Ranging & Localization

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Indoor localization

- A method to find out where a mobile device is positioned
- User location information is essential to provide various location based services
- Relative positioning rather than localization can be effective in something/someone finding => device-to-device positioning

Indoor localization Techniques

- Trilateration estimates the position of an object by measuring a distance between the object and several reference points
- Fingerprinting estimates the position of an object by comparing current measurement like RSS or geomagnetic field strength with pre-built measurement
- Collaborative localization estimates the positions of the objects which cooperate with each other in order to perform localization
- Motion-assisted localization: PDR
- ML-based localization

Trilateration (1)

- Trilateration
  - Trilateration uses geometric properties of triangles to estimate the target location
  - The position of an object can be estimated by measuring its distance from multiple reference points

Trilateration (2)

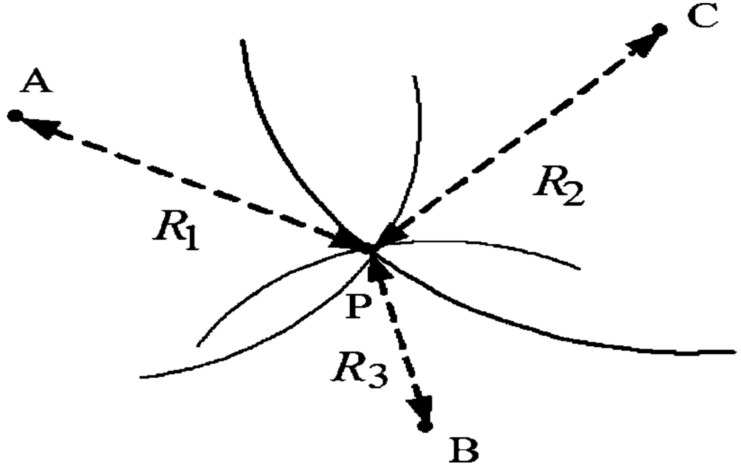
- Time of arrival (ToA) calculates the distance between the object and reference points by measuring the one-way propagation time
- Time difference of arrival (TDoA) determines the relative position of the object by examining the difference of arrival times at multiple points
- Received signal strength (RSS) uses a path loss model to translate the received signal strength at the object to the distance between the object and the transmitter

ToA based Triangulation (1)

- An object (receiver) measures the signal propagation time from the transmitter (TOF: time of flight)
- The distance from transmitter to receiver is proportional to the propagation time

$$R_i = c\,(t_i - t)$$

  - c: propagation speed of light
  - t_i : signal reception time; t : signal transmission time
- Straight forward approach estimates the position as the intersection of circles



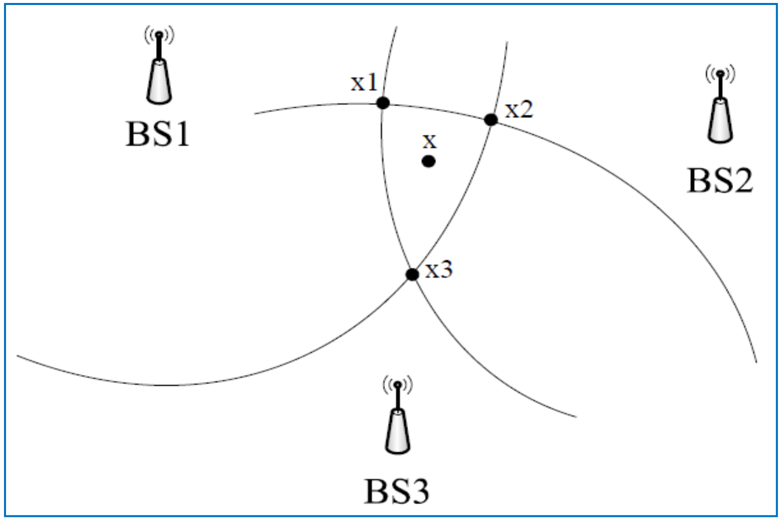
ToA based Triangulation (2)

- The position of the object can also be estimated by other algorithms like least square
- Least square algorithm
  - minimize the weighted sum of squares of function *f*(*x*)

$$f_i(x) = \sqrt{(x_i - x)^2 + (y_i - y)^2} - c(t_i - t)$$

    - The difference between real distance and measured distance from the transmitter to the receiver

  - Minimize $F(X) = \sum(w_i f_i(x))^2$
    - w_i: reliability weight for the receiver *i*



TDoA based Triangulation

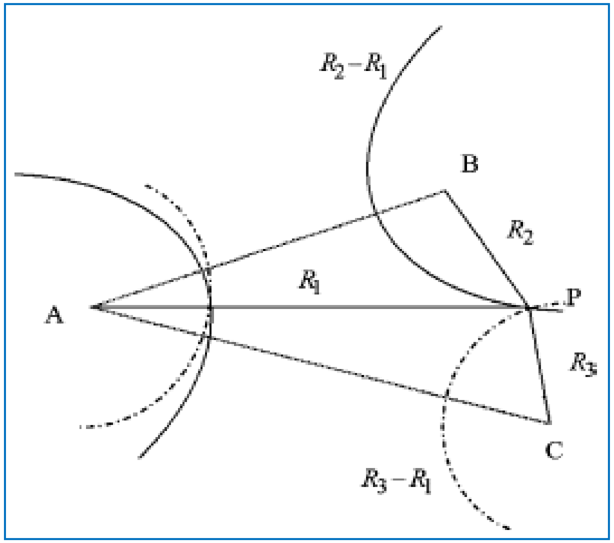
- The idea of TDoA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple measuring units

$$R_{ij} = R_i - R_j = c(t_i - t) - c\left(t_j - t\right) = c(t_i - t_j)$$

- The transmitter must lie on a hyperboloid with a constant range difference between the two measuring units

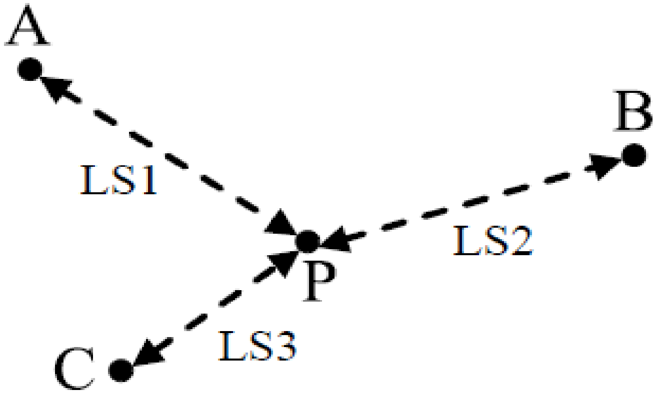
$$R_{ij} = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{\left(x_j - x\right)^2 + (y_j - y)^2}$$

- The position of object (P) is the intersection of two hyperbolas formed from TDoA measurements at three fixed measuring units (A, B, C)



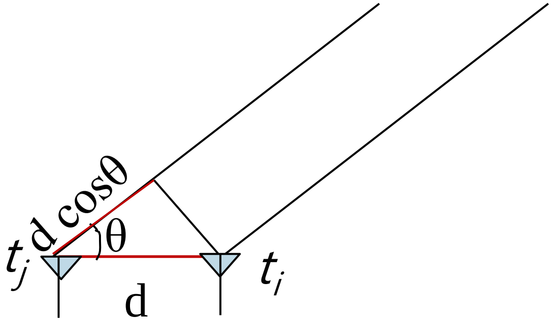
RSS based Triangulation

- An object measures the received signal strength (RSS) from the transmitter
- The distance between the object and the transmitter can be estimated by using a path loss model
- Estimation of the position from the distance is similar to ToA based triangulation

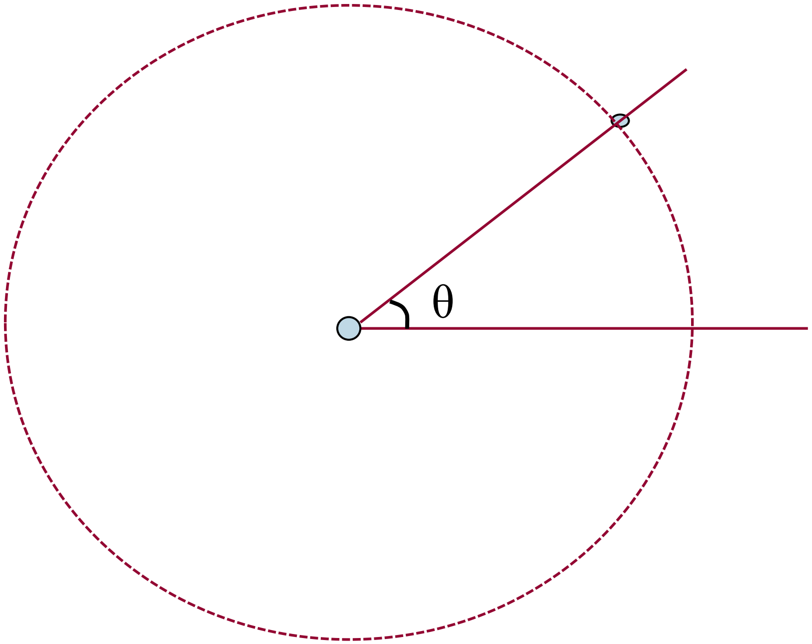


Angle of Arrival

- The receiver is equipped with antenna array
- The distance between the receiver and the transmitter (target object) is measured, based on TDoA or RSS
- The angle between the object and the receiver is estimated.



