Mobile Internet of Things for Sustainable Urban Mobility

Ana Aguiar

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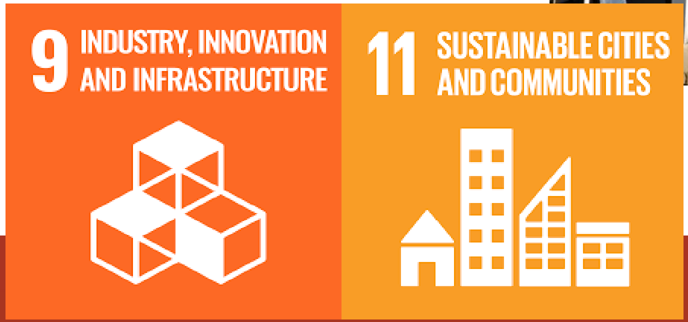
Urban Mobility, Health, Environment

- 95% and 89% of the European urban population was exposed to above threshold levels of fine particulate matter and NOx (EEA)
- Cities produce more than 60% of greenhouse gas emissions (UN Habitat)
  - Mostly buildings and transportation
- 68% of the world population will live in cities by 2050 (UN DESA)
- Cities are key arenas for leading the sustainability transition (EC Sustainable and Smart Moblity Strategy, UN EP, UN)
  - Healthier and environmentally friendlier mobility



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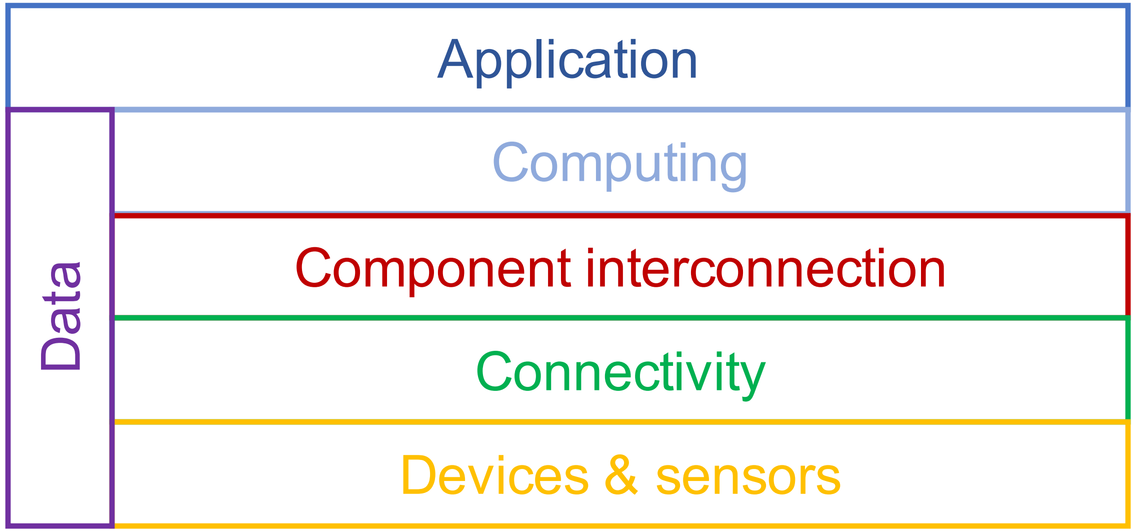
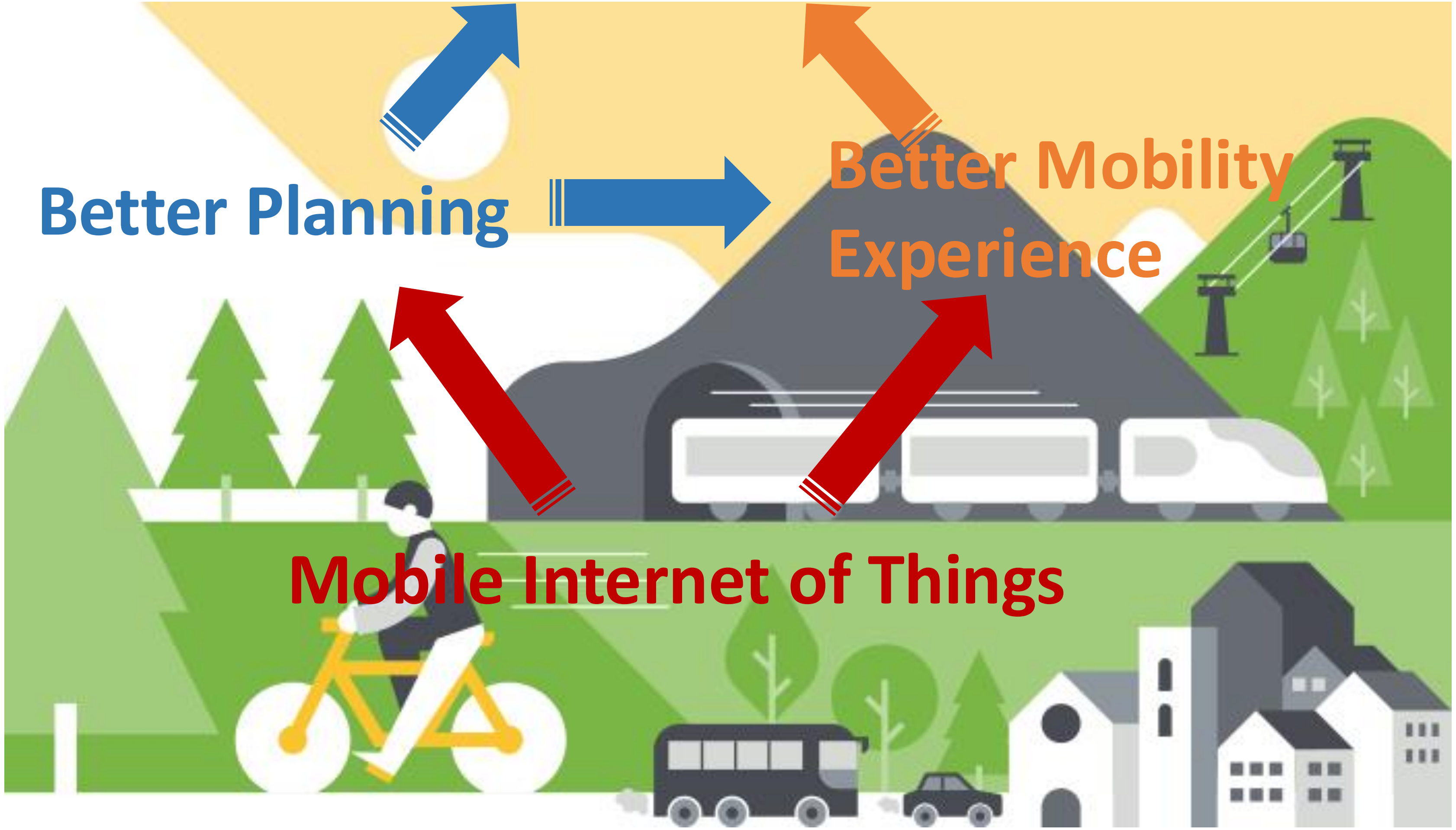
Internet of Things

- network of
- interconnected embedded devices not traditionally connected to the Internet
- and services
- that can be combined to build flexible and modular distributed applications



Change the way people move in urban areas

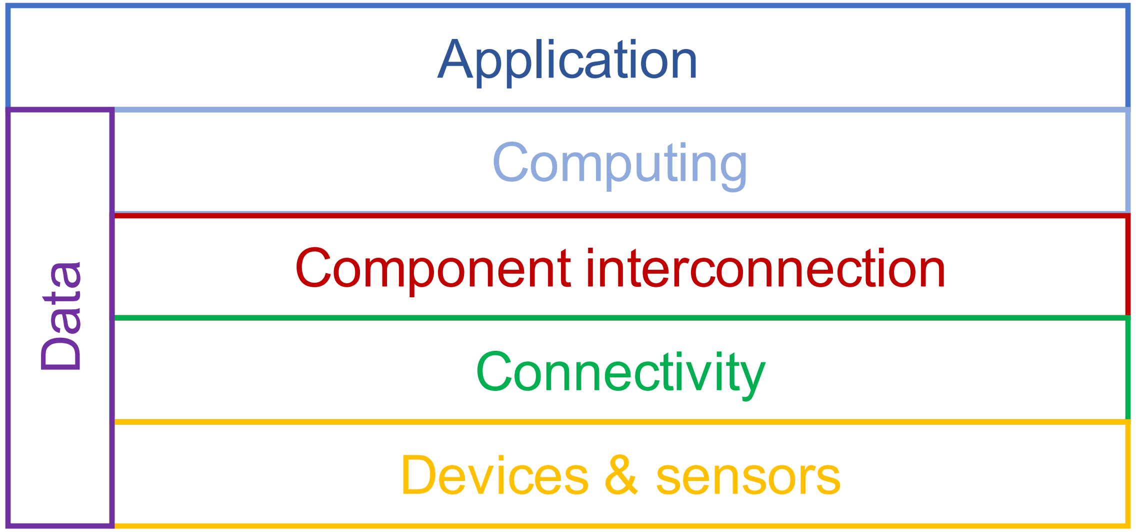


Mobile IoT for Intelligent Urban Mobility

	Better Planning
Usage	• Better understanding of mobility, human factors, decisions processes • Building fine granularity spatial-temporal data, e.g. high precision maps • Monitoring policy impact
Users	• People, policy decision makers
Actuation	• Policy
Network & Computation	• No real-time • Big data, cloud-edge-sensor computing • Data science & engineering, data processing, machine learning

Better Planning Challenges

- Key Performance Indicators's interdisciplinary nature
- Sensing and data collection
- Data quality
- Data interoperability
- Visualisation



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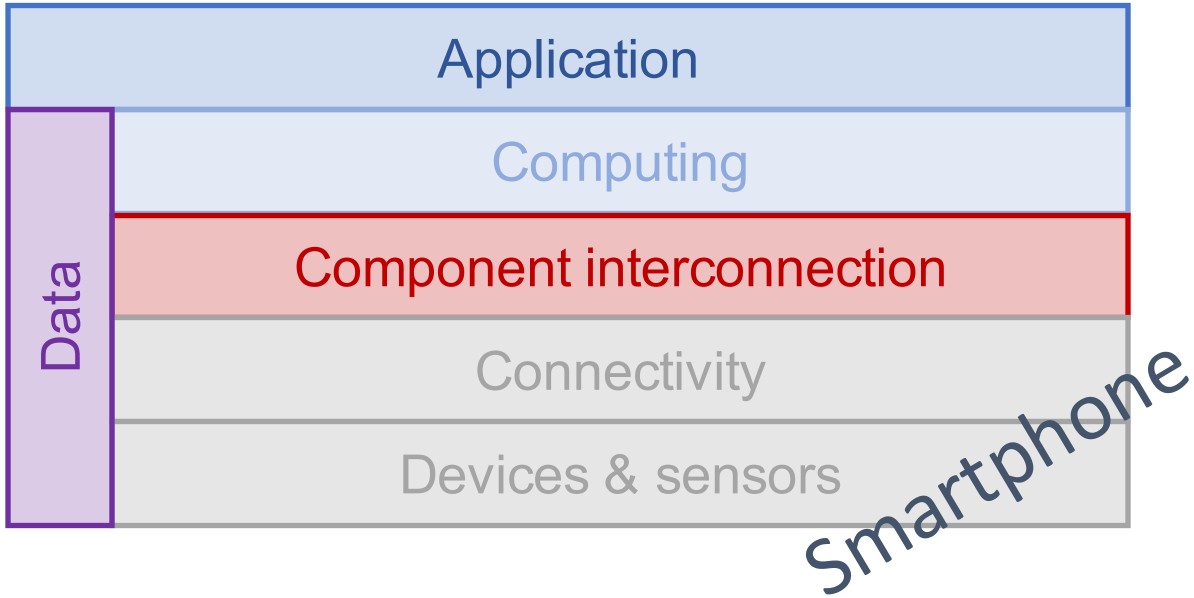
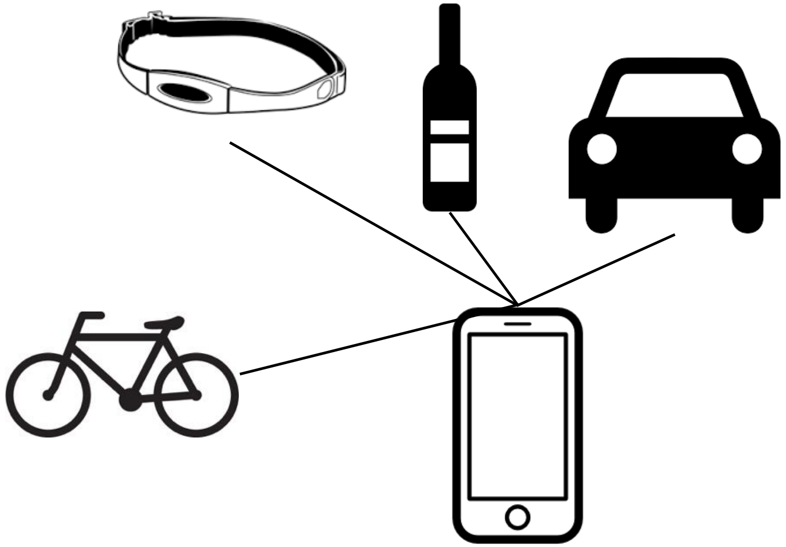
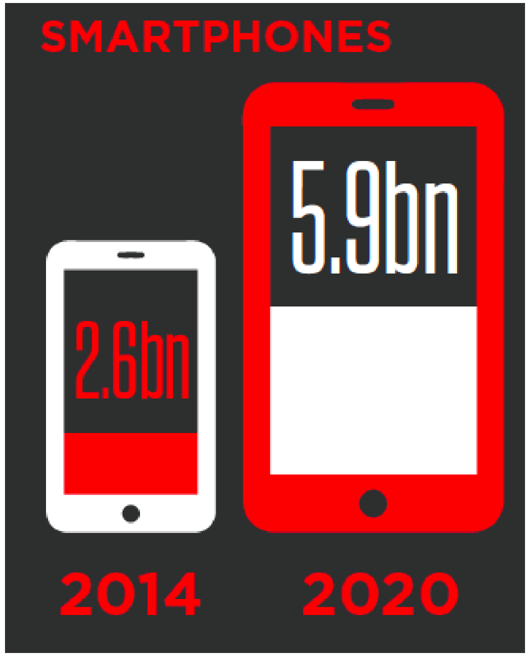


