Manage the Data from Indoor Spaces: Models, Indexes & Query Processing

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Overview

Aims

- To give a brief review introduction to *indoor data management techniques*.
- To review a series of works in this field, including their proposed *models*, *indexes* and *algorithms*.
- To discuss how to bring those advanced theoretical contents into practice.

About This Work...

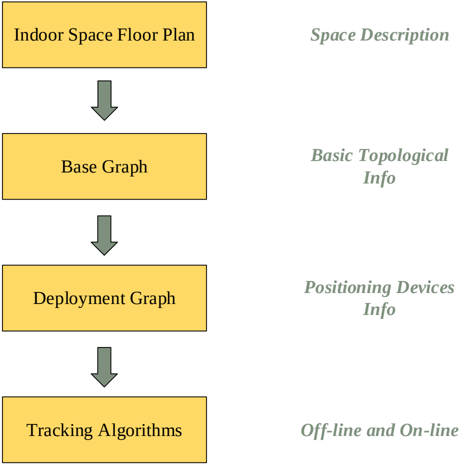
Graph Model Based Indoor Tracking. [2]
C. S. Jensen, H. Lu, and B. Yang.

- Published in year 2009, *MDM* conference.
- A pioneering work that introduces base graph model to indoor data management.
- Detailed tracking algorithms are designed for RFID-based positioning.
- Easy to understand, with comprehensive concepts.

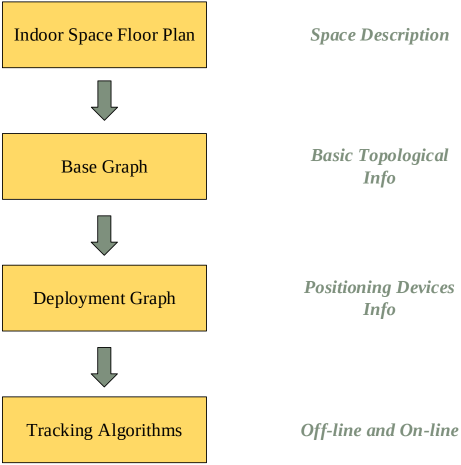
Motivation

- We are spending most of our time in indoor spaces
  - Office building, University, Shopping Centers, etc.
- We cannot use GPS-based tracking indoor movements
  - Indoor navigation and route guidance (museum)
  - Flow analysis
    - how do people use the indoor space → important in pricing of advertisement space in store rental
- We can use other technology...
  - Wi-Fi, Infrared, Bluetooth or RFID
  - This paper is focusing on RFID, since it is now mature and effortless
  - RFID tags are cheap and RFID reader are expensive

Idea


Indoor Space Floor Plan
Space Description
Base Graph
Basic Topological Info
Deployment Graph
Positioning Devices Info
Tracking Algorithms
Off-line and On-line

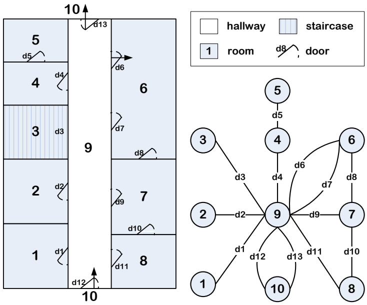
Idea



Goal: Improve indoor tracking accuracy from a data management perspective, to capture where a particular object can be at a particular time.

Base Graph Model

By capturing the essential connectivity and accessibility, **Base Graph** describes the topology of a floor plan of a possibly complex indoor space.



(a) Floor Plan (b) Connectivity Base Graph

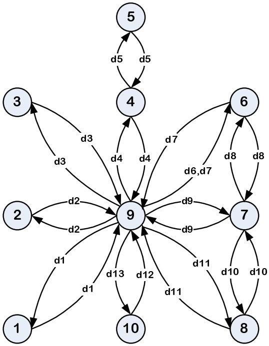
Connectivity Base Graph

a labeled, undirected graph.

- $G_{conn} = \{V, E_d, \Sigma_{door}\}$
- V: each separate partition is represented as a vertex
- E_d: each door is captured as an edge
- Σ_{door}: a set of edge labels that represent connections

Base Graph Model

Accessibility Graph is constructed to represent the movement permitted by doors or connections.



