Universität St.Gallen
Institut für Computer Science
in Vorarlberg

Passive Wireless Tracking in the Wild

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Tridonic, April 1, 2025

From insight to impact

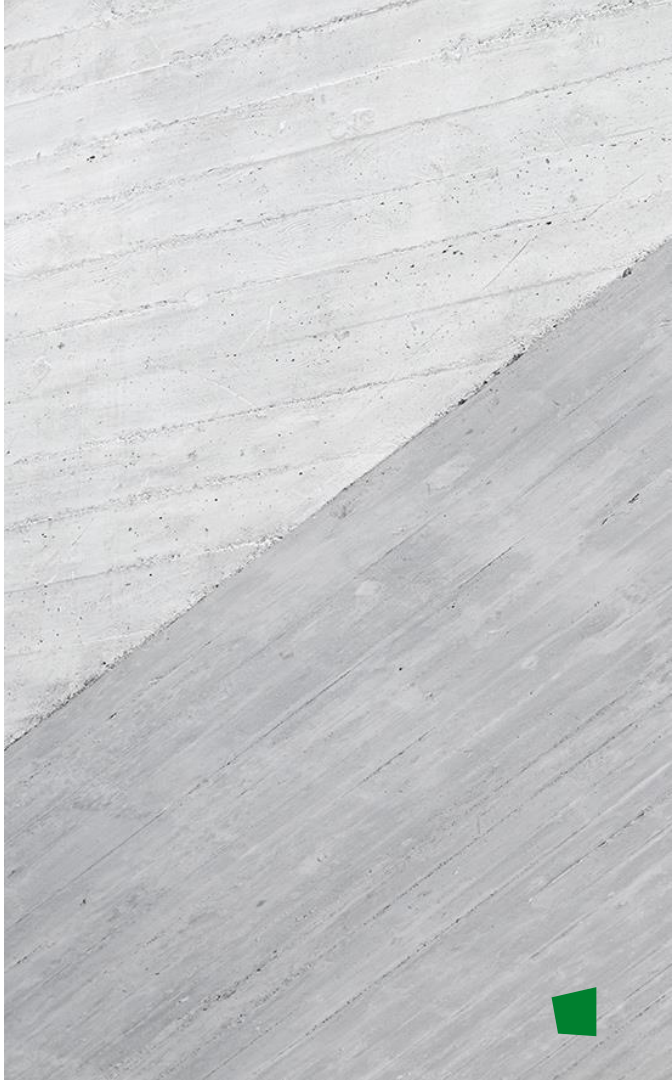
Outline

Introduction
- Tracking in the physical world
- Goals

Overview
- High-level architecture
- BLE/Wi-Fi
- Correlation of sources

Real-world Experiments
- Wi-Fi/BLE
- LiDAR 2D and 3D
- RFID and 3D Cameras

Analysis
- Business, technical, and social dimensions



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Introduction

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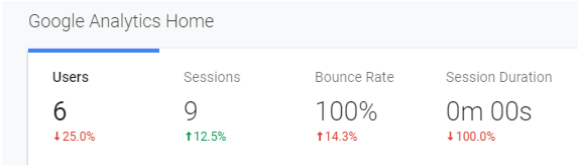
Motivation

Tracking visitor's interest across a Web-page is a relatively straightforward task in contrast to the physical, analog world.

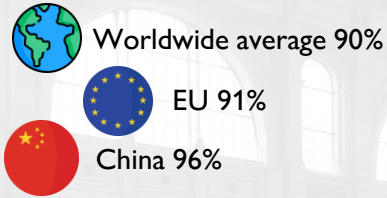
- Web analytics track every step of users and obtaining many KPIs (Key Performance Indicator)



The driving question is how to track visitor's interest in the physical world?