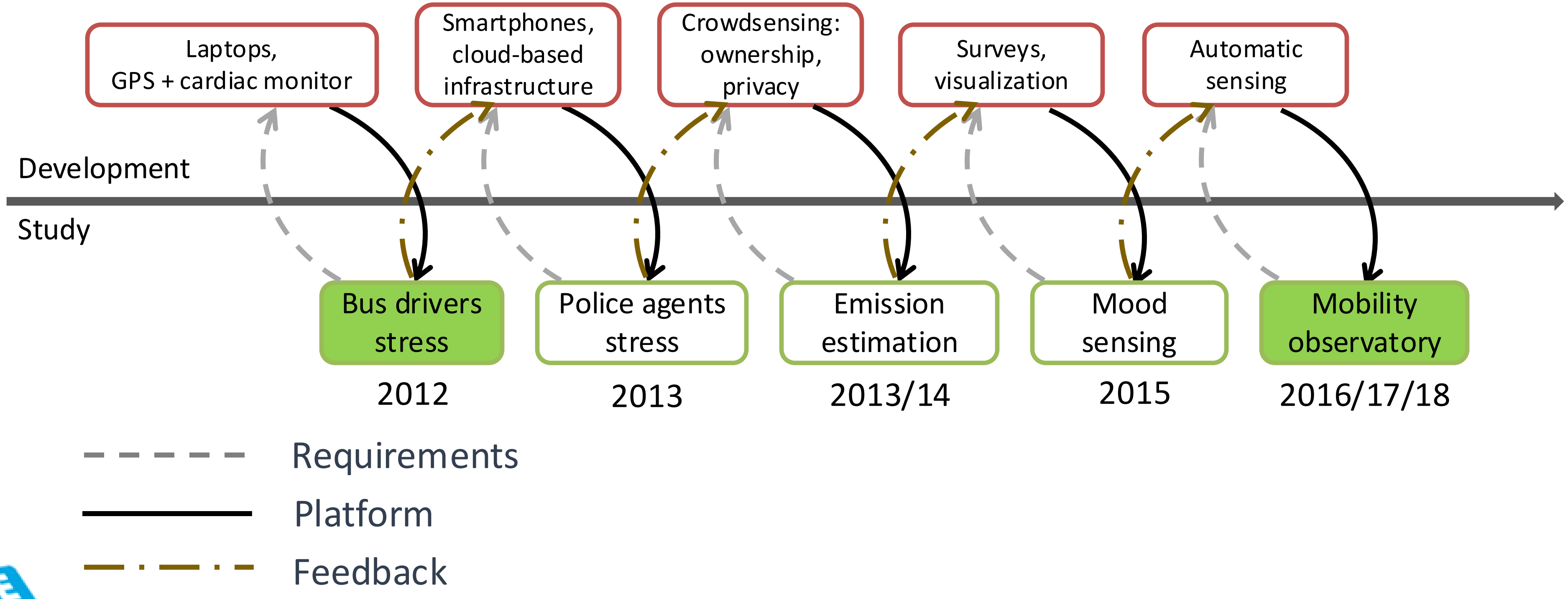
Mobile Internet of Things Crowdsensor





sense large-scale human processes

Iterative Use Case Based System Design



A. Aguiar and J. Rodrigues, "SenseMyCity: a Mobile IoT Tool for Researching Intelligent Urban Mobility," in IEEE 14th International Conference on COMmunication Systems and NETworkS (COMSNETS). Jan 2022. DOI: 10.1109/COMSNETS53615.2022.9668516.

Mobile IoT Crowdsensor Research Challenges

- How to achieve low intrusiveness in data collection in the mobile devices?
  - Automatic starting and stopping sensing
  - Seamless secure and reliable asynchronous synchronisation between local and server databases

- How does position inaccuracy influence information extracted from crowdsensed spatial-temporally referenced data?

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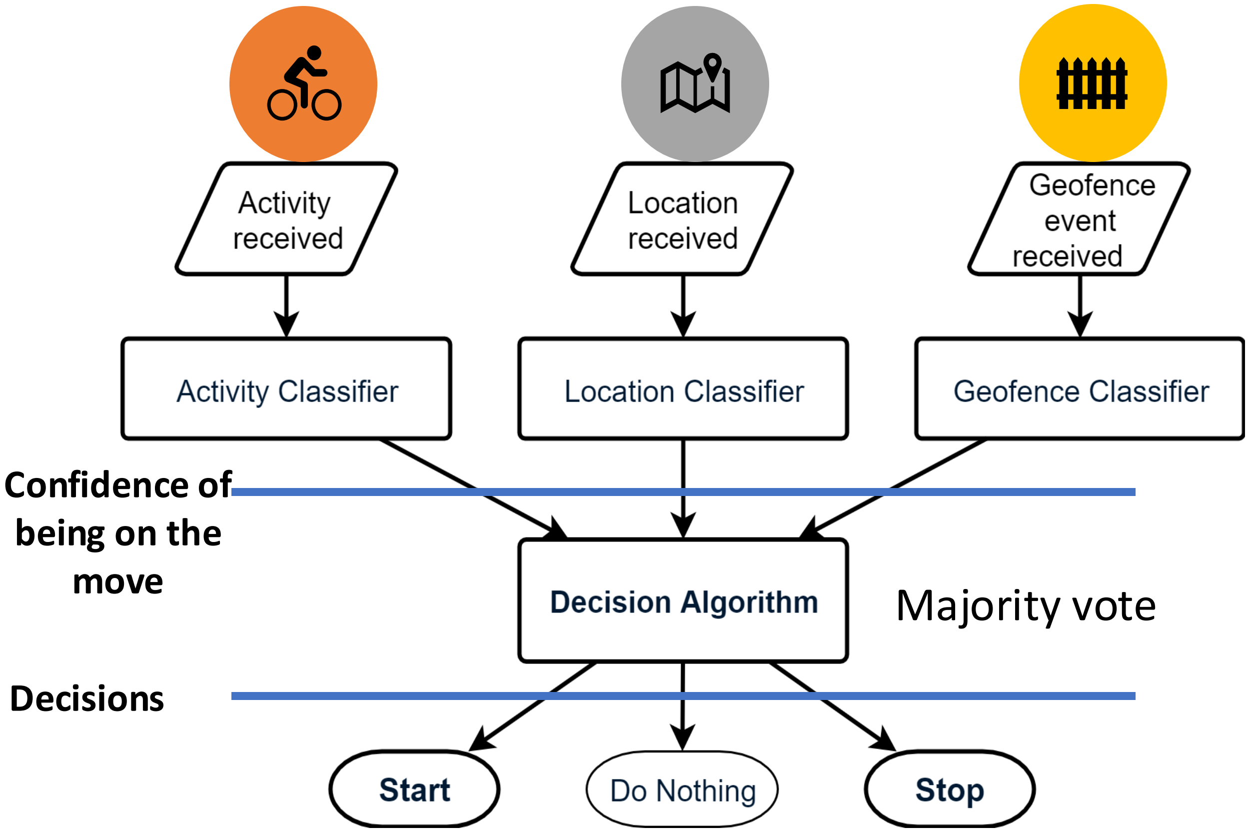
Detecting Urban Movement



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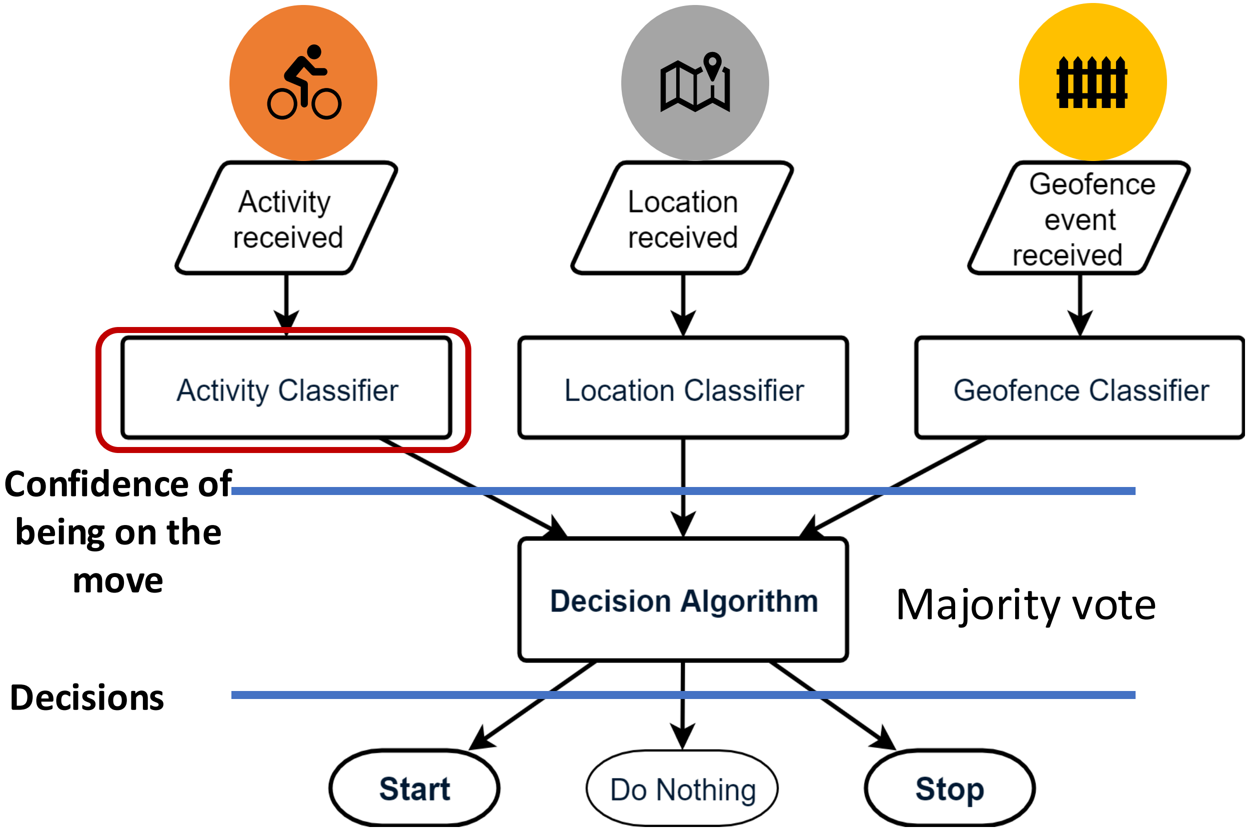

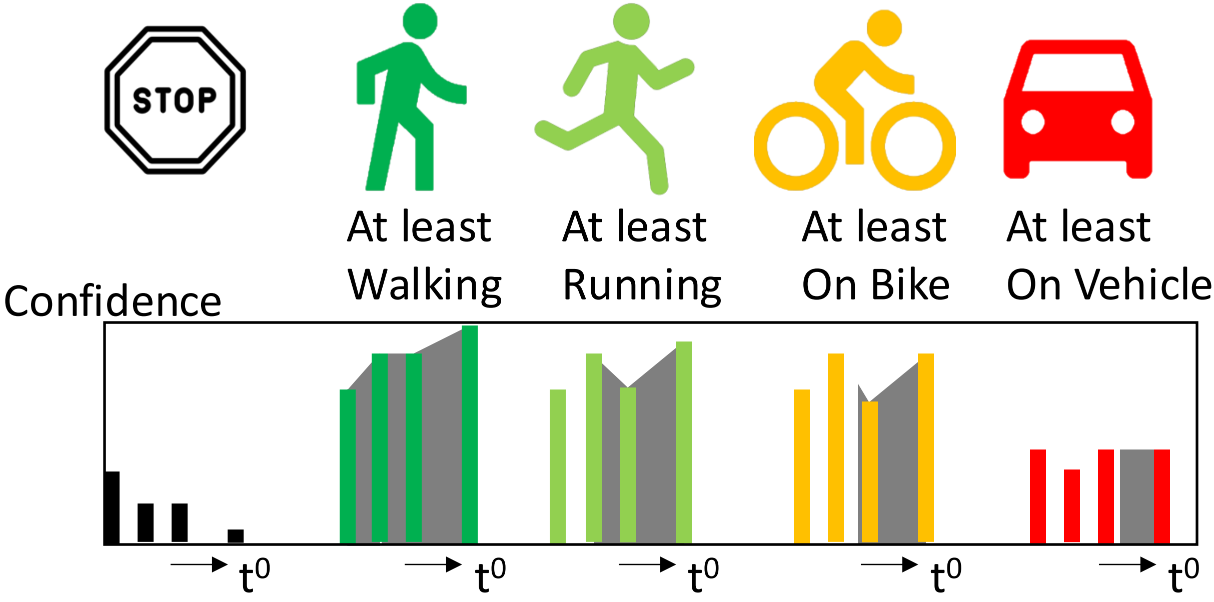

Integrate in time to estimate movement

Different windows for different "speeds"

Moving Confidence = Max(Integral / window_area)

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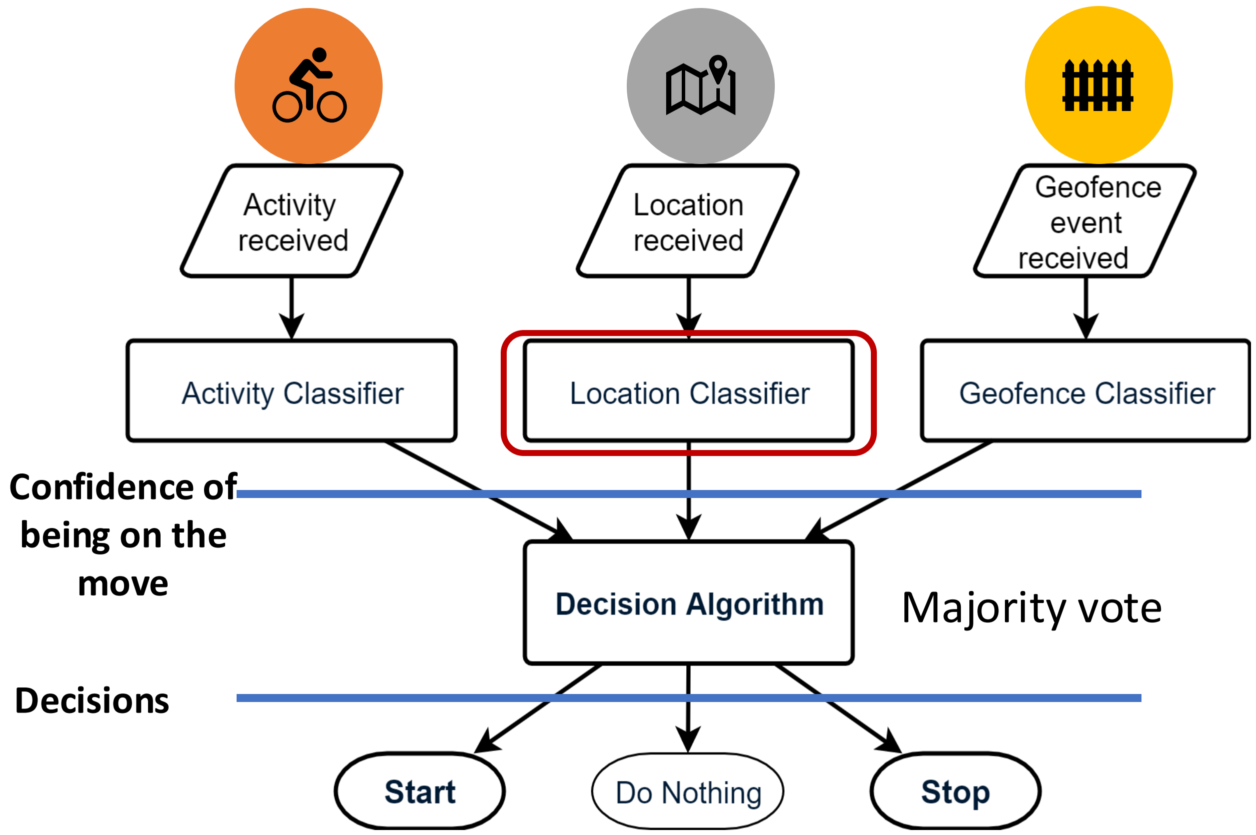