Accessibility Graph

a labeled, directed graph.

- $G_{accs} = \{V, E, \Sigma_{door}, l_e\}$
- V: the set of vertices
- E: the set of directed edges, i.e., $E = \{\langle v_i, v_j \rangle | v_i, v_j \in V \wedge v_i \neq v_j\}$
- l_e: a function that maps edges to subsets of the set of doors, i.e., $l_e : E \rightarrow 2^{\Sigma_{door}}$

Base Graph Model

In addition to the topological information of a floor plan, its geometrical information should also be captured.

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The *Doors Mapping* is defined as:

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The *Building Partitions Mapping* is defined as:

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The *Doors Mapping* is defined as:

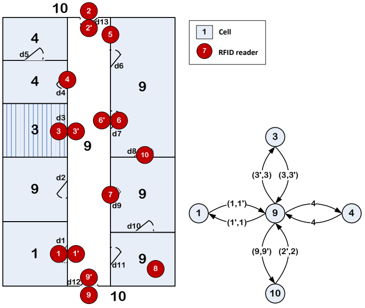
$$Doors : \Sigma_{door} \rightarrow Line\ Segments \tag{2}$$

RFID Deployment Graph Model

- RFID based proximity analysis
  - RFID readers deployment may cover only part of the space, or it may be capable of only detecting some movements in the space.
  - assume that all RFID readers have disjoint activation ranges.
- Types of RFID readers
  - **Partitioning Readers** partition the indoor space into cells in the sense that an object cannot move from one cell to another without being observed.
  - **Presence Readers** simply observe the presence(and non-presence) of tags in their activation ranges.

RFID Deployment Graph Model

Vertices represent cells. A directed edge indicates that one can move from one cell to another without entering other cells, which is detected by a corresponding partitioning reader.



(a) Readers Deployment (b) Readers Deployment Graph

RFID Deployment Graph

a labeled, directed graph.

- $G_{RFID} = \{C, E_r, \Sigma_{reader}, l_e\}$
- C: the set of the vertices
- E_r: An edge is an ordered pair $\langle c_i, c_j \rangle$ of distinct vertices from C
- l_e maps an edge to a partitioning reader (pair), i.e., $E_r \rightarrow 2^{\Sigma_{reader}} \cup 2^{\Sigma_{reader} \times \Sigma_{reader}}$

RFID Deployment Graph Construction

Each cell created by partitioning readers corresponds to one or more base graph partitions.

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$$\begin{aligned} Mapping\ 1 : \Sigma_{reader} \rightarrow \{(loc, range, flag) \mid loc \in R^2 \wedge \\ range \in (0, d_{max}] \wedge flag \in \{PAR, PRE\}\} \end{aligned} \tag{4}$$

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A mapping of readers to the cells that their activation ranges intersect is introduced as:

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A mapping of readers to the cells that their activation ranges intersect is introduced as:

$$Mapping\ 2 : \Sigma_{reader} \rightarrow 2^C \tag{5}$$

RFID Deployment Graph Construction

Algorithm 1 RFIDGraphConstruction (Readers R, ConnectivityBaseGraph G_{conn}, AccessibilityGraph G_{accs})

Readers $R' \leftarrow \emptyset$; $DR(\langle \Sigma_{door}\ k', Readers\ RSet \rangle) \leftarrow \emptyset$; Connected Component $CCs \leftarrow \emptyset$; int $m \leftarrow 0$;
$G_{RFID}(C, E_r, \Sigma_{reader}\ l_e) \leftarrow (\emptyset, \emptyset, R, NULL)$;
for each edge d_a in $G_{conn}.E_d$ **do**
    for each reader r_b in R **do**
        if Circle(Mapping1(r_b).loc, Mapping1(r_b).range) covers $Doors(d_a.k)$ **then**
            insert r_b into R';
    if $|R'| > 0$ **then**
        delete d_a from $G_{conn}.E_d$; insert $(d_a.k, R')$ into DR; $R' \leftarrow \emptyset$;
store all connected components of G_{conn} in CCs;
for each connected component cc_c in CCs **do**
    create a new vertex c_m and add it to $G_{RFID}.C$; m++;
    for each vertex v_x in the vertices of cc_c **do**
        add the mapping $(v_x \rightarrow c_m)$ to $Cells$;
for each dr_n in DR **do**
    for each e_l in $G_{accs}.l_e^{-1}(dr_n.k')$ **do**
        $c_p \leftarrow Cells(e_l.v_i)$; $c_q \leftarrow Cells(e_l.v_j)$;
        if $c_p \neq c_q$ **then**
            if $\langle c_p, c_q \rangle$ is not in $G_{RFID}.E_r$ **then**
                add $\langle c_p, c_q \rangle$ to $G_{RFID}.E_r$;
            add the mapping $(\langle c_p, c_q \rangle \rightarrow readersequence(dr_n.RSet))$ to $G_{RFID}.l_e$;