Tracking Mobile Devices

92% of the Swiss population own a smartphone
- ...of which 97% use it daily (2018)
- The trend is not reducing



Smartphones regularly probe for nearby Wi-Fi networks. From a tracking perspective:
- *Opportunities:*
  - *It is possible to gain insights about nearby people by passively listening to Wi-Fi Probe Requests*
- *Challenges:*
  - *Physical layer: Handling signal variations*
  - *Data link layer: MAC Address Randomization*

https://www2.deloitte.com/ch/en/pages/press-releases/articles/deloitte-in-switzerland-smartphones-become-control-centre.html

Passive Wireless Tracking (PasWITS)

PROJECT

Cooperation between academia and industry funded by Innosuisse

- Passive Wireless Intelligence Tracking System (PasWITS)
- From March 2020 until July 2022

GOALS

- Business: provide live performance benchmarking of exhibitions and events based on passively emitted signals
- Technical: explore the different characteristics of multiple (passive) sources to increase the overall tracking accuracy
  - Including additional sources such as Bluetooth, LiDARs, RFID

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Overview

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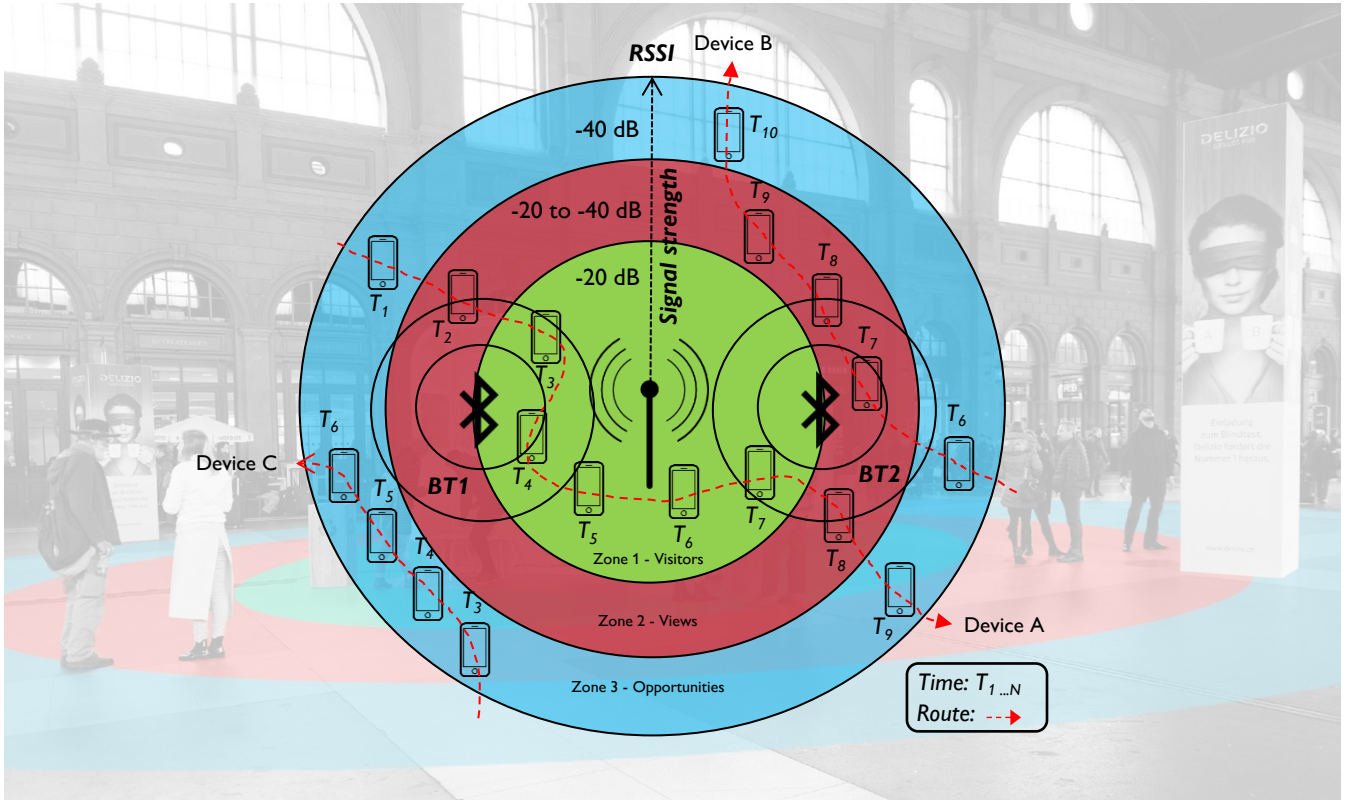
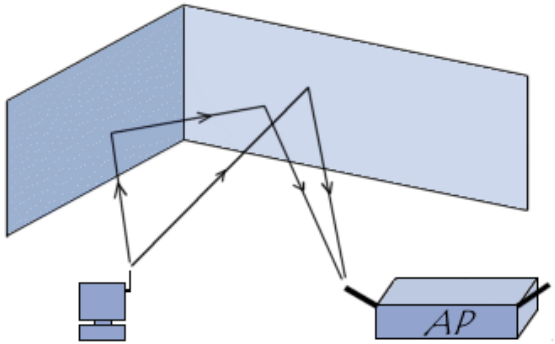
Combining Inputs from Different Sources



