Duet: Estimating User Position and Identity in Smart Homes Using Intermittent and Incomplete RF-Data

DEEPAK VASISHT, ANUBHAV JAIN, CHEN-YU HSU, ZACHARY KABELAC, DINA KATABI
Massachusetts Institute of Technology

Presented by Pargorn Puttapirat
Computer Science and Technology

As part of assignment for
Wireless network and mobile computing class - 2019
Xi'an Jiaotong University

LICENSE | DISCLAIMER

License:

Disclaimer:

This is a presentation made based on this work:

Vasisht, Deepak et al. “Duet: Estimating User Position and Identity in Smart Homes Using Intermittent and Incomplete RF-Data.” IMWUT 2 (2018): 84:1-84:21.

The presentation maker has no contribution to the original work.

Smart home!!

What technology is most needed in smart home?

https://developers.google.com/assistant/smarthome/overview

Sense

- Buttons and switches
- Sensor/sensor array
- Human-like commands :voice, gesture

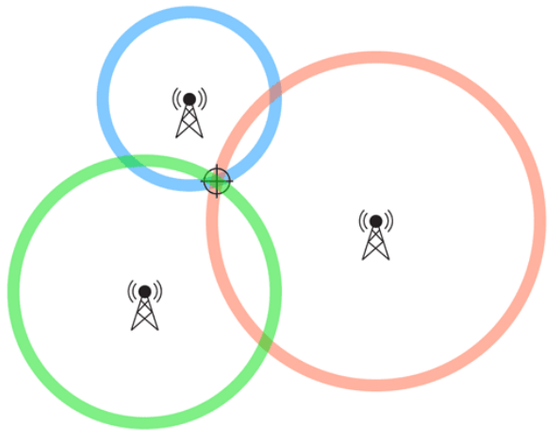
Act

- Turn (things) on/off, adjust
- Give alerts
- etc.

Answer: Human localization

Related work

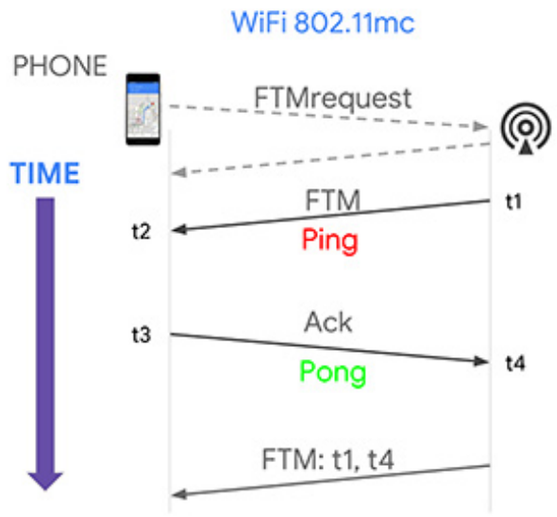
RF-based localization



Relative signal strength indicator
RSSI

https://cryptolok.blogspot.com/2017/08/practical-wifi-hosts-triangulation-with.html

Angle of arrival
AoA



Time of flight

http://people.csail.mit.edu/bkph/ftmrtt_intro

Current state of development: **Sub-meter accuracy**

Device-based systems

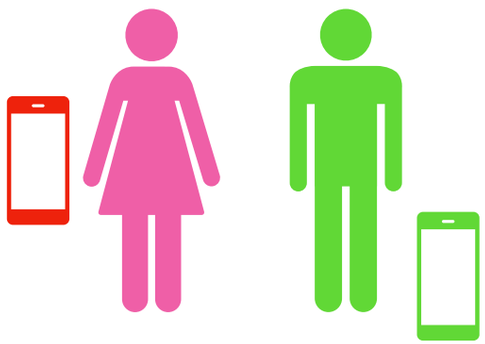
57% = phone-carrying time

Device-free systems

No identification at all!

Problem (1/3): identification

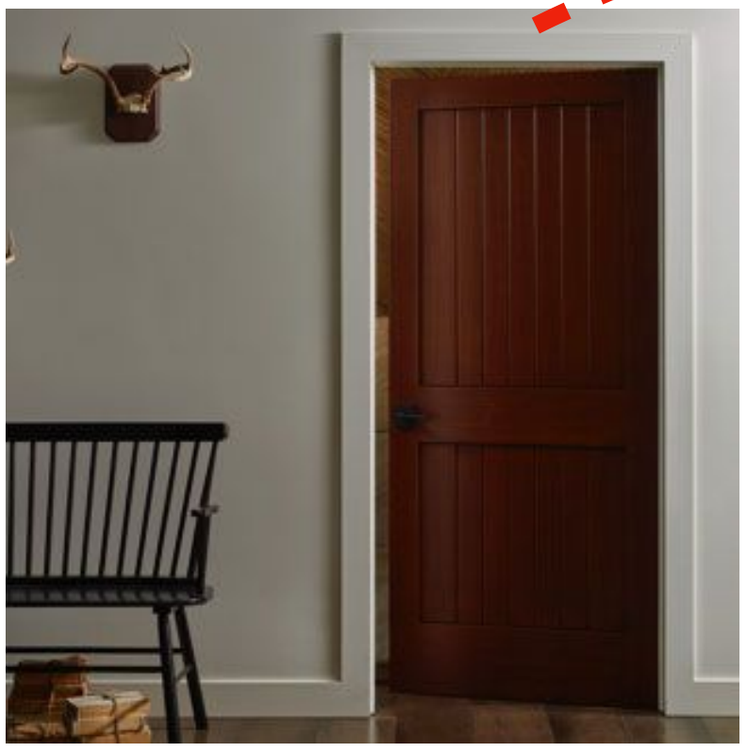
- **Requires several APs**
- **Percentile error can be several meters**
- **People do not carry phone all the time**



