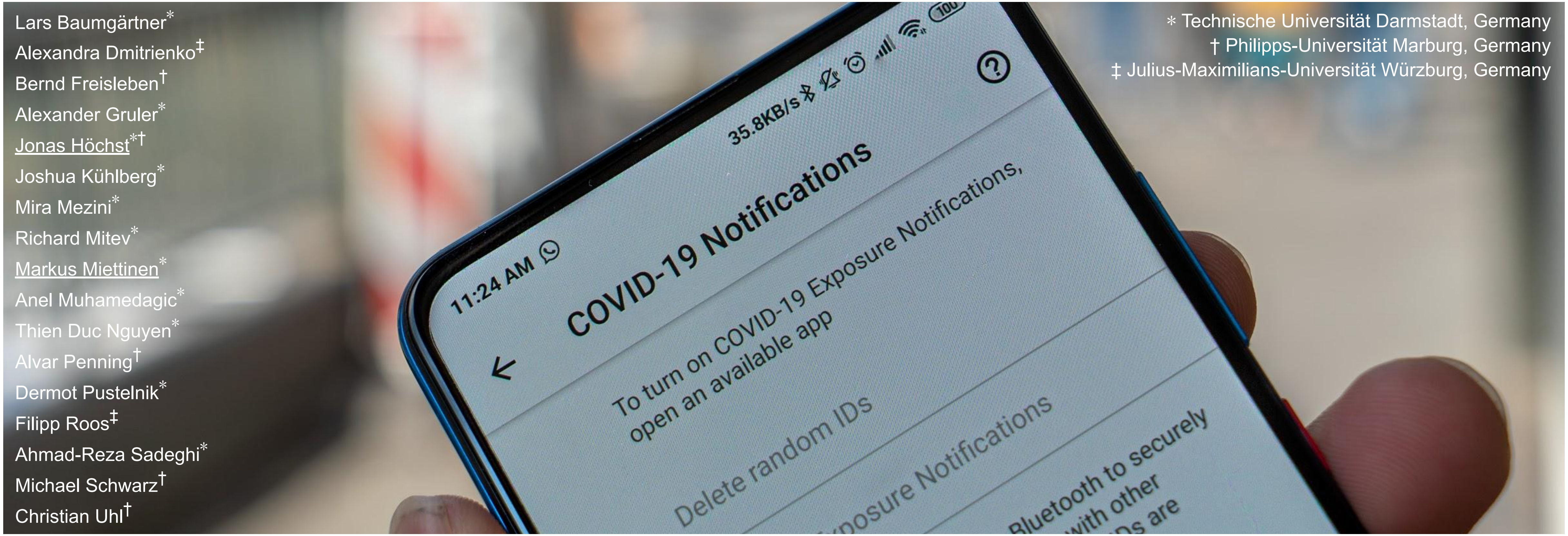
Mind the GAP:
Security & Privacy Risks of Contact Tracing Apps

IEEE TrustCom 2020



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Introduction
Digital contact tracing apps in various countries

Manual vs. Digital

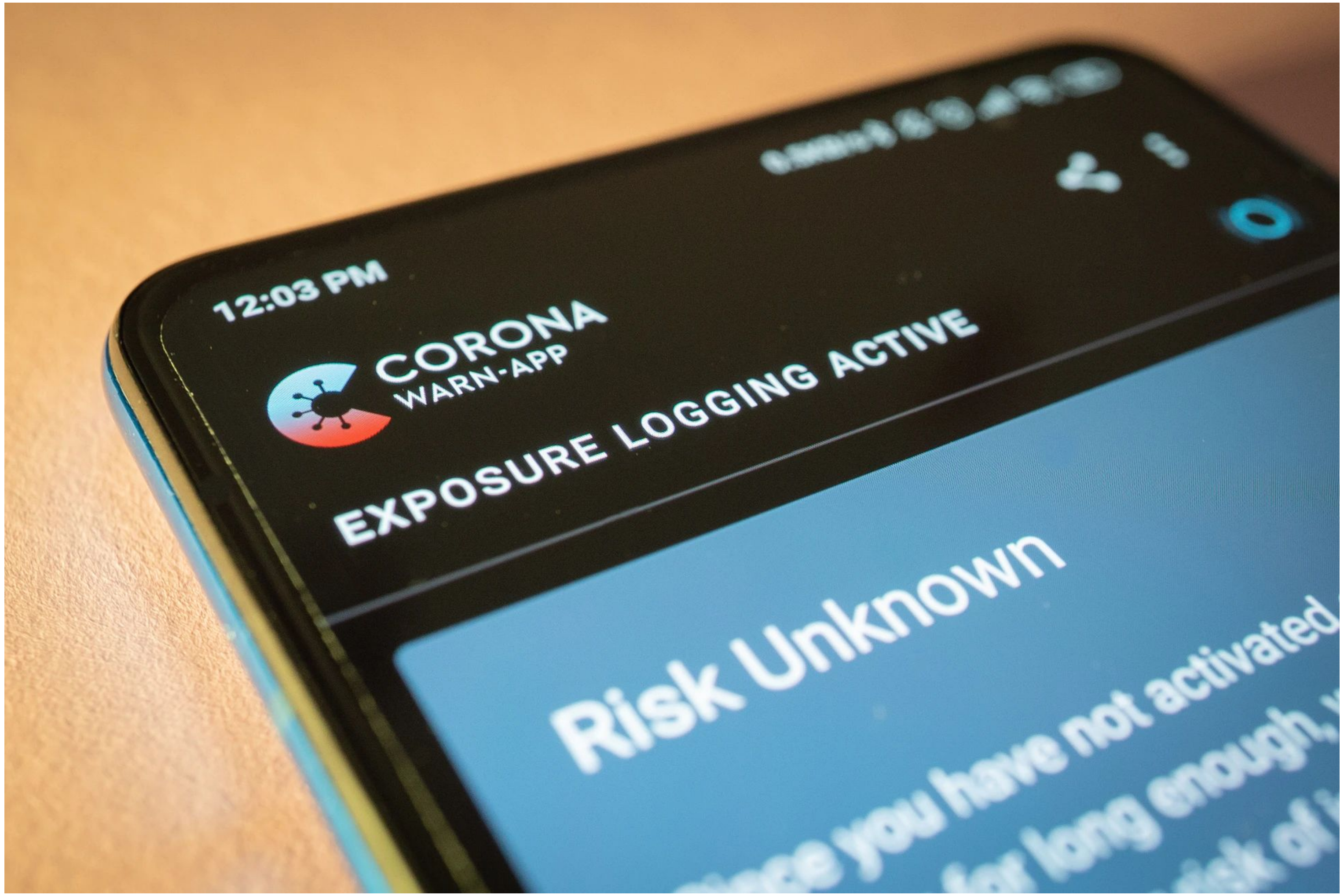
Global Position vs. Local Beaconing

Tracking vs. Tracing

Centralized vs. Decentralized

Base Technologies

OS Integration



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GAP: Google's and Apple's Proposal for Contact Tracing

Joint effort for decentralized digital contract tracing

Contact tracing API to be used by state-specific applications

- Contact information remains in the API, hence is protected by OS security mechanisms
- Access to contact information only through specific functions