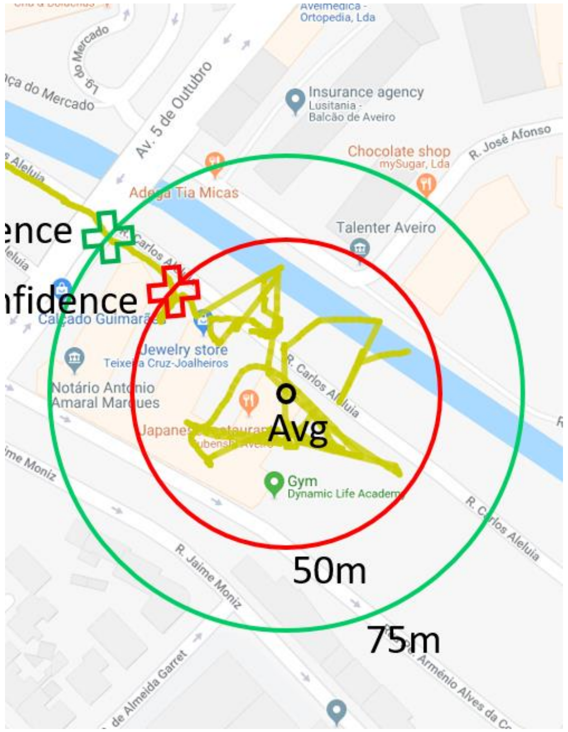

Low frequency locations before starting, often low accuracy
High frequency locations after stopping, often very noisy
Adaptation of radius of gyration

$$D = 2 * \max_i\left(d(p_i, \Delta)\right)$$

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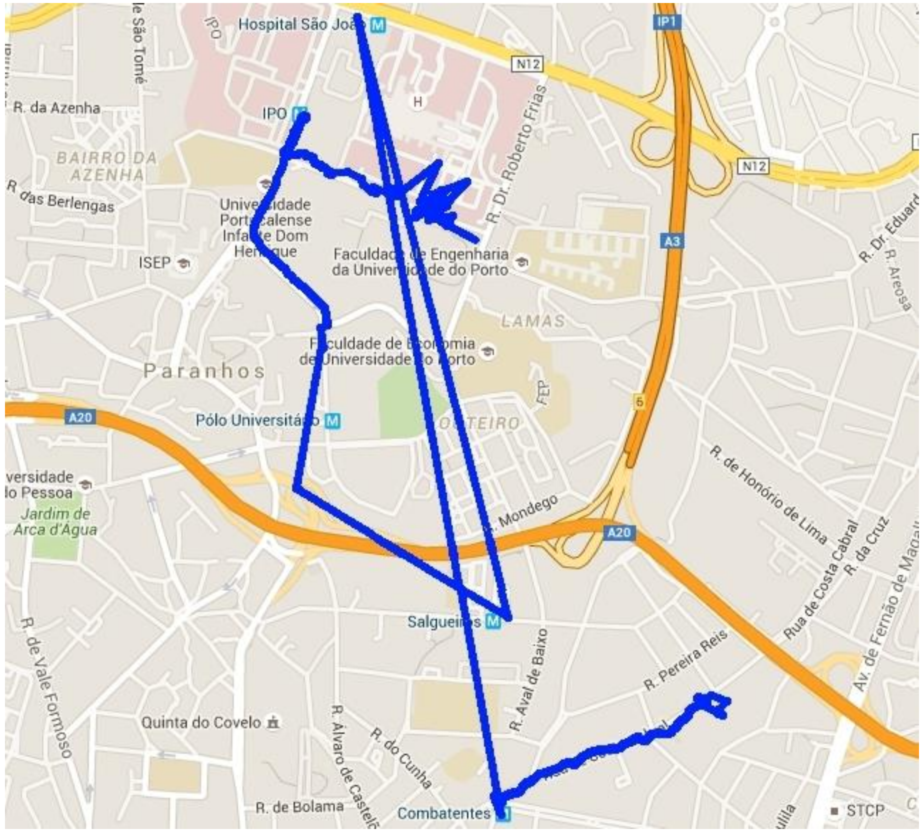
Data Quality for Real GPS Trajectories

- Google Fused Location Provider => Timeseries of locations of very different accuracies
    - GPS technology when available
    - Complemented by network (WiFi and cellular) assisted localisation



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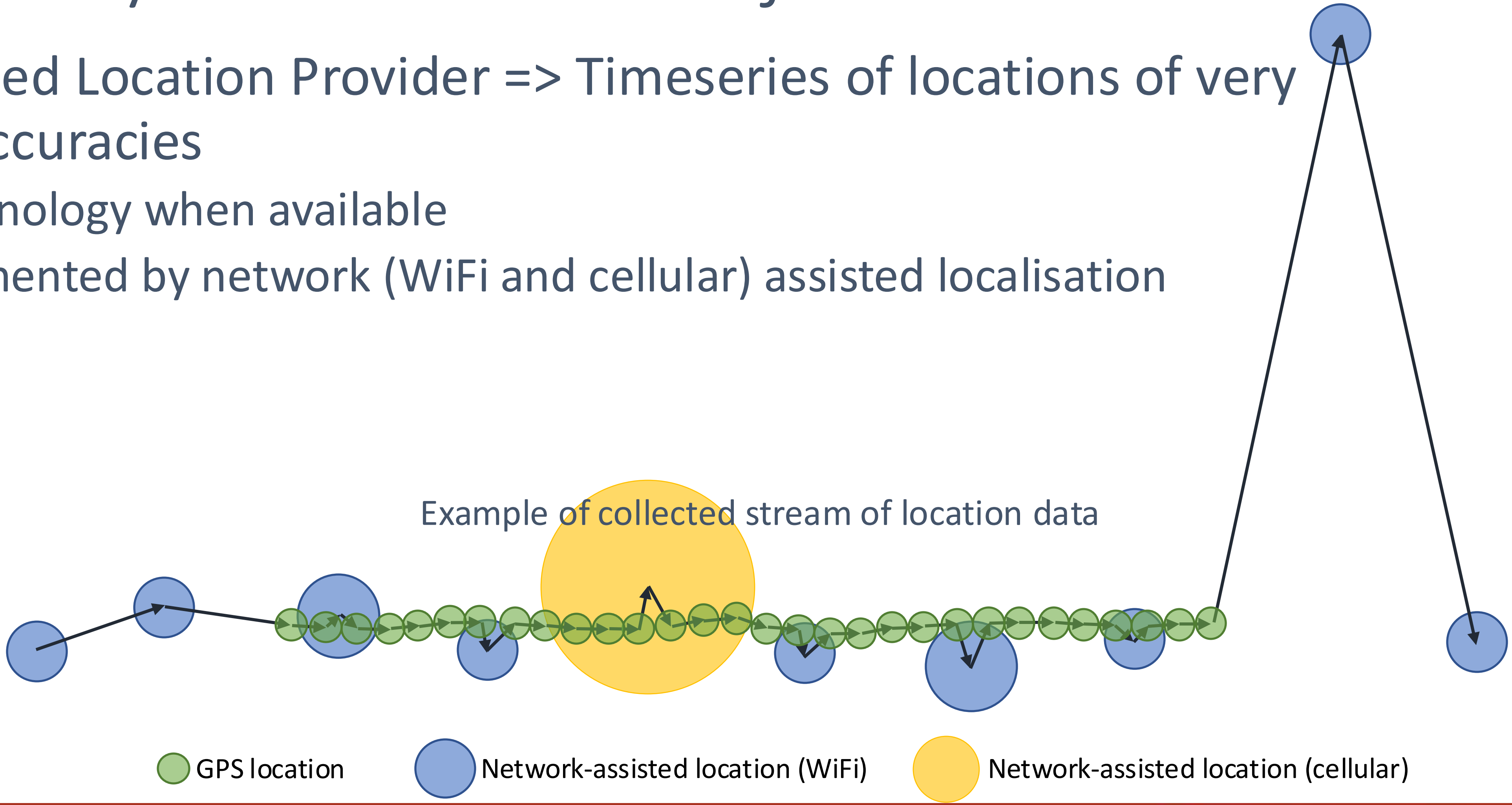

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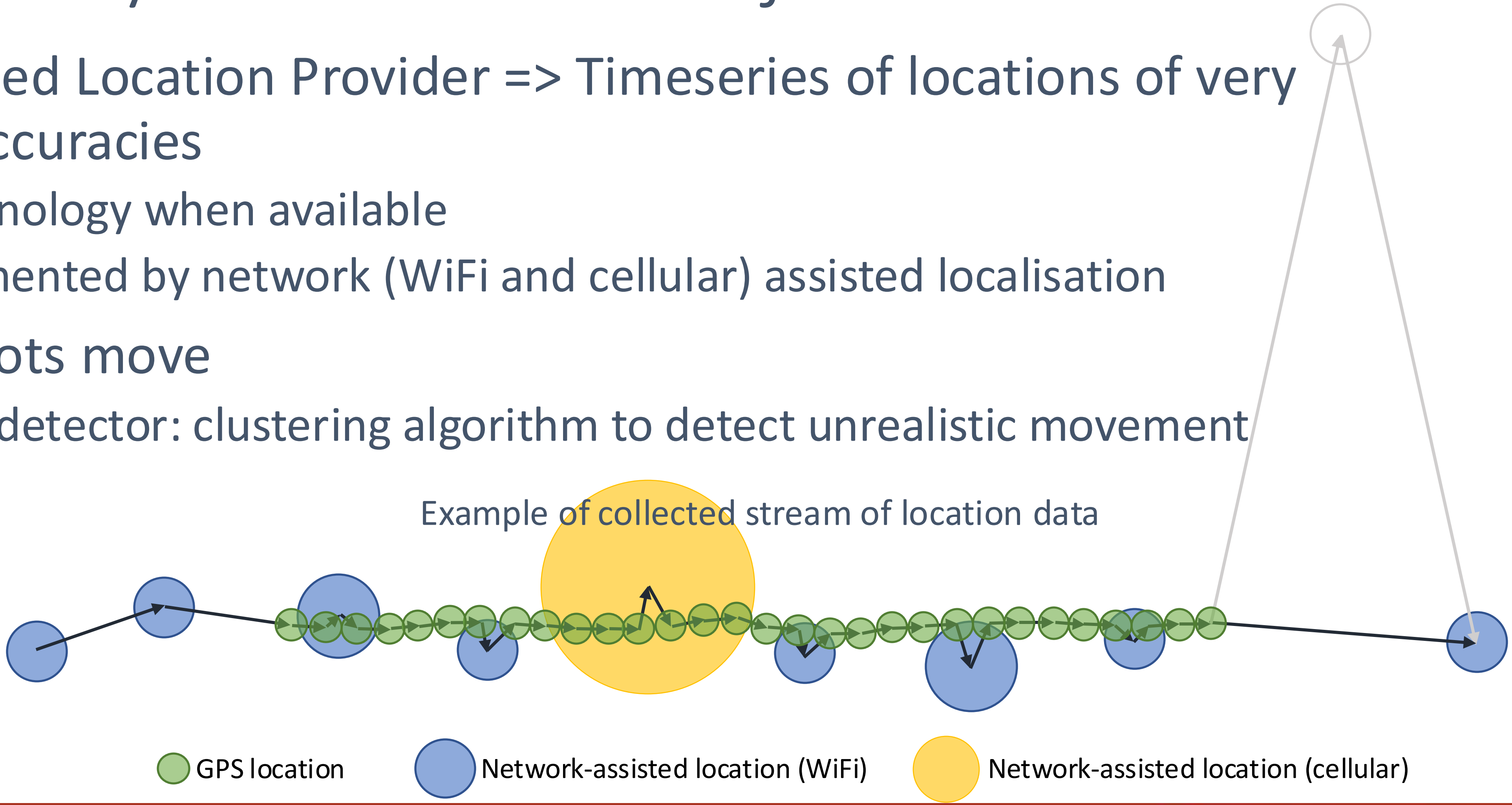
Data Quality for Real GPS Trajectories

- Google Fused Location Provider => Timeseries of locations of very different accuracies
  - GPS technology when available
  - Complemented by network (WiFi and cellular) assisted localisation
- WiFi hotspots move
  - Teleport detector: clustering algorithm to detect unrealistic movement

Example of collected stream of location data



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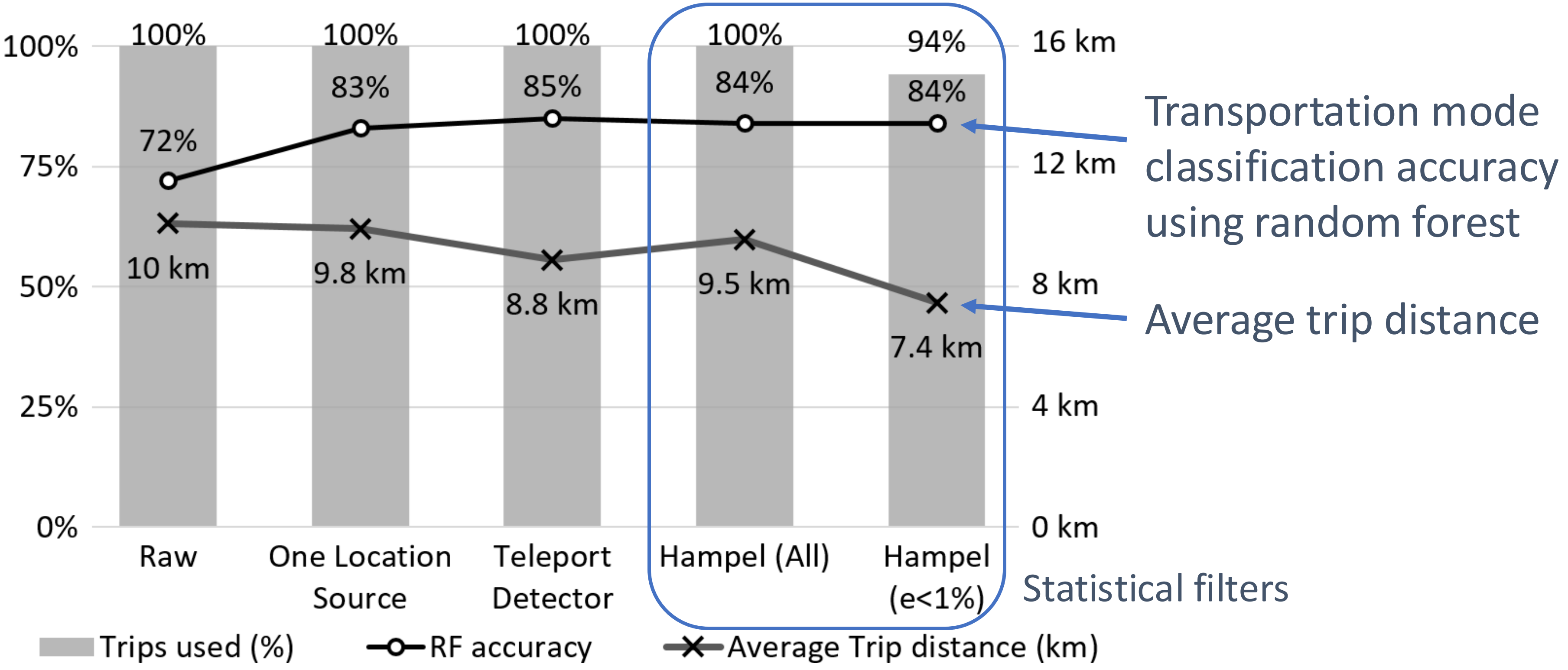
Data Quality: Impact on Extracted Information