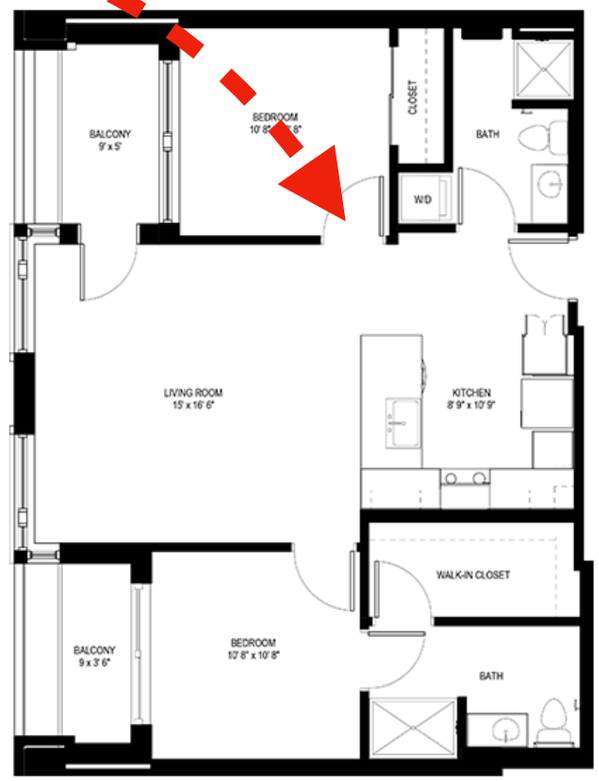
Duet's solution

Match by trajectories, not distance

Problem (2/3): blockage/coverage

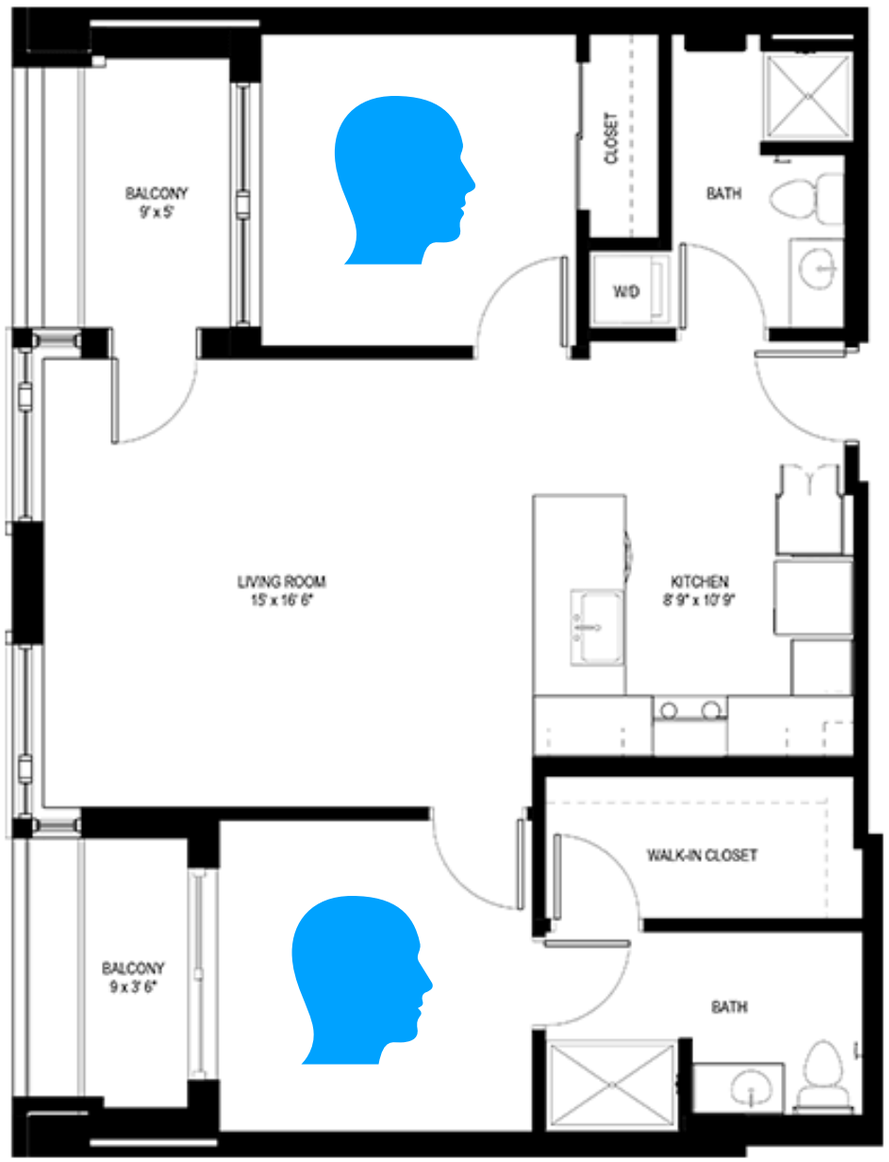


Where did {person} go?



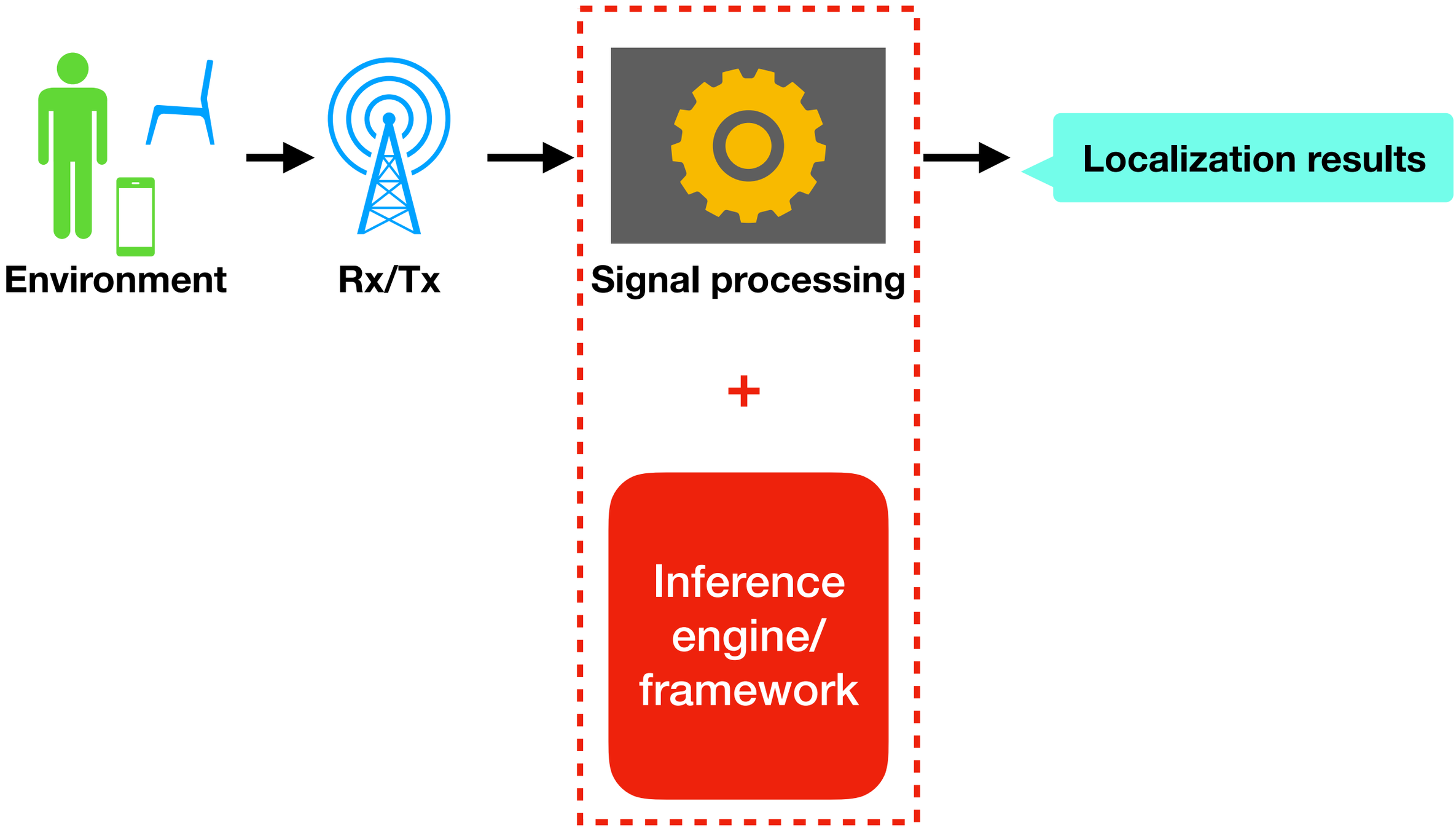
Duet:
Symbolic > absolute location
Hidden Markov Model
Soft constraint

Problem (3/3): dependencies



- One person cannot be in two rooms.
- If a person enter an empty room, there should be one person in there.
- Etc.

What can we do?