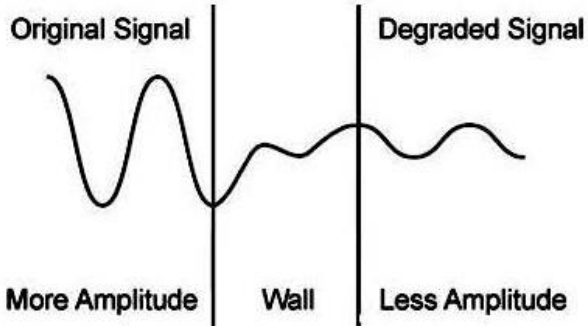
Overall Tracking Challenges

Location of objects and people indoors remains a challenge mostly due to:

- Severe multipath signal reflections (walls, furnitures, people, objects)
  - Sparsity of data points
- Non-Line-of-Sight (NLoS) conditions
  - Signal is obstructed by physical object

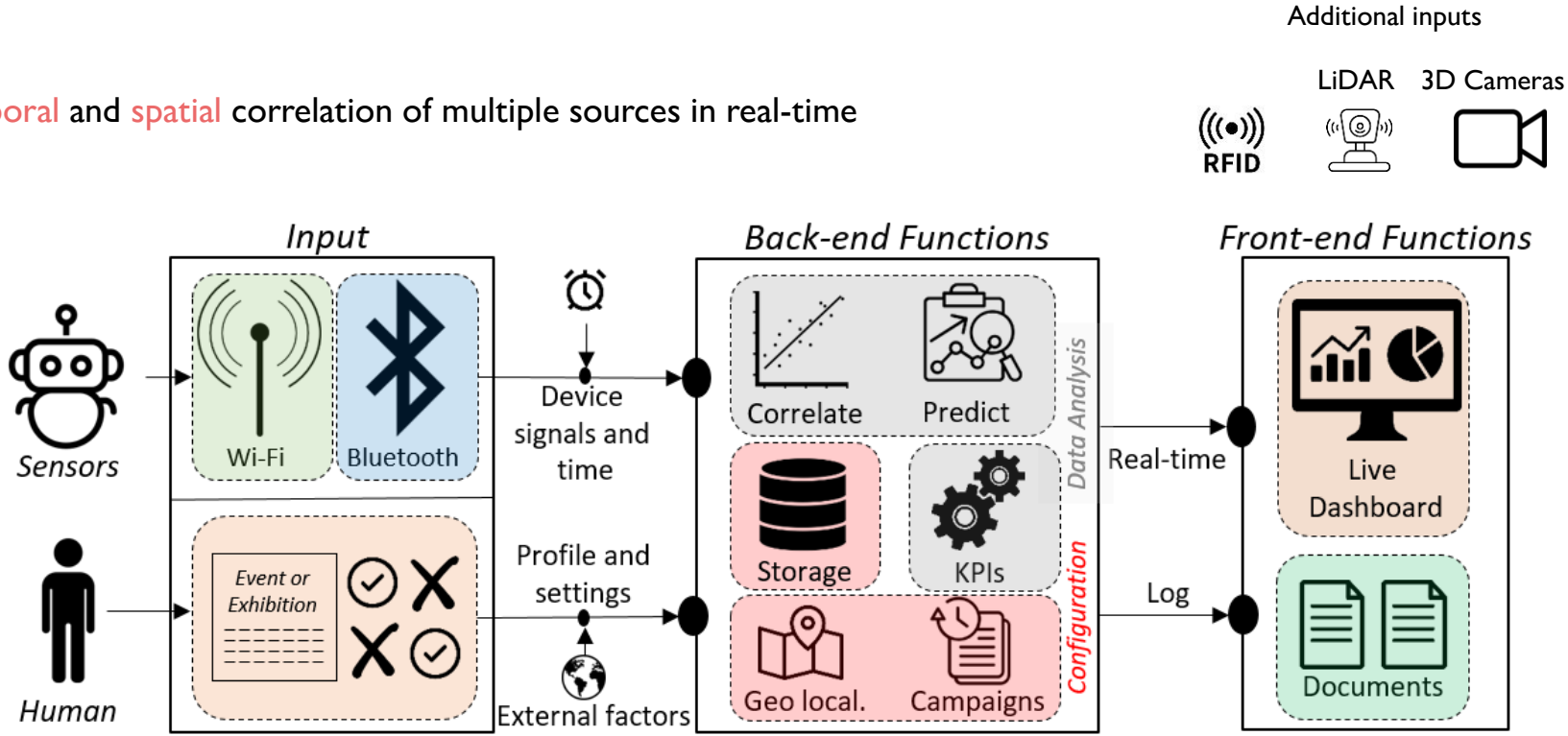


- High attenuation and signal scattering due to obstacles density
  - Reduces signal strenght significantly
- Temporal changes