1. **Input:** the reader set R, the connectivity base graph G_{conn}, the accessibility graph G_{accs}

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8:         delete d_a from $G_{conn}.E_d$; insert $(d_a.k, R')$ into DR; $R' \leftarrow \emptyset$;
9: store all connected components of G_{conn} in CCs;
10: **for** each connected component cc_c in CCs **do**
11:     create a new vertex c_m and add it to $G_{RFID}.C$; m++;
12:     **for** each vertex v_x in the vertices of cc_c **do**
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14: **for** each dr_n in DR **do**
15:     **for** each e_l in $G_{accs}.l_e^{-1}(dr_n.k')$ **do**
16:         $c_p \leftarrow Cells(e_l.v_i)$; $c_q \leftarrow Cells(e_l.v_j)$;
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1. **Input**: the reader set R, the connectivity base graph G_{conn}, the accessibility graph G_{accs}
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3. Lines 3–8: the relationship of which door is covered by which readers is captured in DR

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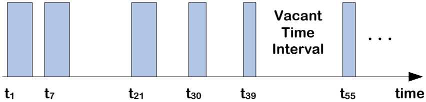
3. Lines 3–8: the relationship of which door is covered by which readers is captured in DR
4. Lines 9–13: a deployment graph vertex is created for each CC, mapping $Cells$ is also stored
5. Lines 14–20: for each door in DR, determine if its edges' head and tail are mapped to different cells. If so, add an edge to deployment graph. Function $readersequence$ returns the possible reader sequence for that edge

RFID-based Indoor Tracking

Raw Trajectories: Sequences of RFID Tag Observation

Table 1. Raw Trajectory of tag_1

readerID	tagID	t	readerID	tagID	t
$reader_9$	tag_1	t_1	$reader_{10}$	tag_1	t_{40}
$reader_9$	tag_1	t_2	$reader_8$	tag_1	t_{55}
$reader_{9'}$	tag_1	t_3	$reader_8$	tag_1	t_{56}
$reader_{9'}$	tag_1	t_4	$reader_{3'}$	tag_1	t_{79}
$reader_{1'}$	tag_1	t_7	$reader_{3'}$	tag_1	t_{80}
$reader_{1'}$	tag_1	t_8	$reader_4$	tag_1	t_{85}
$reader_1$	tag_1	t_9	$reader_4$	tag_1	t_{86}
$reader_1$	tag_1	t_{10}	$reader_4$	tag_1	t_{87}
$reader_1$	tag_1	t_{21}	$reader_4$	tag_1	t_{100}
$reader_1$	tag_1	t_{22}	$reader_4$	tag_1	t_{101}
$reader_{1'}$	tag_1	t_{23}	$reader_4$	tag_1	t_{102}
$reader_{1'}$	tag_1	t_{24}	$reader_{6'}$	tag_1	t_{109}
$reader_7$	tag_1	t_{30}	$reader_{6'}$	tag_1	t_{110}
$reader_7$	tag_1	t_{31}	$reader_6$	tag_1	t_{111}
$reader_7$	tag_1	t_{32}	$reader_6$	tag_1	t_{112}
$reader_{10}$	tag_1	t_{39}	$reader_5$	tag_1	t_{125}



- *vacant time intervals*: unable to observe the moving objects

1. each reader detects and reports tags with a sampling rate
2. formatted as $\langle readerID, tagID, t\rangle$