$$d \cos\theta = c(t_j - t_i)$$



Considerations in Triangulation (1)

- Time synchronization
  - ToA based triangulation : needs the precise time synchronization among the object and all reference points
    - The transmitter should send its transmission time
  - TDoA based triangulation: needs the precise time synchronization among all reference points
  - Synchronization error can cause a lot of estimation error

Considerations in Triangulation (2)

- ToA and TDoA based triangulation
  - Absence of line-of-sight (LOS) path
    - does not work well when LOS path does not exists
  - Multipath
    - In indoor environments, there are various objects that reflect signals and lead to multipath
    - The accuracy of estimated position can be degraded since the propagation time would be affected by multipath effect
    - UWB is very robust in multipath environment

Considerations in Triangulation (3)

- Inaccurate path loss model In RSS based triangulation
  - Path loss model is used for estimating distance from the received signal strength
  - Due to severe multipath fading and shadowing, path loss model may be inaccurate
  - To overcome this problem, site-specific parameters for path loss model may be used

Fingerprinting (1)

- Fingerprinting–based localization algorithm utilizes the position-dependent data
  - Fingerprinting data: RSS, PDR, geomagnetic
- Two phases of offline and online

Offline phase

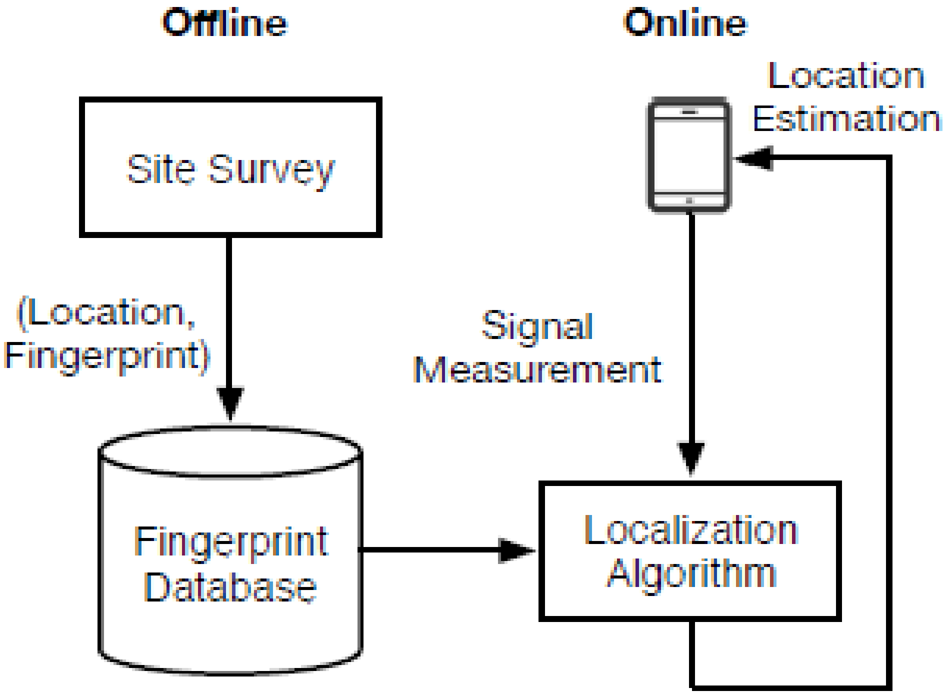
  - The location-dependent data measurements are collected for all feasible locations

Online phase

  - Samples measured at mobile device are compared against the stored fingerprint map to estimate the user’s current location
- Estimation method
  - Deterministic model and Probabilistic model
  - Machine Learning model

Fingerprinting (2)

RSS-based finger printing



Offline

Online

Site Survey

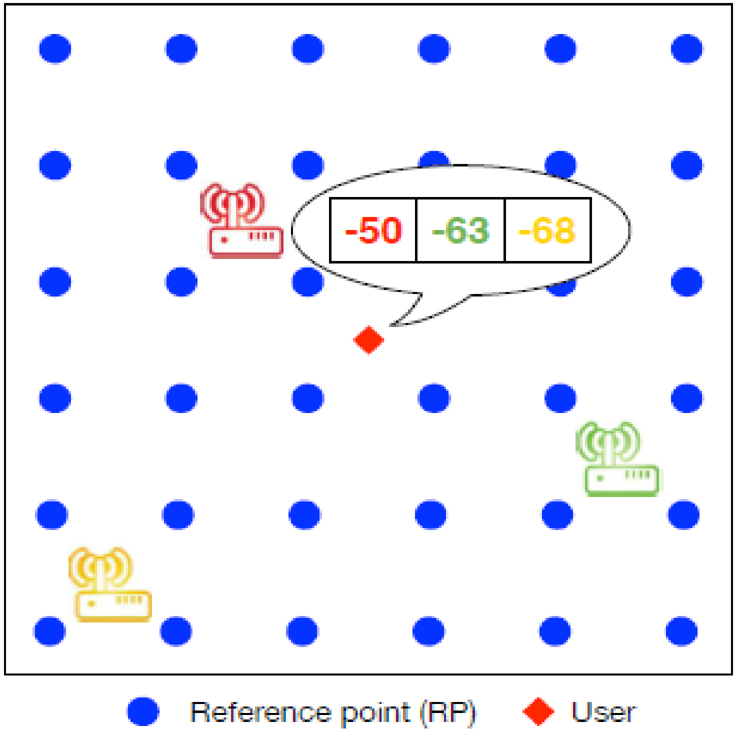
(Location, Fingerprint)

Fingerprint Database

Signal Measurement

Localization Algorithm

Location Estimation



Fingerprinting (3)

- Deterministic algorithm
  - Deterministic algorithms use a similarity metric to differentiate online signal measurement and fingerprint data
  - The position of the object is estimated as the closest fingerprint location in signal space
  - There are several similarity metrics like Euclidean distance, cosine similarity, and so on

Fingerprinting (4)

❖ Deterministic algorithm

Similarity between the online measurement ψ_r and the *j*-th fingerprint ψ_j: $s(\psi_r, \psi_j)$

- Euclidean distance : $s(\psi_r, \psi_j) = \|\psi_r - \psi_j\|^2$
  - Euclidean distance becomes smaller as two vector becomes more similar
- Cosine similarity: $s(\psi_r, \psi_j) = \dfrac{\psi_r \cdot \psi_j}{\|\psi_r\| \; \|\psi_j\|}$
  - Cosine similarity becomes closer to 1 as two vector becomes more similar

Fingerprinting (5)

- Probabilistic algorithm
  - Using a training set, these algorithms find the target's location with the maximum likelihood.
  - Estimates the target location using a probabilistic model reflecting the signal distribution in the site
  - Given a target signal strength vector **s** = (s_1, . . . , s_L) at L APs, the position of object **x** is estimated as

$$\arg\max_{\mathbf{x}} P(\mathbf{x}|\boldsymbol{s})$$

  - $\arg\max_{\mathbf{x}} P(\mathbf{s}|\mathbf{x}) = \arg\max_{\mathbf{x}} \prod P(s_i|\mathbf{x})$
    - $P(s_i|\mathbf{x})$: the probability that signal s_i appears at AP i from given location **x**

Fingerprinting (6)

- Signal Patterns

  The localization accuracy can be improved by exploiting spatial and temporal signal patterns, which can help discriminate the locations

- Temporal signal patterns are the signal sequence patterns during walking in the indoor environments
  - The pattern carries temporal information which can be used to correct the fingerprint-based localization
- Spatial signal patterns are the geographical distribution of signals like RSS order and signal coverage
  - RSS orders can be used for classifying rooms
  - Signal coverage can provide the tighter constraints for localization

Considerations in Fingerprinting (1)

- High cost of offline site survey
  - Constructing the radio map of indoor environment requires relatively high cost
    - too many sites
    - Environments are changed often
- Changes of fingerprints in online phase
  - Fingerprint-based localization is highly affected by environmental changes in online phase
    - If the number of working APs or the structure of the building changes, the radio map of the environment also changes

Considerations in Fingerprinting (2)

- Energy consumption
  - In fingerprint-based approach, the mobile device needs to scan nearby Wi-Fi APs periodically
    - scanning Wi-Fi consumes a lot of energy
    - Transmission of scanning results to the server