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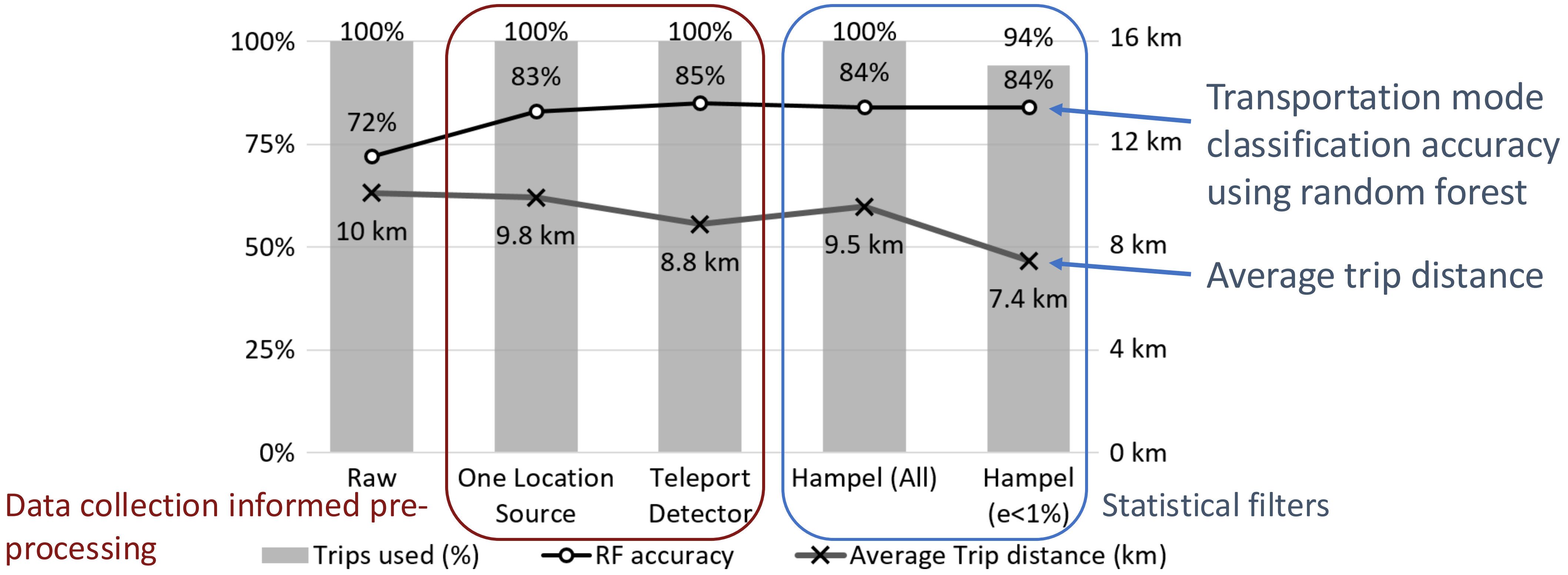

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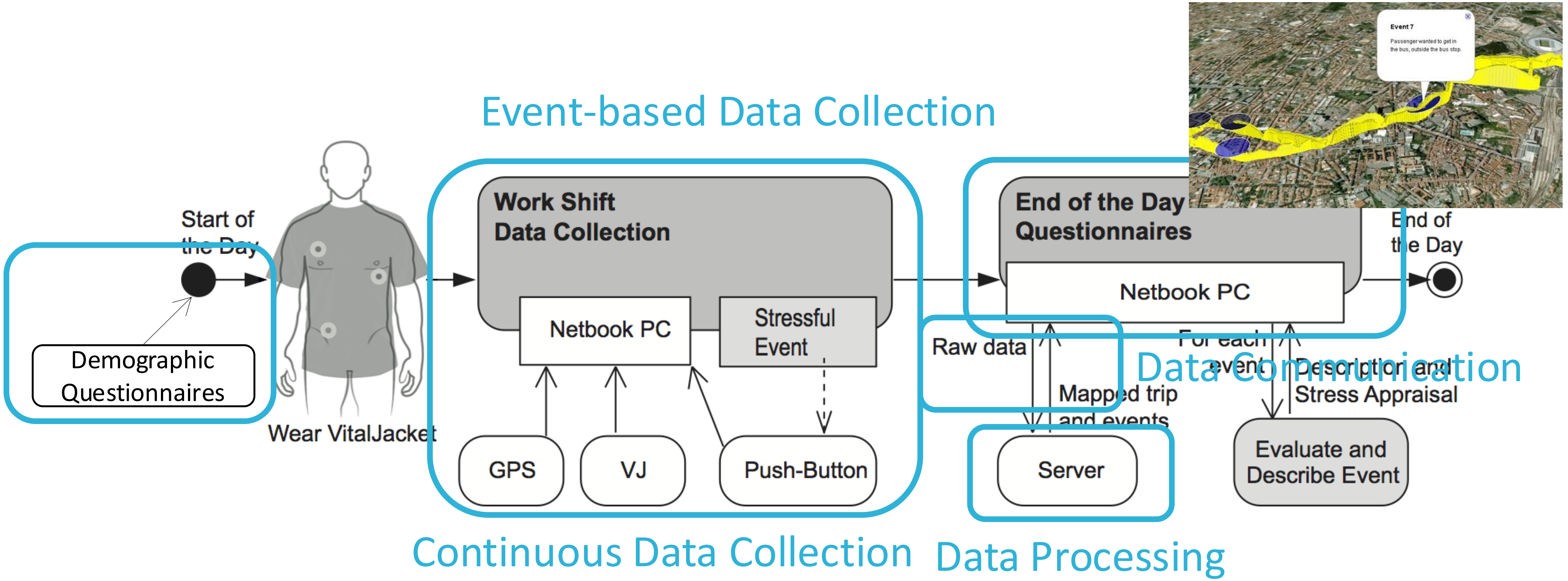
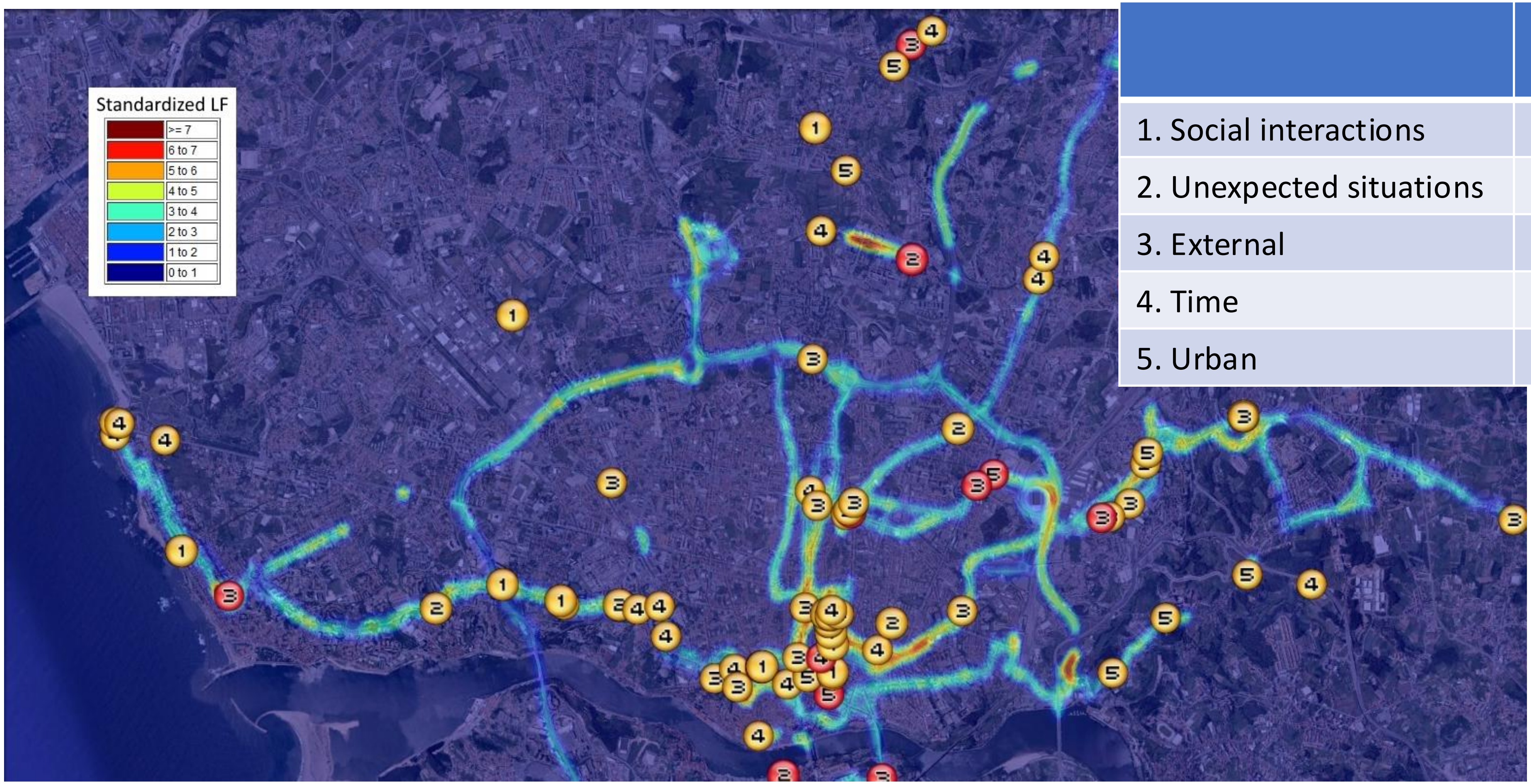
Stress Detection and Memory Activation for Bus Drivers



J.G.P. Rodrigues, M. Kaiseler, A. Aguiar, J.P.S. Cunha, J. Barros. A Mobile Sensing Approach to Stress Detection and Memory Activation for Public Bus Drivers. IEEE Transactions on Intelligent Transportation Systems, 2015

Geo-referenced Bus Driver Stress Analysis



	Freq	Driver freq
1. Social interactions	16%	38%
2. Unexpected situations	8%	21%
3. External	35%	62%
4. Time	19%	41%
5. Urban	22%	41%

J.G.P. Rodrigues, M. Kaiseler, A. Aguiar, J.P.S. Cunha, J. Barros. A Mobile Sensing Approach to Stress Detection and Memory Activation for Public Bus Drivers. IEEE Transactions on Intelligent Transportation Systems, 2015

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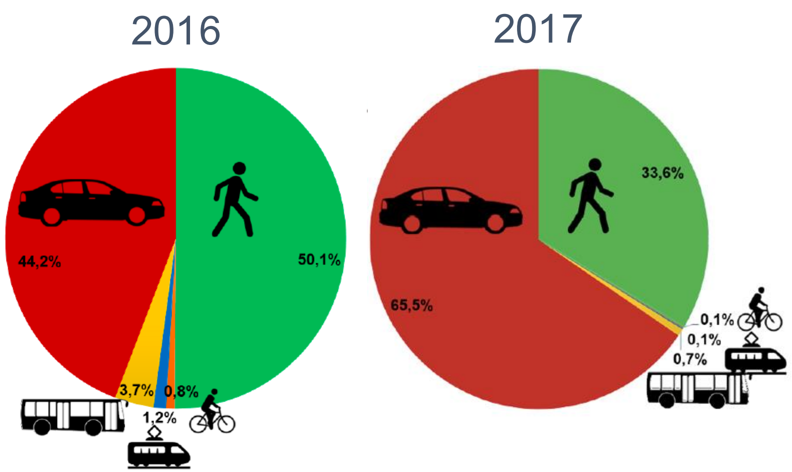
Campus Mobility Observatory/ Survey

Joint work with Cecília Silva, CITTA/ FEUP

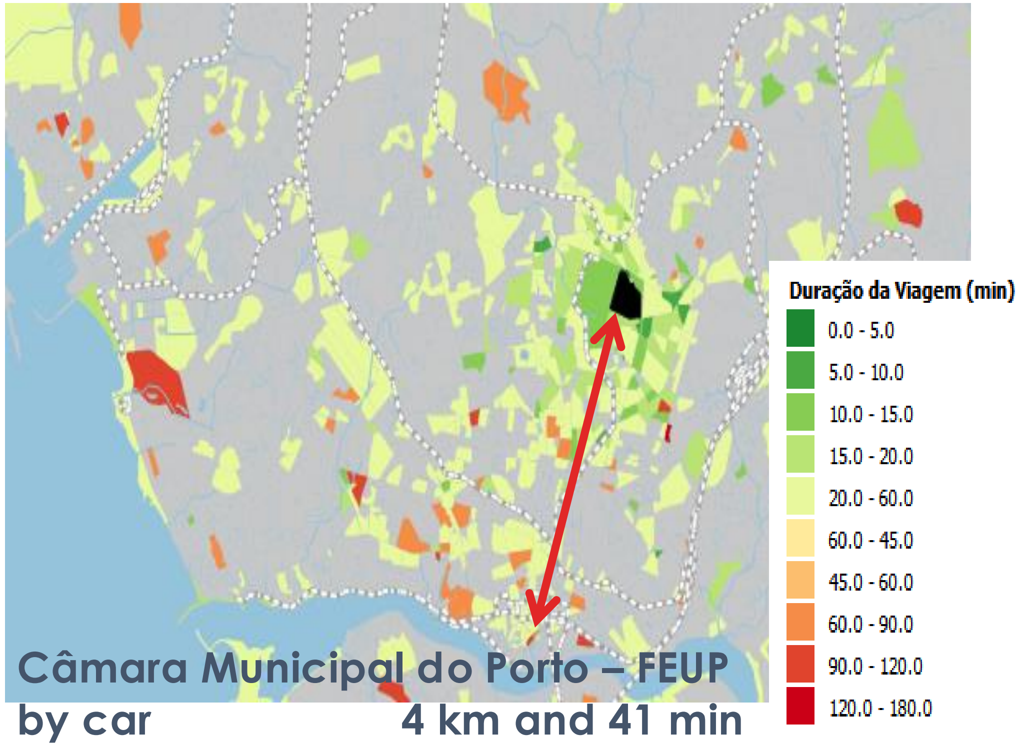
Campus Mobility Observatory/ Survey



Total: 239
Regular: 150

Total: 150
Regular: 79

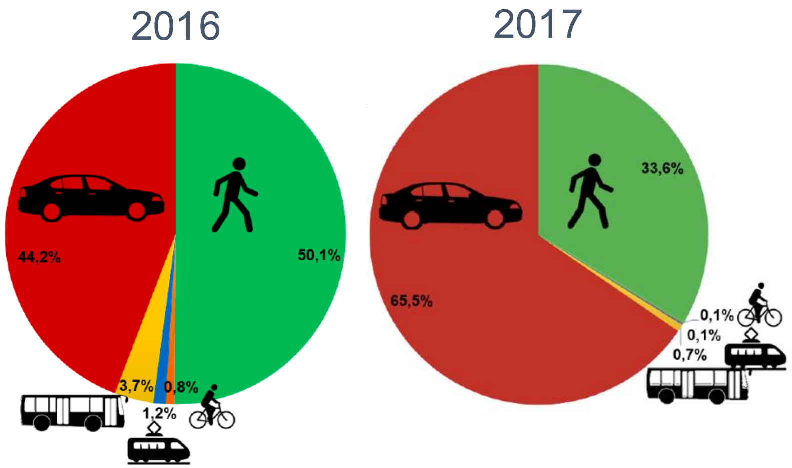
Geographic distribution of door-to-door trip duration



