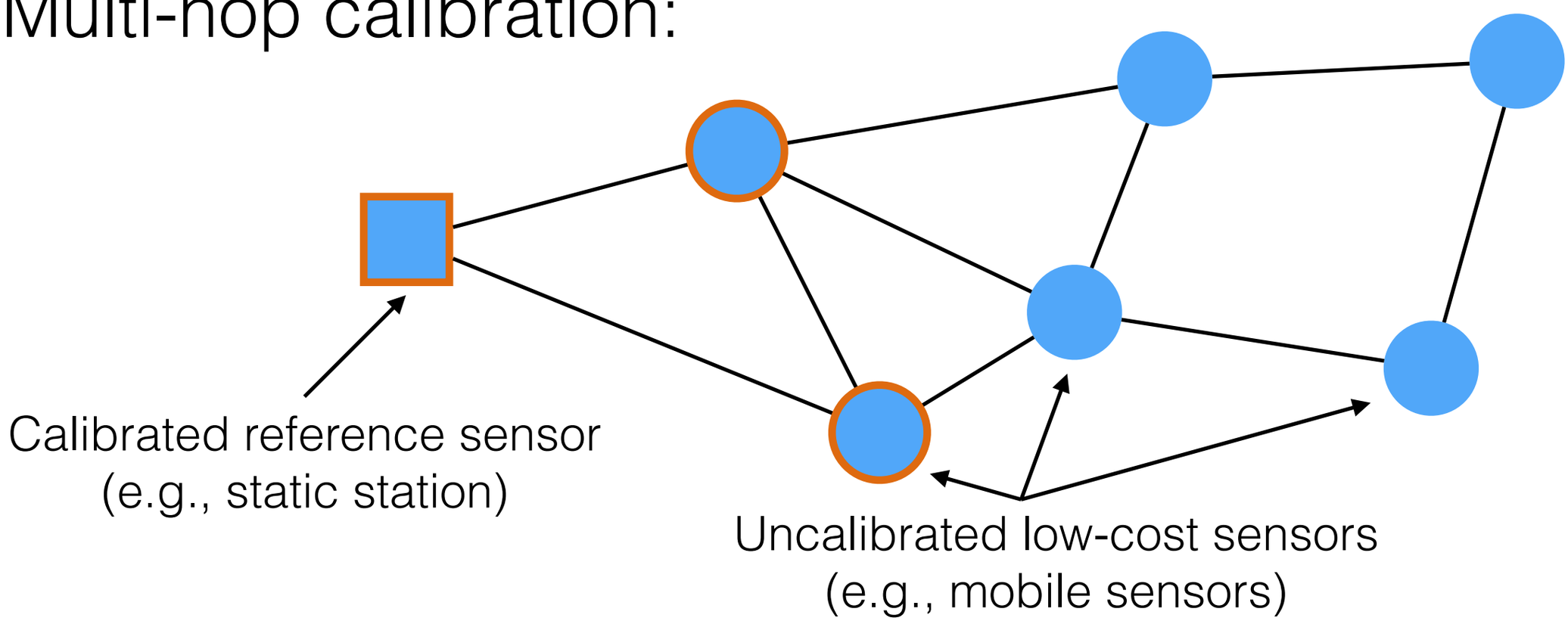
Multi-hop calibration:



Calibration of Mobile Sensor Networks

- Use meeting points between low-cost sensors and reference stations to calibrate sensor network

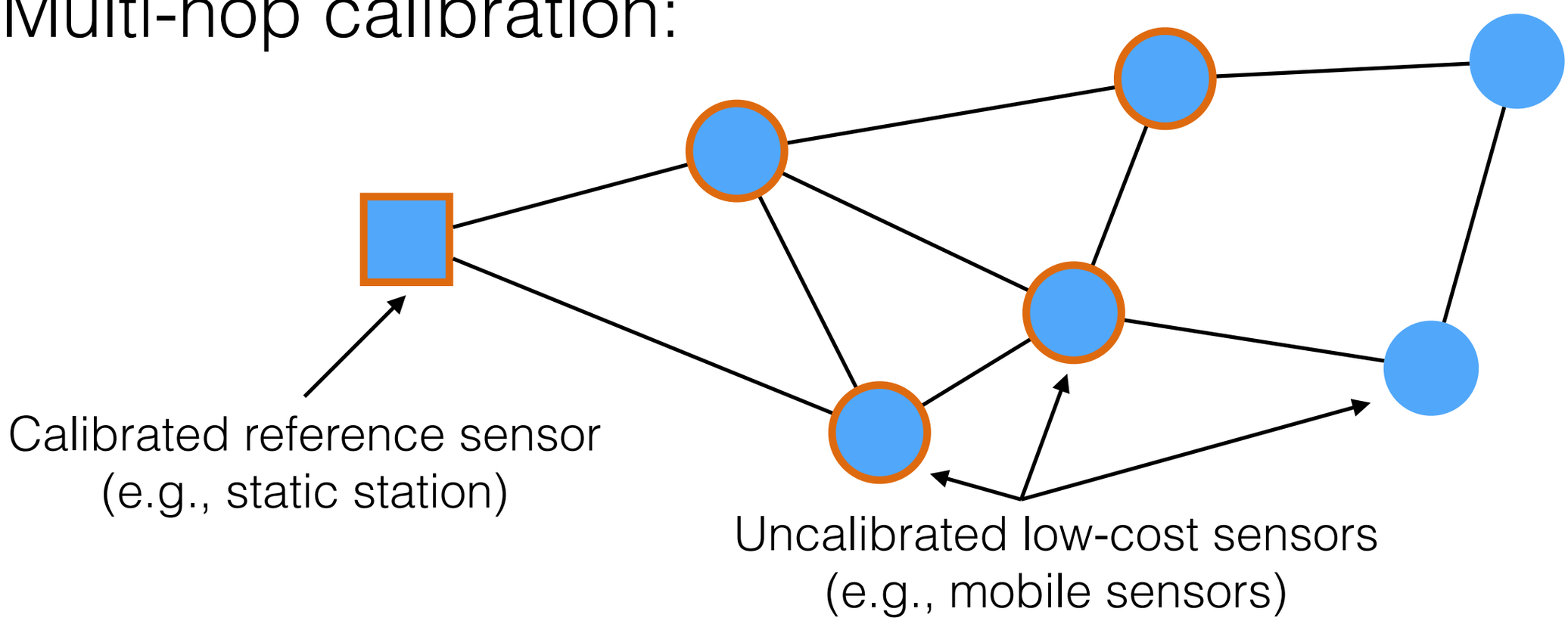
Multi-hop calibration:



Calibration of Mobile Sensor Networks

- Use meeting points between low-cost sensors and reference stations to calibrate sensor network