Decentralized approach

- Contact information stays on the device
- Personal infection state can be shared voluntarily after positive diagnosis
- Matching is based on a state-maintained public list

Academic discussion on GAP contact tracing

- Profiling attacks [14, 15]
- Relay attacks [14], [16]–[19]
- Theoretical attacks discussed in the literature, practical evaluation in this work

GAP: Overview

Basic concept of privacy-preserving contact tracing [29]

Temporary Exposure Keys (TEK)

- Independently generated (daily)

Rolling Proximity Identifier (RPI)

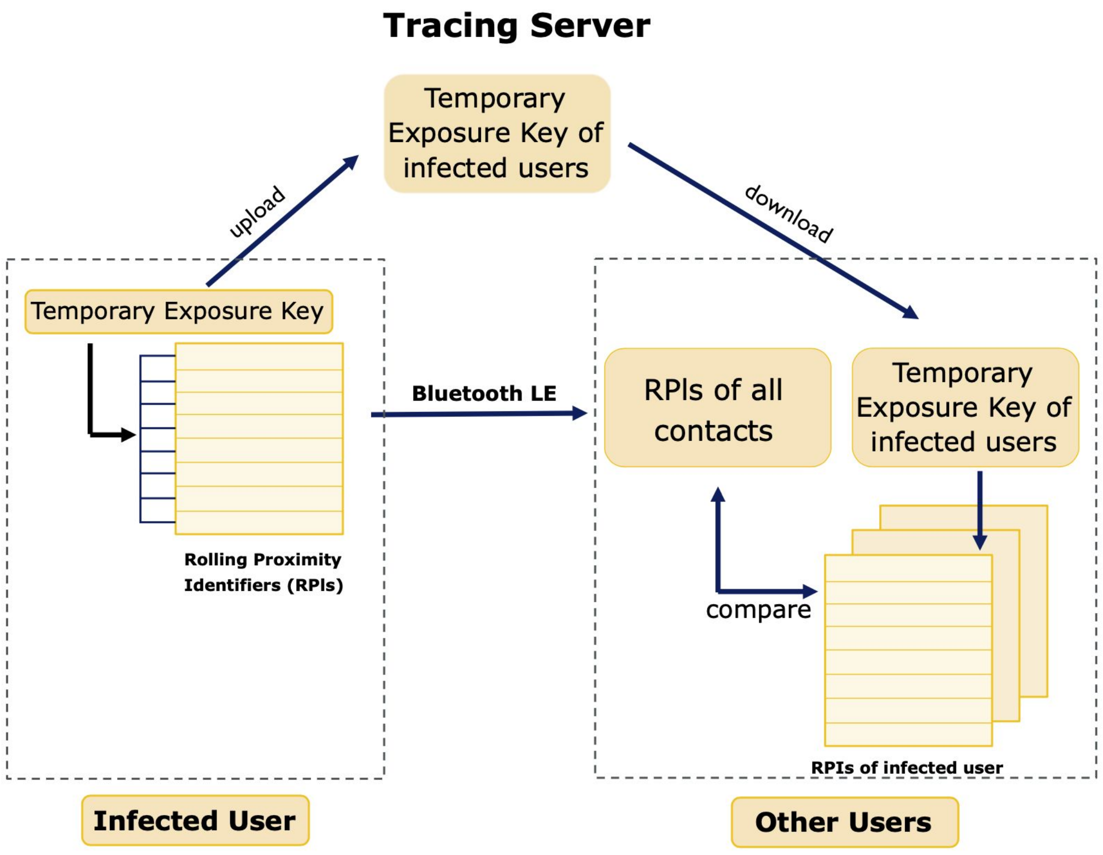
- Derived from TEK (every 10 minutes)
- Broadcasted continuously via Bluetooth LE
- Analogously other users receive and store surrounding RPIs

Infected user

- Shares TEKs of previous 14 days through the tracing server

Other users

- Download publicly available TEKs
- Derive corresponding RPIs
- Match against received RPIs



Overview of the GAP contact tracing approach

[29] Apple Inc, "Exposure Notification Bluetooth Specification v1.2"

Mind the Privacy GAP: Profiling Attacks

Conceptual vulnerability of GAP

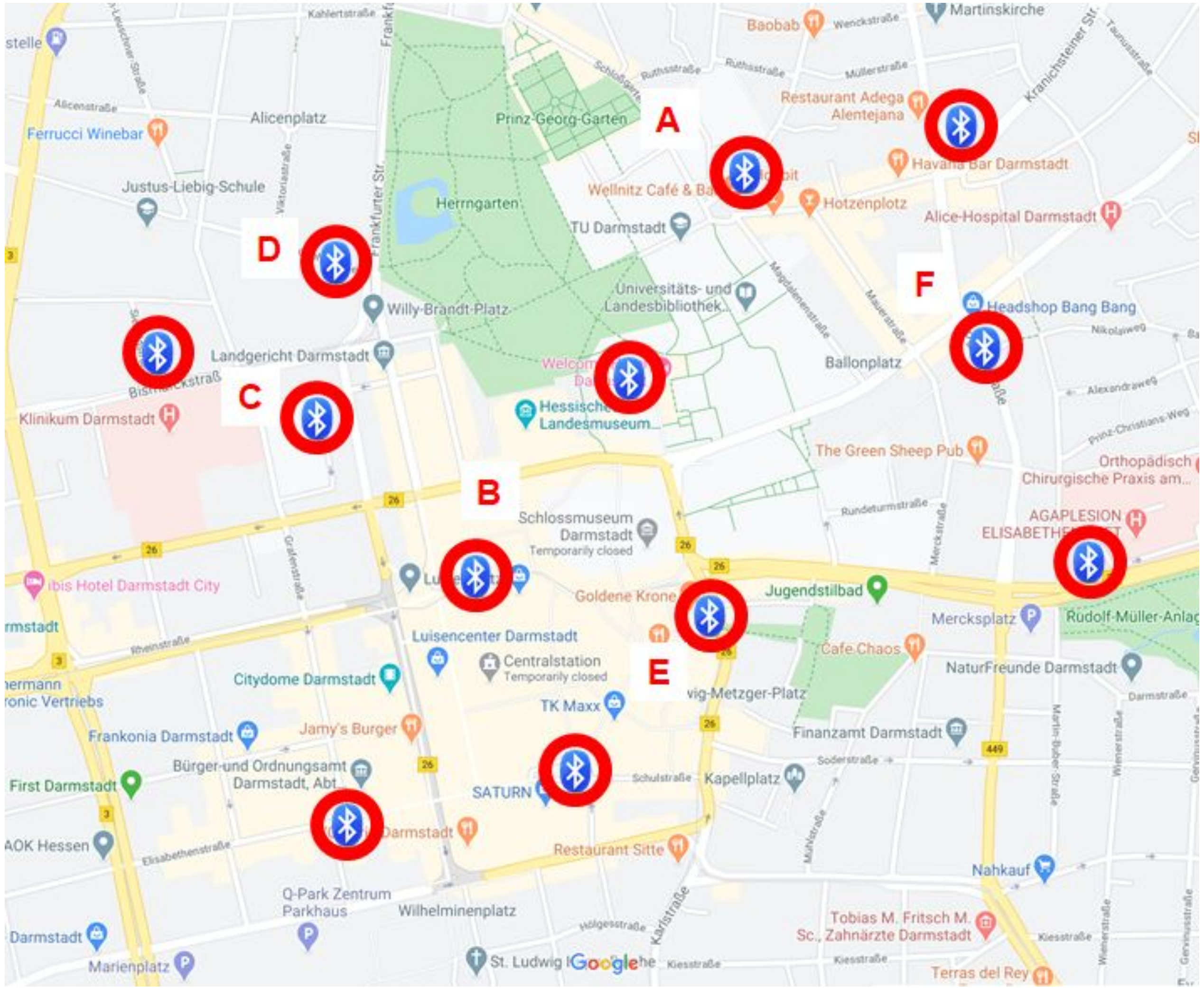
- TEKs are valid for 24 hours during which 144 RPIs are derived from a TEK (one every 10 minutes)
- All RPIs originating from same TEK are **trivially linkable** by all participants in the system **if TEK is known**
- Infected users are expected to **publish their TEKs** of the past 14 days in order to warn others