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$reader_{1'}$	tag_1	t_7	$reader_{3'}$	tag_1	t_{80}
$reader_{1'}$	tag_1	t_8	$reader_4$	tag_1	t_{85}
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$reader_1$	tag_1	t_{10}	$reader_4$	tag_1	t_{87}
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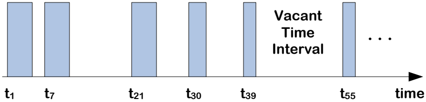

- *vacant time intervals*: unable to observe the moving objects
- to search RFID deployment graph to infer the possible regions of moving object

1. each reader detects and reports tags with a sampling rate
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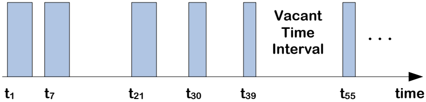

- *vacant time intervals*: unable to observe the moving objects
- to search RFID deployment graph to infer the possible regions of moving object
- to apply maximum speed position interpolation to further shrink the possible regions

1. each reader detects and reports tags with a sampling rate
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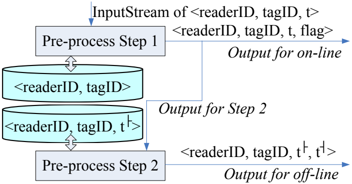
RFID Readings Pre-processing

Step-1's output is used in on-line tracking, while Step-2's is used in off-line tracking



- $Flag \in \{START, END\}$
- $START \rightarrow$ enters the range
- $END \rightarrow$ leaves the range

Off-line Tracking (Refinement Step 1)

Table 2. Off-Line Trajecotry of tag_1

readingID	readerID	tagID	$t^{\vdash}$	$t^{\dashv}$
$reading_1$	$reader_9$	tag_1	t_1	t_2
$reading_2$	$reader_{9'}$	tag_1	t_3	t_4
$reading_3$	$reader_{1'}$	tag_1	t_7	t_8
$reading_4$	$reader_1$	tag_1	t_9	t_{10}
$reading_5$	$reader_1$	tag_1	t_{21}	t_{22}
$reading_6$	$reader_{1'}$	tag_1	t_{23}	t_{24}
$reading_7$	$reader_7$	tag_1	t_{30}	t_{32}
$reading_8$	$reader_{10}$	tag_1	t_{39}	t_{40}
$reading_9$	$reader_8$	tag_1	t_{55}	t_{56}
$reading_{10}$	$reader_{3'}$	tag_1	t_{79}	t_{80}
$reading_{11}$	$reader_4$	tag_1	t_{85}	t_{87}
$reading_{12}$	$reader_4$	tag_1	t_{100}	t_{102}
$reading_{13}$	$reader_{6'}$	tag_1	t_{109}	t_{110}
$reading_{14}$	$reader_6$	tag_1	t_{111}	t_{112}
$reading_{15}$	$reader_5$	tag_1	t_{125}	t_{125}

Table 3. Trajectory After Step 1

tagID	$[t^{\vdash}, t^{\dashv}]$	Graph Element	Reader_1	Reader_2
tag_1	$[t_1, t_4]$	$e\langle 10, 9\rangle$	$reader_9$	$reader_{9'}$
tag_1	$[t_7, t_{10}]$	$e\langle 9, 1\rangle$	$reader_{1'}$	$reader_1$
tag_1	$[t_{21}, t_{24}]$	$e\langle 1, 9\rangle$	$reader_1$	$reader_{1'}$
tag_1	$[t_{30}, t_{32}]$	c_9	$reader_7$	$reader_7$
tag_1	$[t_{39}, t_{40}]$	c_9	$reader_{10}$	$reader_{10}$
tag_1	$[t_{55}, t_{56}]$	c_9	$reader_8$	$reader_8$
tag_1	$[t_{79}, t_{80}]$	c_9	$reader_{3'}$	$reader_{3'}$
tag_1	$[t_{85}, t_{87}]$	$e\langle 4, 9\rangle, e\langle 9, 4\rangle$	$reader_4$	$reader_4$
tag_1	$[t_{100}, t_{102}]$	$e\langle 4, 9\rangle, e\langle 9, 4\rangle$	$reader_4$	$reader_4$
tag_1	$[t_{109}, t_{112}]$	c_9	$reader_{6'}$	$reader_6$
tag_1	$[t_{125}, t_{125}]$	c_9	$reader_5$	$reader_5$