Illustrative example

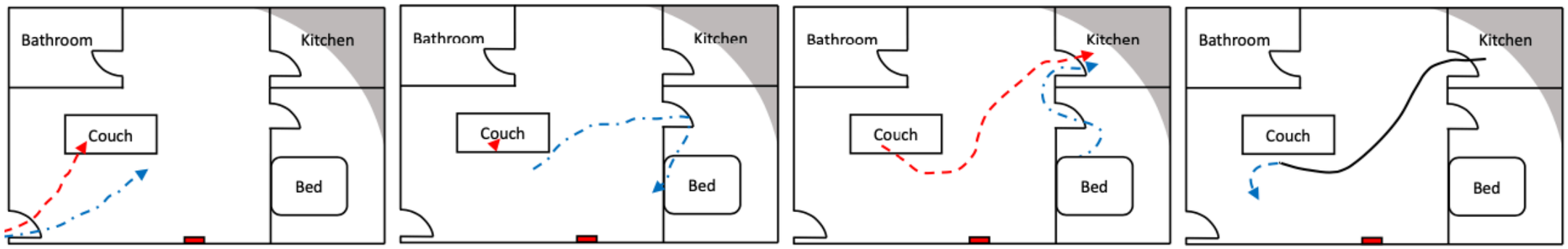
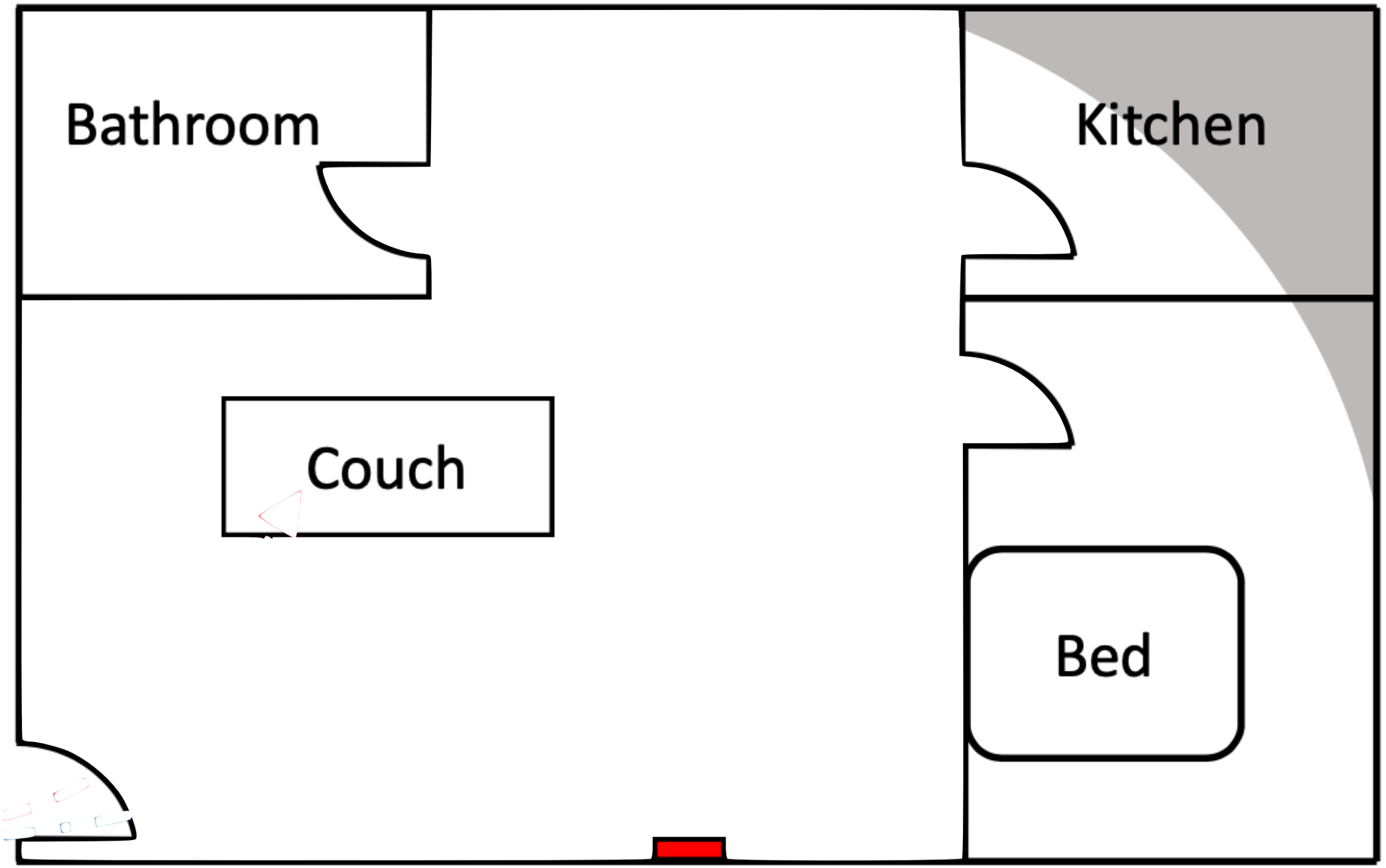
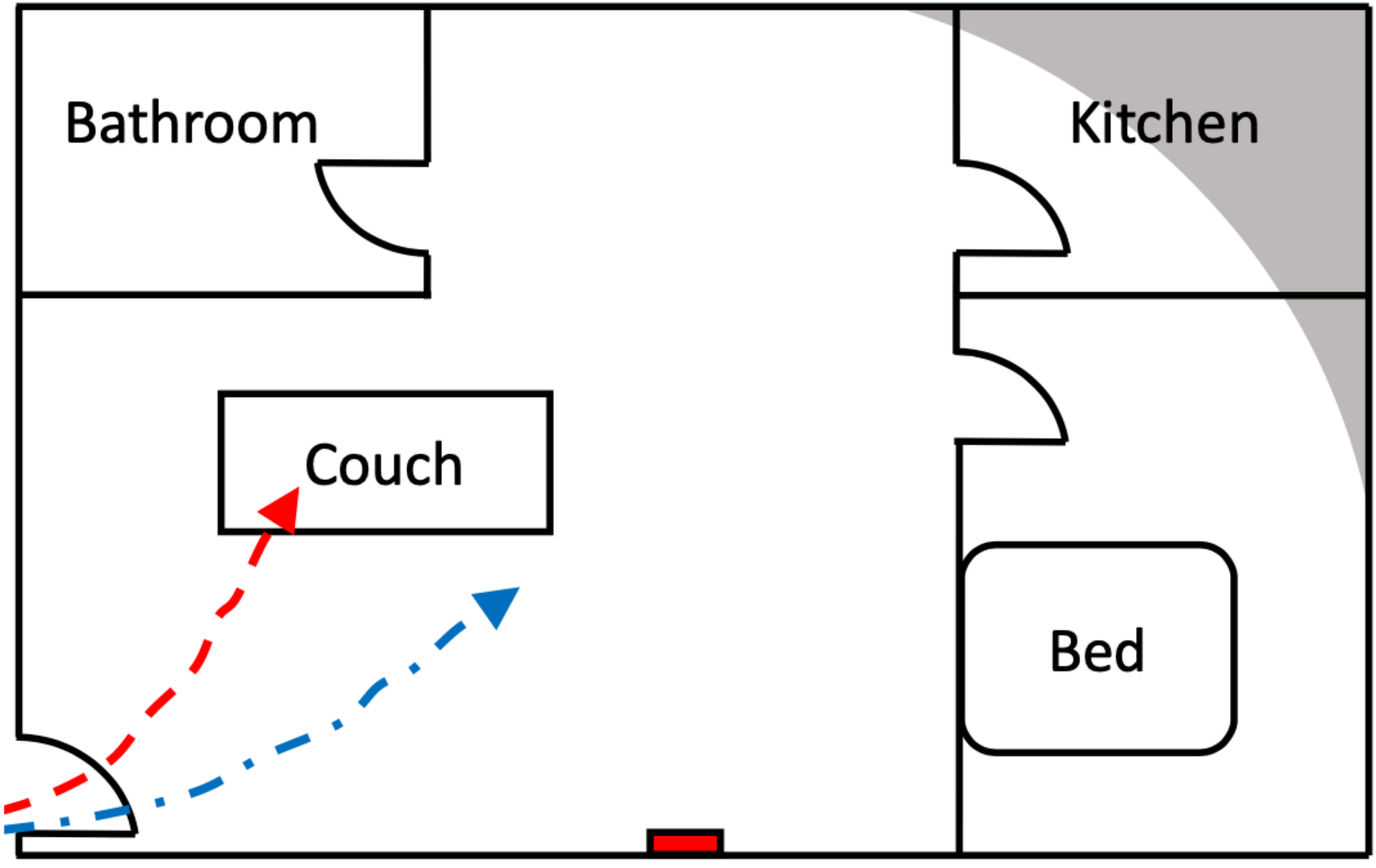


Fig. 1. **Example:** Alice (red) and Bob (blue) are tracked using Duet. The corresponding events and states are described in table 1.