Attack scenario

- Adversary collects observations of RPIs emitted by tracing apps from a number of **strategically-chosen sensing points** in targeted area
- Using **published TEK information**, RPIs of infected users can be after-the-fact trivially **linked** with each other
- Adversary can thus construct **movement profiles** of infected users

Attack Setup

Strategically selected observation points in Darmstadt, Germany



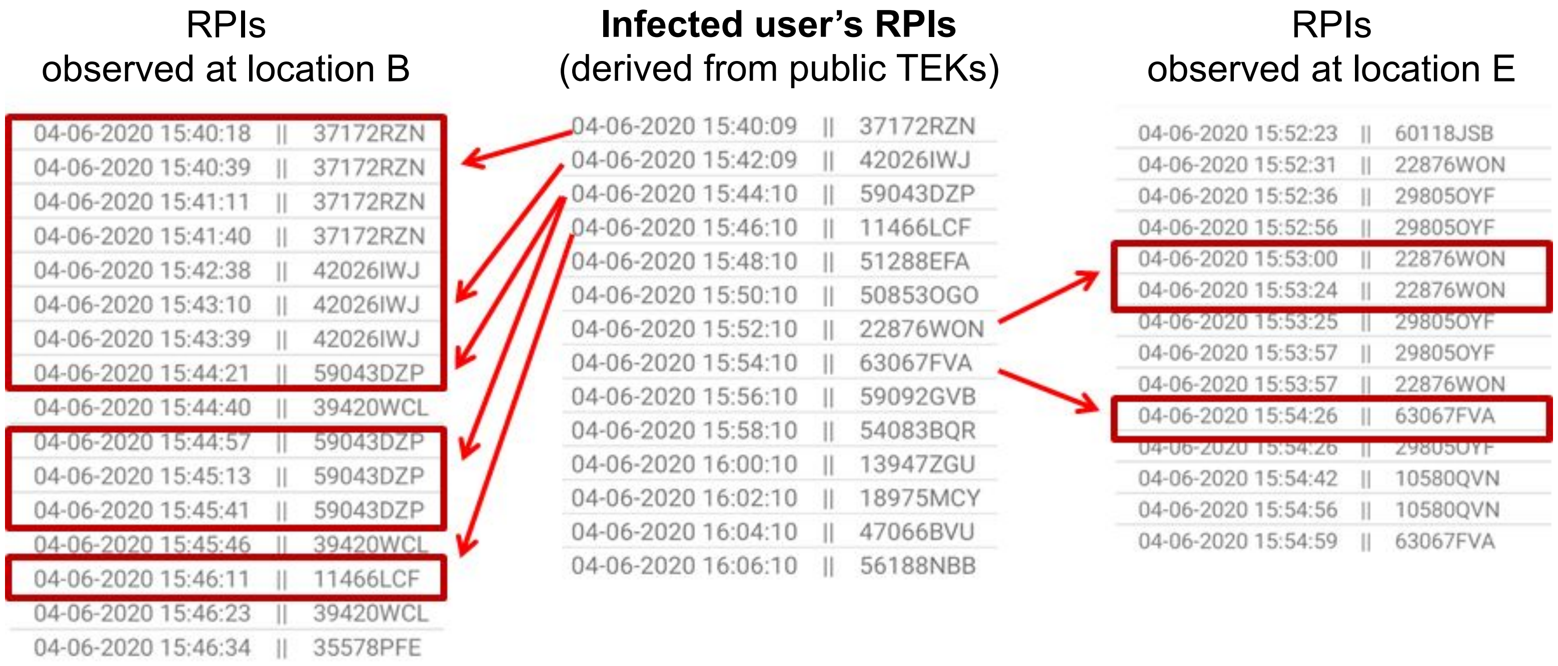
A	Residential area
B	City hall
C	Police station
D	Clinic and pharmacy
E	Outside a pub
F	Outside a head shop and a sports gambling bookmaker

Attack Execution

Observation points record tracing app RPIs emitted in their proximity

RPIs derived from published TEKs are cross-checked against RPI observations

- **Any visits** of infected users to observation points **can be identified** based on emitted RPIs