- Step 1 transforms an RFID reading sequence to corresponding vertices or edges in deployment graph
- If two consecutive reading sequences are *contiguous*, they should stem from a partitioning pair, which map to an edge
- Otherwise, should come from either a single PRE or a PAR reader
- A PAR is replaced by the set of corresponding edges according to $G_{RFID}.l_e{}^{-1}$
- A PRE always corresponds to one or several cells according to $Mapping\ 2$

Off-line Tracking (Refinement Step 2)

Table 3. Trajectory After Step 1

tagID	$[t^{\vdash}, t^{\dashv}]$	Graph Element	Reader$_1$	Reader$_2$
tag_1	$[t_1, t_4]$	$e\langle 10, 9\rangle$	$reader_9$	$reader_{9'}$
tag_1	$[t_7, t_{10}]$	$e\langle 9, 1\rangle$	$reader_{1'}$	$reader_1$
tag_1	$[t_{21}, t_{24}]$	$e\langle 1, 9\rangle$	$reader_1$	$reader_{1'}$
tag_1	$[t_{30}, t_{32}]$	c_9	$reader_7$	$reader_7$
tag_1	$[t_{39}, t_{40}]$	c_9	$reader_{10}$	$reader_{10}$
tag_1	$[t_{55}, t_{56}]$	c_9	$reader_8$	$reader_8$
tag_1	$[t_{79}, t_{80}]$	c_9	$reader_{3'}$	$reader_{3'}$
tag_1	$[t_{85}, t_{87}]$	$e\langle 4, 9\rangle, e\langle 9, 4\rangle$	$reader_4$	$reader_4$
tag_1	$[t_{100}, t_{102}]$	$e\langle 4, 9\rangle, e\langle 9, 4\rangle$	$reader_4$	$reader_4$
tag_1	$[t_{109}, t_{112}]$	c_9	$reader_{6'}$	$reader_6$
tag_1	$[t_{125}, t_{125}]$	c_9	$reader_5$	$reader_5$

Table 4. Trajectory After Steps 2 and 3

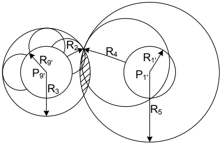
tagID	$[t^{\vdash}, t^{\dashv}]$	Step 2	Step 3
tag_1	$[t_5, t_6]$	c_9	$c_9 \cap \Theta(reader_{9'}, reader_{1'}, t_5, t_6)$
tag_1	$[t_{11}, t_{20}]$	c_1	$c_1 \cap \Theta(reader_1, reader_1, t_{11}, t_{20})$
tag_1	$[t_{25}, t_{29}]$	c_9	$c_9 \cap \Theta(reader_{1'}, reader_7, t_{25}, t_{29})$
tag_1	$[t_{33}, t_{38}]$	c_9	$c_9 \cap \Theta(reader_7, reader_{10}, t_{33}, t_{38})$
tag_1	$[t_{41}, t_{54}]$	c_9	$c_9 \cap \Theta(reader_{10}, reader_8, t_{41}, t_{54})$
tag_1	$[t_{57}, t_{78}]$	c_9	$c_9 \cap \Theta(reader_8, reader_{3'}, t_{57}, t_{78})$
tag_1	$[t_{81}, t_{84}]$	c_9	$c_9 \cap \Theta(reader_{3'}, reader_4, t_{81}, t_{84})$
tag_1	$[t_{88}, t_{99}]$	c_4, c_9	$(c_4, c_9) \cap \Theta(reader_4, reader_4, t_{88}, t_{89})$
tag_1	$[t_{103}, t_{108}]$	c_9	$c_9 \cap \Theta(reader_4, reader_{6'}, t_{103}, t_{108})$
tag_1	$[t_{113}, t_{114}]$	c_9	$c_9 \cap \Theta(reader_6, reader_5, t_{113}, t_{114})$

- The *graph elements* from Step 1 indicates some region(s) within which the object may be in during the vacant time interval
- Check its previous record's tail element and current record's head element, select their intersection as Step 2's candidate