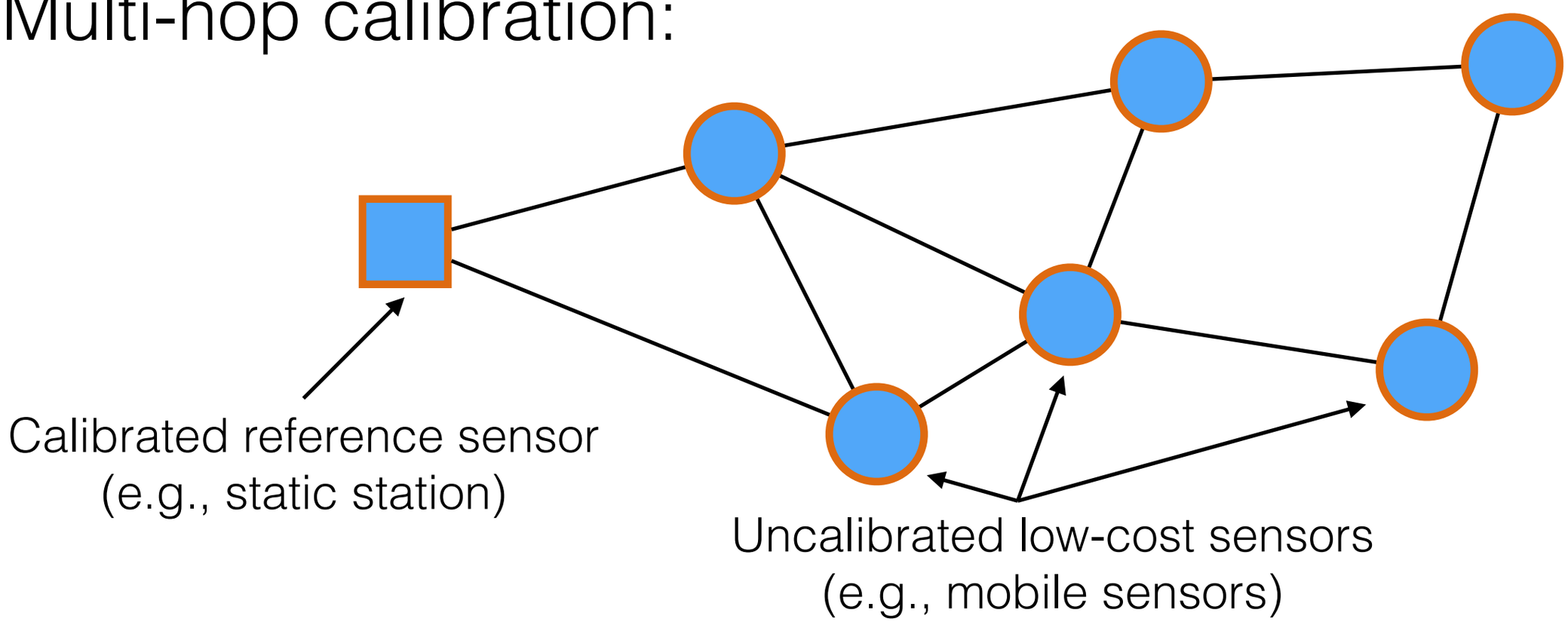
Multi-hop calibration:



Calibration of Mobile Sensor Networks

- Use meeting points between low-cost sensors and reference stations to calibrate sensor network

Multi-hop calibration:

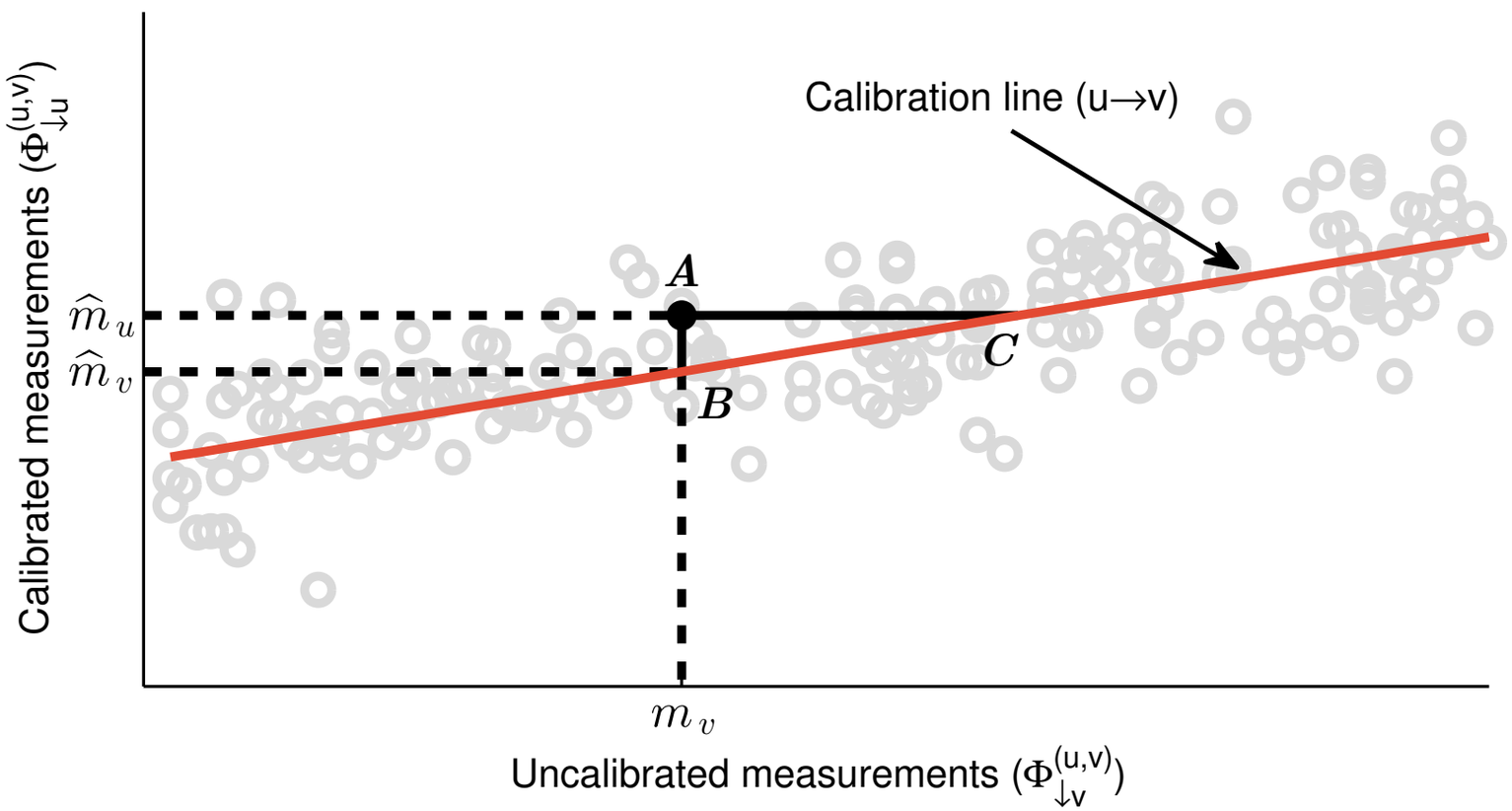


⇒ Main problem: **Error accumulation in the network**

Standard Calibration Approach

Use Ordinary Least Squares (OLS) to compute calibration coefficients (intercept α and slope β):

- Minimizes sum of squared vertical residuals *AB*
- Optimizes the root-mean-square error (RMSE)



- S. Moltchanov et al.: On the feasibility of measuring urban air pollution by wireless distributed sensor networks. Science of The Total Environment, 502:537–547, 2015
- L. Balzano and R. Nowak: Blind calibration of sensor networks. In ACM/IEEE IPSN, 2007

Bias of Ordinary Least Squares (OLS)

Ordinary Least Squares regression has problem of regression dilution

- Calibration has bias towards zero if uncalibrated sensor measurements have noise

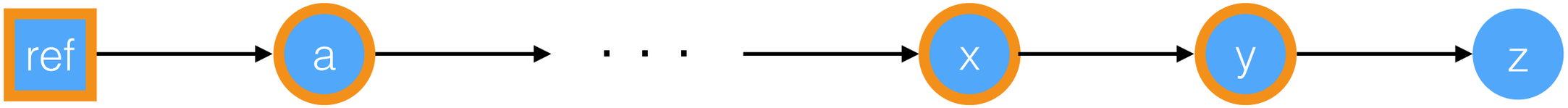
OLS:

- Reference sensor u
- Uncalibrated sensor v with noise e_v
- Slope of sensor v:

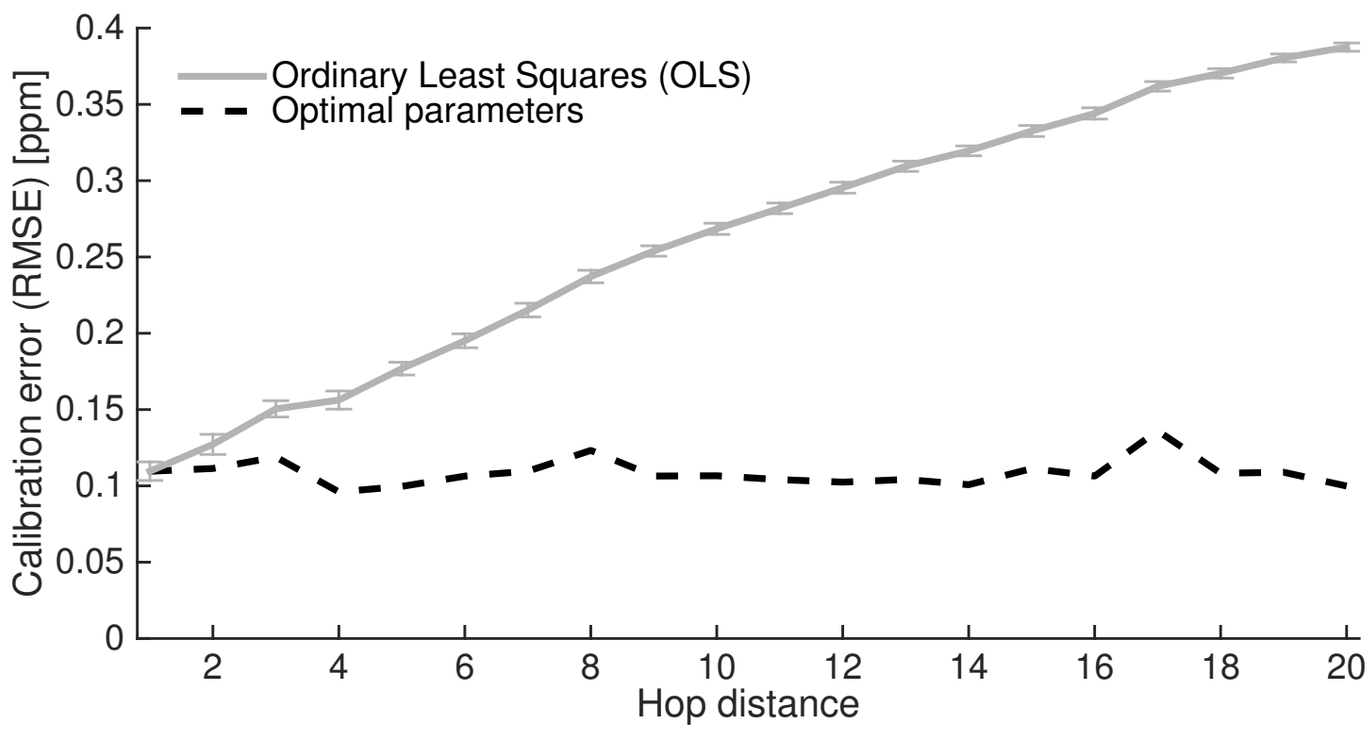
$$\beta_{OLS} = \frac{\mathrm{cov}(u,v)}{\mathrm{var}(v) + \mathrm{var}(e_v)}$$

- Single-hop calibration: regression dilution is not a problem
- Multi-hop calibration: regression dilution leads to high error accumulation in the network

Error Accumulation of OLS



- Calibration of sensor z is strongly biased towards zero: $\beta_{OLS} = \frac{\mathrm{cov}(ref,a)\cdot\ldots\cdot\mathrm{cov}(y,z)}{(\mathrm{var}(a)+\mathrm{var}(e_a))\cdot\ldots\cdot(\mathrm{var}(z)+\mathrm{var}(e_z))}$

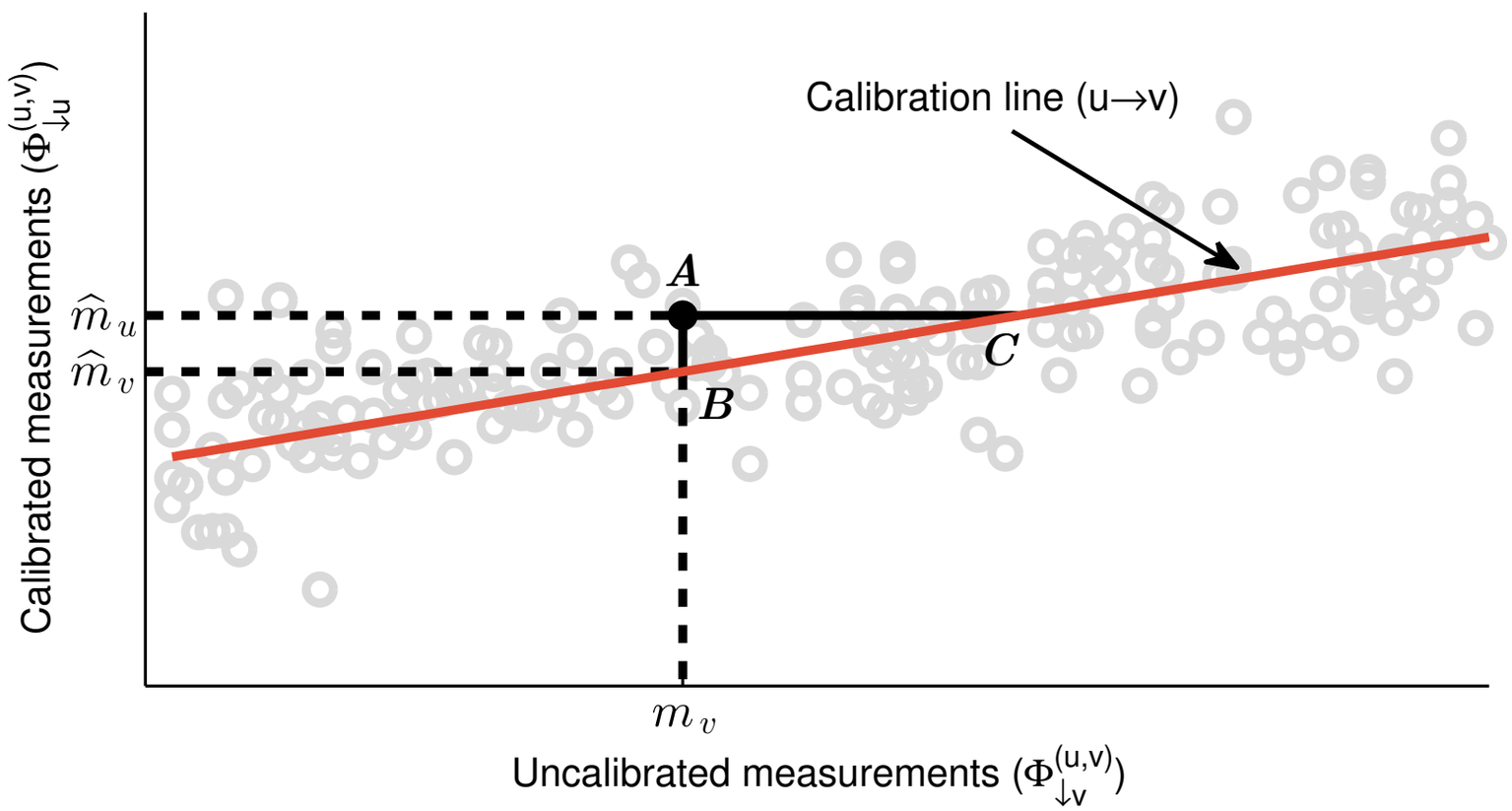


Large error accumulation over number of calibration hops

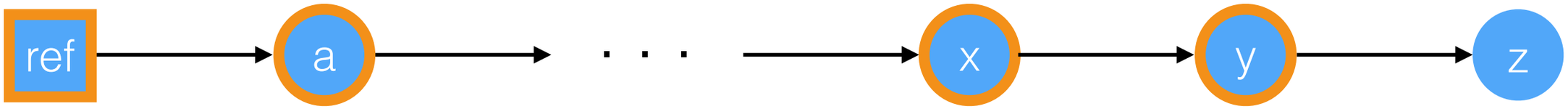
Calibration with Low Error Propagation

Use Geometric Mean Regression (GMR) to compute calibration coefficients (intercept α and slope β):