Identifying Movement Profiles

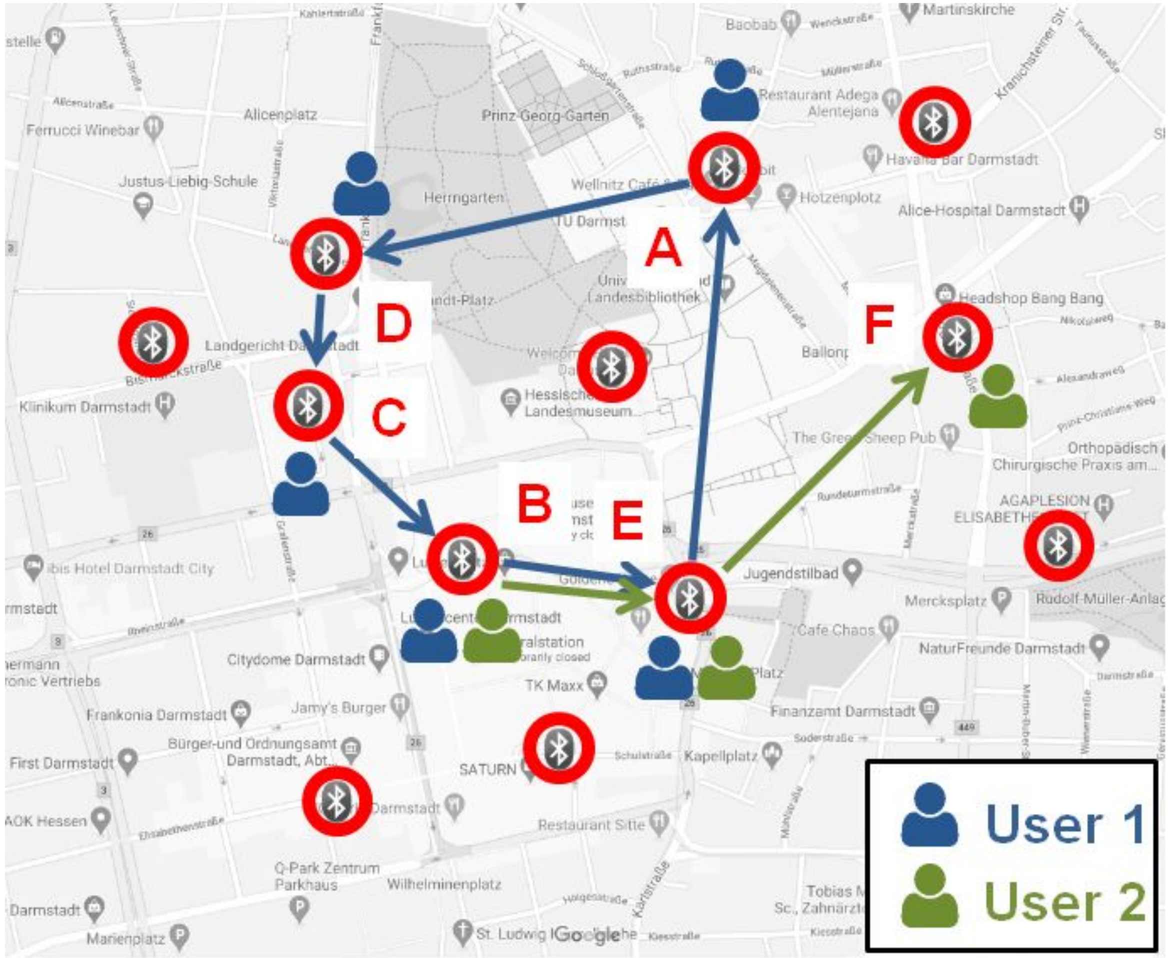
By linking RPI observations, **detailed movement profiles** of infected users can be constructed.

Movement profiles can reveal identifying information about users.

For example:

- Main point of presence during night times identifies person’s likely **home address**
- Main point of presence during working hours identifies likely **workplace**

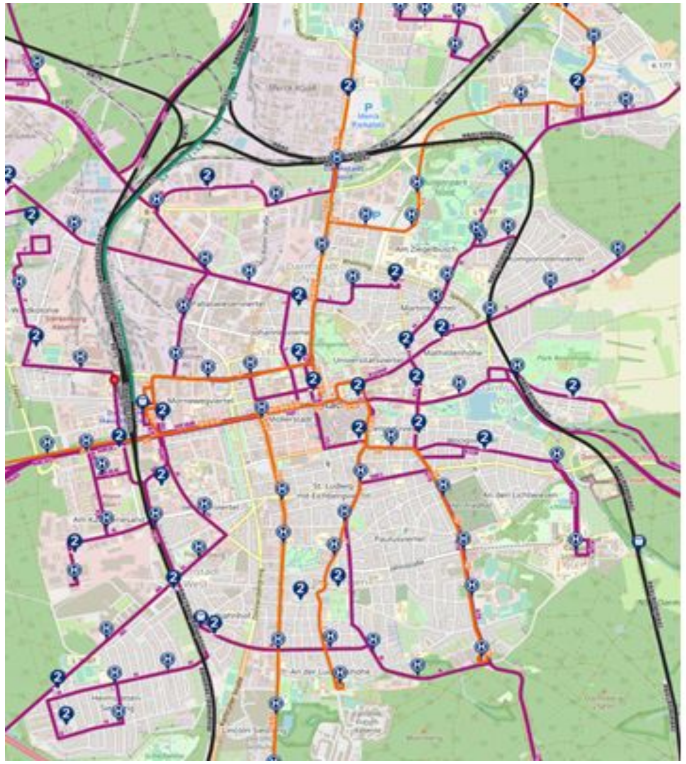
Given sufficient movement profile information potentially allows us to **completely de-anonymize** infected users.



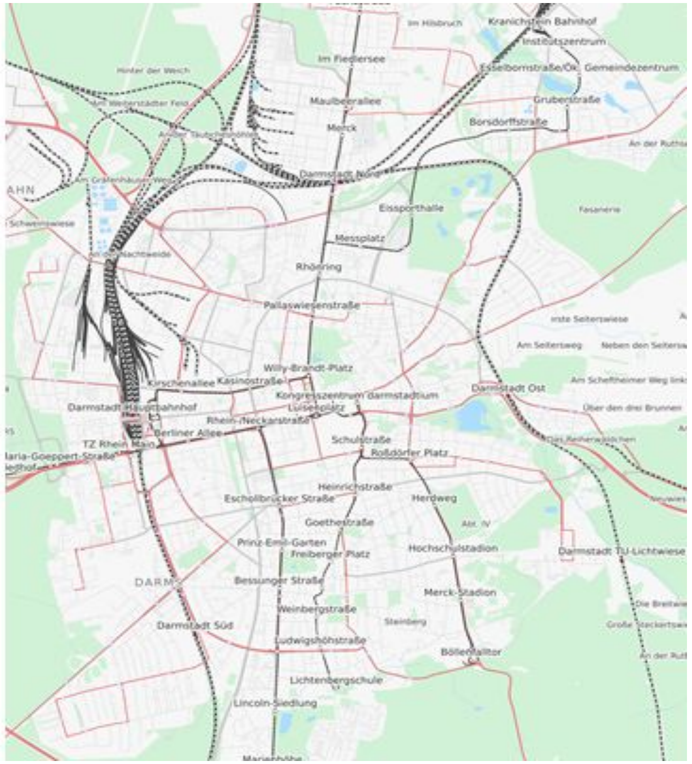
Surveillance Case Study: Darmstadt, Germany

How many sensing points would be necessary to cover a majority of movement profiles in a city of ca. 160 000 inhabitants and an area of ca. 122 km²?