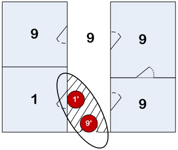
Off-line Tracking (Refinement Step 3)

- Calculate the *possible region* Θ according to maximum speed limit
- Circle based possible region
  - locations: $P_{9'}, P_{1'}$
  - activation ranges: $R_{9'}, R_{1'}$
  - for $t_x \in [t_5, t_6]$,
    $\Delta t_1 = t_x - reading_2.t^{\vdash}$,
    $\Delta t_2 = reading_3.t^{\dashv} - t_x$
  - $R_3 = R_{9'} + V_{max} * \Delta t_1$,
    $R_5 = R_{1'} + V_{max} * \Delta t_2$
- Ellipse based possible region
  - foci: two points belonging to the circle centered at $P_{9'}, P_{1'}$
  - length of major axis is:

$$2a = V_{max} * (\Delta t_1 + \Delta t_2)$$



(a) Circle based possible region



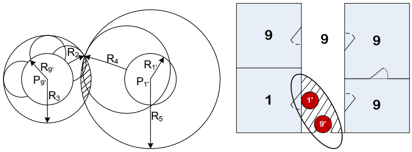
(b) Ellipse based possible region

$$\left.\begin{array}{l}(reading_1, reader_9, tag_1, t_1, t_2)\\(reading_2, reader_{9'}, tag_1, t_3, t_4)\\(reading_3, reader_{1'}, tag_1, t_7, t_8)\\(reading_4, reader_1, tag_1, t_9, t_10)\end{array}\right\} \underrightarrow{Step}\ 1$$

Off-line Tracking (Refinement Step 3)

- Calculate the *possible region* Θ according to maximum speed limit
- Circle based possible region
  - locations: $P_{9'}, P_{1'}$
  - activation ranges: $R_{9'}, R_{1'}$
  - for $t_x \in [t_5, t_6]$,
    $\Delta t_1 = t_x - reading_2.t^{\vdash}$,
    $\Delta t_2 = reading_3.t^{\dashv} - t_x$
  - $R_3 = R_{9'} + V_{max} * \Delta t_1$,
    $R_5 = R_{1'} + V_{max} * \Delta t_2$
- Ellipse based possible region
  - foci: two points belonging to the circle centered at $P_{9'}, P_{1'}$
  - length of major axis is:

$$2a = V_{max} * (\Delta t_1 + \Delta t_2)$$



(a) Circle based possible region (b) Ellipse based possible region

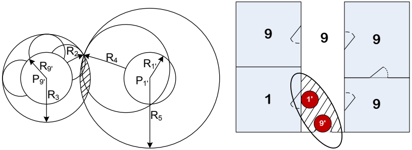
$$\left.\begin{array}{l}(reading_1, reader_9, tag_1, t_1, t_2)\\(reading_2, reader_{9'}, tag_1, t_3, t_4)\\(reading_3, reader_{1'}, tag_1, t_7, t_8)\\(reading_4, reader_1, tag_1, t_9, t_{10})\end{array}\right\} \xrightarrow{Step\ 1}$$

$$\left.\begin{array}{l}(tag_1, [t_1, t_4], e\langle 10, 9\rangle, reader_9, reader_{9'})\\(tag_1, [t_7, t_{10}], e\langle 9, 1\rangle, reader_{1'}, reader_1)\end{array}\right\} \xrightarrow{Step\ 2}$$

Off-line Tracking (Refinement Step 3)

- Calculate the *possible region* Θ according to maximum speed limit
- Circle based possible region
  - locations: $P_{9'}, P_{1'}$
  - activation ranges: $R_{9'}, R_{1'}$
  - for $t_x \in [t_5, t_6]$,
    $\Delta t_1 = t_x - reading_2.t^{\vdash}$,
    $\Delta t_2 = reading_3.t^{\dashv} - t_x$
  - $R_3 = R_{9'} + V_{max} * \Delta t_1$,
    $R_5 = R_{1'} + V_{max} * \Delta t_2$
- Ellipse based possible region
  - foci: two points belonging to the circle centered at $P_{9'}, P_{1'}$
  - length of major axis is:

$$2a = V_{max} * (\Delta t_1 + \Delta t_2)$$



(a) Circle based possible region (b) Ellipse based possible region

$$\left.\begin{array}{l}(reading_1, reader_9, tag_1, t_1, t_2)\\(reading_2, reader_{9'}, tag_1, t_3, t_4)\\(reading_3, reader_{1'}, tag_1, t_7, t_8)\\(reading_4, reader_1, tag_1, t_9, t_{10})\end{array}\right\} \xrightarrow{Step\ 1}$$