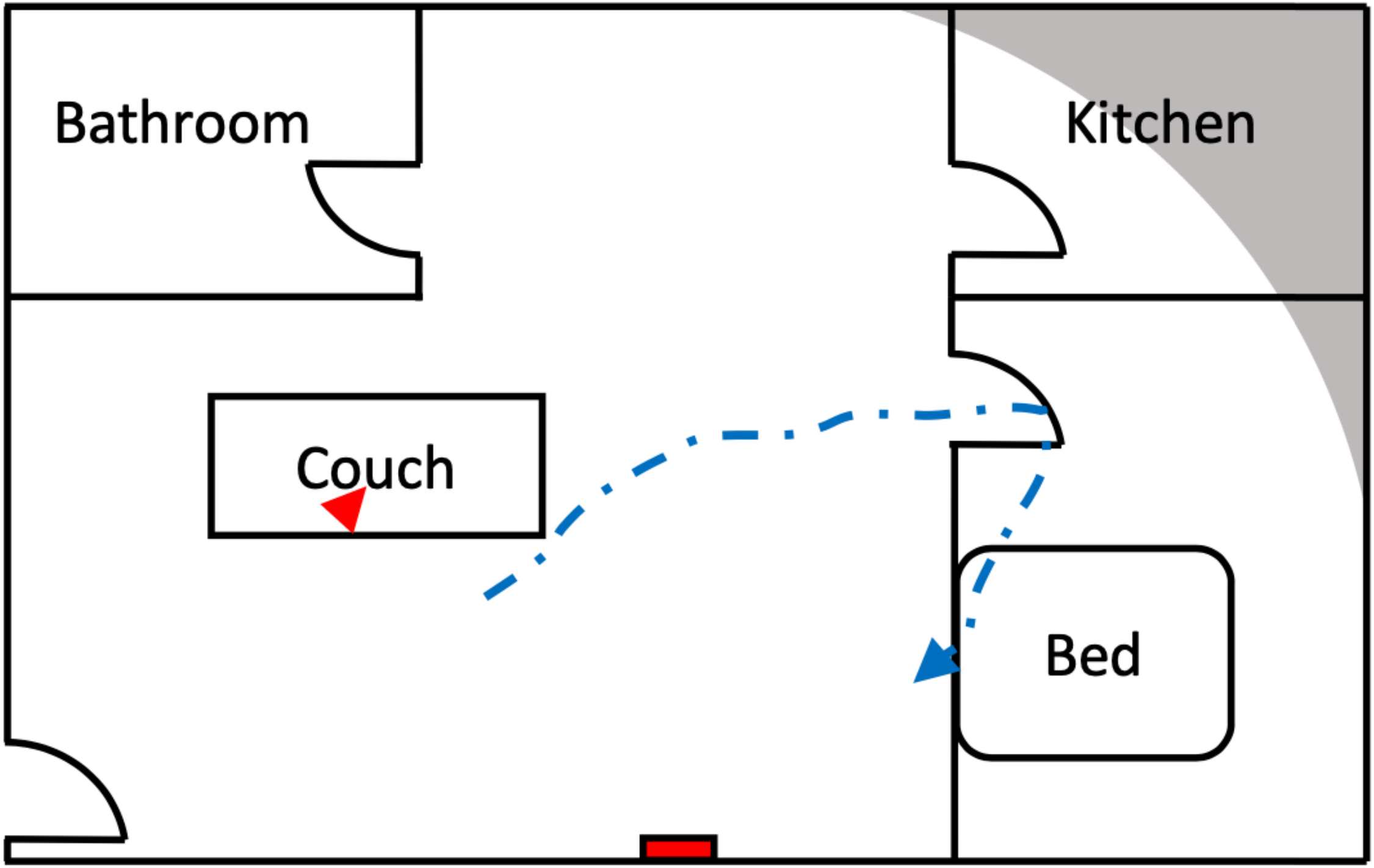
Table 1. **Example:** This table lists a sequence of home events (left column) and the corresponding Duet states (right column).

Event	Duet State
Alice (red) and Bob (blue) come in with their phones (Fig. 1(a)).	$v_1 = (\{Alice\}, LivingRoom), v_2 = (\{Bob\}, LivingRoom)$
Alice and Bob leave their phones behind; Alice goes to the couch to watch TV and Bob goes to the bed.	$v_1 = (\{Alice\}, Couch), v_2 = (\{Bob\}, Bed)$
Alice goes to the kitchen followed by Bob	$v_1 = (\{Alice\}, Kitchen), v_2 = (\{Bob\}, Kitchen)$
Bob comes out of the kitchen	$v_1 = (\{Alice, Bob\}, Kitchen), v_2 = (\{Alice, Bob\}, LivingRoom)$
Bob checks email on his phone	$v_1 = (\{Alice\}, Kitchen), v_2 = (\{Bob\}, LivingRoom)$