Collaborative Localization (1)

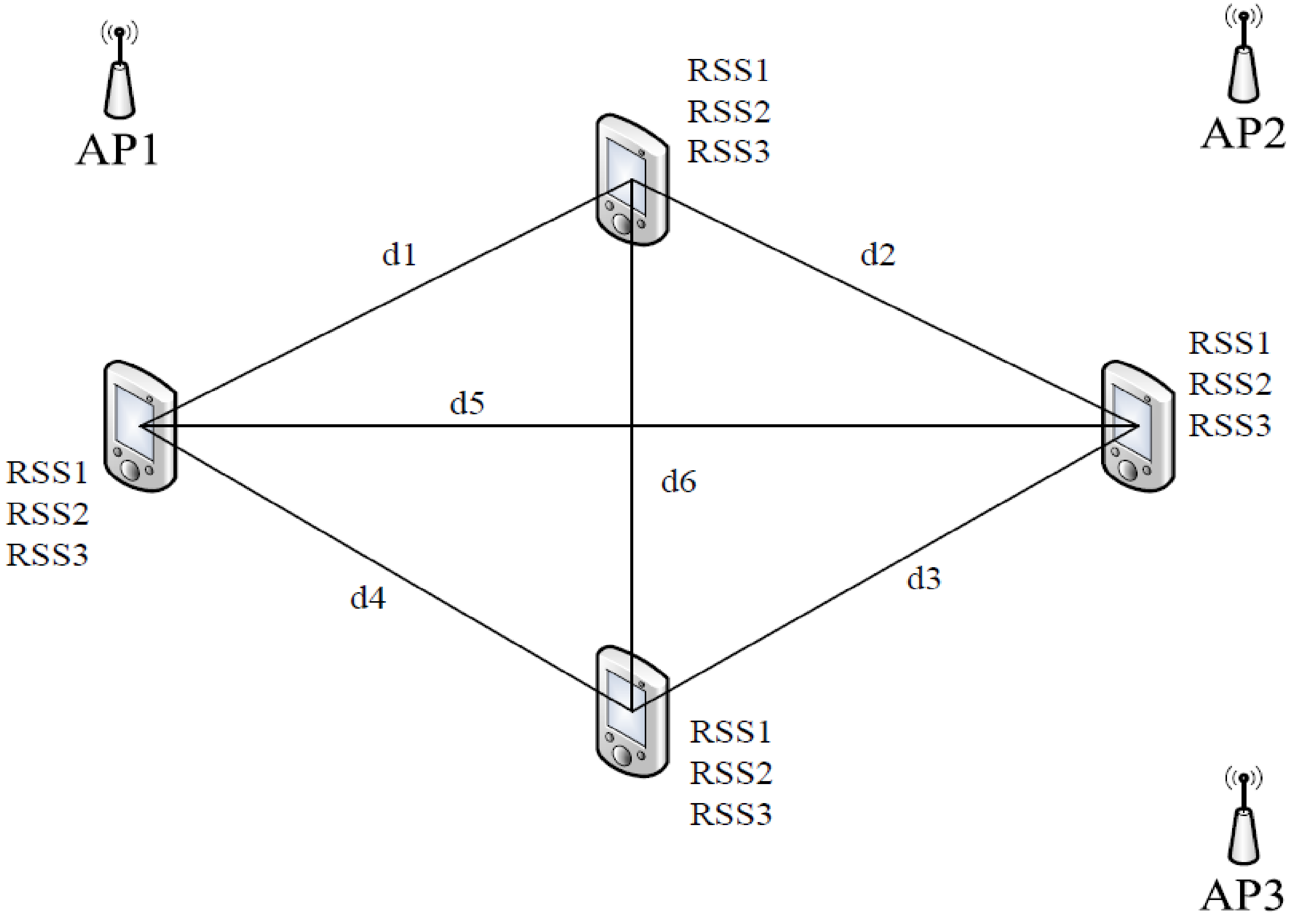
- The information of relative positions between the objects as well as RSS vectors are utilized to estimate the position
  - A mobile device can easily discover others in its neighborhood via various protocols such as BLE, WiFi-Direct, LTE-Direct
  - A mobile device has many embedded smart sensors
  - Location context of social interaction: In typical social scenarios of indoor environment (museum), people (friends, family) may gather together.
- Collaborative localization can be categorized into distance-based scheme and proximity-based scheme

Collaborative Localization (2)

- Distance-based scheme
  - The distances between users (pairwise distance) are calculated using data from advanced sensors
    - Both radio signals and sound can be used for calculating pairwise distances
  - Pairwise distances can be utilized to form the network graph of different users
  - The rotation and translation of network graph is helpful to jointly find the reference points of users such that the overall Euclidean distance between target signals and fingerprints is minimized.

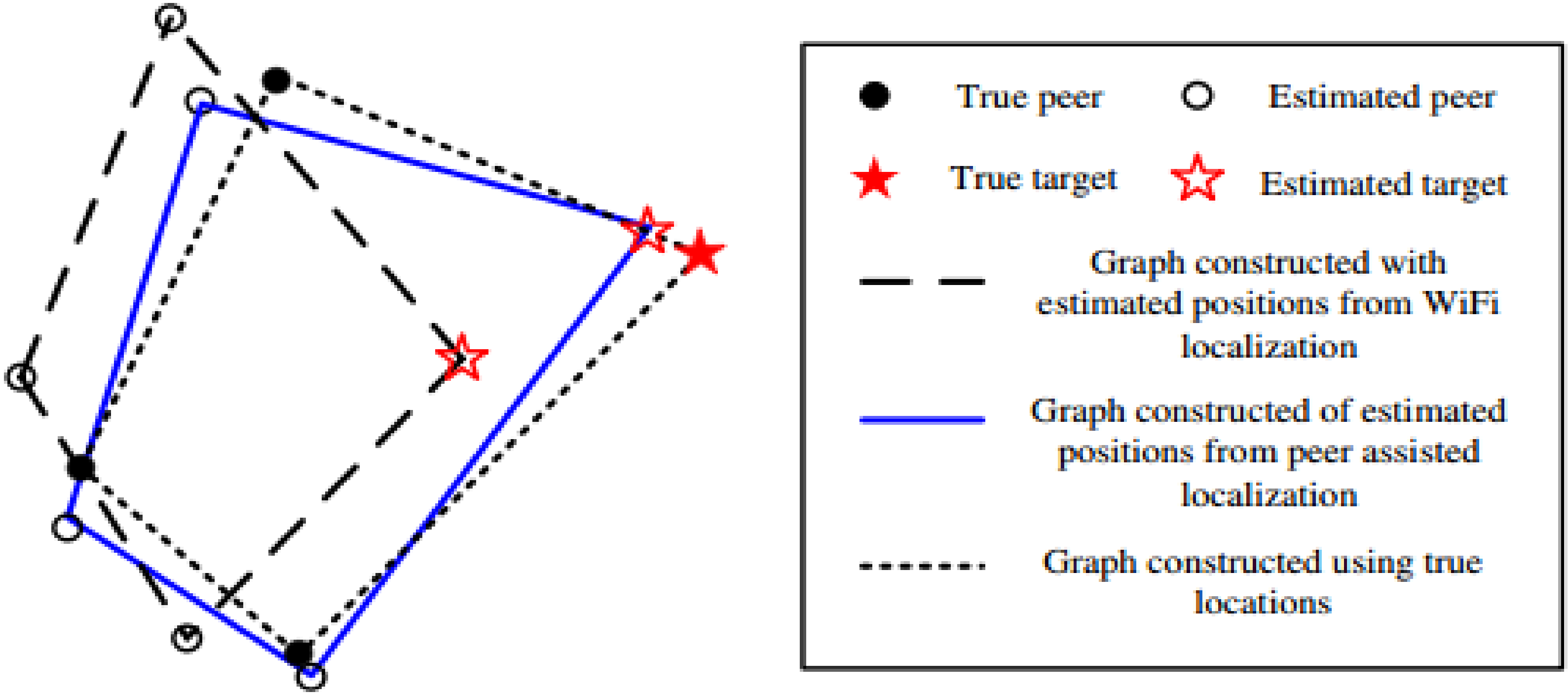
Collaborative Localization (3)

Distance-based scheme



Collaborative Localization (4)