Câmara Municipal do Porto – FEUP

by car 4 km and 41 min
by metro 6 km and 35 min

Campus Mobility Observatory/ Survey



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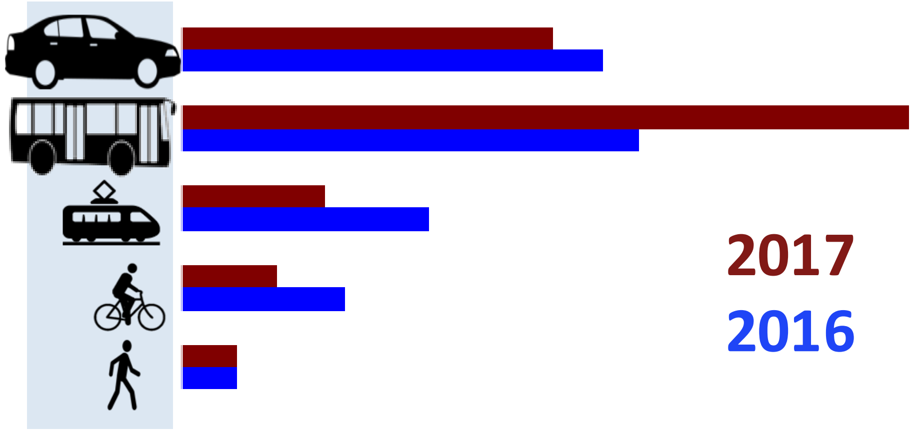
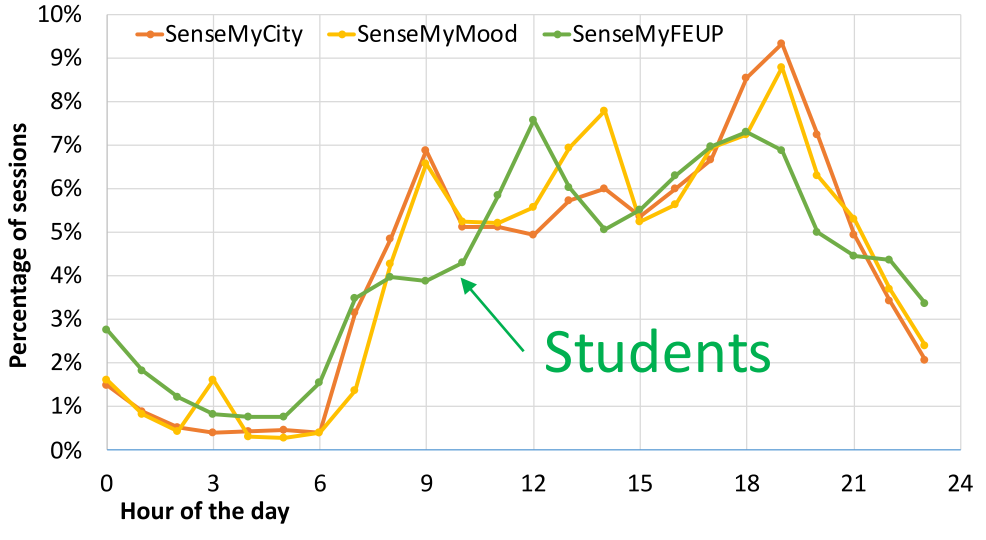
Average Door-to-door Speed [km/h]



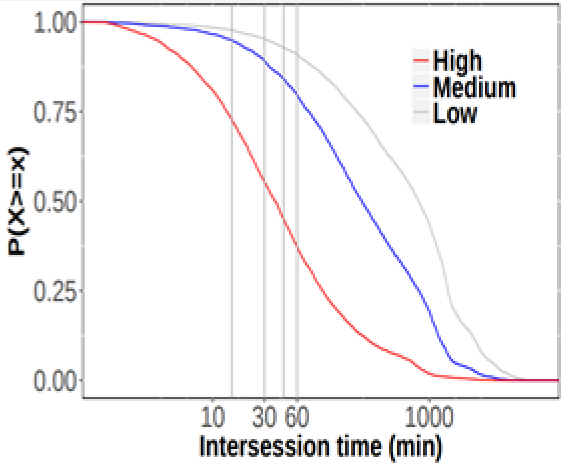
- Bus is the fastest mode
- Bus average door-to-door speed increased
- Car average door-to-door speed decreased
  - Due to increased parking spot search as consequence of paid parking?
- Metro speed comparable to bike
  - > 7min access to station by foot

Data Quality: Crowdsensed Data for Traffic Estimation



Population bias

J GP Rodrigues, A. Aguiar, C. Queirós. Opportunistic Mobile Crowdsensing as a Transportation Systems Tool, in Proc. 19th IEEE Intelligent Transportation Systems Conference (ITSC). 2016.



Sparsity, imbalance

D. Socas Gil, P. M. d'Orey, A. Aguiar. 2017. On the Challenges of Mobile Crowdsensing for Traffic Estimation. ACM Conference on Embedded Network Sensor Systems (SenSys '17).

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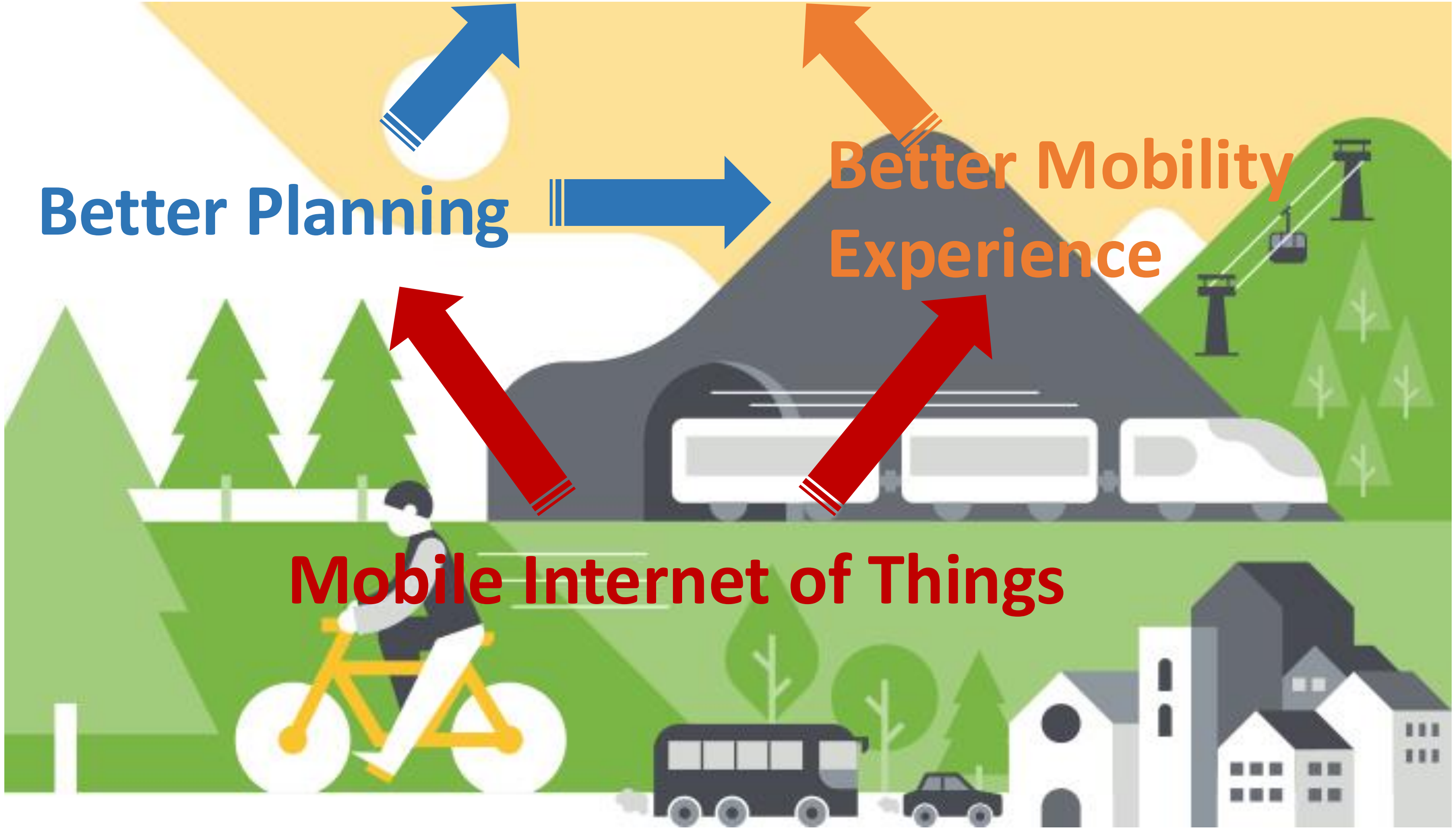
Granular 3D Maps

J. G. P. Rodrigues and A. Aguiar, “Extracting 3D Maps from Crowdsourced GNSS Skyview Data,” in The 25th Annual International Conference on Mobile Computing and Networking - MobiCom ’19. New York, USA, 2019. DOI: 10.1145/3300061.3345456.

Change the way people move in urban areas

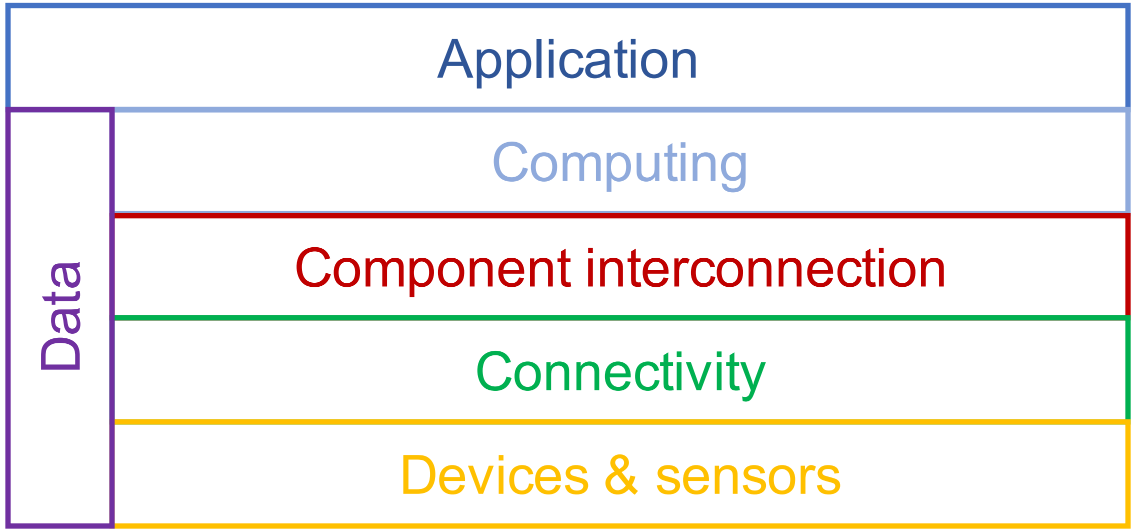


IoT for Intelligent Urban Mobility-Centric

	Better Planning	Better Experience
Usage	• Better understanding of mobility, human factors, decisions processes • Monitoring policy impact • More granular spatial-temporal historic data, e.g. high precision maps	• Inform decision making: routing, driver assistance systems • Safety • Autonomous driving • Traffic management • Infotainment
User	• People, policy decision makers	• People, citizens • Machines
Actuation	• Short, medium and long term policy	• Interactive services • Automation
Network & Computation	• No real-time • Big data, cloud-edge-sensor computing • Data science & engineering, machine learning	• Real-time • Connectivity & network management • Computation distribution

Better Experience Challenges

- Collect, process and manage large amounts of small data pieces in real-time
- Full system integration
- Low end-to-end virtualized service chain latency
- Leveraging all available spectrum
  - Licensed and unlicensed
- Computation distribution
- Data quality
  - Positioning quality
- Privacy and trust



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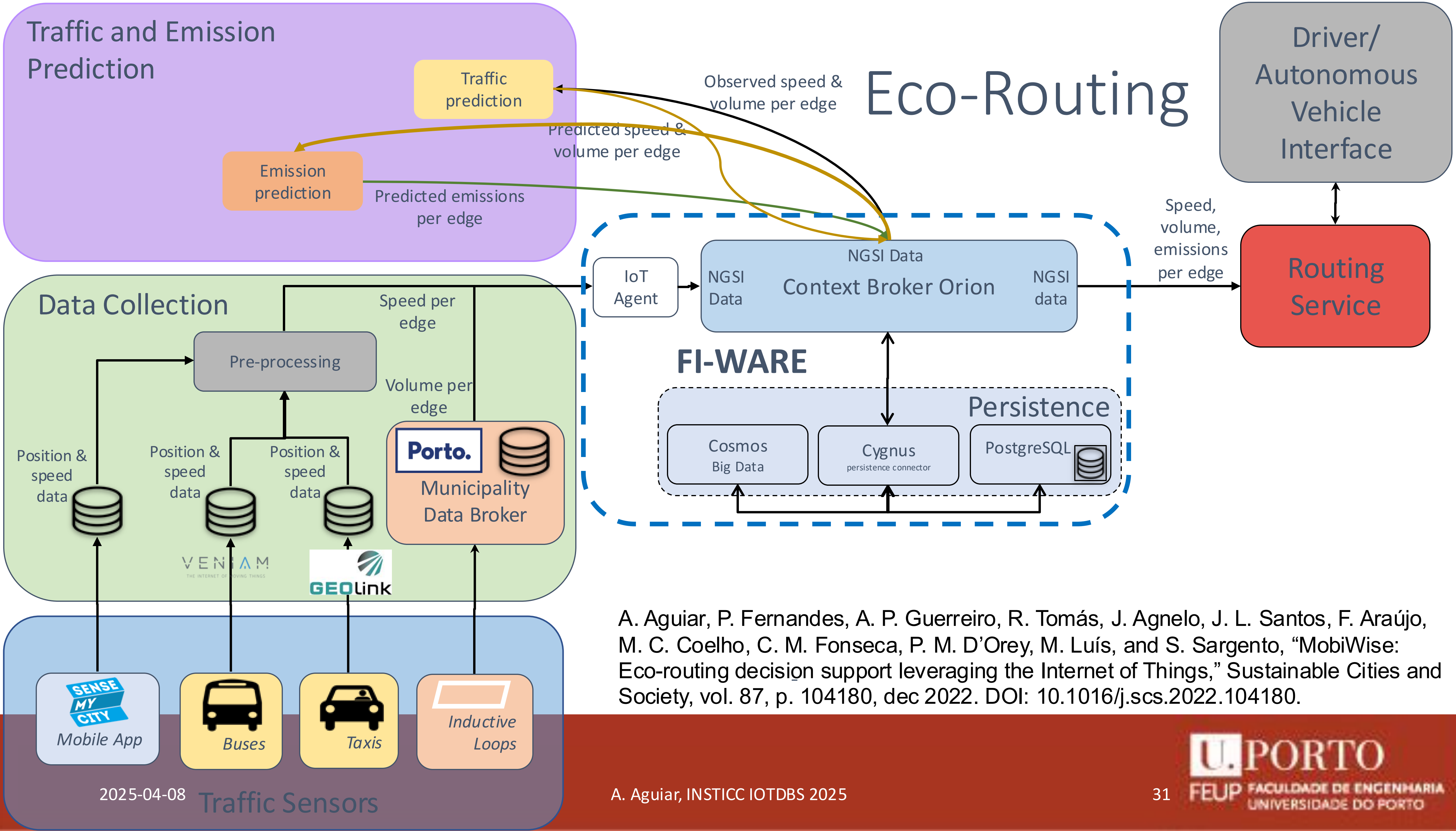
Eco-Routing



A. Aguiar, P. Fernandes, A. P. Guerreiro, R. Tomás, J. Agnelo, J. L. Santos, F. Araújo, M. C. Coelho, C. M. Fonseca, P. M. D'Orey, M. Luís, and S. Sargento, "MobiWise: Eco-routing decision support leveraging the Internet of Things," Sustainable Cities and Society, vol. 87, p. 104180, dec 2022. DOI: 10.1016/j.scs.2022.104180.