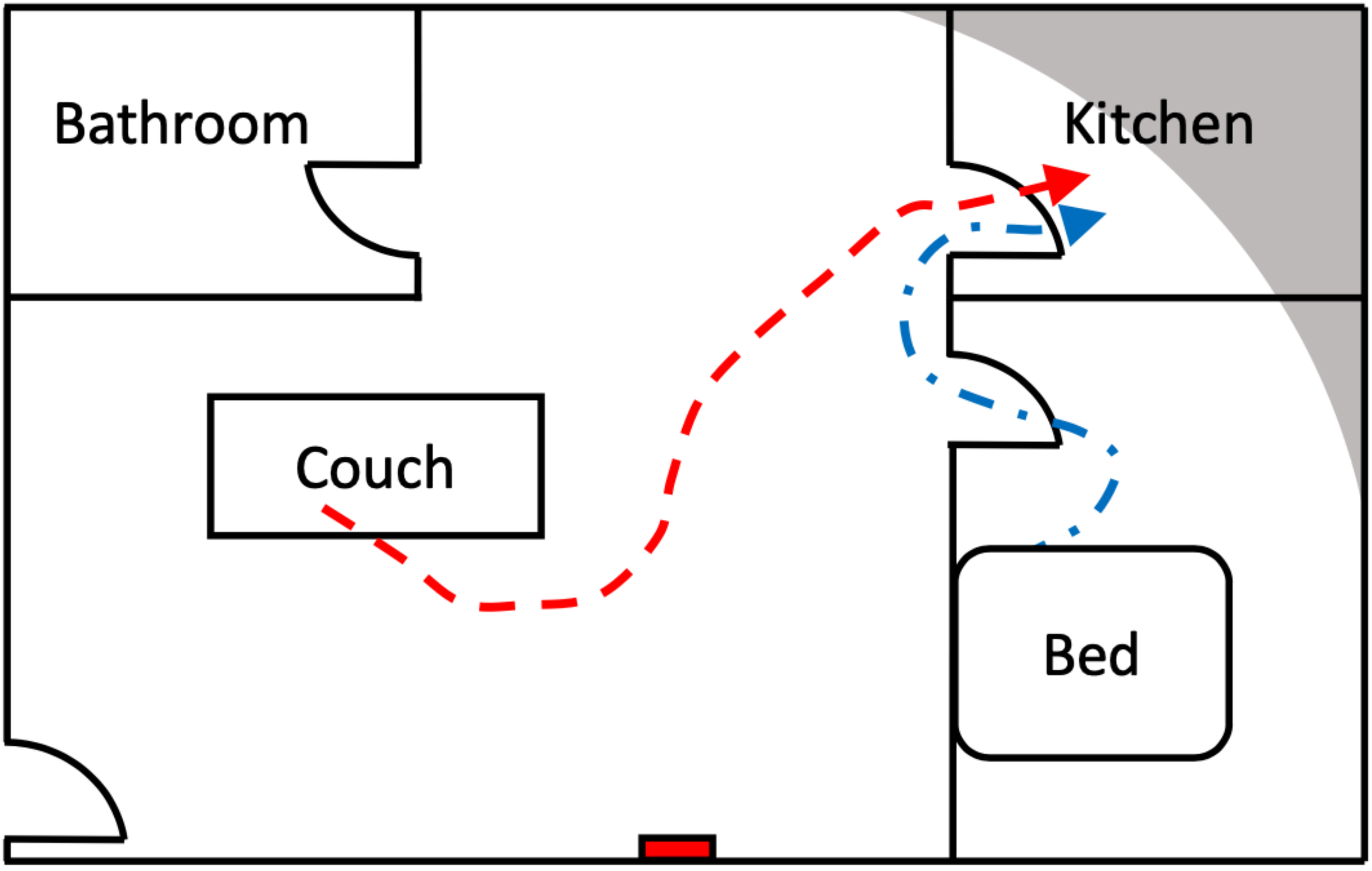




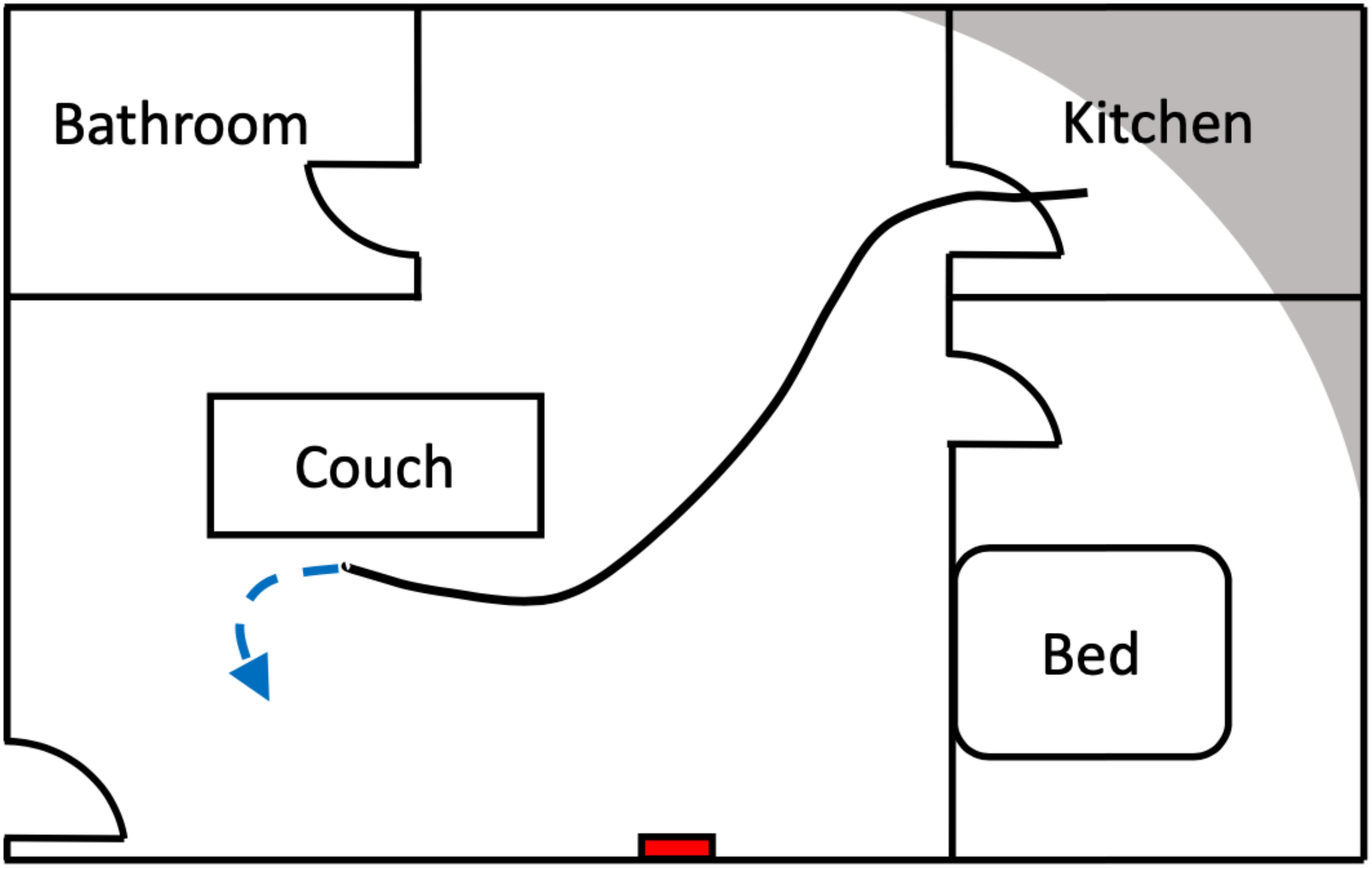
$$v1 = (\{Alice\}, LivingRoom), v2 = (\{Bob\}, LivingRoom)$$



$$v1 = (\{Alice\}, Couch), v2 = (\{Bob\}, Bed)$$



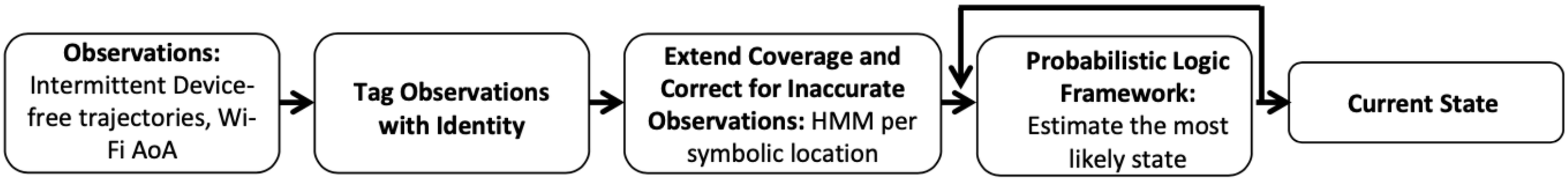
$$v1 = (\{Alice\}, Kitchen), v2 = (\{Bob\}, Kitchen)$$



$$v1 = (\{Alice, Bob\}, Kitchen), v2 = (\{Alice, Bob\}, LivingRoom)$$

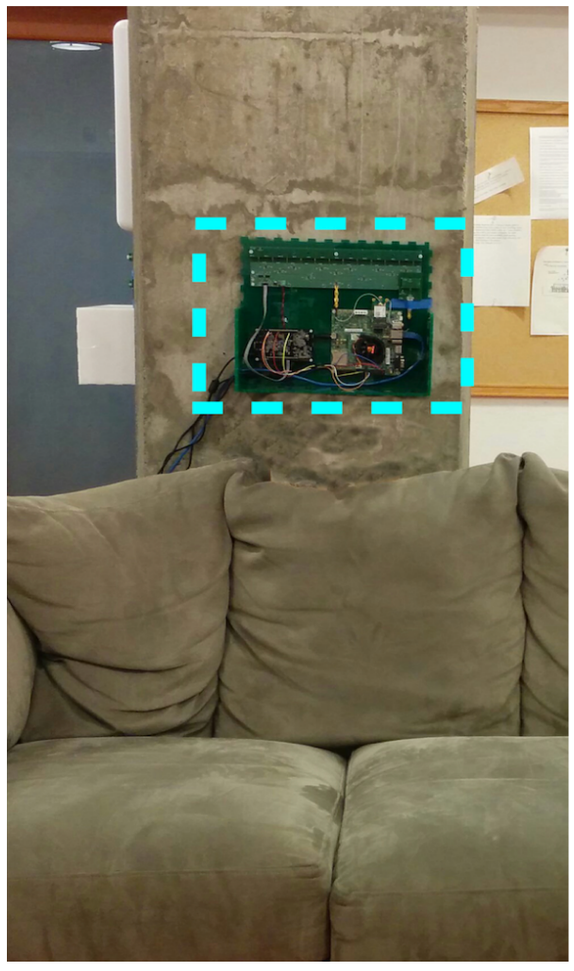
$$v1 = (\{Alice\}, Kitchen), v2 = (\{Bob\}, LivingRoom)$$

Method



Components of Duet

Component	Description
Location observation	Device-free *and* WiFi-based observations
Tagging observation	Trajectory matching
Extending coverage & correction	HMM
Reasoning and probabilistic framework	Probabilistic framework based on first-order logic theory



Method

Device-free observations

- FMCW (RF reflection)
- Sampling rate: 20ms
- Establish *tracklets*
- No identity
- Track only movements