Distance-based scheme

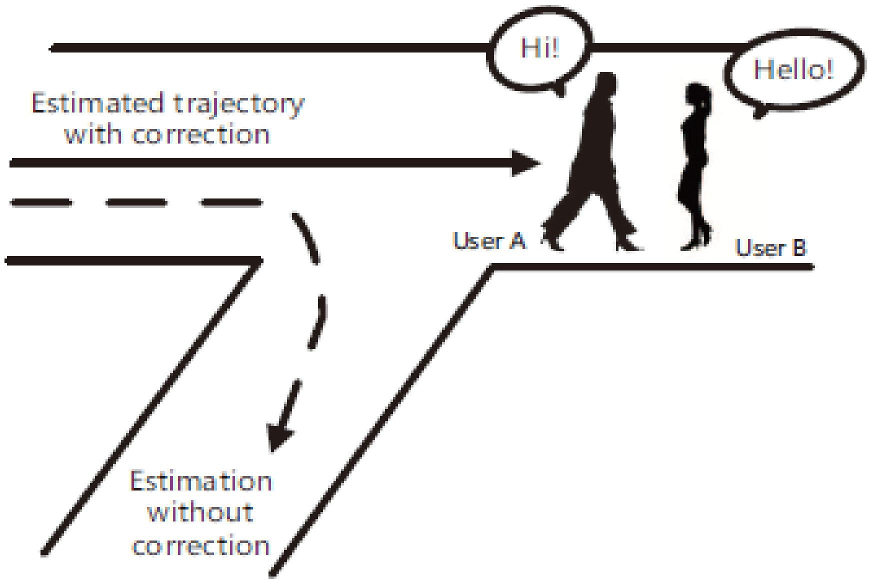


Collaborative Localization (5)

- Proximity-based scheme
  - Not the distance between two objects but proximity information is used for estimating the position of the object
  - The interaction between users (encounter, missing) can also be utilized to constrain the location estimation of the involved users

Collaborative Localization (6)

- Example of Proximity-based Scheme
  - The user locations are first initialized through traditional fingerprint-based localization. Each user estimation has multiple candidates.
  - If two users encounter each other, their estimated locations should have overlapping
  - The candidate location which does not satisfy encounter information of two users would be filtered out



Considerations in Collaborative Localization (1)

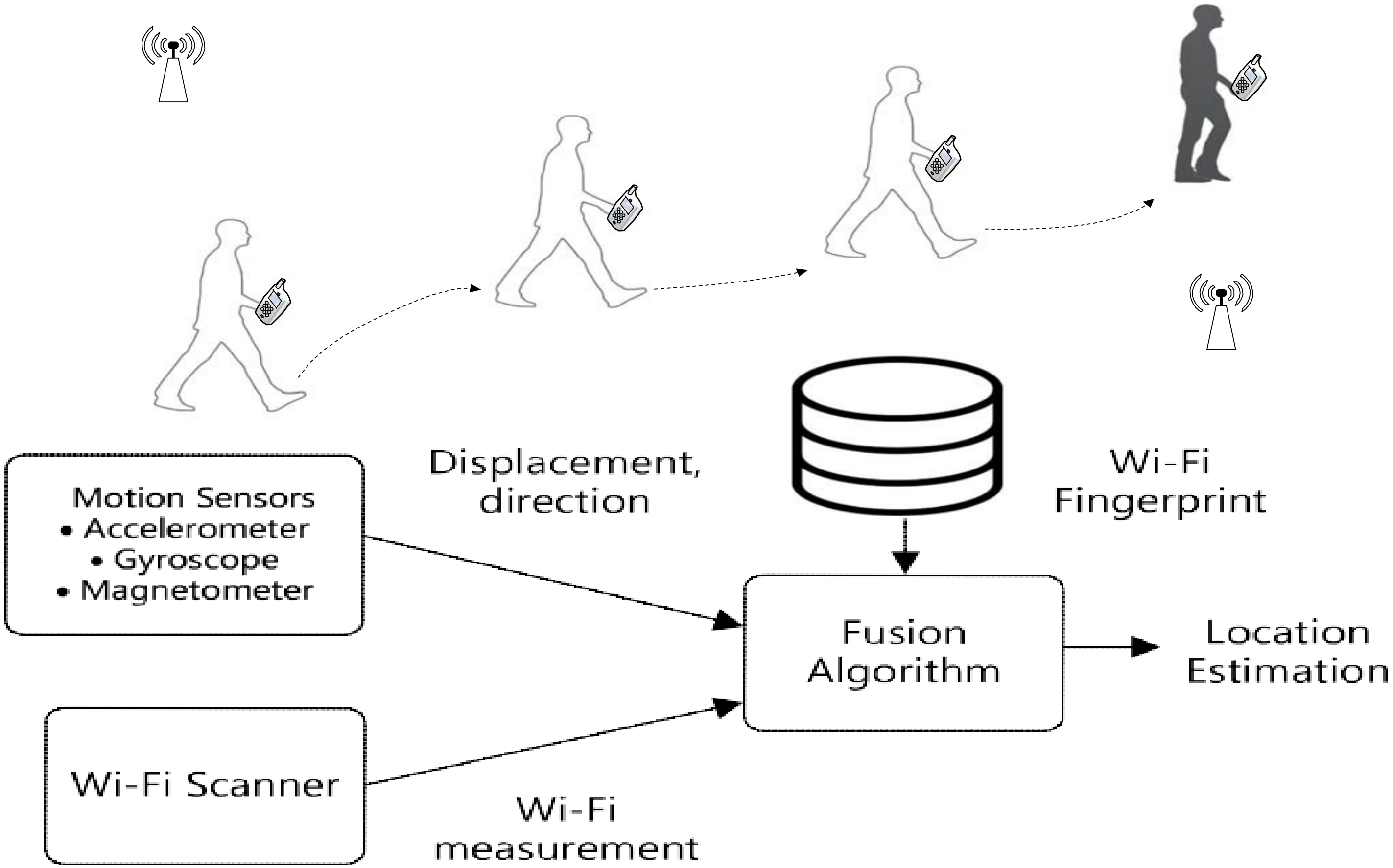
- Inaccurate pairwise distance
  - In distance-based collaborative localization, accurate pairwise distance is needed to estimate the accurate position of the object
  - However, pairwise distance may be inaccurate due to the high mobility of users
- High computational complexity
  - Computational complexity is high due to pairwise communication and synchronization
  - High computation complexity may lead to long delay and large energy consumption for localization

Considerations in Collaborative Localization (2)

- Privacy issue
  - Since collaborative localization utilizes the social interaction, the users may share the device information with each other
  - To address the privacy issues, a specific secured protocol for location share may be required

Motion-Assisted Localization (1)

Pedestrian Dead Reckoning



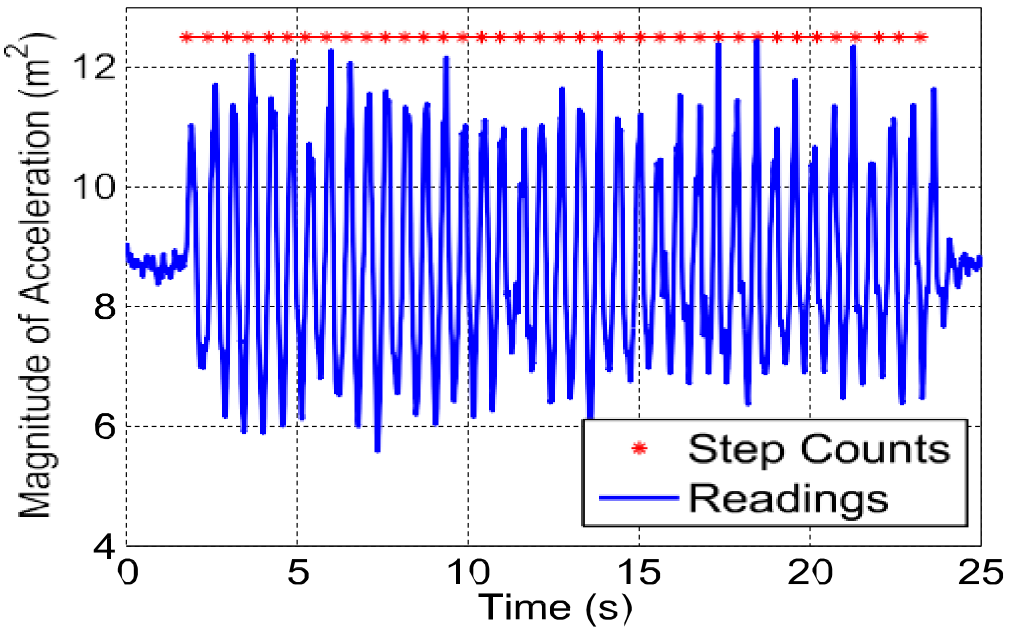
Fusing WiFi and motion sensors

Motion-Assisted Localization (2)

- Motion measurements with sensors
  - Sensors
    - Accelerometer: the 3D linear acceleration
    - Gyroscope: the angular velocity
    - Magnetometer: the strength and direction of magnetic fields
    - Gyroscopes and magnetometers: the heading direction of user
  - Motion Detection
    - Walk Detection
      - classifies the motion state of the target
      - when the state is “moving”, the step counting starts
    - Step Counting
      - Pedometer (step counter)
    - Stride Length Measurement

Motion-Assisted Localization (3)

- Step Counting
  - Peak detection or zero crossing of acceleration readings



  - Finding repetitive step patterns from sensors
    - Autocorrelation of step patterns
    - Extracting the step frequency patterns through FFT

Motion-Assisted Localization (4)

- Stride Length
  - depends on the step frequency, user height, etc.
  - Models for calibrating the relationship between stride length and step frequency,
  - Models for the relationship between stride length and height change of user waist during walking

Motion-Assisted Localization (5)

- Challenges
  - Motion measurement
    - Heterogeneity of motion patterns : Specific calibration for different users are required
    - Change in the relative position of smartphone
  - Fusion algorithm
    - Motion information filters the incorrect positions returned from WiFi localization
  - Simultaneous Location and Mapping (SLAM)
    - Simultaneously localizing the target and constructing the indoor maps
    - utilizes fusion of Wi-Fi and motion measurement to jointly minimize the location difference with the indoor structure and infer the map.