Main transport routes in Darmstadt



Train, tram and bus line network

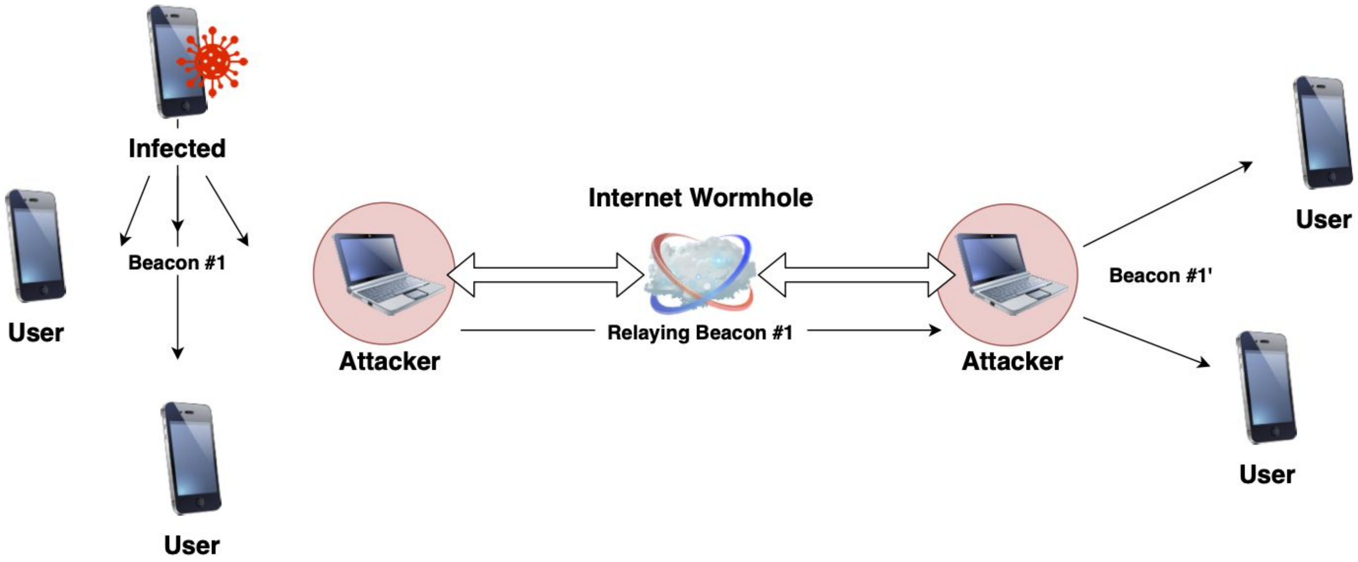


Main roads (cars & railways)

Transport system	**Sensing stations needed**
Trams	25
Buses	60-80
Railways	60
Car traffic	200-250
Pedestrians	50
Total	**395 - 465**

Mind the Security GAP: Wormhole attacks on Bluetooth beaconing

- **Replay attack:** Record BLE signal at location A, replay at other location
  - Countermeasure: limit validity period of BLE signal / introduce handshake
- **Relay attack:** Satisfy domain-specific real-time requirements
  - 10-minute RPI validity period in GAP
- **Wormhole attack:** Link physical locations and forward BLE signals in between these locations
  - Combination of replay and relay



Wormhole attack setup to relay BLE beacons

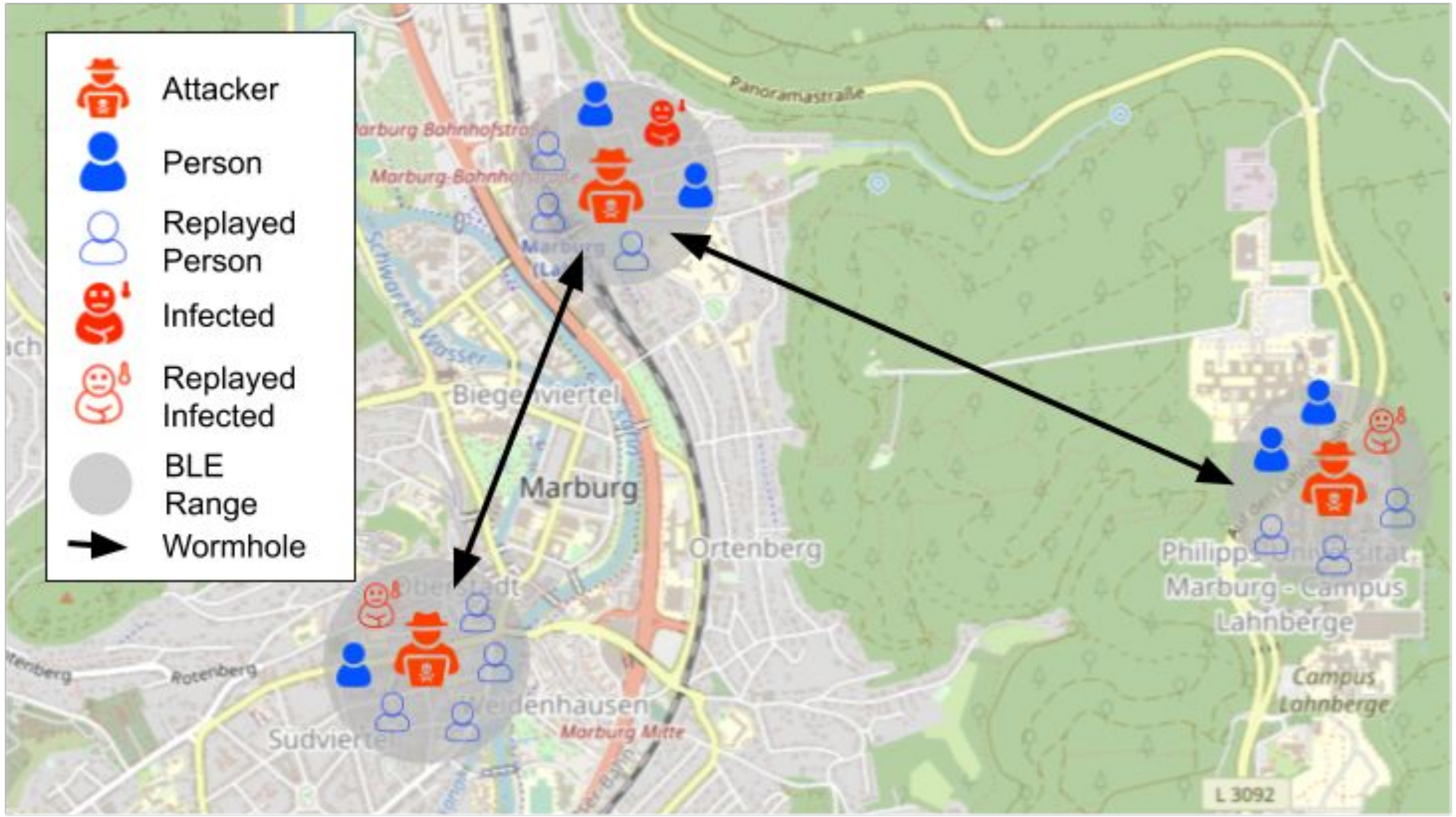
Wormhole Attack: Experiment 1

Devices and setup

Raspberry Pi-based wormhole receivers distributed at multiple locations:

1. Receive Bluetooth beacons
2. Send beacons to central server
3. Query server for new beacons and redistribute at own location

Tests conducted with DP-3T sample app.