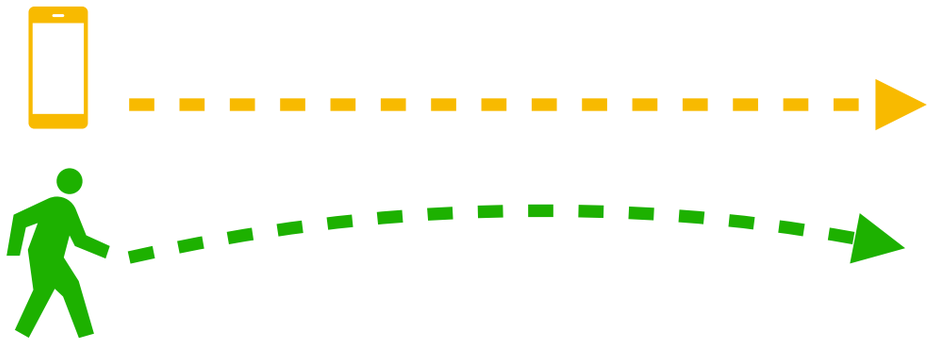
WiFi-based observations

- Single WiFi device
- Identification using MAC address
- Location estimation: angle of arrival (AoA)

trackets + spatial ***direction***

Method

Tagging observations with identity



- Tagging observations
- Trajectories matching
- More correlation = higher score
- Users with no phones are matched to virtual phones

Method

Extending coverage & correcting observations

- HMM Observations: entry event (O_{entry}), exit event (O_{exit}) number of tracklets ($O_{tracklets}$)
- HMM States: $S_k, S_{k \to k+1}, S_{k \to k-1}$
- Learning: Viterbi algorithm —> emission & transition prob.
- Result: environment-independent HMM

Method

Reasoning with probabilistic logic

Context model and updating

Constraints:

- The same person can only be in ONE PLACE.
- Cannot enter certain region TWICE.
- Cannot leave if {person} is not IN.

Algorithm 1 Hypothesis Update Algorithm

▷ Given: Hypothesis $\mathcal{H}_{in} = (C_{in}, b_{in})$; Event as 4-tuple of person, area, type and score, e
▷ Output: A set of hypothesis, $\mathcal{H}_{out}$
▷ Initialize H_{out} to an empty set.
if $type == entry$ **then**
  $v_{new}.P = p, v_{new}.I = [], v_{new}.R = r$
  for $v \in C_{in}$ **do**
    if $p \neq \mathcal{U}$ **then** $v.I = v.I \cup p$ **end if**
  end for
  $\mathcal{H}_{out} = \{(C_{in} \cup v_{new}, b_{in} \times score)\}$
else if $type == exit$ **then**
  for $v \in C_{in}$ **do**
    if $|(v.P - v.I) \cap \{p\}| > 0$ **and** $v.R == r$ **then**
      $C_{new} = C_{in} \backslash v$
      for $v' \in C_{new}$ **do**
        if $p \neq \mathcal{U}$ **then** $v'.I = v'.I \cup p$ **end if**
      end for
      $\mathcal{H}_{out} = \mathcal{H}_{out} \cup \{(C_{new}, b_{in} \times score)\}$
    end if
  end for
else
  for $v \in C_{in}$ **do**
    if $|(v.P - v.I) \cap \{p\}| > 0$ **and** $v.R == r$ **then**
      $C_{new} = C_{in} \backslash v$
      for $v' \in C_{new}$ **do** $v'.I = v'.I \cup p$ **end for**
      $v.P = \{p\}, v.I = \{\}$
      $\mathcal{H}_{out} = \mathcal{H}_{out} \cup \{(C_{new} \cup v, b_{in} \times score)\}$
    end if
  end for
end if

Method

Reasoning with probabilistic logic

Checking state validity:

- One identity for one variable
- No impossible states (invalid states)
- No invalid configurations

$$\exists x_1, \ldots, x_K \bigwedge_{i=1}^{K} [In(x_i, v_i.P \backslash v_i.I) \wedge Ar(x_i, v_i.R)] \bigwedge_{i=1}^{K} \bigwedge_{j=1}^{i-1} [x_i \neq x_j]$$

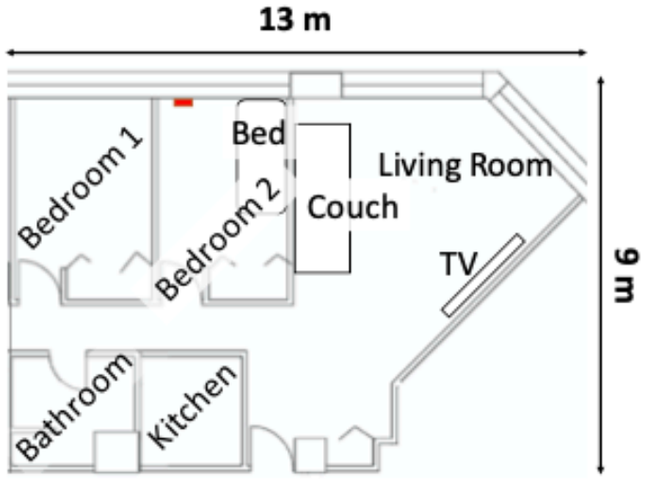
First-order logic

Implementation and evaluation

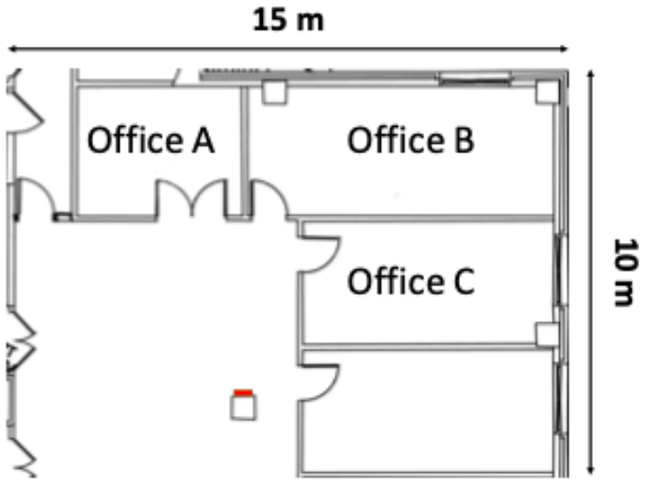
Implementation

Location observation	Off-the-shelf WiFi array and custom PCB
Programming	Python and MATLAB
HMM	9 days training data