  - People and objects moving
- High demand for precision and accuracy
  - Real time?
- MAC address randomization

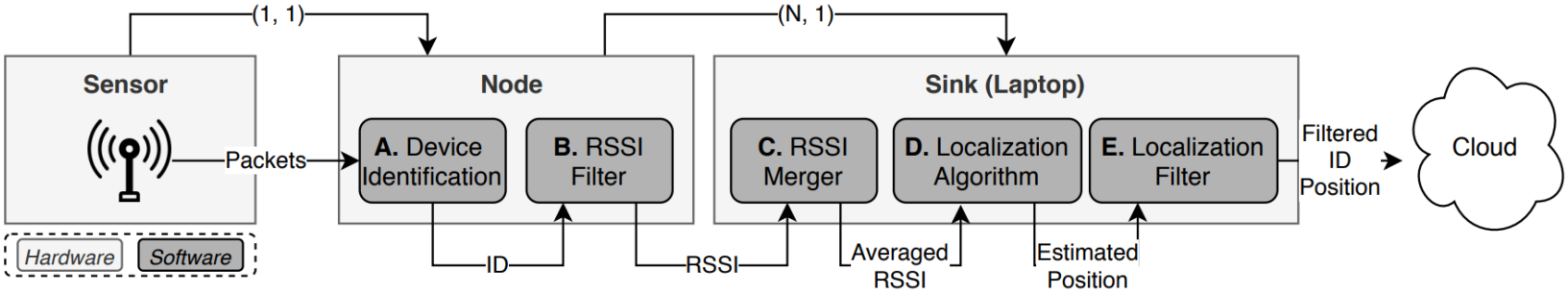


High-level PasWITS Architecture

Temporal and spatial correlation of multiple sources in real-time



Wi-Fi/BLE Streaming Architecture



Five steps in a **distributed, near-real-time, streaming** processing pipeline:

a) Device identification (extrating UID) from packets
b) Filtering RSSI
c) Merging RSSI in a time window
d) Estimating positioning
e) Applying filter

