CAESAR: Carrier Sense-Based Ranging in Off-The-Shelf 802.11 Wireless LAN

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Summary

- Wireless LAN is crucial in navigation systems
- Current solutions do not meet a set of conflicting requirements
- We present CAESAR, a ranging technique that
  - combines time of flight and signal-to-noise ratio measurements to calculate the distance to a remote WLAN device
  - can be employed in off-the-shelf devices
  - shows high accuracy
  - can track the distance to smartphones

Outline

- Scenario
- Time of flight
- Problems
  - ACK detection time
  - Implementation in off-the-shelf devices
- Evaluation
- Conclusion

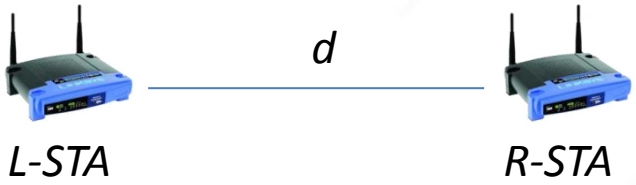
WLAN localization

- Advantages
  - WLAN *available* in most of today's mobile devices
  - *no* additional infrastructure cost
- **Problem**
  - **WLAN position based on *limited* device capabilities**

Signal strength

1. SNR fingerprint of the environment
   - *cost of maintenance*
2. Signal strength-based *ranging* techniques

L-STA=Local Station
R-STA=Remote Station



– SNR of frames from remote stations

– distance = f(SNR)

- *Theoretical or empirical model*

Signal strength

Why are they used?

Only software changes
in off-the-shelf WLAN devices!

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TOF (time of flight) ranging

- Calculate the time of propagation t_p
  - From the remote station to the local station
  - *used in GPS*
- *Linear* function of the distance $d=c \cdot t_p$
  - 1 μs=300 m
  - Apart of the multi-path propagation
- *No offline measurements* for radio-mapping

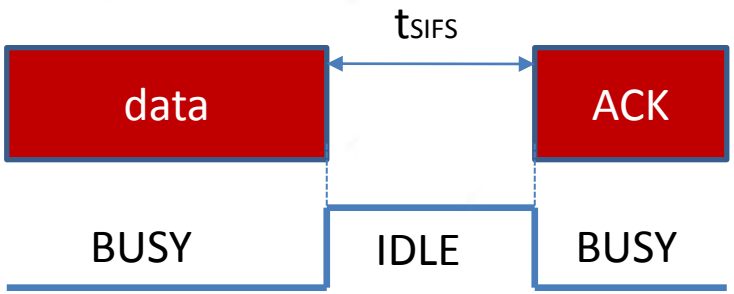
TOF in WLAN?

What can we exploit from the 802.11 protocol?

- No reference 802.11 clock
  - *Echo techniques* (round-trip-time)
- Precision depends on the clock resolution
  - →clock as *fast* as possible
- *Workload independent* estimation
  - of local station and network traffic
- *Software-based solution*
  - cost-effective, like in SNR-based ranging techniques

MAC Idle Time

- 802.11 WLAN uses a CSMA/CA protocol
  - Data/ACK pair
- Channel is *idle* between the data and ACK
- The idle time duration is
  - *predefined* and expected to be *constant*
    - MAC SIFS time (t_{SIFS})

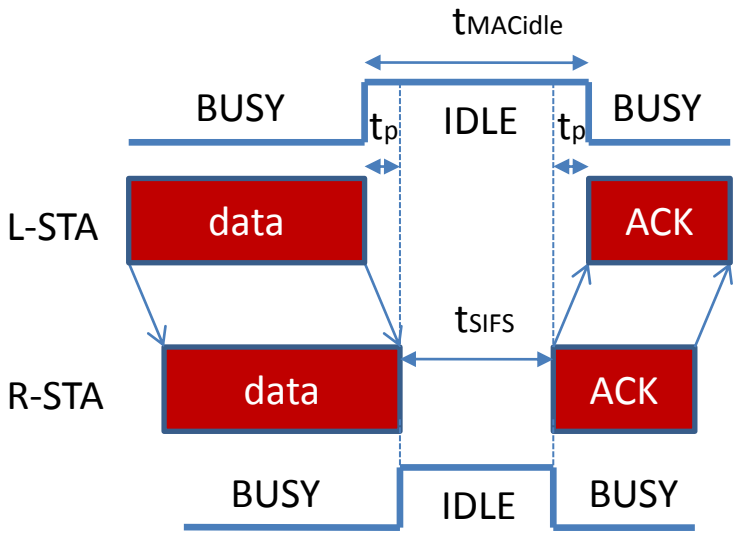


Variation of MAC Idle Time

- The idle time at the local station *varies*
  - with the *physical distance* between the two stations
  - because of time delay of t_p