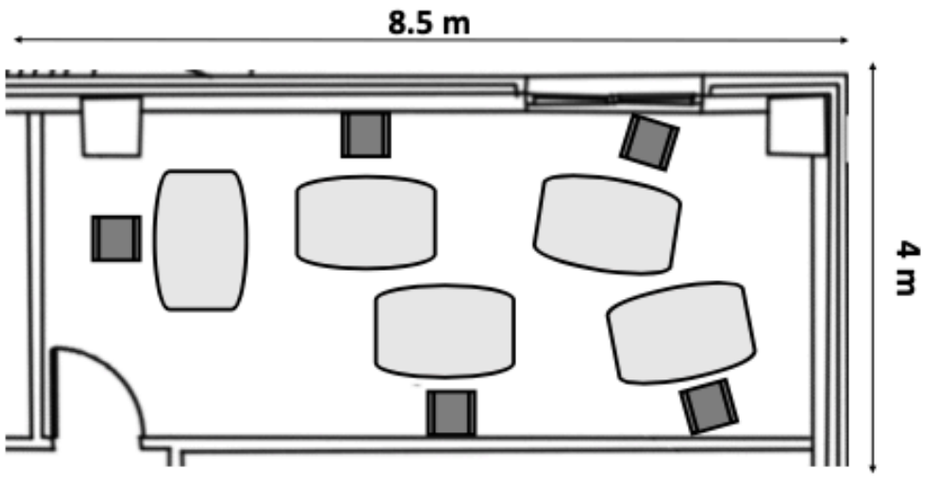
Evaluation



(a) Home



(b) Office



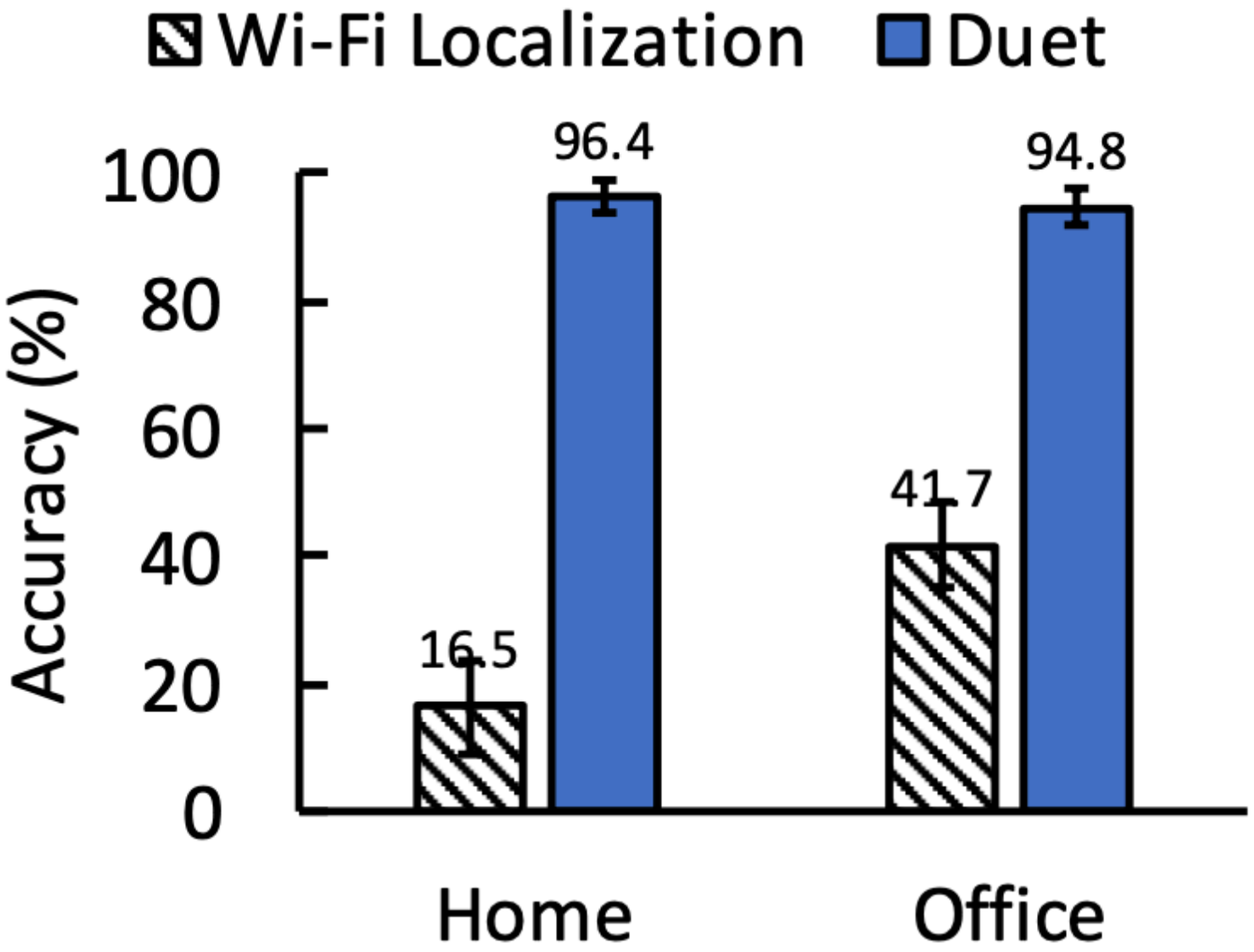
(c) Office B (Zoomed In)

2 people
2 visitors

9 occupants

2 weeks
Manually labelled ground truth

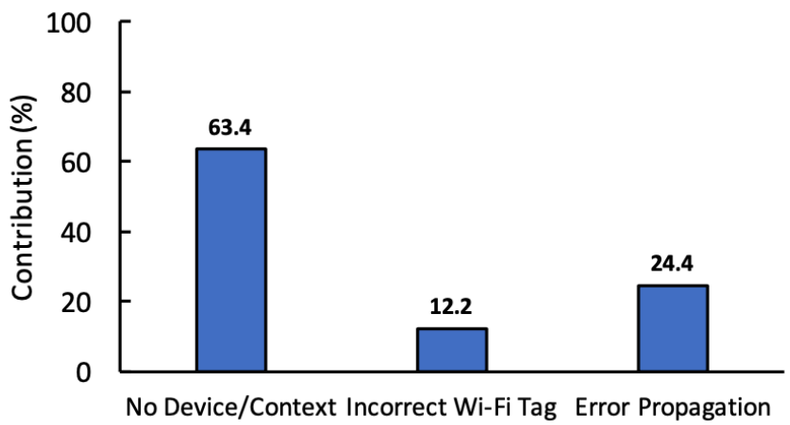
Results



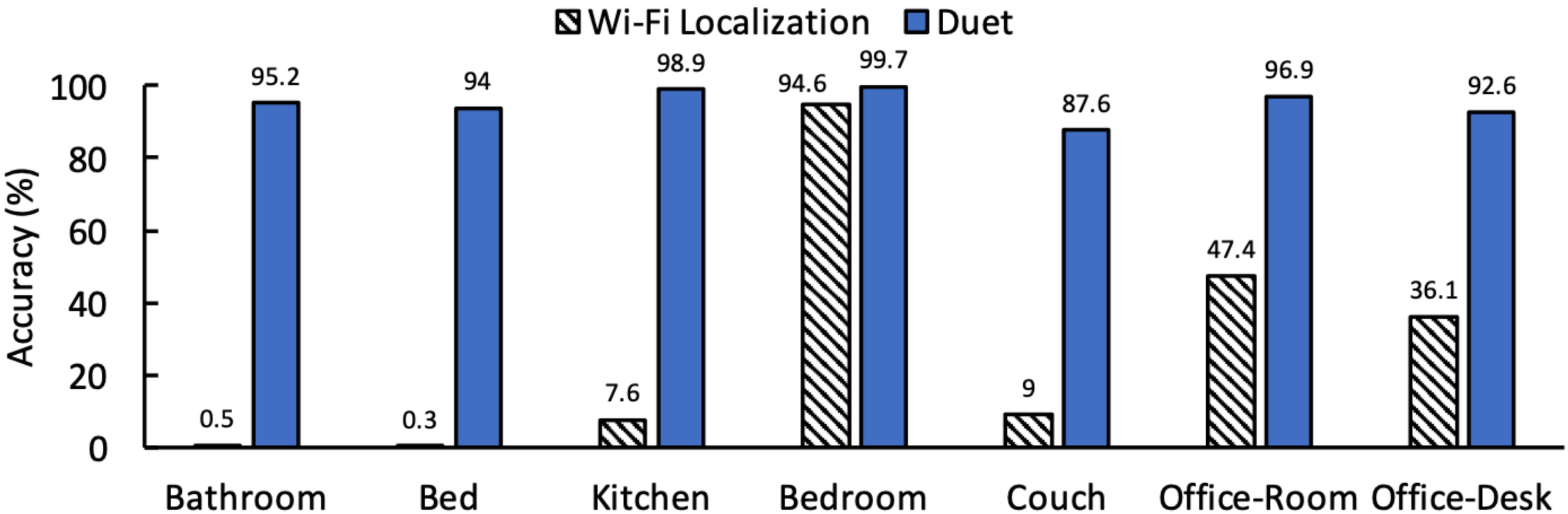
Overall accuracy

Errors:

- Insufficient context
- Incorrect Wi-Fi tagging
- Error propagation



Results



Accuracy results for different symbolic locations

Wi-Fi Localization Error:

- People do not carry their phones with them ALL THE TIME.
- Duet can correct the errors while both observation methods make errors.