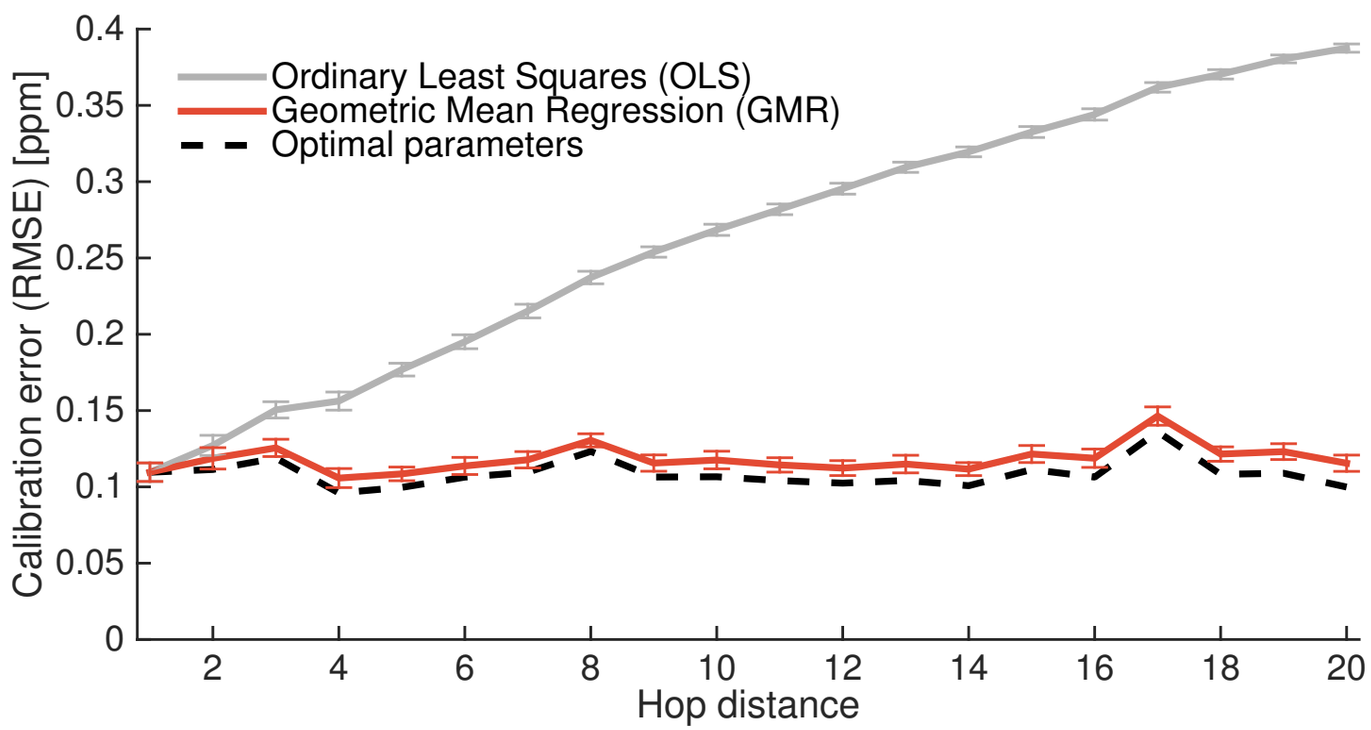
- Minimizes the sum of the areas of triangles *ABC*
- No bias towards zero



No Error Accumulation with GMR

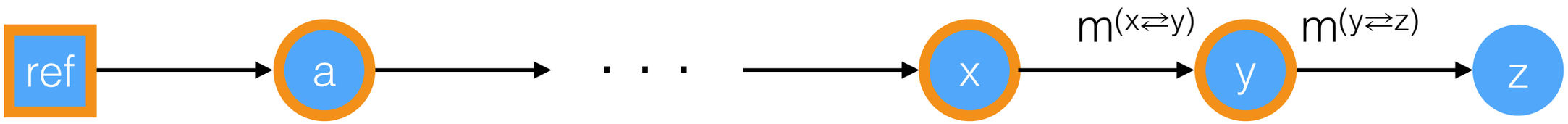


- Slope of sensor z **is independent** of the noise and variance of sensors a…z: $\beta_{GMR} = \sqrt{\frac{\mathrm{var}(ref) + \mathrm{var}(e_{ref})}{\mathrm{var}(z) + \mathrm{var}(e_z)}}$



Calibration does not depend on the calibration path

What is the Assumption?



The calibration of sensor z is independent of sensor y

if **var($m^{(x \rightleftarrows y)}$) == var($m^{(y \rightleftarrows z)}$)**

$m^{(x \rightleftarrows y)}$: Set of measurements of sensor y at meeting points with sensor x

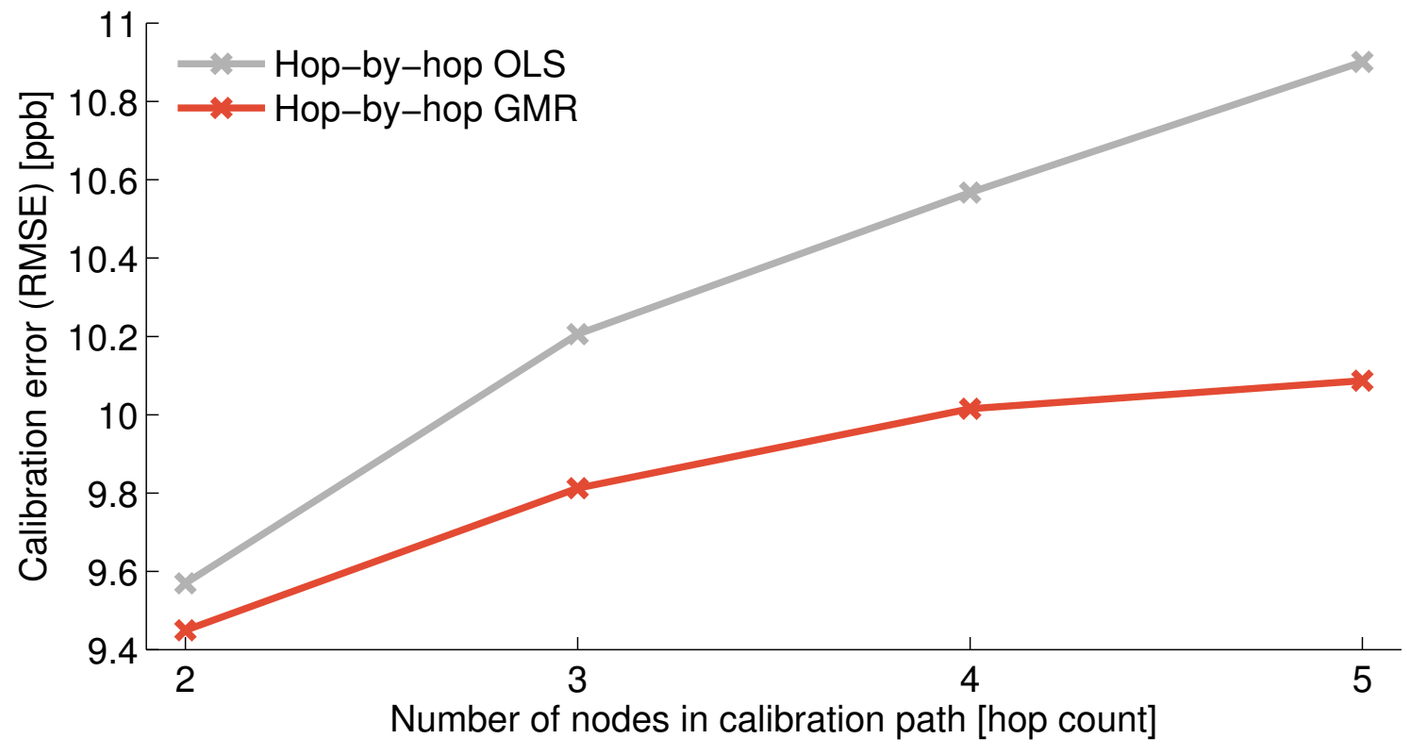
$m^{(y \rightleftarrows z)}$: Set of measurements of sensor y at meeting points with sensor z