CAESAR

- Key idea
  - exploit variation of idle time for ranging



$$t_{MACidle} = 2t_p + t_{SIFS}$$

$$d = c \cdot (t_{MACidle} - t_{SIFS})/2$$

- Variation based on *channel state transitions* of CSMA/CA →CAESAR: CArriEr Sense-baSed Ranging

Solved?

- ✓ Precise Time Measurement
  - CAESAR uses carrier sense samples
    - with resolution of the *main WLAN clock*
      - (44 MHz in 802.11b/g, at least 88 MHz in 802.11n)
    - 300/(2·44)=3.4 m of accuracy for the single sample
  - Short duration: no clock drift
- ✓ No protocol extensions
  - CAESAR only needs *information at the local station*
    - E.g. $t_{MACidle}$
  - No need of any information from the remote station
    - t_{SIFS} is constant

Not really…

- CAESAR is a *MAC-based solution*
- $t_{MACidle}$ depends on MAC operations
  - *Delay* caused by ACK detection time
  - Synchronization on the *strongest* path
- no inherent support in WLAN hardware
  - for calculating $t_{MACidle}$

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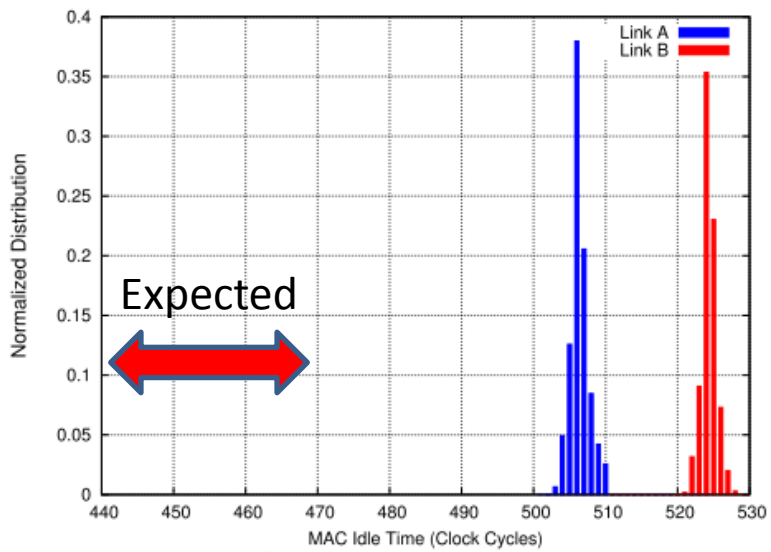
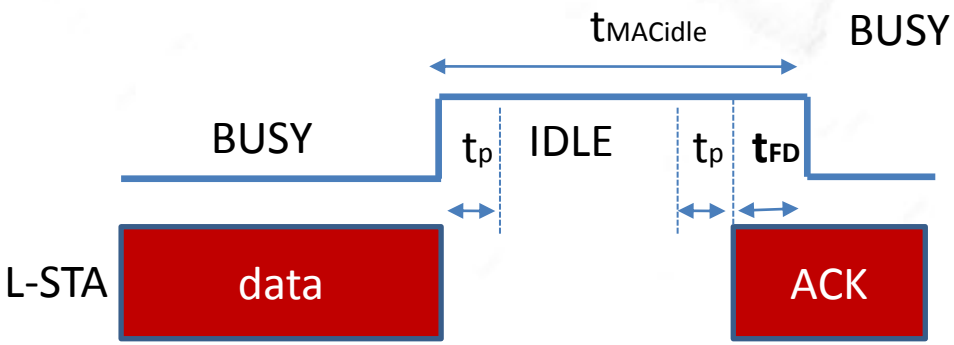
Problem: MAC Idle Time Distribution

- Two links, fixed distance (< 15 m)
- Multiple samples
- $t_{MACidle}$ in the range of 500 - 530
  - 11.3-12 µs @44 MHz > 10-10.1 µs expected !