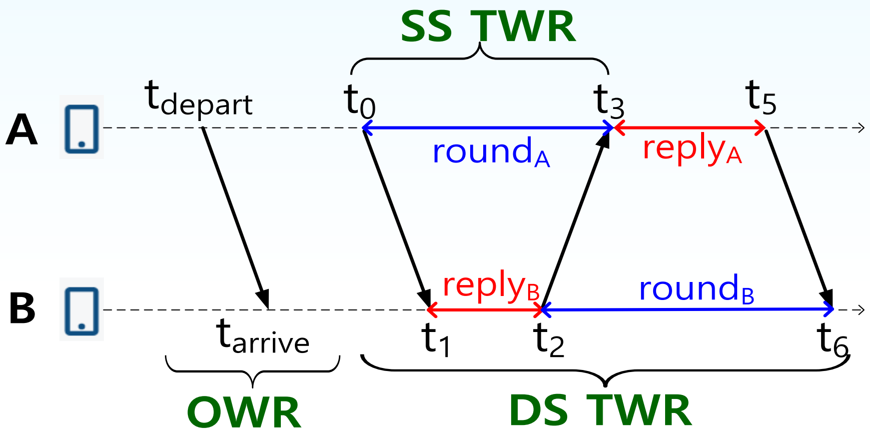
UWB-based Positioning

- Device 간 상대적인 위치 및 자세 추정
  - 거리 추정(Ranging)
  - 방향 추정
  - 자세 추정
- 앵커 활용 UWB device의 위치 추정
  - 삼변/삼각 측량
  - 측위 시스템 구성 시나리오

UWB 기반 Ranging

- Device 간 거리 추정(Ranging)
  - 두 device 사이의 LOS 경로 길이인 ToF (time-of-flight) 측정
    - LOS Path: Power-Delay Profile에서 First Path Component
  - Device A와 B 사이의 거리 = ToF × speed of light
  - ToF 측정 기법
    - One-way ranging (OWR): 단말 간 clock 동기화 필수 => TDOA based localization
    - Single-sided Two-way ranging (SS-TWR)
    - Double-sided TWR (DS-TWR)

ToA based localization



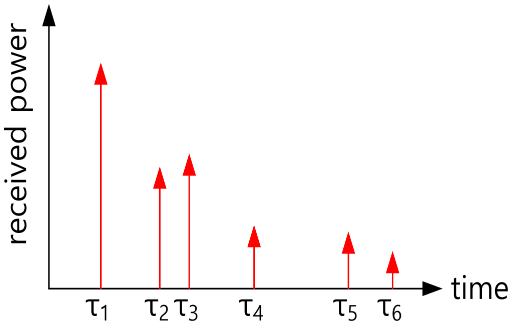
OWR: $\text{ToF} = t_{arrive} - t_{depart}$

SS-TWR: $\text{ToF} = \dfrac{\text{round}_A - \text{reply}_B}{2}$

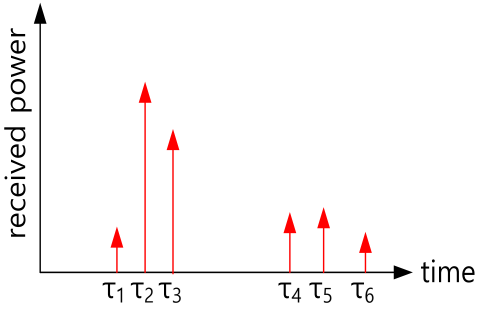
DS-TWR: $\text{ToF} = \dfrac{\text{round}_A \text{round}_B - \text{reply}_A \text{reply}_B}{\text{round}_A + \text{round}_B + \text{reply}_A + \text{reply}_B}$

UWB 기반 Ranging

- LOS가 존재하지 않을 시
  - First path component (FPC)의 TOF 기반 거리 계산은 부정확함.
- LOS의 존재 유무 판별
  - UWB는 짧은 길이의 pulse를 전송하기 때문에 multipath 구별에 용이
  - 수신 device에서 power-delay profile을 활용하여 판별
  - 판별 기준: FPC와 나머지 multi path components (MPC)의 수신세기 비
    - ✓ $\rho = \frac{P_{\mathrm{FPC}}}{P_{\mathrm{MPC}}}$
    - ✓ $\rho > \delta_{\mathrm{LOS}}$ → LOS 존재, $\rho < \delta_{\mathrm{NLOS}}$ → NLOS 환경 (LOS 부재)



[LOS 확보 시 power-delay profile 예]

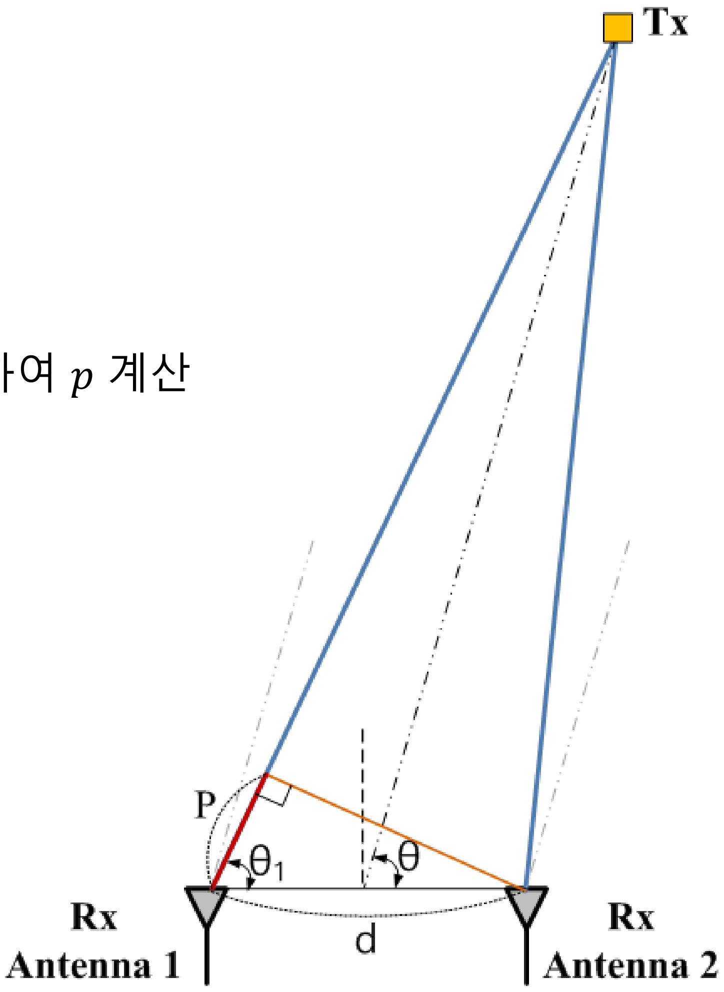


[LOS 미확보 시 power-delay profile 예]

UWB 기반 Ranging

- 방향 추정
  - 안테나의 전파 송수신 각도를 이용하여 방향 추정
  - 방향(θ) 추정 기법: **수신 안테나 2개**인 경우를 가정
    - ToF 활용 기법
      - ✓ 송신안테나와 수신 안테나 A, B 사이의 ToF 차이를 이용하여 p 계산
      - ✓ $p = d \times \cos(\theta)$ 이므로, $\theta = \arccos(p/d)$
    - 위상차 활용 기법(안테나 간 거리는 파장 미만, $d < \lambda$)
      - ✓ 두 수신 안테나에서의 수신 신호 위상차($\Delta\phi$) 활용
      - ✓ $\Delta\phi = 2\pi \frac{p}{\lambda} \rightarrow p = \frac{\lambda \Delta\phi}{2\pi}$
      - ✓ $\theta = \arccos(p/d) = \arccos\left(\frac{\lambda \Delta\phi}{2\pi d}\right)$
      - ✓ 안테나 간격 $d = \lambda/2$ 인 경우, $\theta = \arccos\left(\frac{\Delta\phi}{\pi}\right)$