In reality this assumption usually does not hold, but simulations and real sensor measurements show:

- GMR accumulates much less error even if the above assumption does not hold

Real Air Pollution Measurements

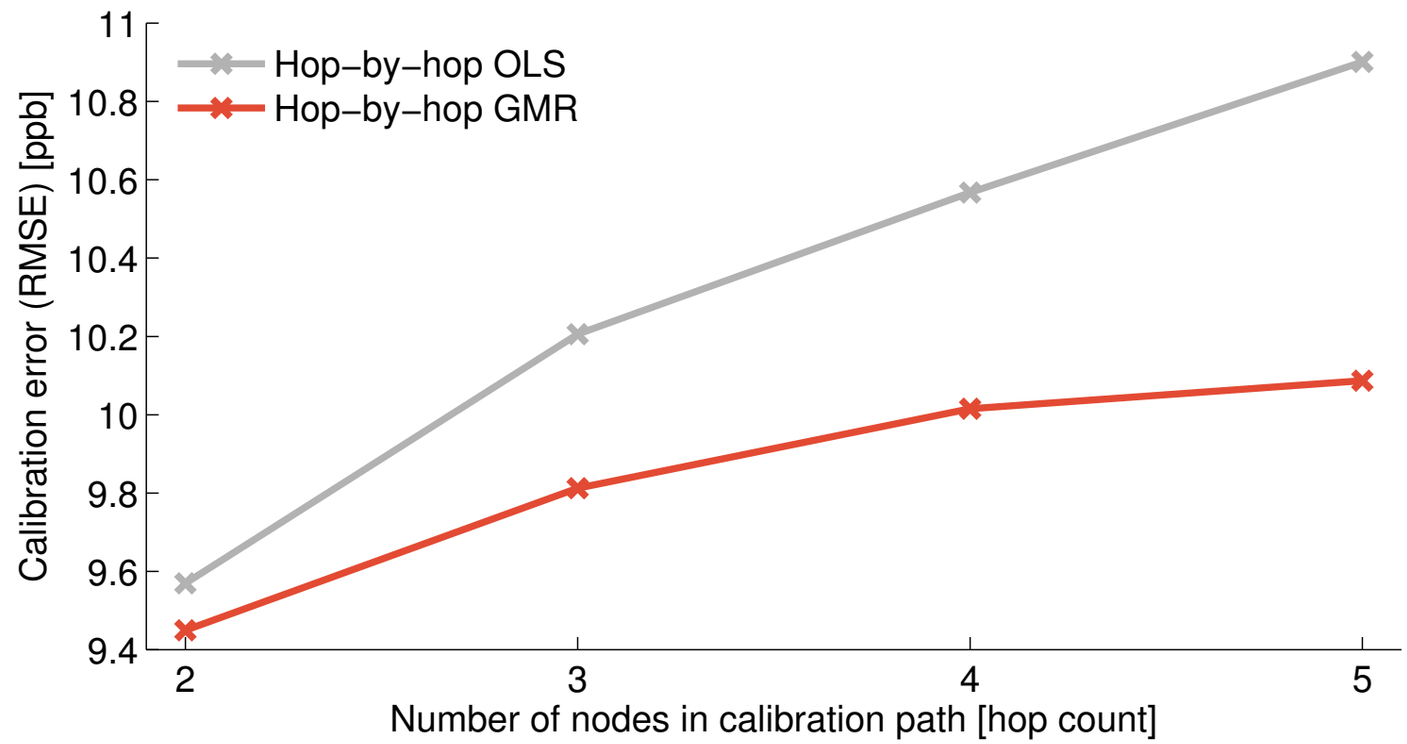
Calibration of ozone measurements from the mobile sensor network



Proposed algorithm is suitable for the calibration of large, mobile, and heterogeneous sensor networks

Real Air Pollution Measurements

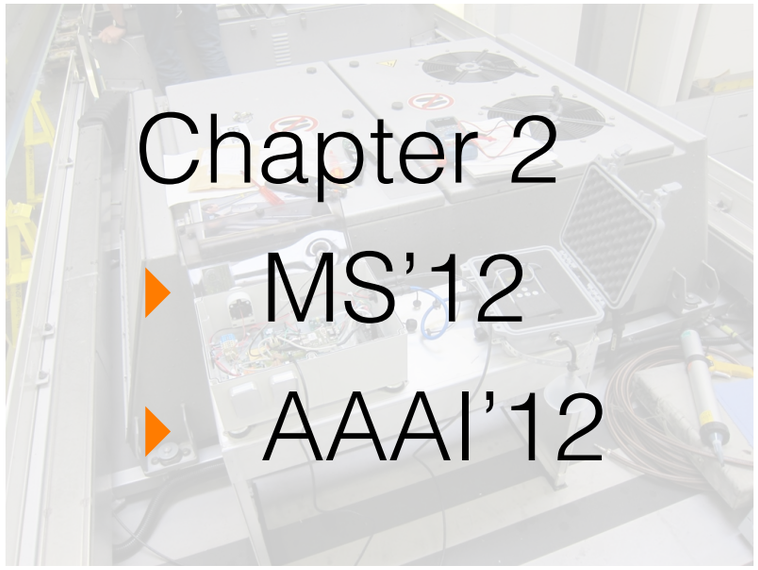
Calibration of ozone measurements from the mobile sensor network



Proposed algorithm is suitable for the calibration of large, mobile, and heterogeneous sensor networks

- Assess quality of measurements and outlier detection by integrating **generic models** for the **phenomena** monitored and the **sensors** used