What causes this delay?

- ACK detection time t_{FD}

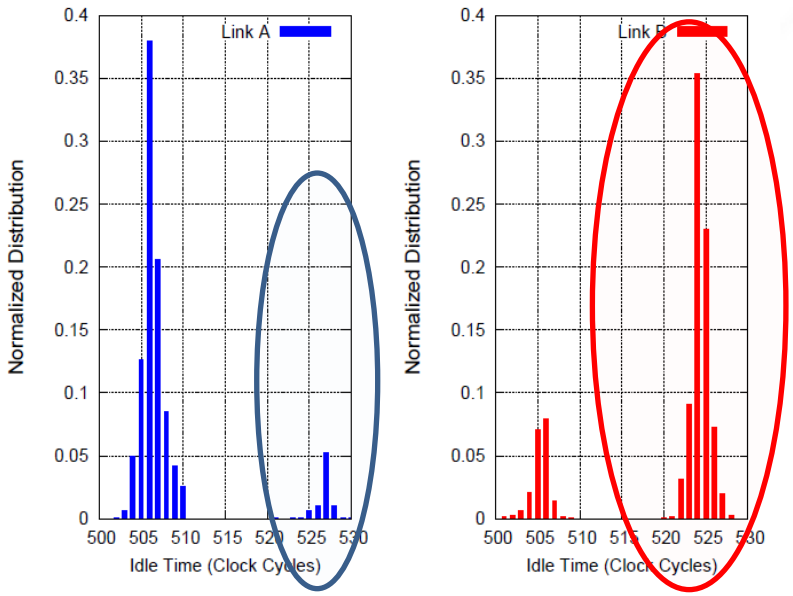


$$t_{MACidle}=2t_p + t_{SIFS}+t_{FD}$$

$$d=c\cdot(t_{MACidle}-t_{SIFS}-t_{FD})/2$$

More details

- $t_{MACidle}$ distribution is bimodal
  - → two spikes on the same link
  - ≈ 20 clock cycles
  - link A: 2nd spike at lower SNR
  - link B: 2nd spike at higher SNR



Frame detection time

$t_{MACidle}$ is a function not only of the distance, but also of the SNR of the received ACK from the remote station

$$t_{MACidle} = f(TOF, SNR)$$

$$t_{MACidle} = 2t_p + t_{SIFS} + t_{FD}$$

$$t_{FD} = f(SNR)$$

?

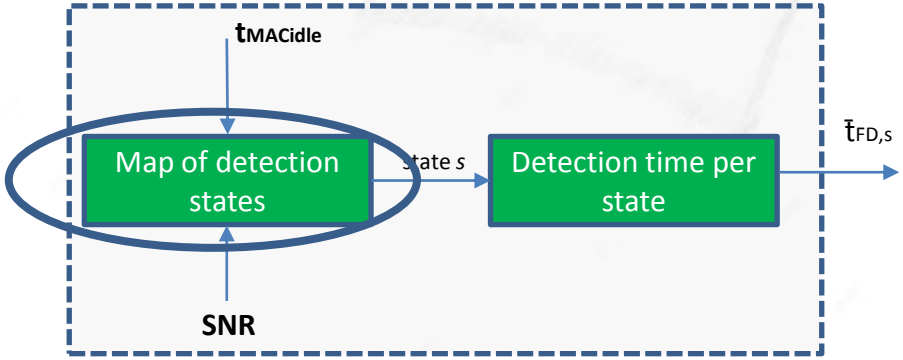
Automatic gain control

- When ACK is received, medium is declared busy:
  1. after the *energy* of ACK frame has been detected
  2. signal gain adjusted by the *Automatic Gain Control*
     - *function of the SNR*

AGC and SNR

- When the received signal is within a preferred range
  - PR: no operation (gain control) by the AGC
- For signals out of PR range
  - SSD = strong signal detection
  - WSD = weak signal detection
- SSD/WSD: AGC tunes the signal level to the desired range
  - *delay* in the ACK detection