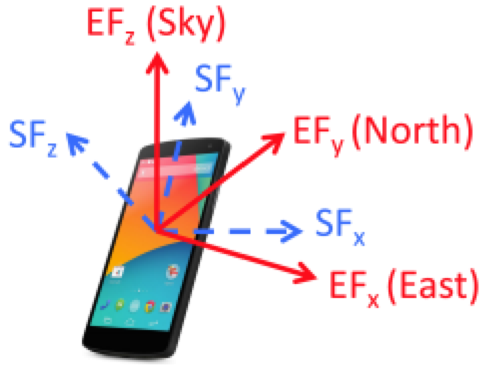
        * $\Delta\phi = \big((\phi_A - \phi_B + \pi) \bmod 2\pi\big) - \pi$ 측정 후 θ 도출



[수신 안테나 2개를 활용한 방향 추정]

UWB 기반 Ranging

- 자세 추정
  - Device 자세: Earth-Frame (EF)에 대한 Smartphone-Frame (SF) 회전각
  - Device 자세 표현 방법
    - Euler angle (roll, pitch, yaw)
    - Quaternion (임의의 축,회전각)



  - 스마트 폰 자세 산출 원리
    - 관성측정장치(가속도/각속도/지자기 센서) 센싱 값 기반 계산
      - ✓ 초기화: 지자기 센서와 가속도 센서를 활용 EF 추정 후, 자이로 센서를 통하여 자세 추정
      - ✓ 가속도 센서와 자이로(각속도) 센서 값에 기반하여 스마트폰의 상대적인 자세 변화를 반영
      - ✓ 자이로 센서 값 기반 자세 추정은 시간이 갈수록 오차가 누적되는 단점 존재
  - 스마트폰 자세 도출 방법
    - 스마트폰 OS: 자세도출 API 제공 (단점: 시간에 따른 오차 누적)
    - 자이로 센서 측정값에 calibration (예, Extended Kalman Filter) 기법 적용하여 보정
  - Device 간 상대적 자세는 UWB 데이터 통신으로 전달 가능

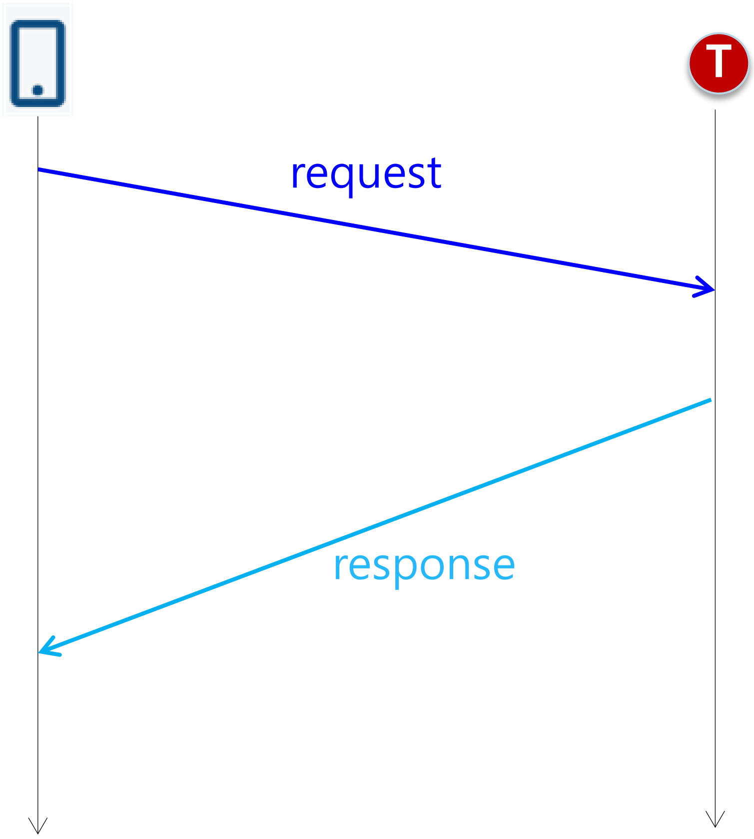
UWB 기반 device 측위

- Device 간 위치 추정
  - device 간 거리 추정
  - device 간 방향 추정

- 다수의 Anchor를 활용한 device (tag) 측위
  - Anchor: 정확한 위치 정보 (known position)를 가지고 있으며 측위의 기준 시간/위치 정보를 제공하는 device
  - 측위 기술
    - Time-to-Arrival (ToA) 기반
    - Time Difference-to-Arrival (TDoA) 기반
    - Angle-of-Arrival (AoA) 기반

두 UWB Device 간 위치 추정

- Two way-Ranging 활용
  - Initiator (Smartphone): 수신 안테나 2개 장착
  - Responder (Tag)

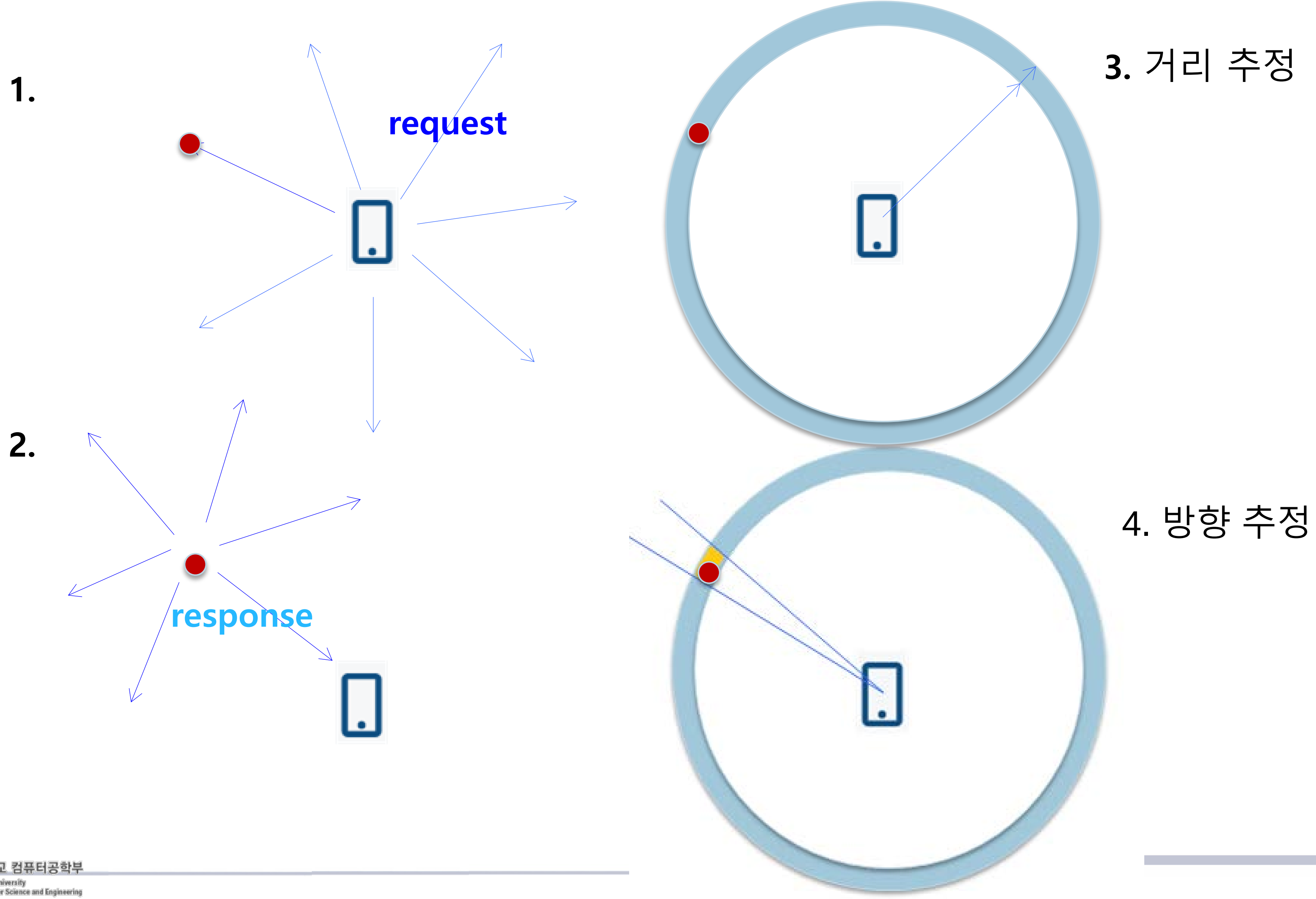


SS-TWR:

ToF 측정: 거리 추정

AoA 측정: 방향 추정

두 UWB Device 간 위치 추정



1.

request

2.