Ubertooth One (BLE passive capture)

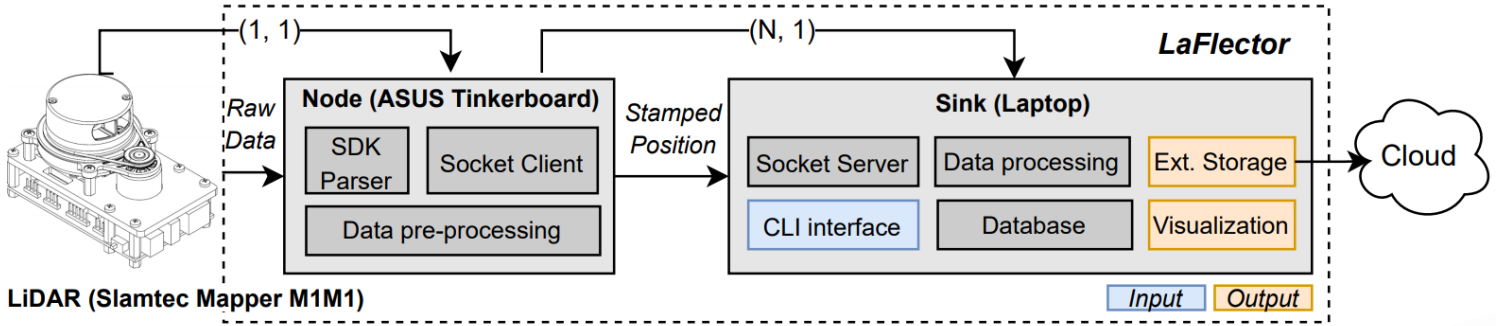
ASUS Tinkerboard

RSSI: Received Signal Strength Indicator

Rodrigues, Bruno, et al. "BluePIL: A Bluetooth-based Passive localization method." *2021 IFIP/IEEE International Symposium on Integrated Network Management (IM)*. IEEE, 2021.

Ribeiro, Rafael Hengen, et al. "Asimov: a fully passive wifi device tracking." *2021 IFIP Networking Conference (IFIP Networking)*. IEEE, 2021.

LiDAR 2D/3D Streaming Architecture

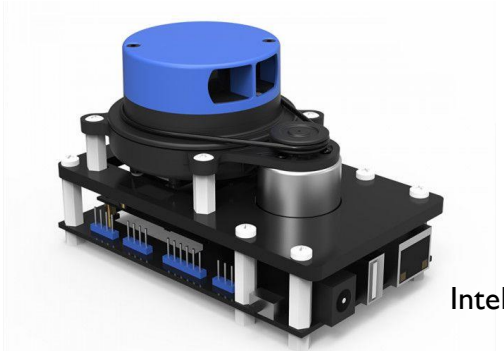


Calibration
- Map the environment without dynamic objects (default in the Slamtec mapper)

Detection
- Filter dynamic objects from the environment

Classification
- Uniquely tagging dynamic objects
- Based on the angle of reflection

Identification
- Tagging based on movement
  - Pros: True position
  - Cons: Hindered by visible light