Results

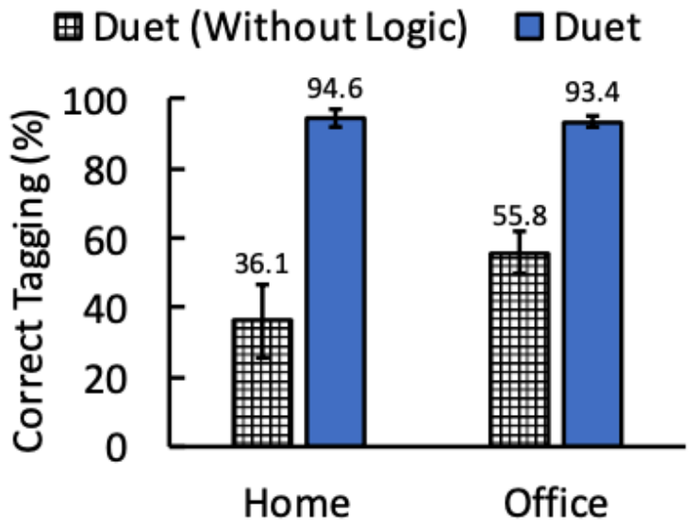


Fig. 8. **Tagging Accuracy:** Duet's reasoning framework improves the accuracy of identifying people corresponding to tracklets.

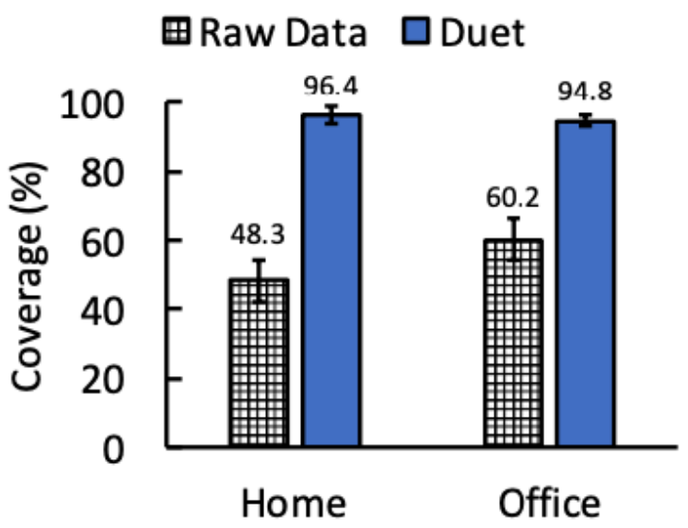


Fig. 9. **Coverage:** Duet expands the coverage of the underlying device-free system in both home and office deployments.

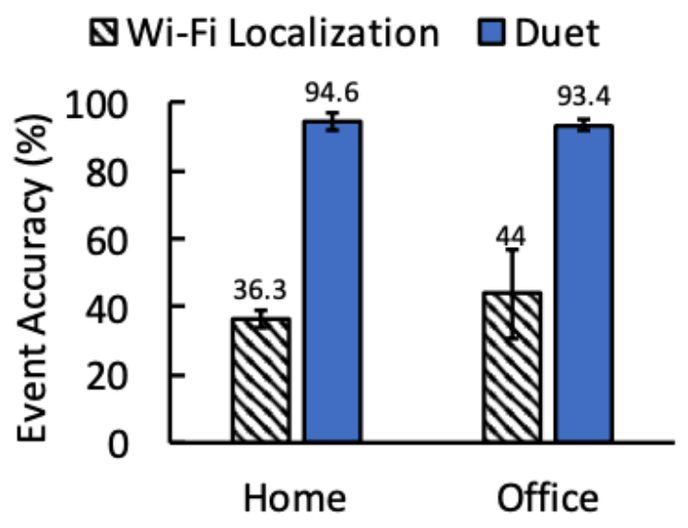


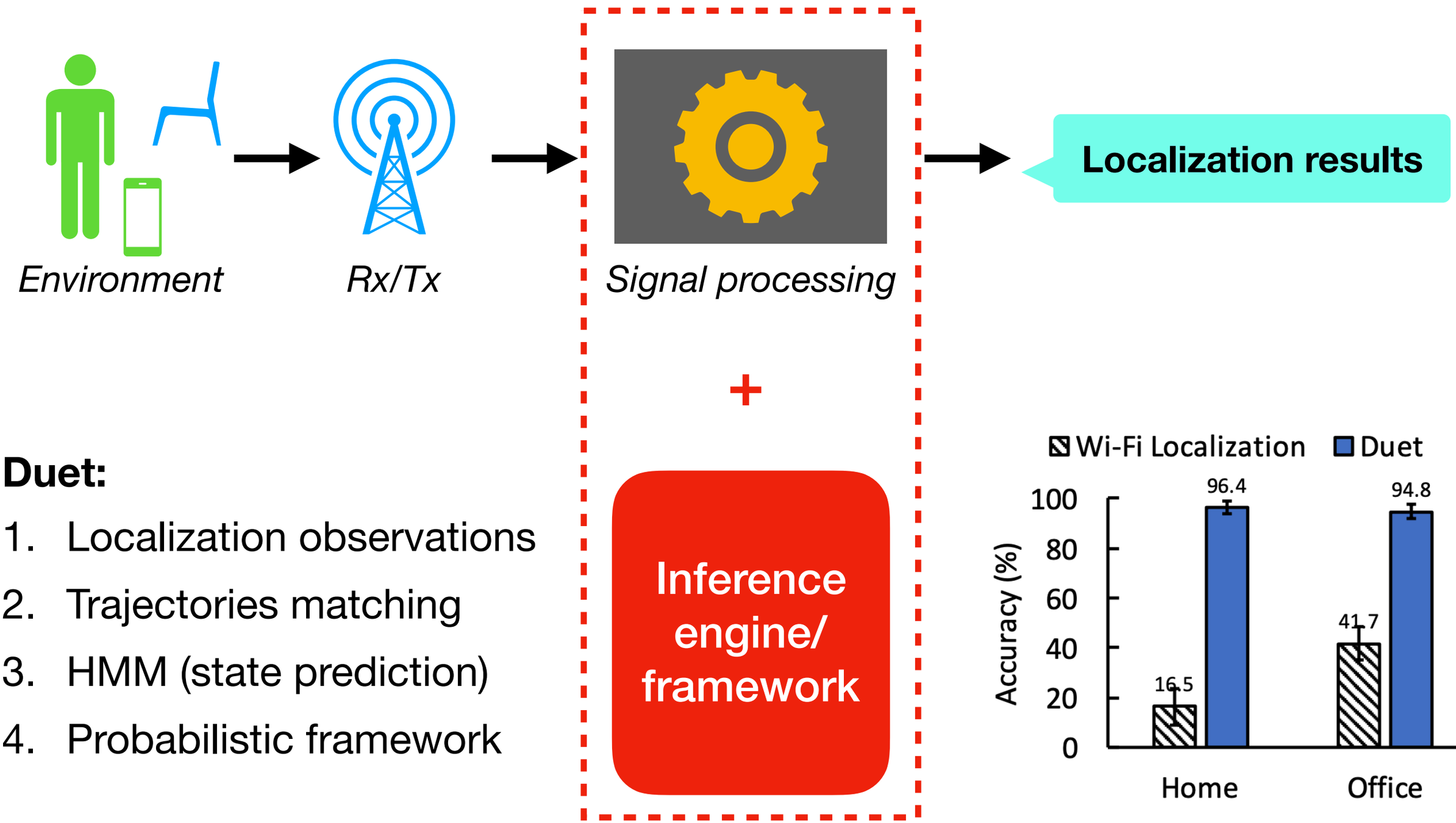
Fig. 10. **Event Accuracy:** The figure plots the accuracy of detecting entry and exit events.

Trajectory tracking & matching

Completely blocked Stay stationary

Entry-exit detection (5 seconds waiting time)

Conclusion



Duet:

1. Localization observations
2. Trajectories matching
3. HMM (state prediction)
4. Probabilistic framework