ROAD TRAFFIC FATALITIES IN THE EU IN 2023

by road user and (other) 'main vehicle' involved in the crash

FATALITIES	IN A COLLISION WITH... Pedestrian	e-scooter	Bicycle	Moped	Motorbike	Car	Lorry (<3.5t)	Heavy goods vehicle (>3.5t)	Bus or coach	Other vehicle/unknown	No other vehicle involved	TOTAL
Pedestrians	-	3	27	13	100	2378	452	414	139	172	-	3698
e-scooter riders	1	0	1	0	2	43	5	7	2	3	46	110
Cyclists	13	5	45	10	36	880	158	172	43	74	514	1948
Moped riders	2	0	1	9	7	201	56	52	2	17	181	488
Motorcyclists	13	3	10	3	99	1495	246	167	39	92	1324	3491
Car occupants	7	0	4	4	25	2740	558	1342	148	214	4014	9056
Lorry (<3.5t) occupants	2	0	0	0	0	106	60	194	11	20	256	651
Heavy goods vehicle (>3.5t) occupants	1	0	0	0	1	28	7	150	3	10	133	333
Bus or coach occupants	0	0	0	0	0	14	3	15	3	4	50	90
Other/unknown	1	0	0	1	1	124	27	40	5	26	294	519
TOTAL	40	9	88	40	271	8011	1552	2534	395	632	6812	20384

European Commission | Mobility and Transport

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How could we warn pedestrians?

Luís Mendes, Marta Campos Ferreira, sAna Aguiar

Related Work

Implementation of DSRC stack within Wifi-Chipset

Very intrusive UI

Taeho Kim, Wongoo Han, Hyogon Kim, and Yongtae Park. 2017. Vulnerable Road User Protection through Intuitive Visual Cue on Smartphones. In Proceedings of the 2nd ACM International Workshop on Smart, Autonomous, and Connected Vehicular Systems and Services (CarSys '17).

Evaluate WiFi Direct & BLE

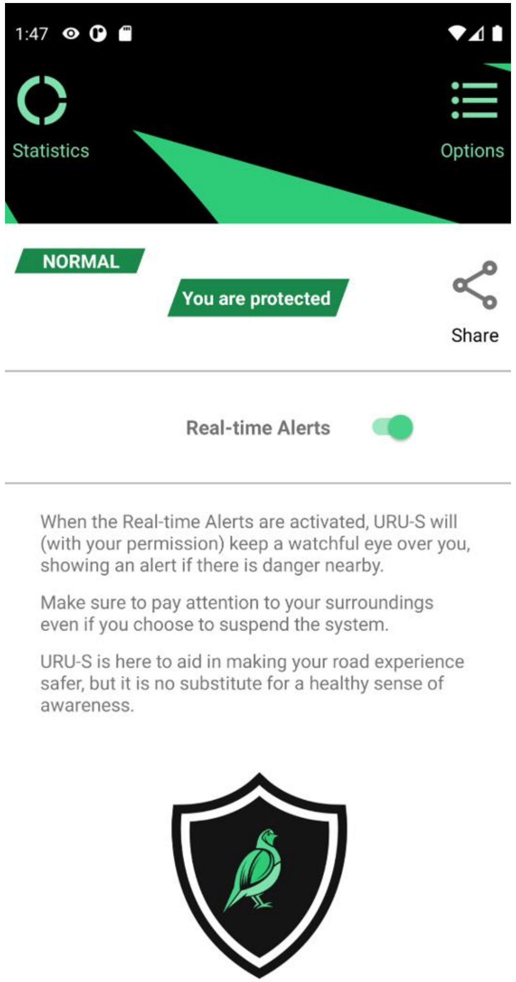
T. Waldemar, F. Boehm and T. Schlegel, "Prototyping Approach of Networking Road Users for Cooperative Collision Avoidance using Smartphones," *2019 Sixth International Conference on Internet of Things: Systems, Management and Security (IOTSMS)*, Granada, Spain, 2019

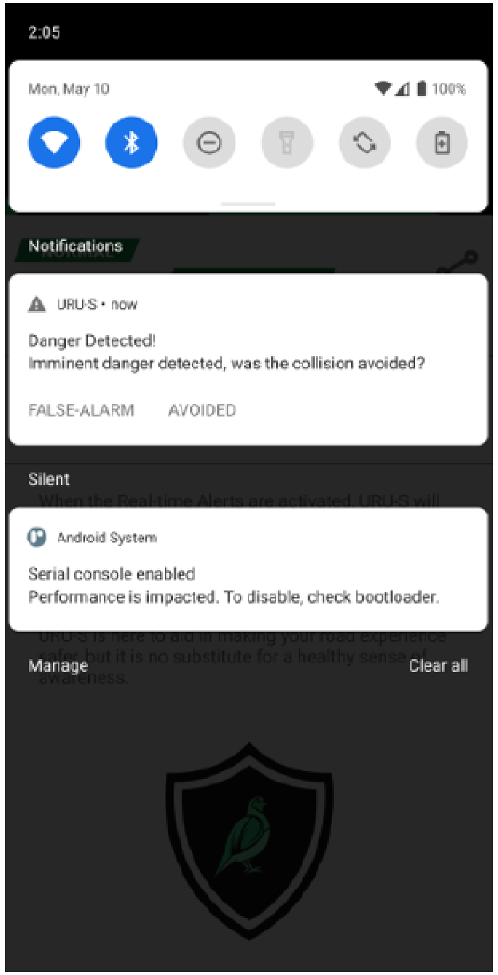
Use Cases from Focus Group

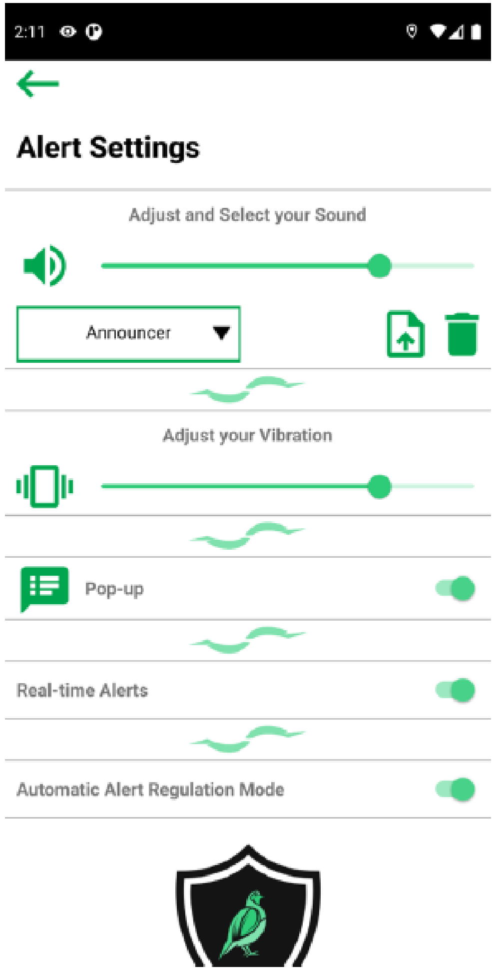
- 5 participants, mainly engineering researchers
- Preferece for audio and haptic warnings
- Users want control of application settings

Priority	Name	Description
High	*Protection Status*	As a VRU, I want to consult the app's status so that I may know that I am being protected.
High	*Notification Volume*	As a VRU, I want to change the volume of the URU-S notifications so that I may adjust it to my liking.
High	*Notification Suspension*	As a VRU, I want to suspend the URU-S notifications so that I may have control over the alert system.
High	*Receive Notifications*	As a VRU, I want to receive URU-S notifications so that I may know that I am in imminent danger and avoid it.
High	*Notification Vibration*	As a VRU, I want to adjust the intensity of the vibrations so that I may be more comfortable with them.
Medium	*Language*	As a VRU, I want to change the language so that I may change it to one I am more comfortable with.
Medium	*Options menu*	As a VRU, I want to access the options menu so that I may change configurations that are relevant to my interests.
Medium	*Select Sound*	As a VRU, I want to select different sounds for the notification so that I may choose a sound that I prefer.
Medium	*Customize Sound*	As a VRU, I want to upload my sound so that I may give the app my personal touch.
Medium	*Access Statistics*	As a VRU, I want to access the statistics feature so that I may have an added component to the real-time alerts.
Medium	*Access Heat-map*	As a VRU, I want to have a heat-map of the most dangerous spots so that I may know which places to avoid.
Medium	*Receive Danger-Zone Notifications*	As a VRU, I want to receive a warning emitted whenever I enter a dangerous zone so that I may be more aware.
Medium	*Disable Danger-Zone Notifications*	As a VRU, I want to disable the warnings emitted whenever I enter a dangerous zone so that I may control them.
Low	*Neutralize Notification*	As a VRU, I want to signal the app that I have avoided danger, to count that as a true positive.
Low	*Sharing*	As a VRU, I want to share the app with others so that I may tell others about it.
Low	*Documents*	As a VRU, I want to consult the documentation so that I may know more about the app and who made it.
Low	*Ignore Notifications*	As a VRU, I want to ignore URU-S notifications so that I may dismiss them in case of a false positive.

Built and Tested Prototype







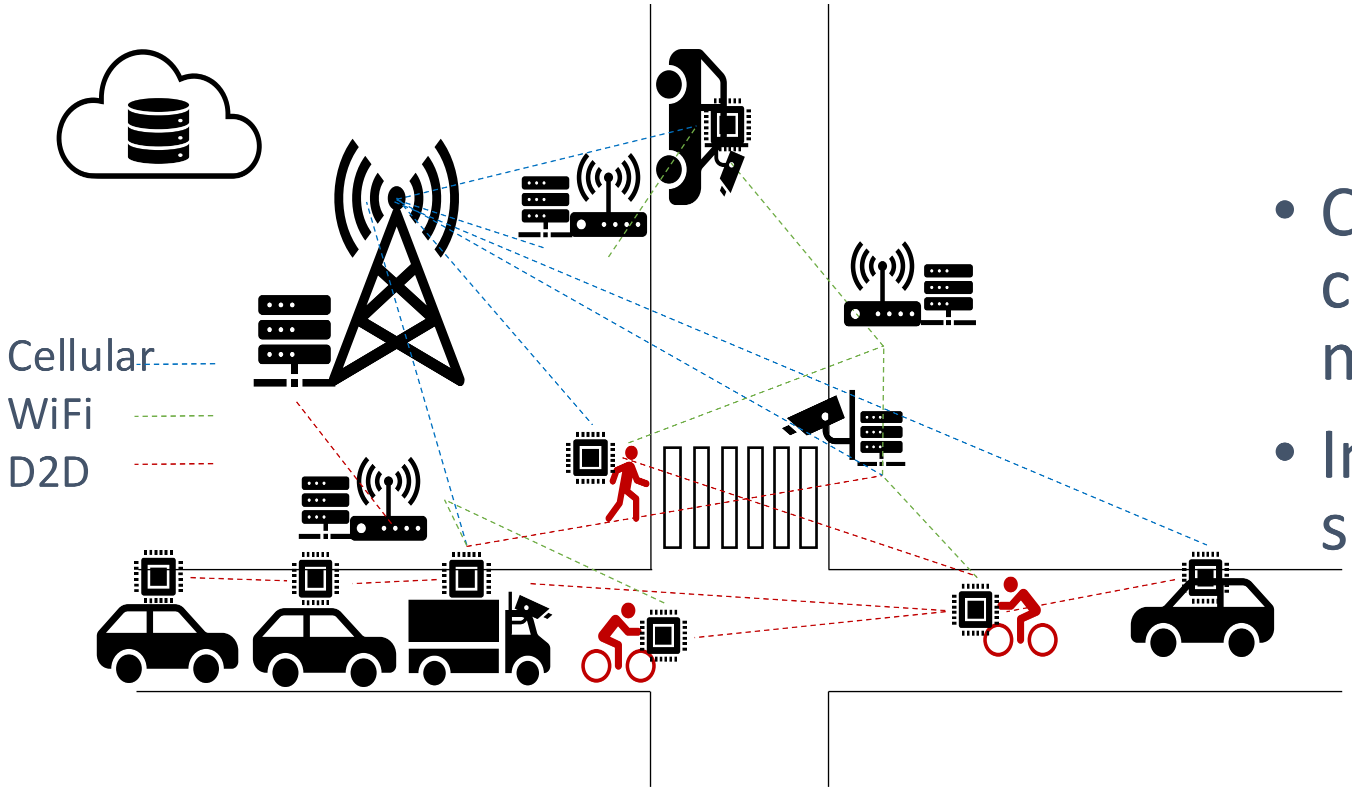
Context awareness

- Indoor/ outdoor
- Walking/ standing
- Walking/ other transport mode
- Accident hotspot geo-fences

Many Open Issues

- Which device to use?
- How to manage/ filter notifications?
  - How to manage context?
- How many resources (energy, computation)?
- Should we warn pedestrians at all? Resposibility is with vehicles

Networked Computing Fabric for VRU Safety



- Applications
  - Enhancing GNSS positioning
  - Path prediction
  - Collision detection
- Context-based computation, connectivity and network management
- Integration of WiFi in (open source) 3GPP networks
  - O-RAN
  - AT-SSS
  - Multipath transport

Connecting Bikes

Use case

Ad hoc Detection of Stolen Bicycles

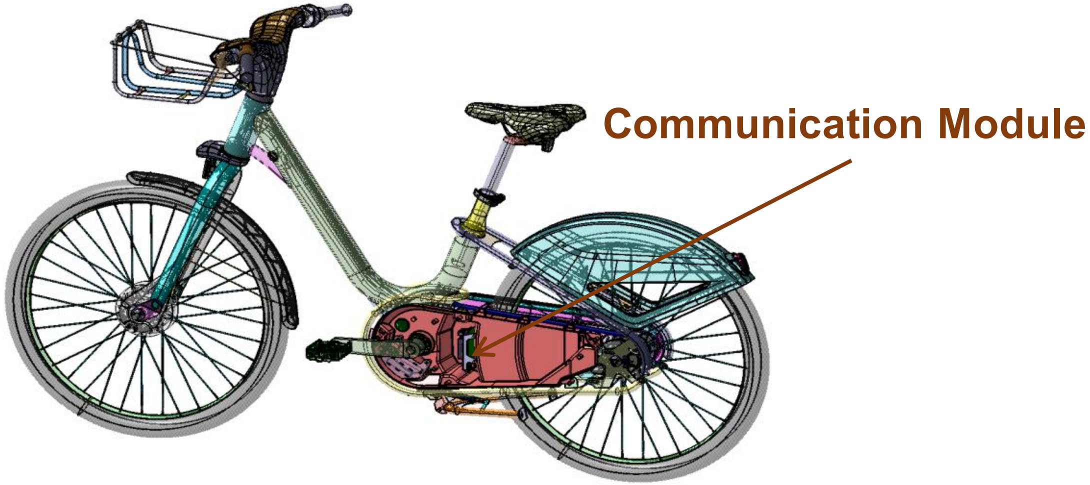
1. **Stolen bicycle:** loses connection to cloud, but broadcasts Bluetooth beacons
2. **Regular bicycle:** captures beacons and reports stolen bicycle