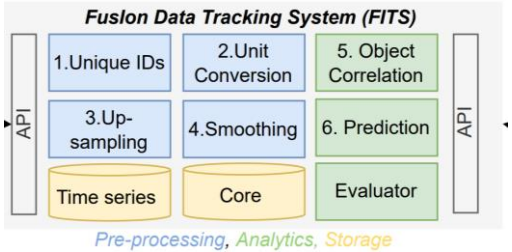
Slamtec M1M1 Mapper

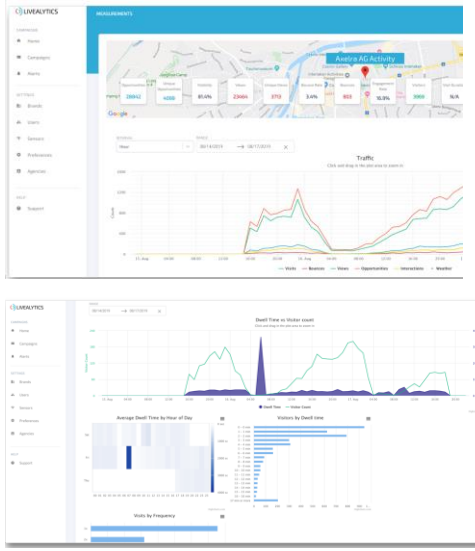
Intel RealSense L515 (3D)

ASUS Tinkerboard

Correlation Engine

Delay





"FITS" main tasks:

- Pre-processing: Upsampling sparse data points for every T and smoothing using Kalman Filter
- Analytics: Clustering objects across diferent sensors and predicting for every T due to the upsampling

Rodrigues, Bruno, et al. "Fusion data tracking system (fits)." *IEEE Sensors Journal* 22.19 (2022): 19060-19072.

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Real-world Experiments

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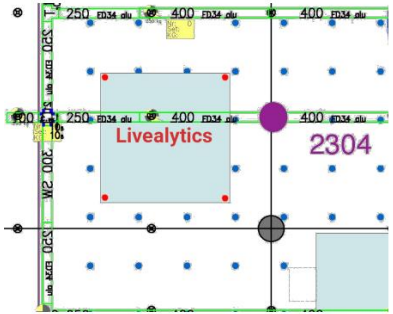
Wi-Fi and Bluetooth



liveAlytics AG tracking an event at The Circle, Zurich Airport

Live experiments

- Initial trials (2020)
  - Indoor and outdoor experiments
- One attempt at a real event
- Collecting data and post-processing

Indoor experiments, Zurich

Outdoor experiments, Zurich

Lessons learned

- **Accurate tracking is not feasible** solely based on passive Wi-Fi and Bluetooth signals
  - Data points are **sparse** and arrive at **irregular** time intervals
  - Fewer data points makes it difficult to distinguish real positions due to signal attenuations and reflections
- However, it was **possible to count nearby visitors**
  - Sligthly better results than only relying on Wi-Fi probe requests
- Proposed data-streaming architecture was effective

LiDAR 2D and 3D

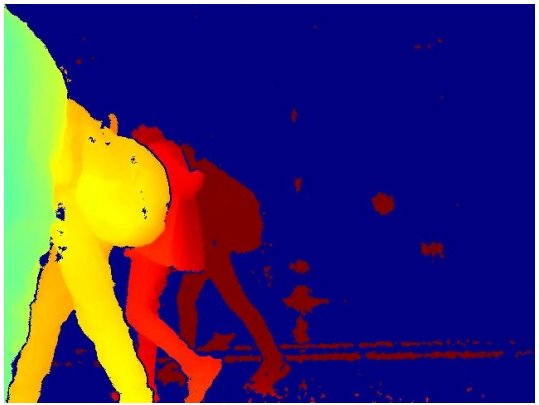
Live experiments

- 2D LiDAR in a closed scenario (FS 2021)
- 3D LiDAR in a semi-open scenario (HS 2021)
  - Development and calibration within UZH
  - Counting people at the Oerlikon train-station
- Near real-time processing

Lessons learned

- Positioning the sensor is key due to non-line-of-sight conditions
- 2D LiDAR was reliable but without capturing depth of objects
- Intel Real-sense L515 unreliable device
  - Discontinued by Intel in 2022