Thesis Contributions

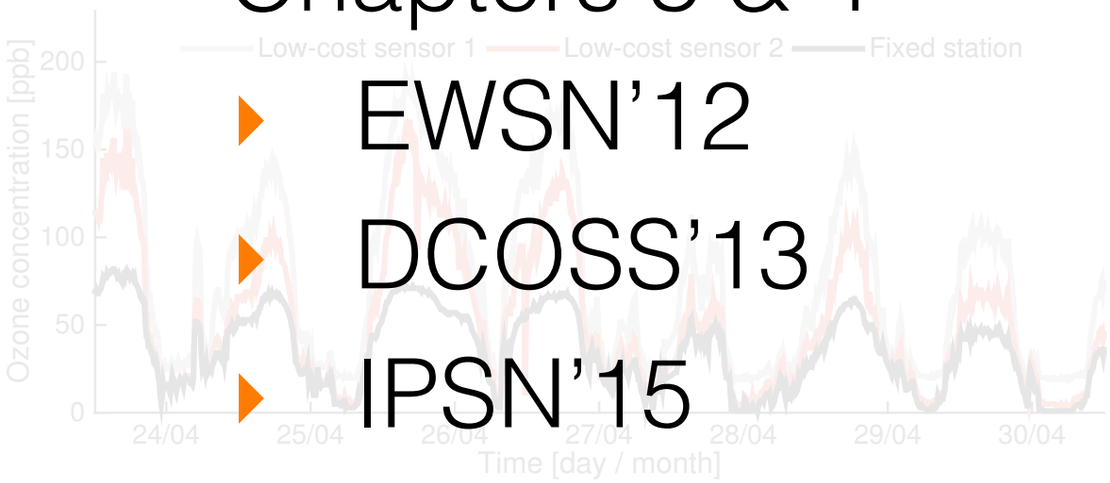


Chapter 2

- MS'12
- AAAI'12

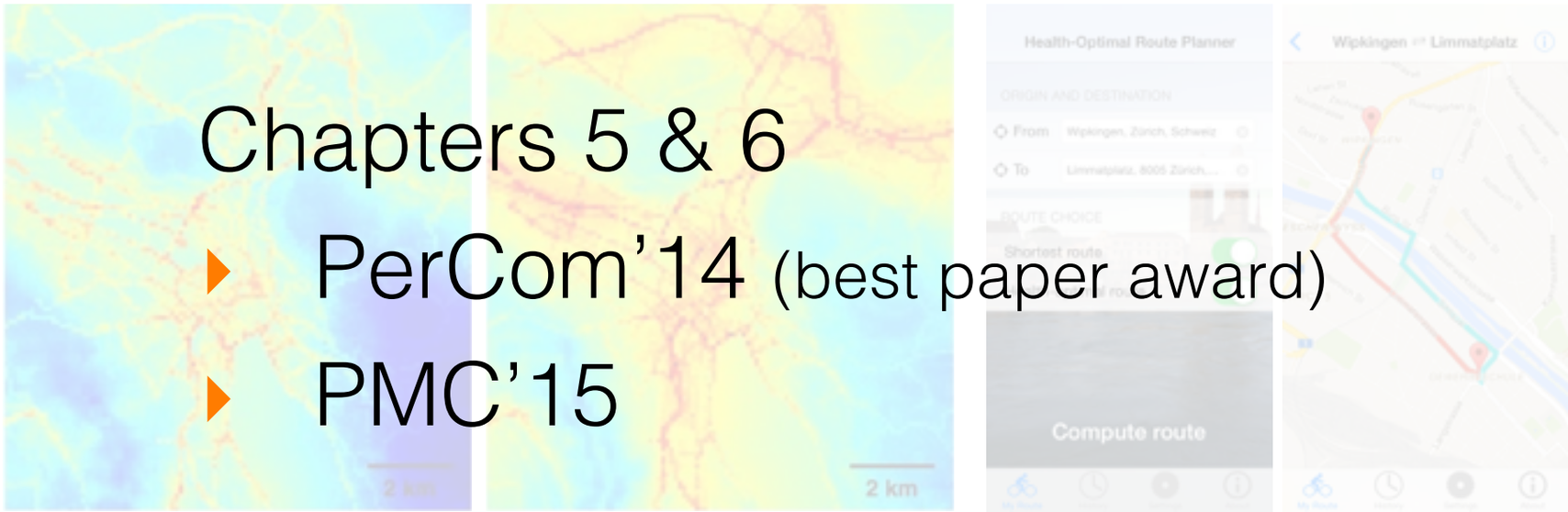
Mobile measurement system

Chapters 3 & 4



- EWSN'12
- DCOSS'13
- IPSN'15

Data quality assurance

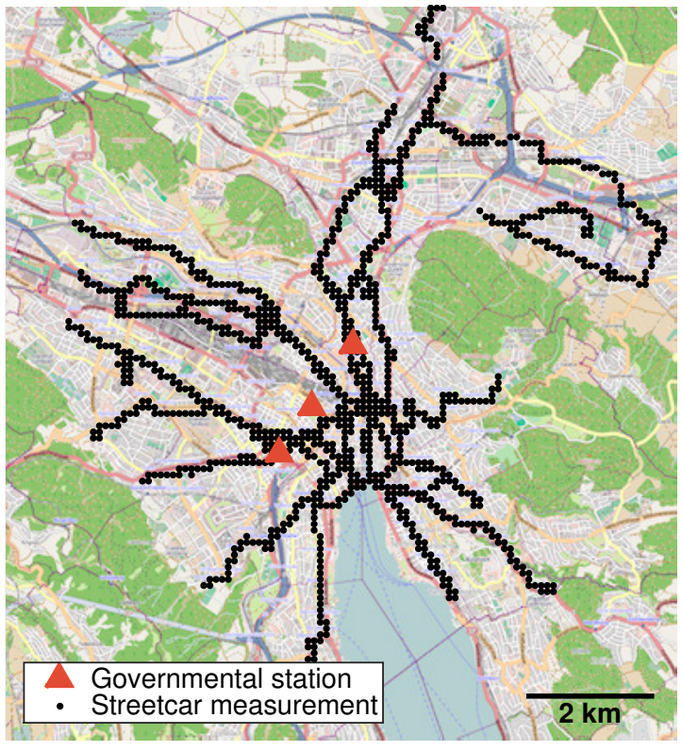


Chapters 5 & 6

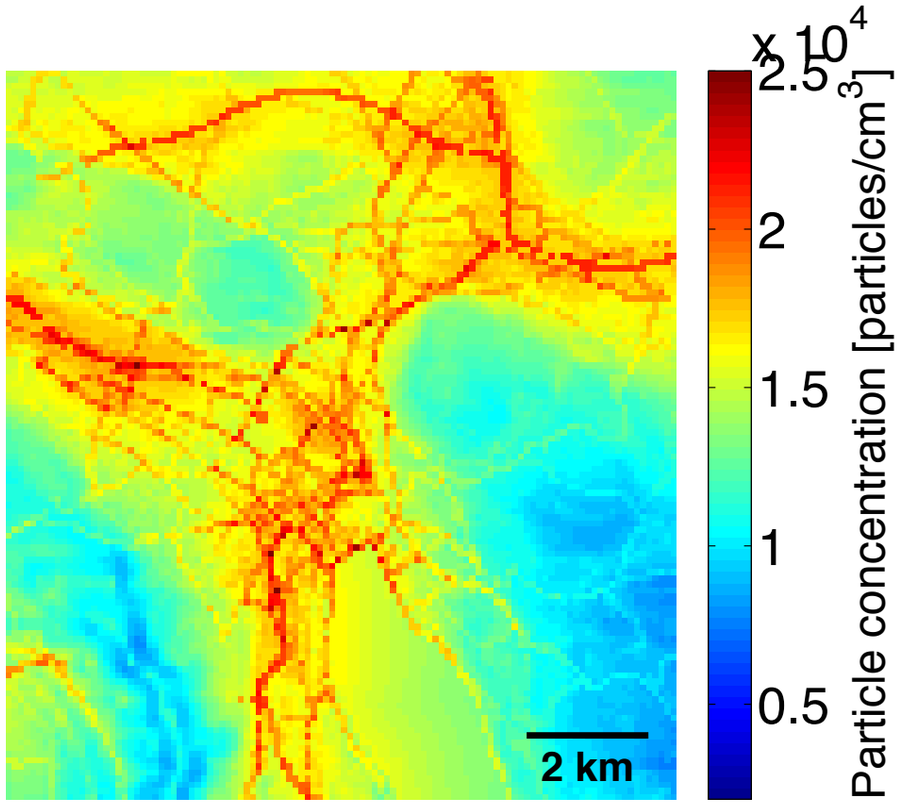
- PerCom'14 (best paper award)
- PMC'15

High-resolution air quality models and its applicability

From Single Measurements to High Resolution Pollution Maps



Single measurements



Fine-grained pollution map

Processing steps:

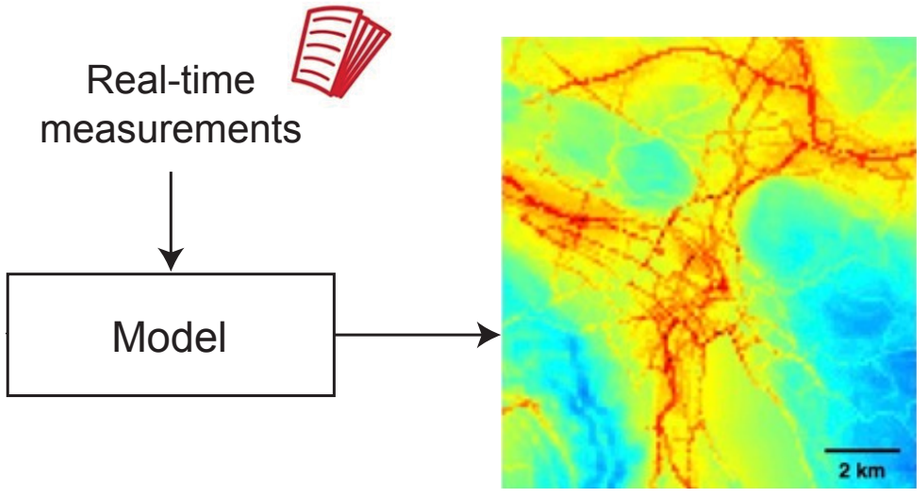
Single measurements → Data filtering → Data validation → Land-use regression modeling → Pollution maps

Developing Land-Use Regression Air Quality Models

- Land-use regression (LUR) models are widely used to assess spatial variation of air pollutants
- Pollution levels are modeled based on land-use and traffic characteristics (explanatory variables)
  1. Evaluate dependency between explanatory variables and monitored pollution levels
  2. Use found dependencies to model pollution levels at locations without measurements but land-use data

Increasing the Temporal Resolution

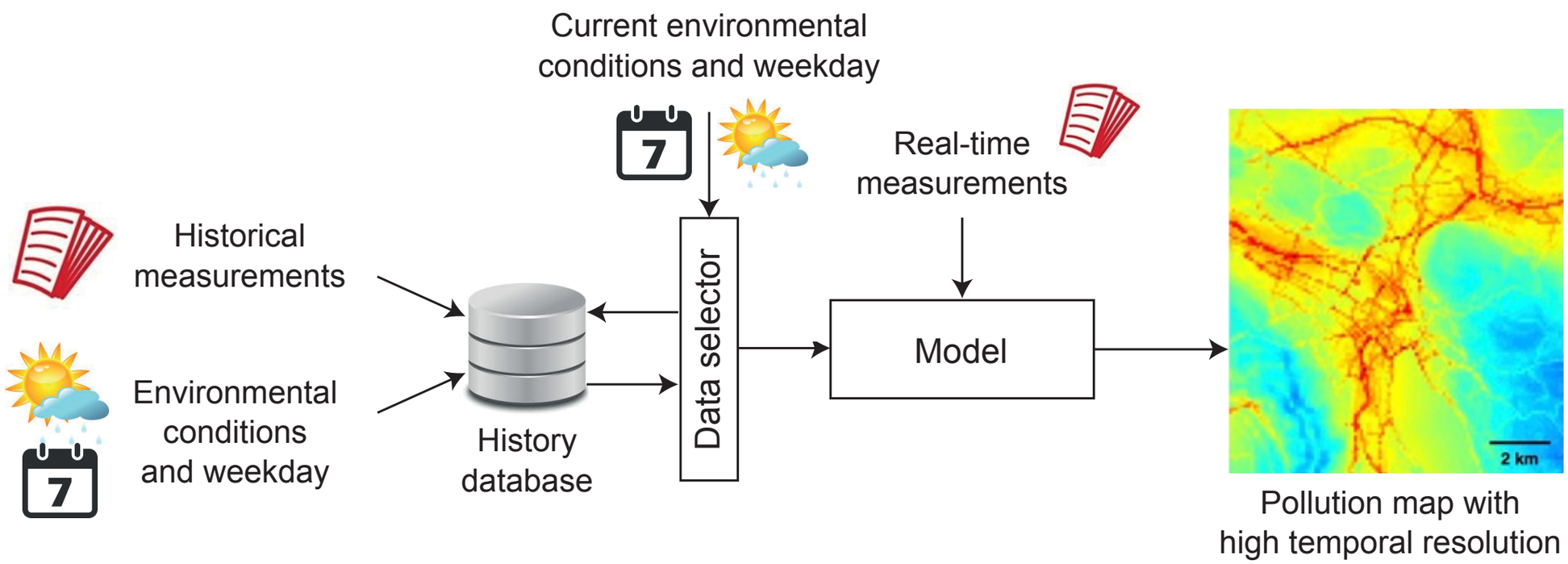
Challenging due to reduced number of measurements



Pollution map with
high temporal resolution

Increasing the Temporal Resolution

Challenging due to reduced number of measurements

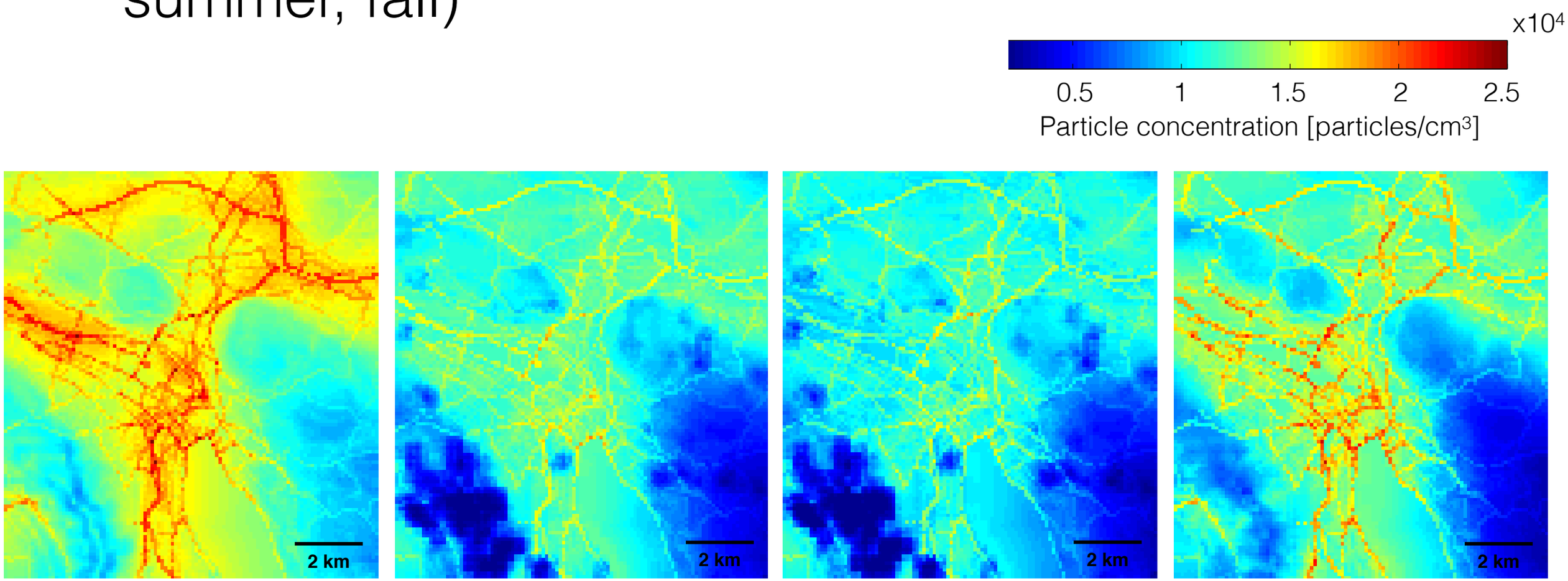


- Additional data from a database with historical measurements enhances the original data set