P. M. Santos, M. Rosa, L. R. Pinto and A. Aguiar, Cooperative Bicycle Localization System via Ad Hoc Bluetooth Networks, IEEE VNC 2020

Use case: Walkie-Talkie for Bike Platoon

E. Soares, P. Santos, L. Pinto, P. Brandão, R. Prior, A. Aguiar. Demo: VoIP System for Bicycle Platoons
IEEE VNC 2018

Bike-to-bike Link Performance in 2.4GHz ISM band

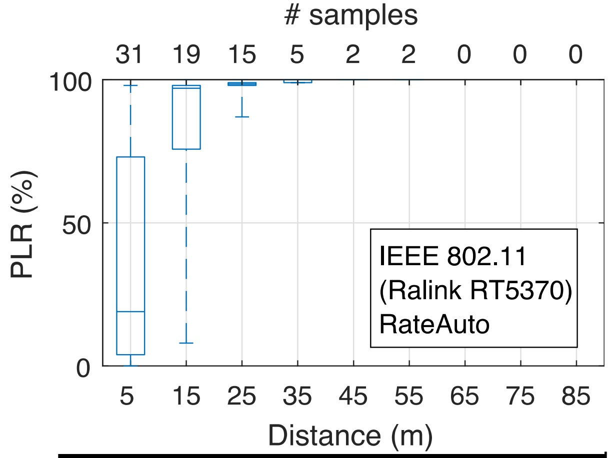


	802.11	802.15.4	Bluetooth EDR
Nominal Rate	1 Mbit/s / 24 Mbit/s / auto-rate	250 kbit/s	3 Mbit/s
Payload	1472B	128B	682B
Reliability	2 re-txs	None	Re-tx until ACK
Conn. type	UDP	n/a	ACL 3-DH5
Offered rate	700 kbit/s / 17 Mbit/s / 40 Mbit/s	40 kbit/s	1.72 Mbit/s

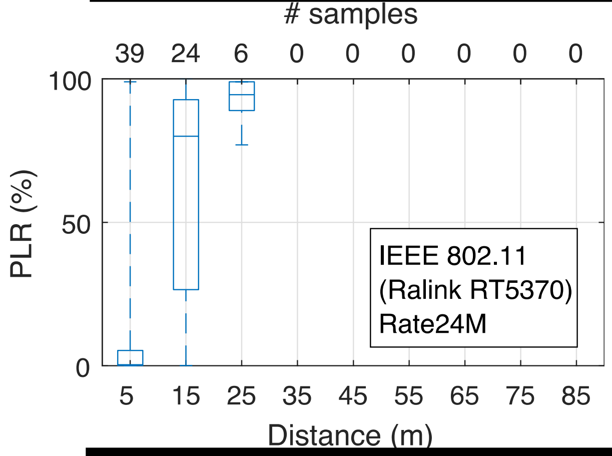
P. Santos, L. Pinto, A. Aguiar, L. Almeida. A Glimpse at Bicycle-to-Bicycle Link Performance in the 2.4GHz ISM Band
IEEE PIMRC 2018

Bike-to-bike Link Performance: Packet Loss Rate

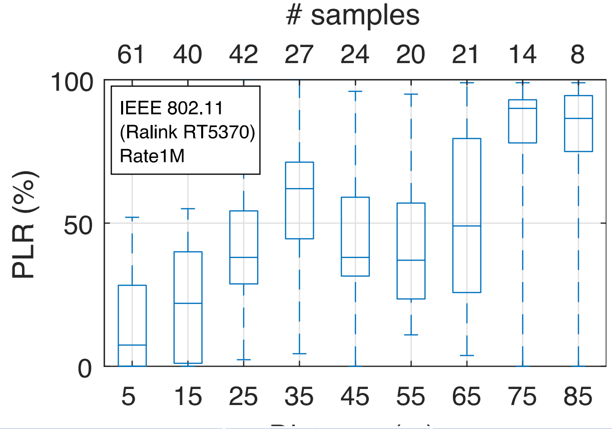
WiFi - Auto



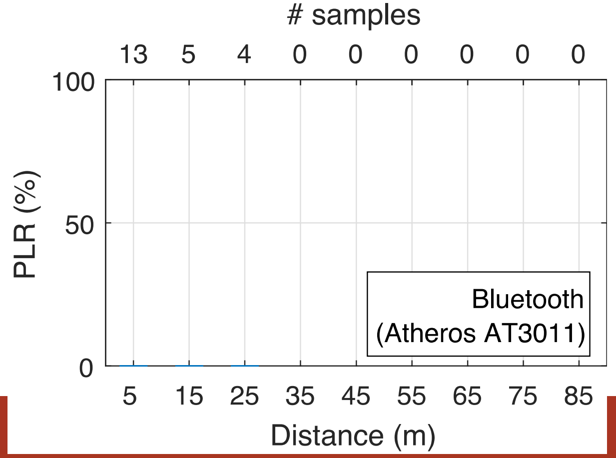
WiFi – 24 Mbit/s



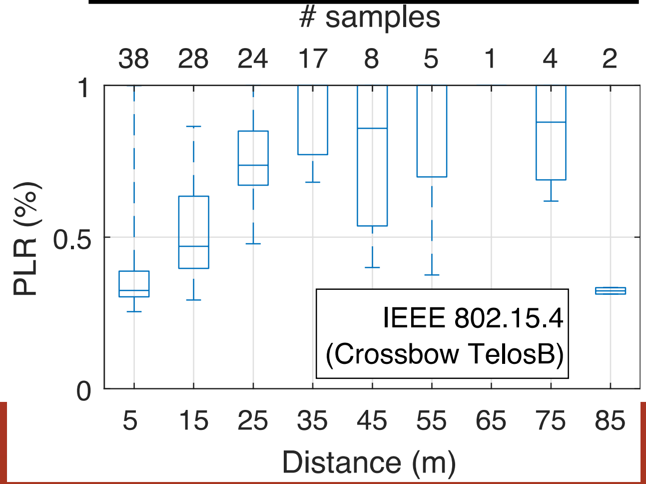
WiFi – 1 Mbit/s



Bluetooth



ZigBee



	Peak Thru.	Dist. 10% thru
WiFi - Auto	25 Mbit/s	10 m
WiFi - 24M	17 Mbit/s	15m
WiFi - 1M	800 kbit/s	40m
BT	1.4 Mbit/s	10m
ZigBee	50 kbit/s	30m

Take Aways

- Communication range depends on relative position of bikes

- WiFi with automatic rate adaptation performs poorly
- WiFi@24 Mbps and BLE also

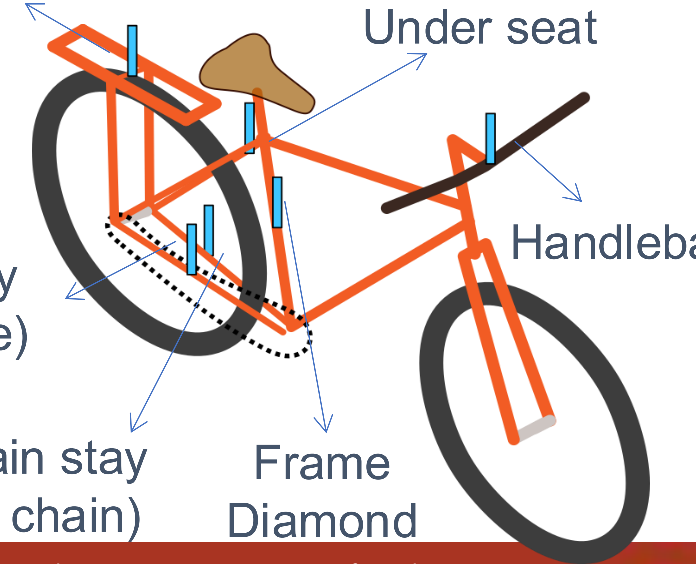
- WiFi@1 Mbps achieved range > 50m

- BLE strongly depends on device

Modeling the Bicycle-Antenna System @ 2.4GHz

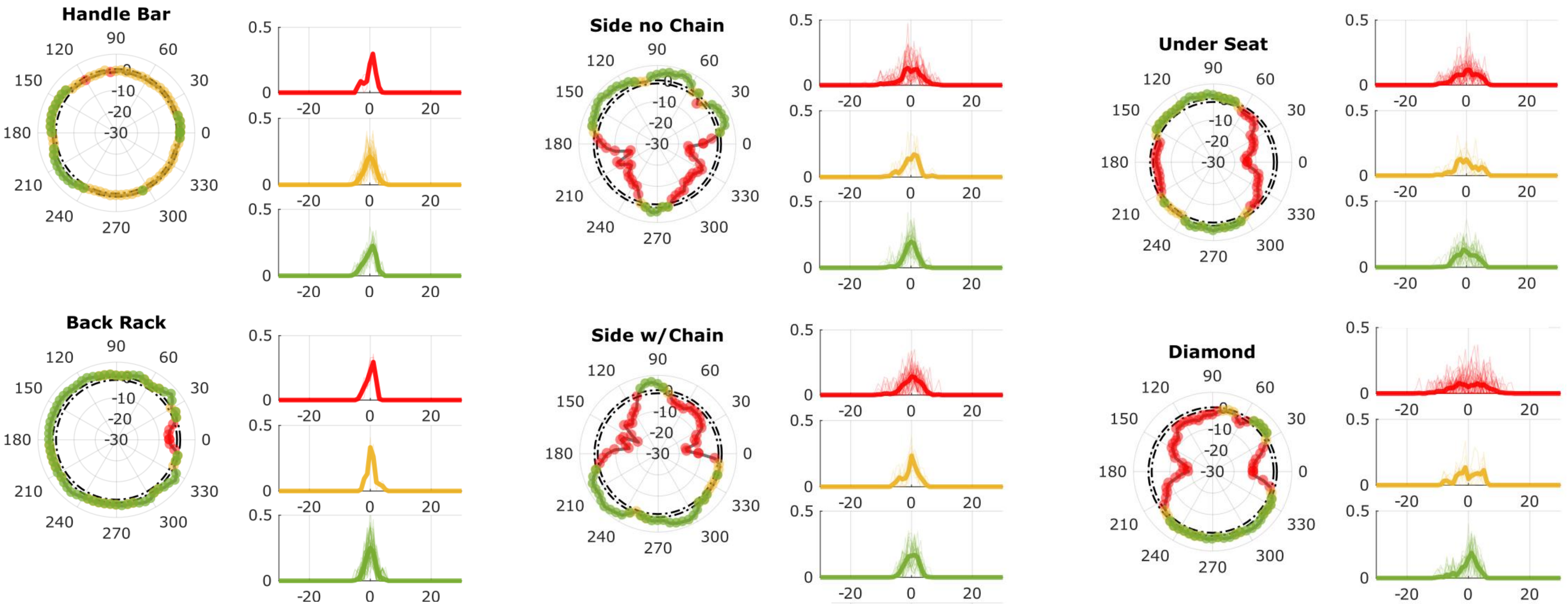
$$P_{rx\ [dBm]} = P_{tx} + G_{B\text{-}A}\,(tx) + L_{pl} + G_{B\text{-}A}\,(rx) + X(0,\sigma)$$

- Bike metal structure impacts radiation pattern => Measure GB-A
- Variables
  - Antenna position: 6 positions
  - Antenna orientation
  - Frame format
  - Frame material: 3 steel + 3 Al



P. Santos, L. Pinto, L. Almeida , A. Aguiar. "Characterization and Modeling of the Bicycle-Antenna System for the 2.4GHz ISM Band IEEE VNC 2018

Average GB-A w.r.t Antenna without Bike



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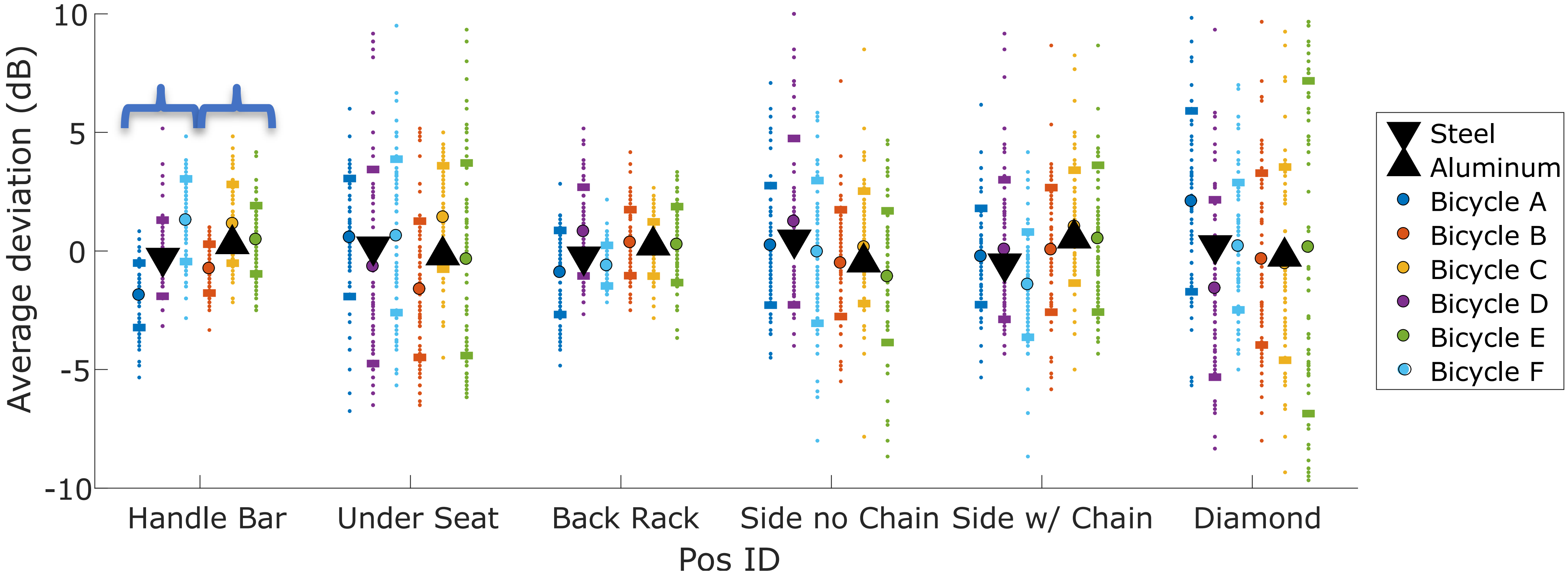
Impact of Material