Setup Oerlikon Trainstation



Segmented image based on the depth sensor

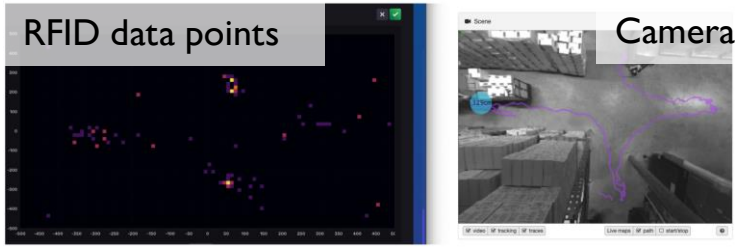
RFID and 3D Cameras

Live experiments

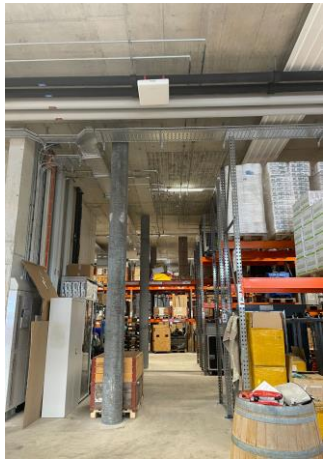
- Restricted environments (HS 21-FS 22)
  - Closed office and warehouse in Zurich
- Collecting data from a single RFID Reader and a 3D camera
  - Correlating both RFID/Camera inputs in near real-time

Lessons learned

- Best combination of sources in terms of accuracy
- RFID becomes noisy when tags are grouped (e.g., 5+ tags)
  - Signal scattering, attenuation
- Later became a product in liveAlytics portfolio
  - Approach to verify/ensure distancing at counters



Warehouse, Schlieren ZH



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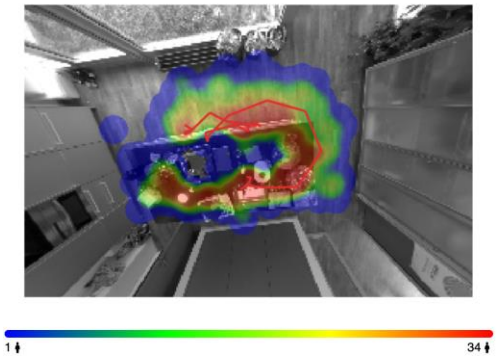

Local tests, Axelra office, ZH

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Analysis

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Business and Technical Dimensions

Business-dimension

- The idea of benchmarking real-world events is still great for event producers and companies advertising products/services
- ... However, the project happened in a very bad timing
  - Company did not survive

Technical-dimension

- **Radio-based** technologies (Wi-Fi, Bluetooth, RFID) are effective for counting, not tracking
  - Passive RFID was the best available alternative in terms of accuracy
  - Ultra-wideband (UWB) is an interesting alternative in terms of accuracy
    - Slowly becoming popular in flagship phones
- **Image-based** technologies (LiDAR, Cameras) are effective for tracking, not counting

Technical and Social Dimensions

- Real-world applications requires optimization of deployment and operation tasks
  - Not feasible to calibrate sensors in real-world events
  - **Key question**: How to automate and reduce the time to calibrate sensors?
- Combining different sources (radio/image) is the path for passive tracking
  - Positive takeaway: the proposed node-sink data streaming architecture was effective and applicable to different sources
  - The trade-off is **accuracy X real-time**, once the approach requires heavy post-processing
  - **Key question**: How to increase accuracy and reduce processing-time?

Social-dimension

- Privacy must be discussed from a social aspect and technically enforced
- Every digital movement on the Web is tracked and traced for benchmarking web-pages and targeted advertising
  - What about public spaces?

Personal viewpoint

- Applied research is fun!

Danke für Ihre Unterstützung!

Questions?

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