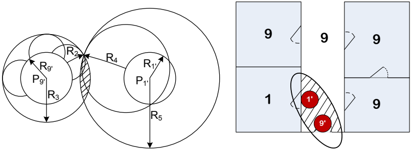
$$\left.\begin{array}{l}(tag_1, [t_1, t_4], e\langle 10, 9\rangle, reader_9, reader_{9'})\\(tag_1, [t_7, t_{10}], e\langle 9, 1\rangle, reader_{1'}, reader_1)\end{array}\right\} \xrightarrow{Step\ 2}$$

$$(tag_1, [t_5, t_6], c_9, reader_{9'}, reader_{1'}) \xrightarrow{Step\ 3}$$

Off-line Tracking (Refinement Step 3)

- Calculate the *possible region* Θ according to maximum speed limit
- Circle based possible region
  - locations: $P_{9'}, P_{1'}$
  - activation ranges: $R_{9'}, R_{1'}$
  - for $t_x \in [t_5, t_6]$,
    $\Delta t_1 = t_x - reading_2.t^{\vdash}$,
    $\Delta t_2 = reading_3.t^{\dashv} - t_x$
  - $R_3 = R_{9'} + V_{max} * \Delta t_1$,
    $R_5 = R_{1'} + V_{max} * \Delta t_2$
- Ellipse based possible region
  - foci: two points belonging to the circle centered at $P_{9'}, P_{1'}$
  - length of major axis is:

$$2a = V_{max} * (\Delta t_1 + \Delta t_2)$$



(a) Circle based possible region (b) Ellipse based possible region

$$\left.\begin{array}{l} (reading_1, reader_9, tag_1, t_1, t_2) \\ (reading_2, reader_{9'}, tag_1, t_3, t_4) \\ (reading_3, reader_{1'}, tag_1, t_7, t_8) \\ (reading_4, reader_1, tag_1, t_9, t_{10}) \end{array}\right\} \xrightarrow{Step\ 1}$$

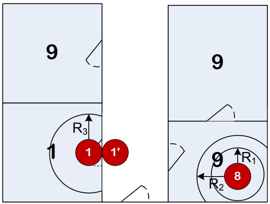
$$\left.\begin{array}{l} (tag_1, [t_1, t_4], e\langle 10, 9\rangle, reader_9, reader_{9'}) \\ (tag_1, [t_7, t_{10}], e\langle 9, 1\rangle, reader_{1'}, reader_1) \end{array}\right\} \xrightarrow{Step\ 2}$$

$$(tag_1, [t_5, t_6], c_9, reader_{9'}, reader_{1'}) \xrightarrow{Step\ 3}$$

$$(tag_1, [t_5, t_6], c_9 \cup \Theta(reader_{9'}, reader_{1'}, t_5, t_6))$$

On-line Tracking

Given $\langle readerID, tagID, t, flag\rangle$. On-line tracking is intended to infer the trajectory in the time interval between the last observation and the current time or even in the future.



- $flag = START$, object $tagID$ is in the activation range of $readerID$ at time t.
- $flag = END$, the object is beyond the activation range of $readerID$ and not in the range of any other readers.
  - constrains by a circle determined by the most recent observing reader's range.
  - further refined if an object has recently been detected by a partitioning reader pair.

Research Directions

- Extend the deployment graphs to accommodate RFID readers with large and overlapping activation ranges.
- Using multiple deployment graphs for several positioning technologies.
- To enhance on-line tracking. Historical data $\rightarrow$ association rules $\rightarrow$ better prediction.

1. Outlines
2. Indoor Space Models & Applications
3. Indoor Data Cleansing
4. Indoor Movement Analysis
5. Appendix

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The End. Thanks :)