No significant impact of material observed

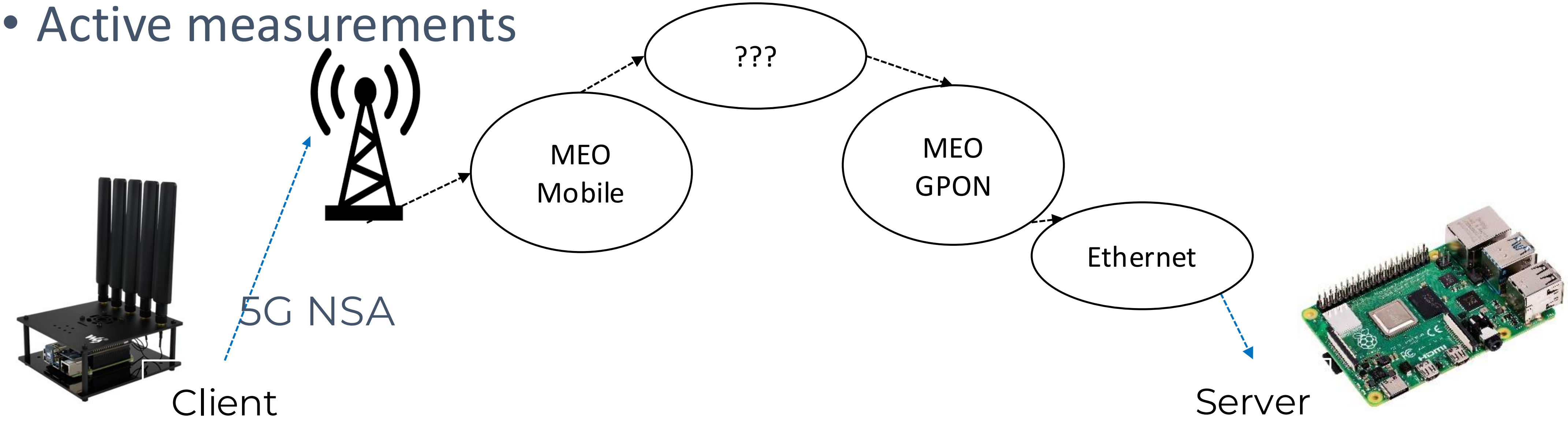
P. Santos, L. Pinto, L. Almeida , A. Aguiar. Characterization and Modeling of the Bicycle-Antenna System for the 2.4GHz ISM Band IEEE VNC 2018

Take Aways

- Good antenna positions from a product perspective are not good from a connectivity perspective
- Disc model is a good model only for bike rack and handlebar position
- Cyclist shadowing has an impact (~10dB), but only for very few angles
- Explore other use cases to ease technology adoption

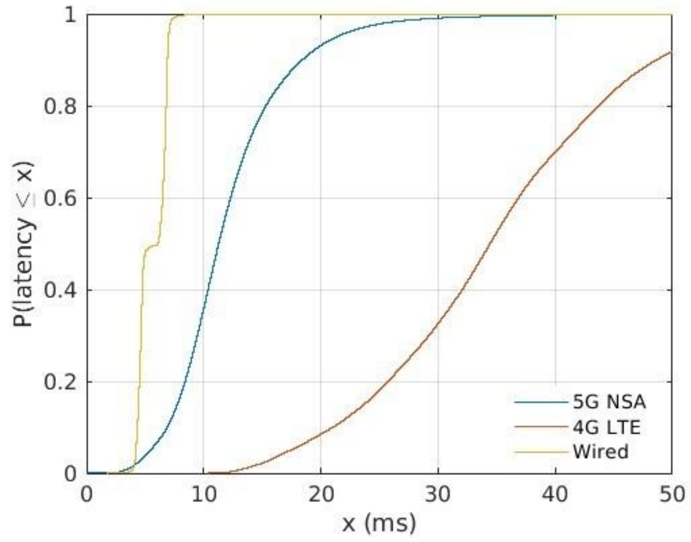
Mobile Node to Edge Service Latency Today

- What latecies can we expect between current 5G NSA networks and edge services?
  - Mobile to service outside mobile operator
  - Networks not optimised for low latency yet
- Active measurements

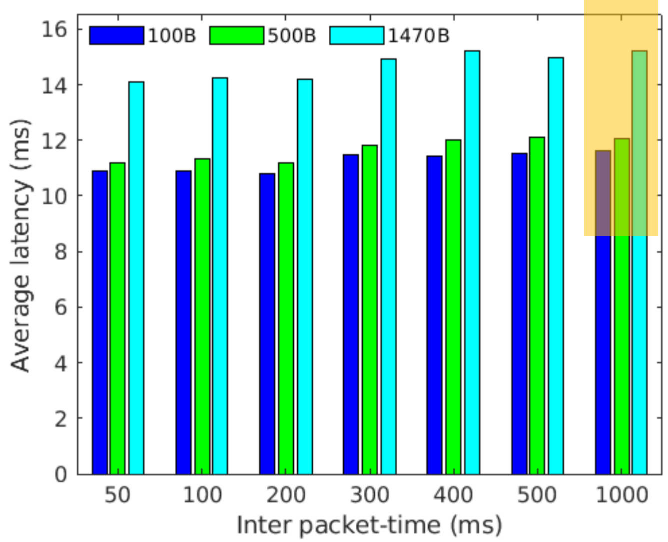


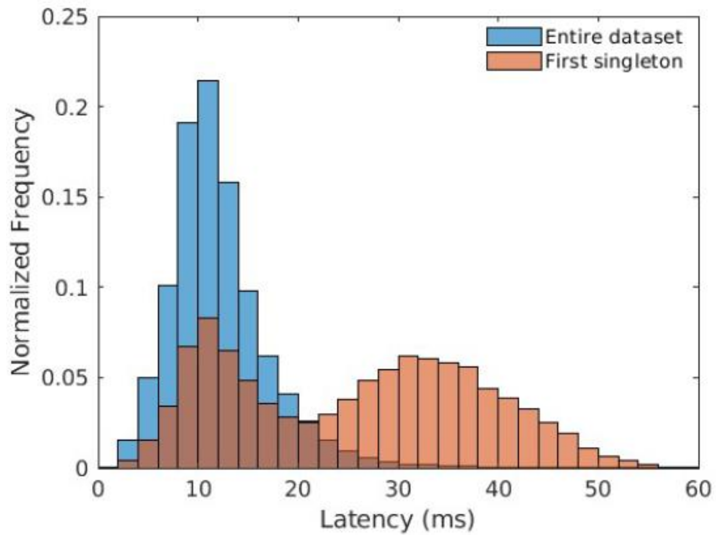
O. Contreras, A. Aguiar, P. Steenkiste, “Uplink End-to-End Latency Characterization of a 5G NSA Access”, ACM/SPEC International Conference on Performance Engineering, Toronto, May 2025

Important Things



downlink-uplink periodicity





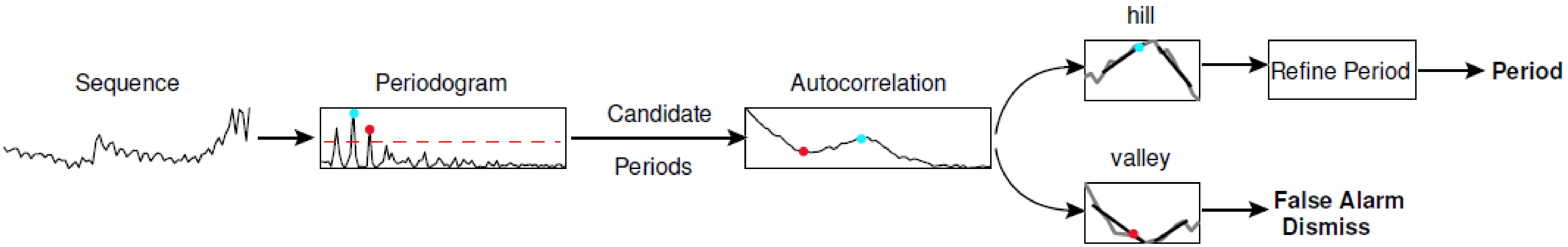
5G is a step towards wired performance

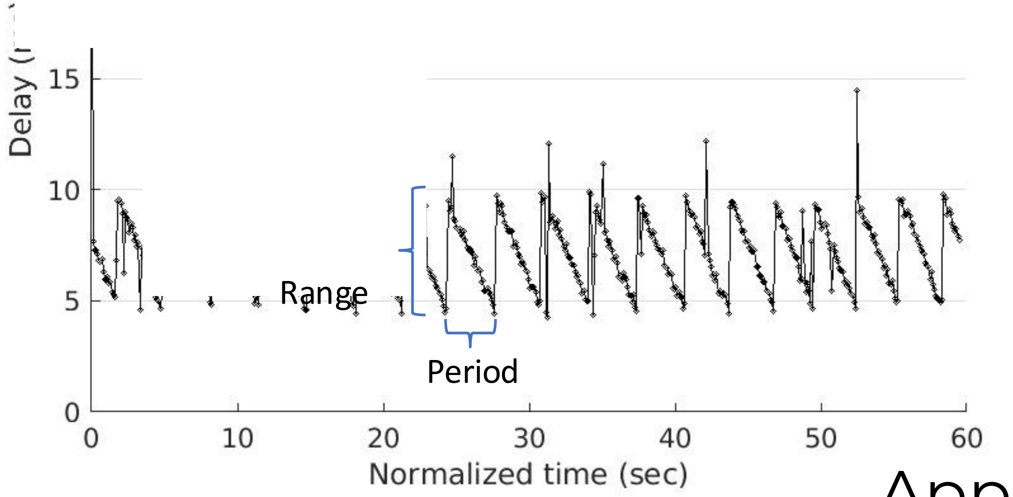
Large packets take longer on the wireless access

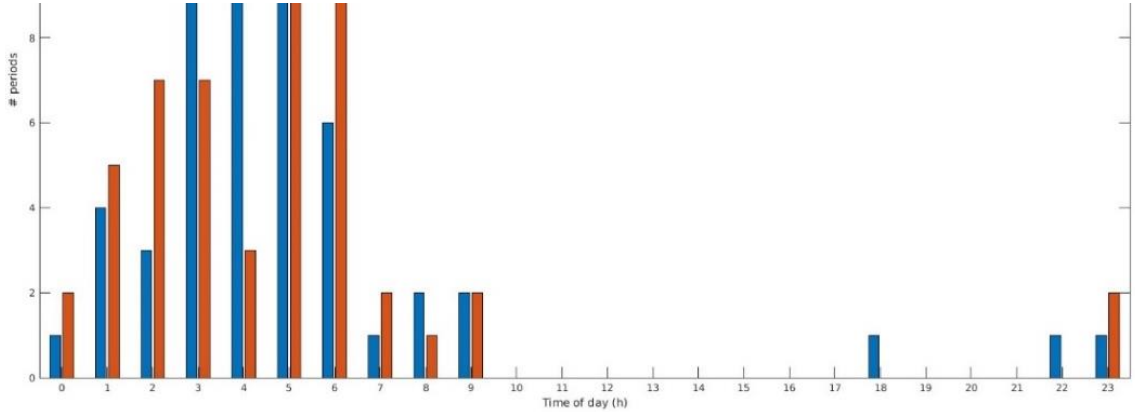
On 5G NSA access, first packets often have very large dealys

O. Contreras, A. Aguiar, P. Steenkiste, "Uplink End-to-End Latency Characterization of a 5G NSA Access", ACM/SPEC International Conference on Performance Engineering, Toronto, May 2025

Abnormal Sawtooth Patterns





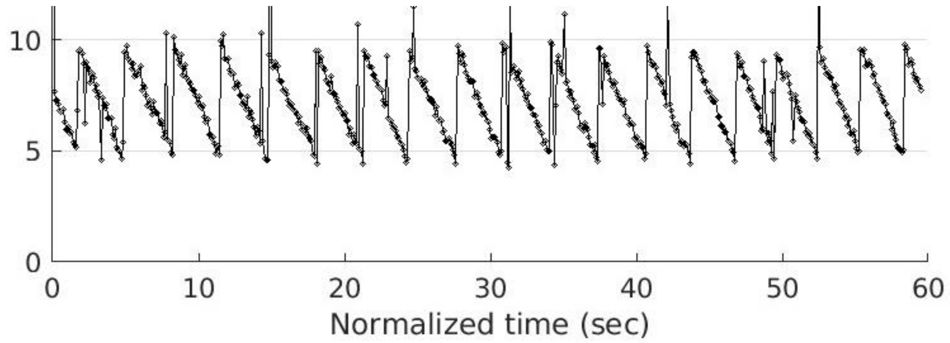


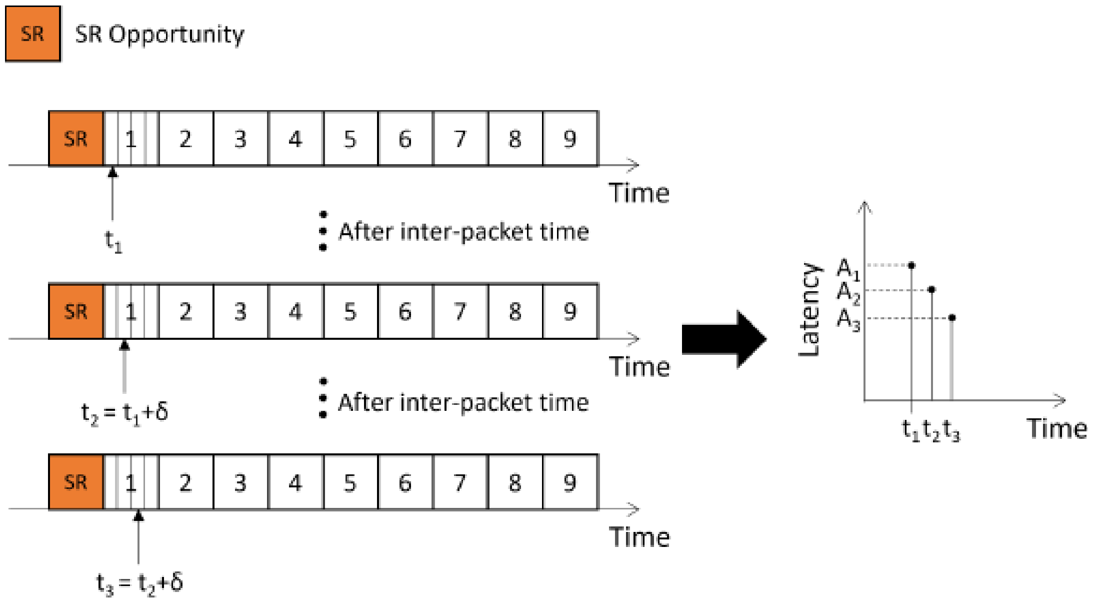
Appear in period of very low average delay

Masked by larger delay variations

O. Contreras, A. Aguiar, P. Steenkiste, “Uplink End-to-End Latency Characterization of a 5G NSA Access”, ACM/SPEC International Conference on Performance Engineering, Toronto, May 2025

Cause and Consequences





- Period and range determined by network parameters
  - Frame length
  - Schedule request opportunities
- Impacts Age of Information
- Network should be the time source

O. Contreras, A. Aguiar, P. Steenkiste, "Uplink End-to-End Latency Characterization of a 5G NSA Access", ACM/SPEC International Conference on Performance Engineering, Toronto, May 2025

Many Open Research Questions

- Sensing, computation and connectivity
  - Take advantage of heterogeneous connectivity technologies
  - Runtime information and automation for network and information management
  - All forms of edge computing and distributed learning
  - AI accuracy
  - Low latency

- Trust, authentication, dependability
- Usability
- Metrics for application performance

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Thank you

“An ounce of practice is worth more than tons of preaching.”

M. Ghandi