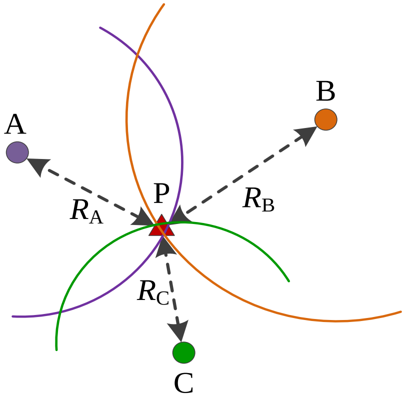
response

3. 거리 추정

4. 방향 추정

Anchor 활용 UWB device 측위

- ToA (Time of arrival) 기반 삼변 측량
  - 각 앵커-태그 사이의 거리 추정
    - SS-TWR, DS-TWR, OWR (앵커-태그: clock sync)



Anchor: A, B, C

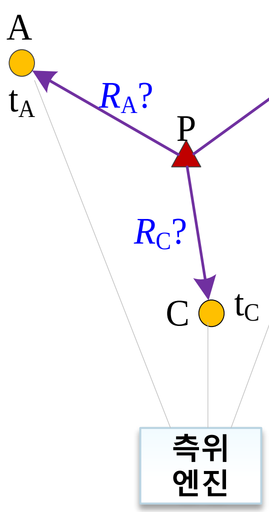
Tag: P

- 추정 거리에 기반한 삼각 측량 기법을 통해 태그의 위치 추정
  - [방식 1] 원의 교점 계산
    - ✓ 앵커 위치(원 중심)와 추정 거리(반지름) 활용
  - [방식 2] 최소 오차 위치
    - ✓ 앵커와 태그간 기하학적 거리와 ranging 값 차이를 최소화
    - ✓ $P^* = \text{argmin}_P\{(dist(P,A) - R_A)^2 + (dist(P,B) - R_B)^2 + (dist(P,C) - R_C)^2\}$

Anchor 활용 UWB device 측위

- TDoA (Time difference of arrival) 기반 삼변측량
  - 태그로부터 앵커들 사이의 거리 차 추정
    - 앵커들 사이에 시간 동기화
    - 태그가 전송한 신호를 주변 앵커들이 수신 (OWR)
      - ✓ $R_A - R_B = c\,(t_A - t) - c\,(t_B - t) = c\,(t_A - t_B) = k_{AB}$

        두 앵커와의 거리 차가 주어진 일정한 값(k_{AB}): hyperbolic

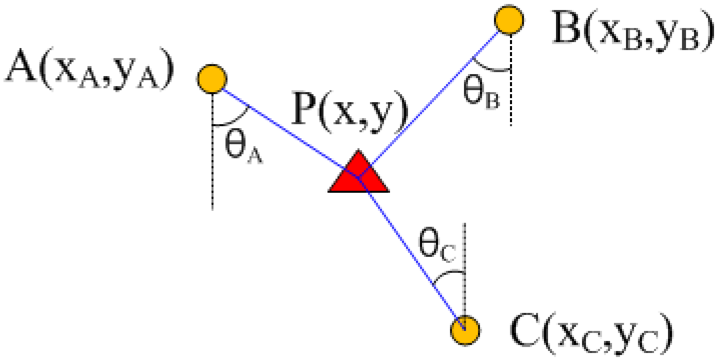


  - 추정 거리 차이에 기반한 대상의 위치 추정
    - [방식 1] 쌍곡선의 교점 계산
      - ✓ 앵커 위치(초점)와 거리 차 활용
    - [방식 2] 최소 오차 위치
      - ✓ 태그로부터의 앵커간 거리 차이와 추정 거리 차이를 최소화

$$P^* = \operatorname{argmin}_P \left\{ \begin{array}{c} \big(dist(P,A) - dist(P,B) - (R_A - R_B)\big)^2 + \big(dist(P,B) - dist(P,C) - (R_B - R_C)\big)^2 + \\ \big(dist(P,C) - dist(P,A) - (R_C - R_A)\big)^2 \end{array} \right\}$$

Anchor 활용 UWB device 측위

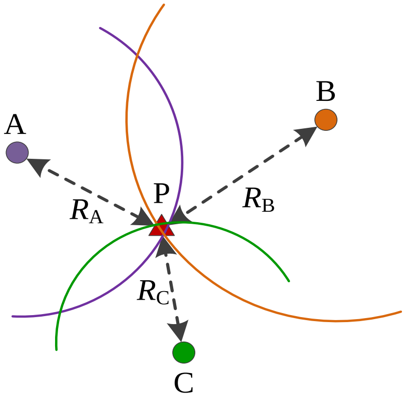
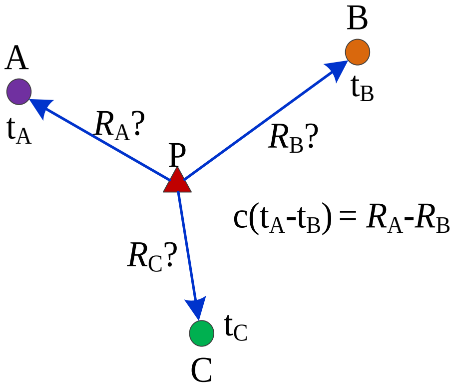
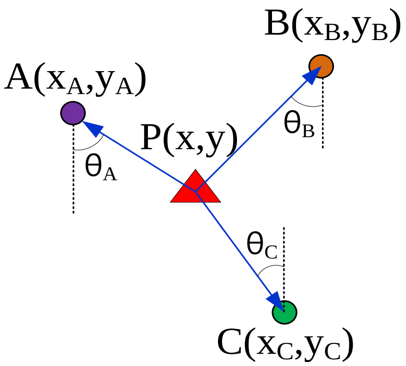
- AoA (Angle of arrival) 기반 삼각측량
  - 앵커-태그 사이에 방향각을 추정



  - 이들의 교차점을 계산하여 위치 추정
    - [방식 1] 방정식 풀이
      - ✓ $\begin{cases} x - x_A = (y_A - y)\tan(\theta_A) \\ x_B - x = (y_B - y)\tan(\theta_B) \end{cases}$
    - [방식 2] 최소 오차 위치
      - ✓ 앵커-태그를 빗변으로 하는 직각삼각형의 삼각비 활용
      - ✓ $P^* = \mathrm{argmin}_P \left\{ \left(\frac{x - x_A}{dist(P,A)} - \sin(\theta_A) \right)^2 + \left(\frac{x_B - x}{dist(P,B)} - \sin(\theta_B) \right)^2 + \left(\frac{x_C - x}{dist(P,C)} - \sin(\theta_C) \right)^2 \right\}$

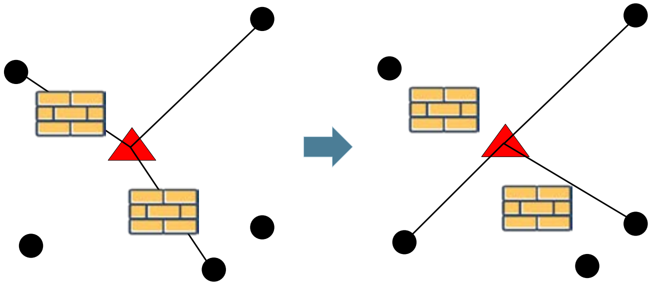
Anchor 활용 UWB device 측위

- Anchor 활용 device 측위 기법 비교

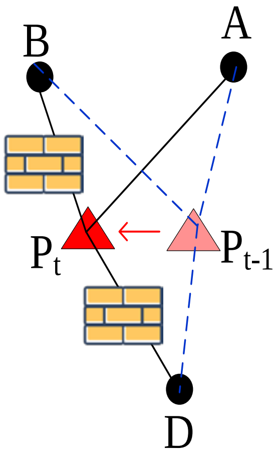
	ToA	**TDoA**	**AoA**
장점	- 앵커간 시간 동기화 불필요 (안정성)	- ToA 대비 동시에 처리할 수 있는 태그 수 많음 (확장성) - 배터리 소모 적음	- 동기화 필요 없음 - 2차원 평면의 경우, 앵커 2개로 측위 가능
단점	- TDoA 대비 일정 구간 내 신호를 전송할 수 있는 태그 수 제한됨 - 배터리 수명 단축됨	- 시간 동기화가 되지 않으면, 측위 정확도 떨어짐	- 상대적으로 수신기가 크고 복잡 - Device 간 거리가 긴 경우 오차 증가
측위 예			

Anchor 활용 UWB device 측위

- LOS 미확보 시 측위 보정
  - LOS가 확보된 ranging 값이 기준 미만 (2차원 평면 측위 시 삼변측량: 3개, 삼각측량: 2개)이면 측위 정확도 떨어짐
  - [기법 1] : 다른 앵커와 ranging 재시도
    - LOS 확보 가능성