Using the detection time for ranging estimates



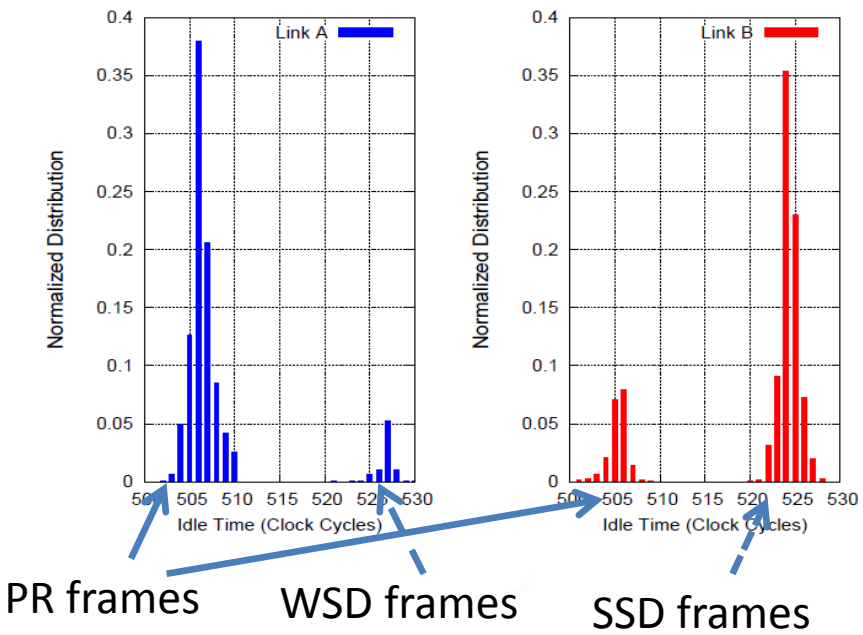
$$t_{MACidle} = 2t_p + t_{SIFS} + \bar{t}_{FD,s}$$

$$d = c \cdot (t_{MACidle} - t_{SIFS} - \bar{t}_{FD,s})/2$$

- Multiple samples are then smoothed

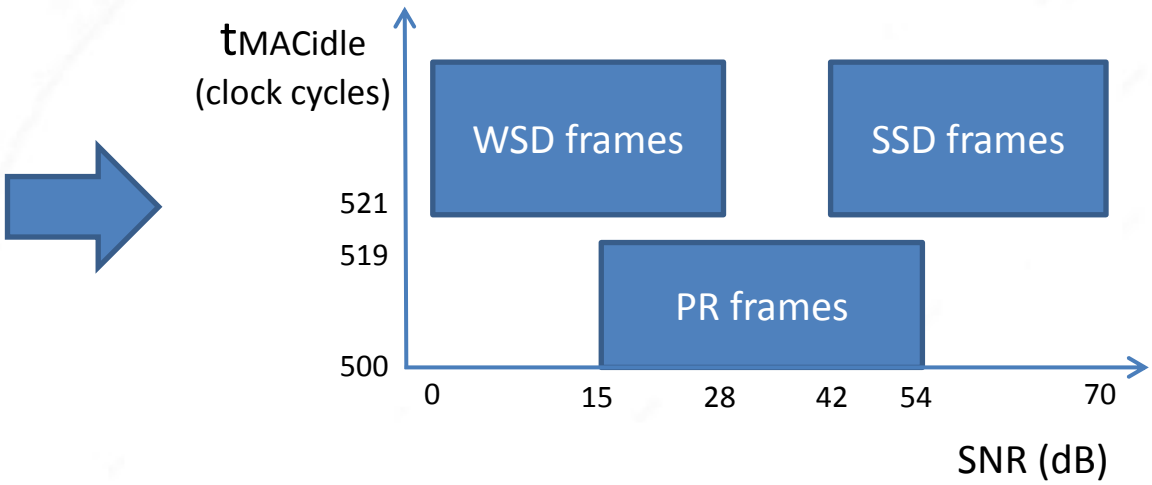
Map of detection states

- Based on MAC idle time and SNR
  - Frames are associated to states
  - each frame is classified in WSD, PR or SSD state