Wormhole attack in the city of Marburg

Wormhole Attack: Experiment 1

Devices and setup: server logs

Raspberry Pi-based wormhole receivers distributed at multiple locations:

1. Receive Bluetooth beacons
2. Send beacons to central server
3. Query server for new beacons and redistribute at own location

Tests conducted with DP-3T sample app.

```
1 Jun 09 20:45:13 wormpi-mr wormhole[472]: [provider    ] [
      INFO] [in ] [7E:09:47:A6:EE:7F] [Dp3t_ScanRequest]
      fd68
2 Jun 09 20:45:13 wormpi-mr wormhole[472]: [wormhole-out] [
      INFO] [7E:09:47:A6:EE:7F]       [Dp3t_ScanRequest]
      fd68
3 Jun 09 20:45:13 wormpi-mr wormhole[472]: [wormhole-in ] [
      INFO] [5A:A2:81:40:7A:B3]       [Dp3t_ScanResponse]
      fd68 6d:72:34:32:30:80:1d:62:d7:c9:ff:d0:71:a3:37:b0
4 Jun 09 20:45:13 wormpi-mr wormhole[472]: [provider    ] [
      INFO] [out] [5A:A2:81:40:7A:B3] [Dp3t_ScanResponse]
      fd68 6d:72:34:32:30:80:1d:62:d7:c9:ff:d0:71:a3:37:b0
```

Raspberry Pi with our wormhole implementation

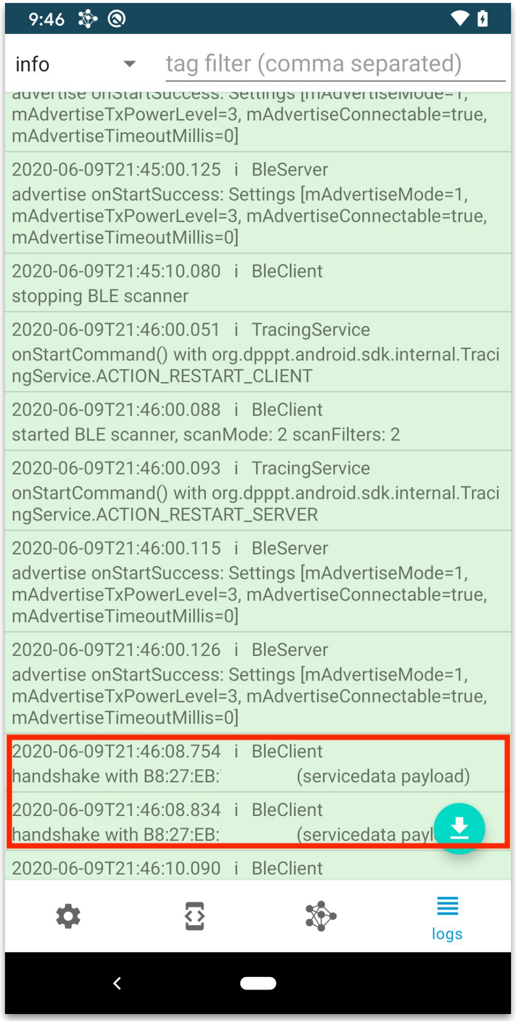
Wormhole Attack: Experiment 1

Devices and setup: successful RPI wormholing

DP-3T prestandard SampleApp instances with confirmed beacons transmitted through the wormhole "wormpi"

a) **Android:** handshake conducted with MAC address of wormhole device (Raspberry Pi)

b) **iOS:** confirms receipt of a beacon with the manually set ephemeral ID of "mr42"



Wormhole Attack: Experiment 2

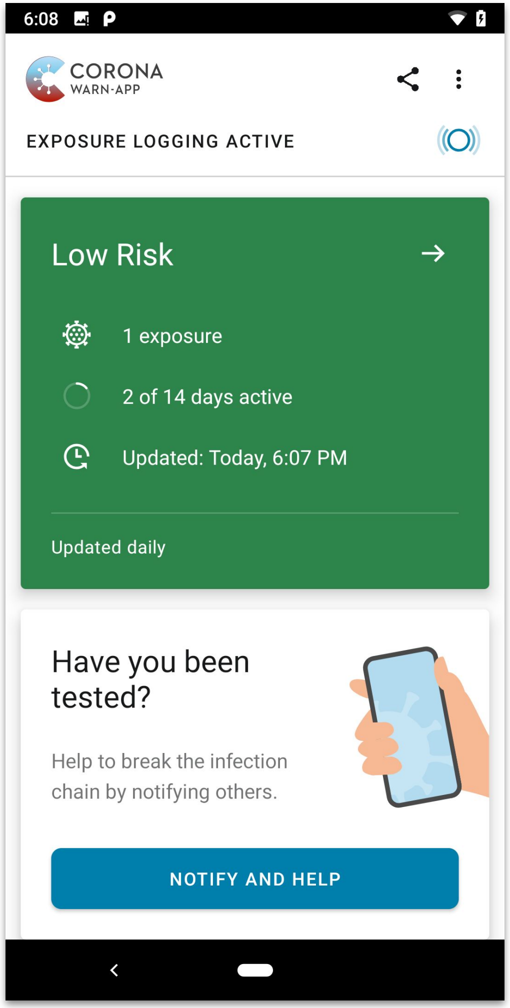
Validation with GAP and the German “Corona-Warn-App”

Access to the GAP API is restricted:

- Impossible to access the API without being *whitelisted* by Google / Apple
- Whitelisting only for one Government approved institution per country

Using real-world TEKs

- Download list of “positive” TEKs from official server
- Derive RPIs from a TEK
- Block access to the official server for our test device
- Set the system time to the time in which an RPI was valid
- Install and activate the official Corona-Warn-App
- Send the RPIs (together with valid metadata) using our wormhole
- After ~ 10 - 15 min:
  - Reset the date/time
  - Unblock access to the server and force the app to download the list
- => The app will then trigger a warning



Exposure Notification Wormholing

Technical limitations: basic considerations

Beacons according to the Bluetooth LE standard

- Transmission speed up to 1 Mbps
- GAP payload size of 26 bytes [29]
  - Advertisement size of 39 bytes [28]
  - Packet data unit size of 47 bytes
  - Airtime of 376 µs + inter-frame space of 150 µs
- 10^6µs / (376µs + 150µs) = **1,901 packets/s**

Real-world factors

- Receivers hop between three Bluetooth announcement channels
- Connection intervals forced by device vendors
- Receiver / sender distance and transmission power
- Interferences and collisions


Bluetooth®

Bluetooth Core Specification

Bluetooth® Specification

- Revision: v5.2
- Revision Date: 2019-12-31
- Group Prepared By: Core Specification Working Group
- Feedback Email: core-main@bluetooth.org

Abstract:
This specification defines the technologies required to create interoperable Bluetooth devices.

Bluetooth SIG Proprietary

[28] Bluetooth Special Interest Group (SIG), “Bluetooth Core Specification 5.2”
[29] Apple Inc, “Exposure Notification Bluetooth Specification v1.2”

Exposure Notification Wormholing

Technical limitations: practical evaluation

Experimental Evaluation

- HackRF One (sender & receiver)
- Raspberry Pi (receiver)
- Surrounding WiFi and BLE device for disruptions
- **4.3% of theoretical maximum achieved: 82 packets/s**

Findings

- Bluetooth / host communication batched, scheduled in 2 second windows
- Stable tests in 10 meter range, up to 50 meter enhanced range when using hardware amplification