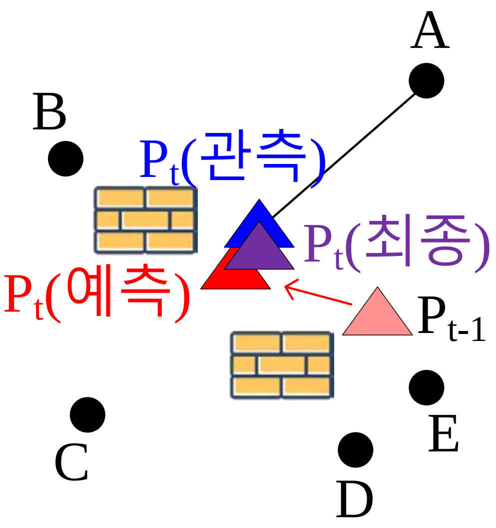


  - [기법2] : 연속적인 측위(실시간 tracking)의 경우, 이전 측위(ranging) 결과 활용
    - 태그의 이동이 예상이 안되거나 이동 패턴이 없는 경우
    - (예) Ranging 보정
      - ✓ 앵커 A로부터의 ranging 그대로 사용
      - ✓ 앵커 B로부터의 ranging: 태그가 P_{t-1} 에 있다고 가정하고 B와 P_{t-1} 사이의 거리를 ranging 값으로 사용
      - ✓ 앵커 D로부터의 ranging: 이전 측위 시점의 ranging 값을 사용

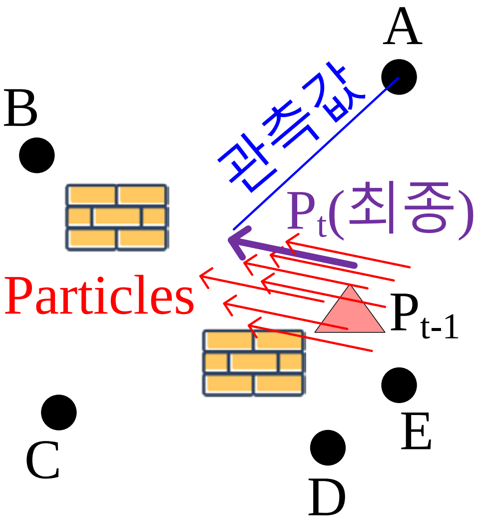


Anchor 활용 UWB device 측위

- LOS 미확보 시 측위 보정
  - [기법 3]: 필터링 기법 활용(Kalman filter, Particle filter 등)
    - 태그의 이동이 예측이 되는 경우 적용(즉, 속도 및 방향 예측이 가능한 경우)
    - 예측 모델 예: 최근 T 시간 동안의 평균 속도 및 방향
    - 관측 값: LOS 확보된 ranging 값(하나도 없는 경우 예측 모델에 의하여 최종 위치 도출)



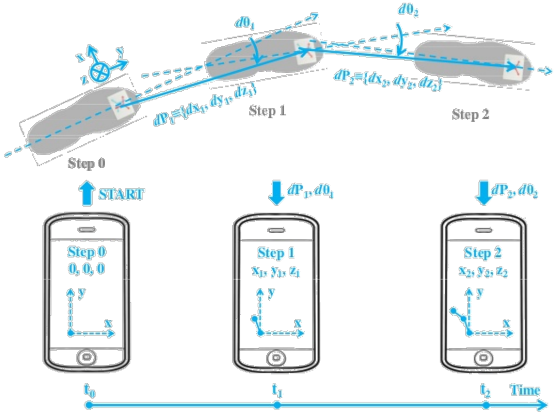
[Kalman filtering 예시]



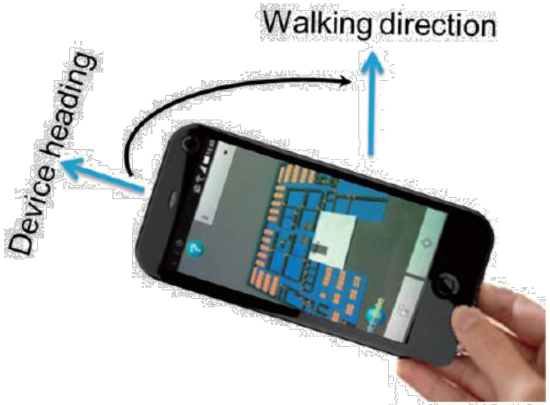
[Particle filtering 예시]

Anchor 활용 UWB device 측위

- LOS 미확보 시 측위 보정
  - [기법 4] 보행자 추측 항법(Pedestrian dead reckoning, PDR) 활용
    - PDR: 스마트폰 내 관성측정 장치 기반 보행 패턴 추정
      - ✓ 보행 감지 & 보폭: 가속도 기반
      - ✓ 보행방향: 스마트폰의 y축 방향을 보행자 방향으로 간주
        (스마트폰 방향과 보행 방향이 다르면 측위 성능 저하)
      - ✓ 방향 차이 보정 연구: 초기단계
        - * 센서 값 기반 스마트폰 자세를 몇 가지로 판별
        - * 보정 성능 향상 시 매우 효과적인 솔루션
    - PDR 장&단점
      - ✓ 장점: 스마트폰 만으로 측위 가능
      - ✓ 단점: 시간이 갈수록 추정 오차 누적
    - LOS 미확보 시 PDR을 활용하여 LOS 재확보 시까지 측위
      - ✓ UWB와 결합하여 PDR 단점 완화



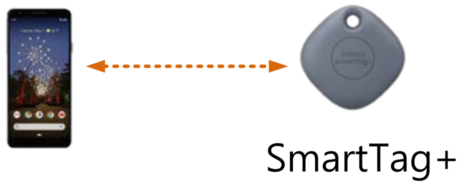
[스마트폰 기반 PDR]



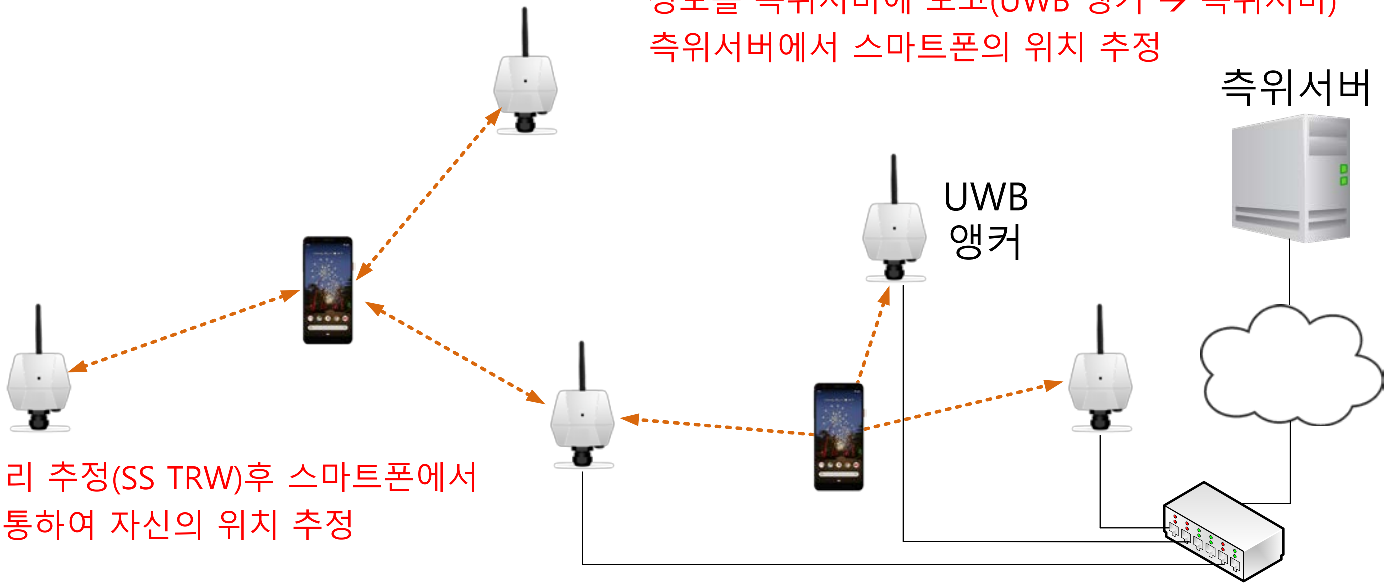
[스마트폰 방향과 보행방향 차이 예시]

UWB 측위 시스템 구성 시나리오

- 측위 타입 및 측위 알고리즘 구현 위치 별 시나리오



1) 스마트폰에서 SmartTag+ 의 상대적인 위치 추정
(거리 및 방향 추정)



3) 스마트폰에서 측위 신호를 방송한 후 TDoA 관련 정보를 측위서버에 보고(UWB 앵커 → 측위서버)
측위서버에서 스마트폰의 위치 추정

2) 주변 앵커와의 거리 추정(SS TRW)후 스마트폰에서 삼변측량(ToA)을 통하여 자신의 위치 추정