Our approach enables constructing pollution maps with good accuracy and high spatial and temporal resolution

Ultrafine Particle Pollution Maps for Zurich

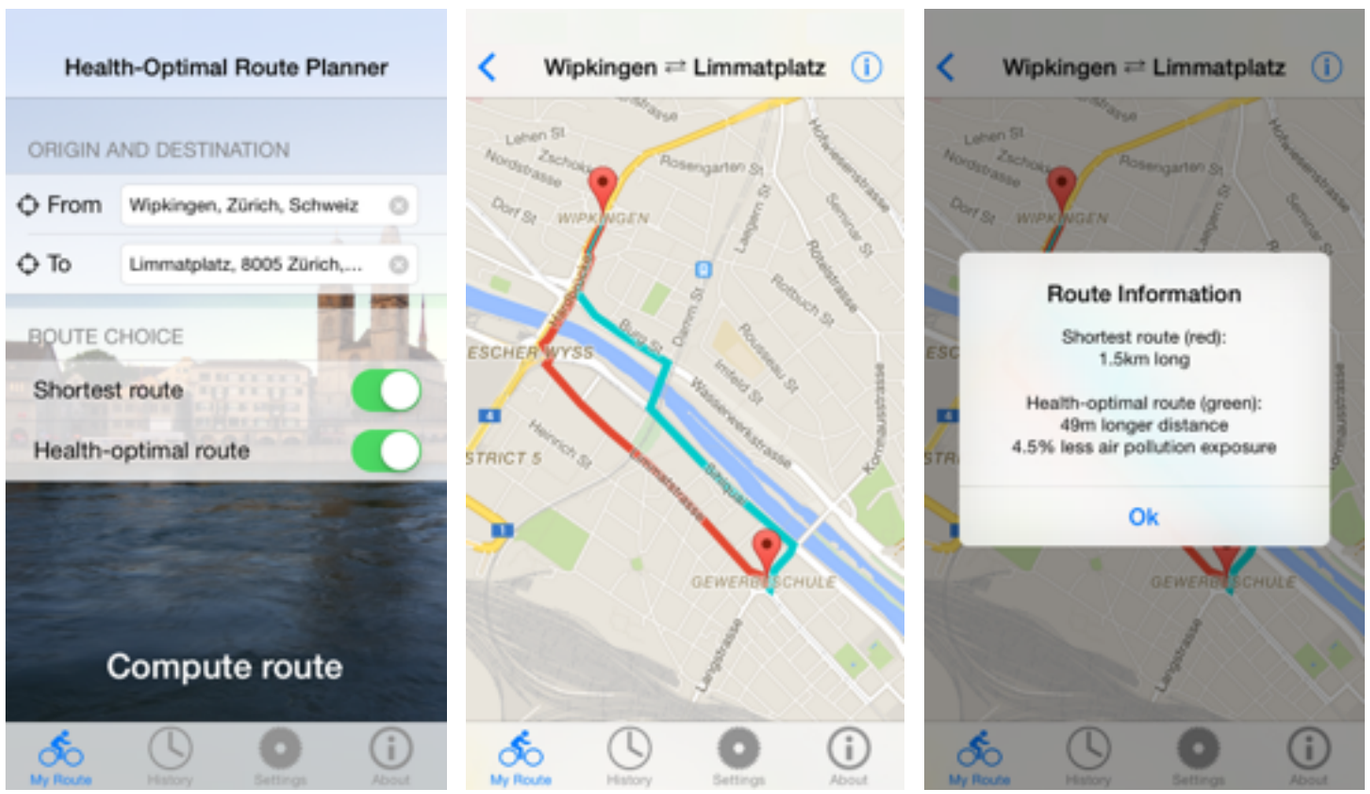
- Spatial resolution: 100m x 100m
- Temporal resolution: seasonal (winter, spring, summer, fall)



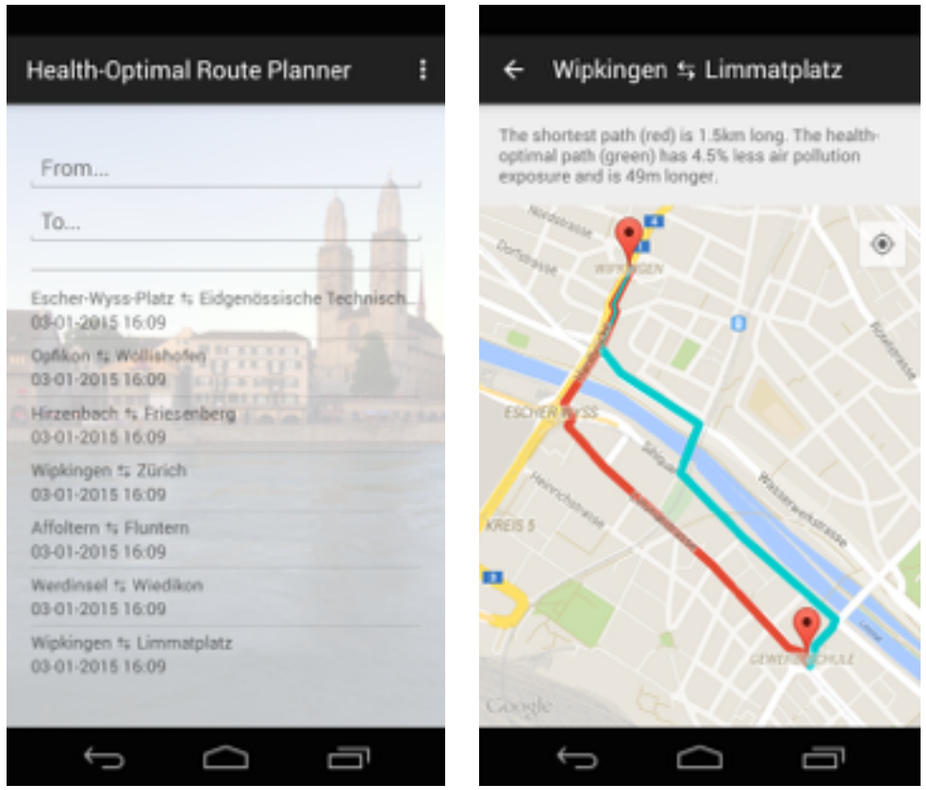
Winter (Jan.—Mar.) Spring (Apr.—June) Summer (July—Sept.) Fall (Oct.—Dec.)

Smartphone App for iOS and Android Devices

The Health-Optimal Route Planner



iPhone/iPad App



Android App

High-resolution pollution maps make new useful applications possible and raise the citizens' awareness

Conclusions

- Built a **mobile monitoring system** and collected today's **largest** spatially resolved air pollution **data set**
- Developed algorithms to **calibrate** mobile sensor networks and to **assess data quality**
- Derived pollution maps with an **unprecedented spatio-temporal resolution** and showed their utility

These findings can serve as stepping stone towards accurate, detailed, and real-time pollution assessment