Exposure Notification Wormholing

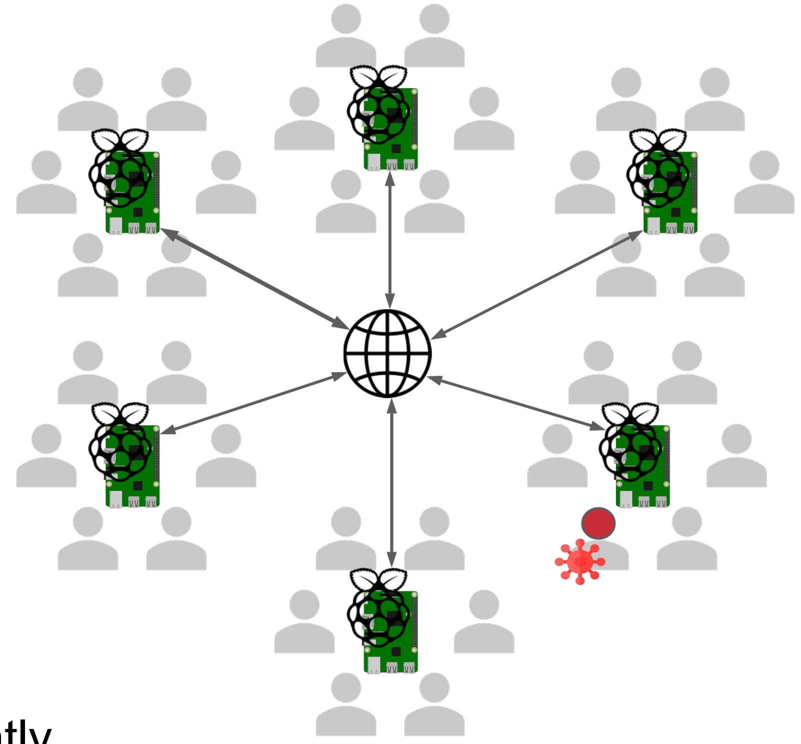
Attack scenario: opportunistic linking (1)

Idea:

- Bridging multiple high traffic locations with wormholes
- Increasing the impact of later positively reported beacons
- Getting at least one positive advertisement each 10 minutes

Parameters:

- **5.1** infections per 100.000 (Germany, week 32 of 2020)
- **30.43** unique BLE advertisements per minute
  - Obtained by field study at Central Train Station in Frankfurt, Germany



Results:

- On avg., **1 per 9,804 RPIs** will be positive
- => **65 wormhole devices** to have on avg. one positive RPI constantly
- High-risk warning requires contacts for over 10 minutes

Exposure Notification Wormholing

Attack scenario: opportunistic linking (1)

Idea:

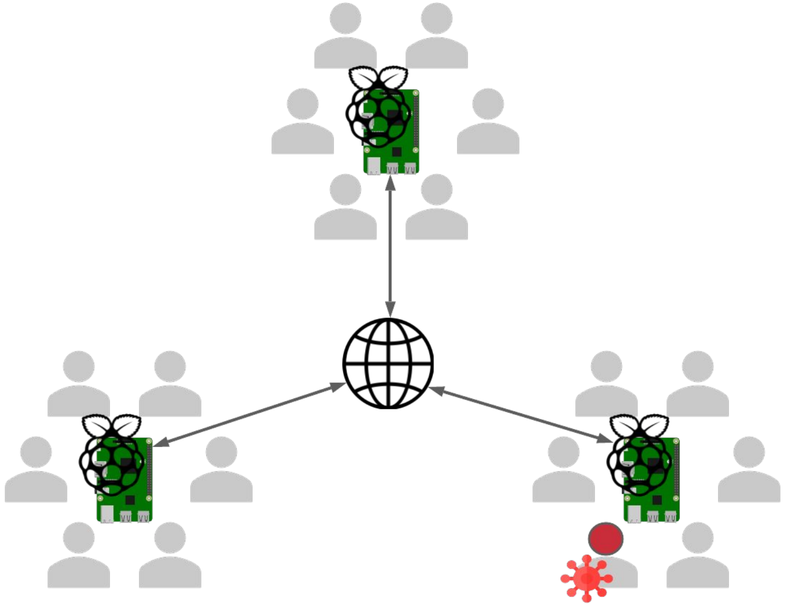
- Bridging multiple high traffic locations with wormholes
- Increasing the impact of later positively reported beacons
- Getting at least one positive advertisement each 10 minutes

Parameters:

- **45.4** infections per 100.000 (Germany, week 42 of 2020)
- **30.43** unique BLE advertisements per minute
  - Obtained by field study at Central Train Station in Frankfurt, Germany

Results:

- On avg., **1 per 1,101 RPIs** will be positive
- => **8 wormhole devices** to have on avg. one positive RPI constantly
- Still relatively high load for the system to handle



Exposure Notification Wormholing

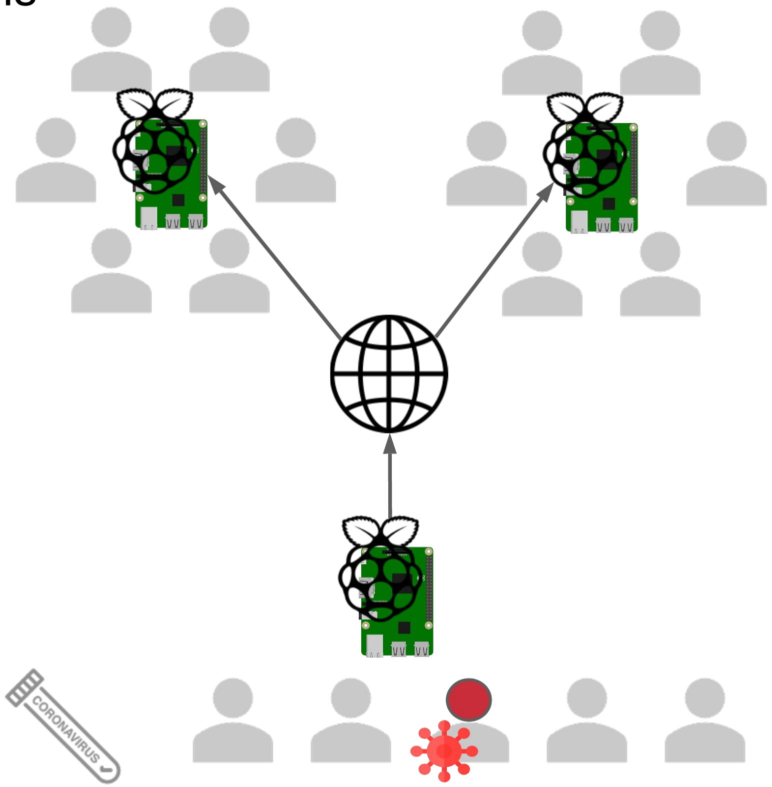
Attack scenario: opportunistic linking with high infection probability

Idea:

- Bridging a location with a high infection probability with other locations
- Getting at least one positive advertisement each 10 minutes

Parameters:

- **300** unique beacons per hour
  - Obtained from a local testing facility near Frankfurt, Germany
- **9.84%** of infected persons share their infection status using the app
  - Based on submitted TEKs in correlation to overall infections in week 41 and 42, 2020 in Germany
- **3.62%** positive test rate (Germany, week 42 of 2020)



Results:

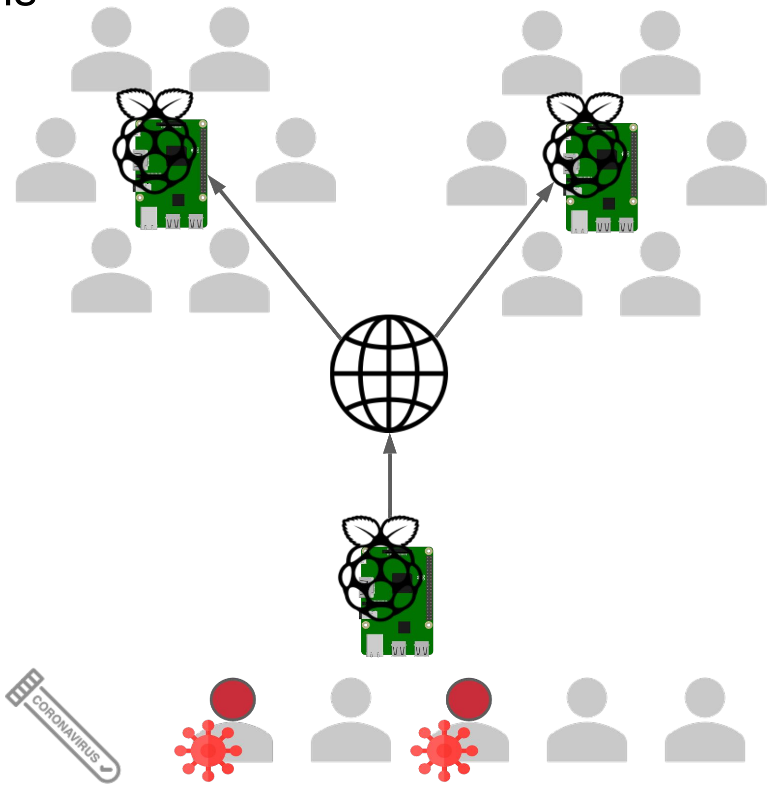
- **1.07** positive RPIs per hour
- **Limited effect** with one test center, **better scalability** due to relatively low number of total RPIs.

Exposure Notification Wormholing
Attack scenario: opportunistic linking with high infection probability

Idea:
- Bridging a location with a high infection probability with other locations
- Getting at least one positive advertisement each 10 minutes

Parameters:


- **300** unique beacons per hour
  - Obtained from a local testing facility near Frankfurt, Germany
- **9.84%** of infected persons share their infection status using the app
  - Based on submitted TEKs in correlation to overall infections in week 41 and 42, 2020 in Germany
- **41%** positive test rate (Mexico, October of 2020)



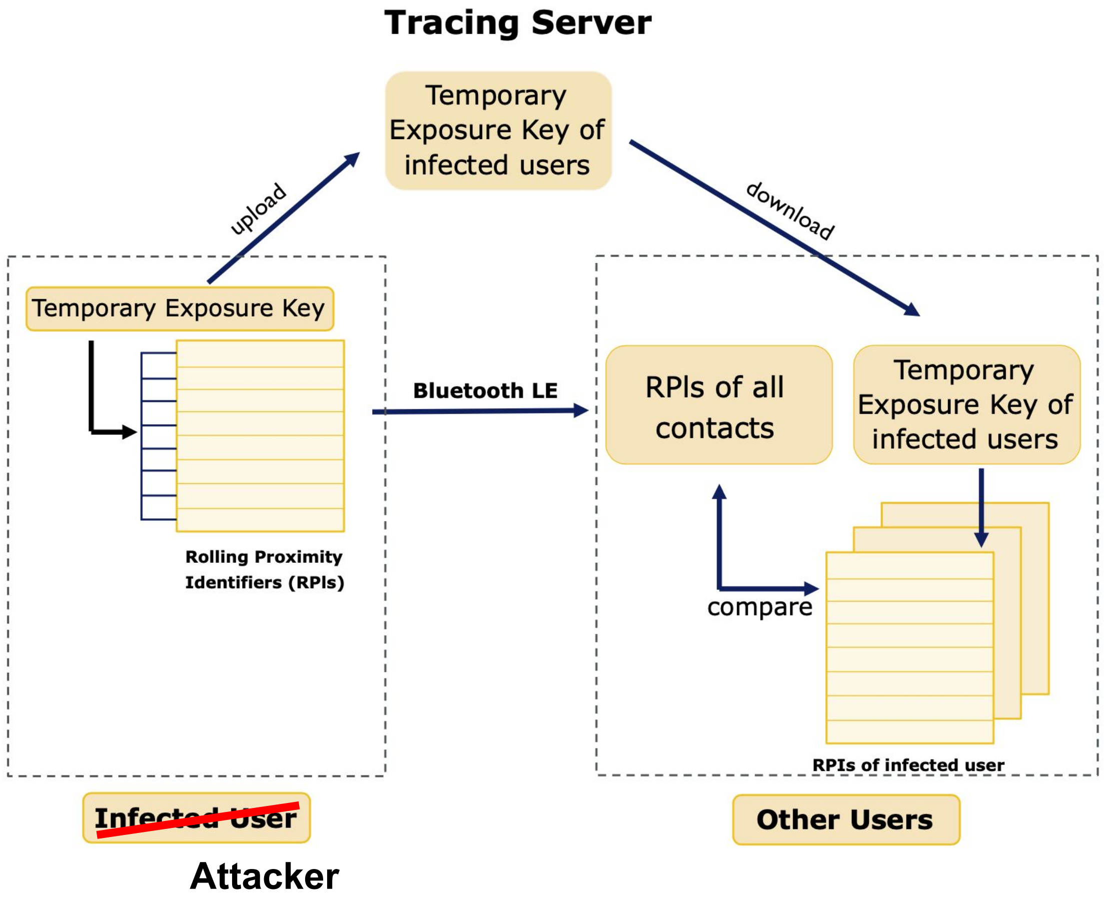
Results:
- **12.10** positive RPIs per hour
- **Reduced attacker effort**, good scalability properties, effectively allowing the attacker to invalidate the app for reached users.

Exposure Notification Wormholing
Attack scenario: targeted attack

Idea:
- Flood own beacons to as many people as possible
- Upload own key by using a valid TAN of a (fake) infection to the official servers

Parameters:
- **825** contacts per hour per wormhole (based on field study)
- Submitting for **14 days**, 12 hours per day
- High traffic location (e.g., train station)

Results:
- **306.600** registered, positive RPIs
- **High-risk warnings** for users if targeted > 10 minutes



Conclusion

Demonstration of theoretical vulnerabilities:

- Profiling and possibly de-anonymizing infected persons
- Relay-based wormhole attacks to generate fake contacts that may affect the accuracy of GAP-based contact tracing apps
- Evaluated with DP-3T development app and German Corona-Warn-App, applicable to all GAP-based apps

Countermeasures:

- Increase TEK rollovers to limit de-anonymization
- Reduce 2 hour RPI validity period to reduce impact of wormhole attack [29]
- Validate time and location of received RPIs by additional metadata
- Revise protocol to include a handshake mechanism [25]

Questions?

- Questions now @TrustCom
- Offline via mail: hoechst@informatik.uni-marburg.de

[25] ConTra Corona: Contact Tracing against the Coronavirus by Bridging the Centralized–Decentralized Divide for Stronger Privacy
[29] Exposure Notification Bluetooth Specification v1.2

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