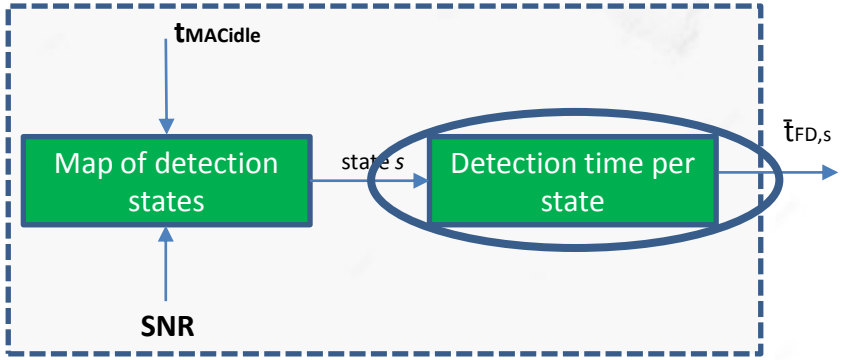


Map of detection states

- Several tests, measurements of $t_{MACidle}$ and SNR
- We distinguish 3 different regions/states



Using the detection time for ranging



$$t_{MACidle} = 2t_p + t_{SIFS} + \bar{t}_{FD,s}$$

$$d = c \cdot (t_{MACidle} - t_{SIFS} - \bar{t}_{FD,s})/2$$

Using the ACK detection time for ranging

- the average detection time per state is used to estimate the distance

$$t_{MACidle}=2t_p + t_{SIFS}+\bar{t}_{FD,s}$$
$$d=c\cdot(t_{MACidle}-t_{SIFS}-\bar{t}_{FD,s})/2$$

- PR frames: t_{FD} is only due to preamble detection
  - ~ *2 OFDM short symbols* was measured
- SSD and WSD frames: A longer t_{FD}
  - L-STA AGC varies the amplifier gain of the ACK signal
  - *an additional delay of ~ 0.4 us* was measured

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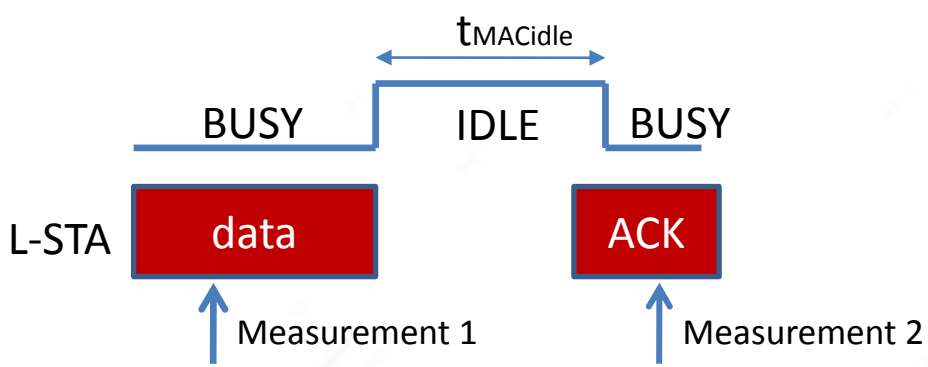
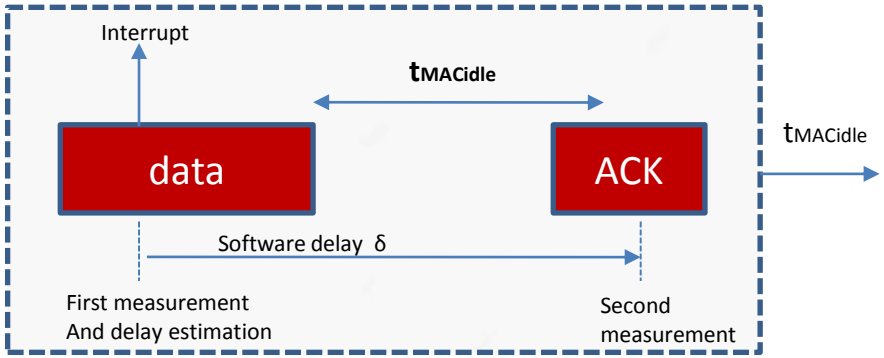
Problem: Measuring the Idle Time

- Channel state transitions
  - Occur only twice between the data and the ACK
    - At the end of the data transmission
    - When the ACK is received
  - We *don't* need to continuously monitor the idle time
- Measuring the channel in two instants of time:
  1. when data transmission is ongoing
  2. when ACK reception is ongoing



Not trivial to implement

- not trivial to implement
  - $t_{MACidle}$ occurs in *very short period of time (<12us)*
  - the ACK duration is in the order of tens of secs
- we require a fine-grained detection of the time of ongoing data transmission and ACK reception



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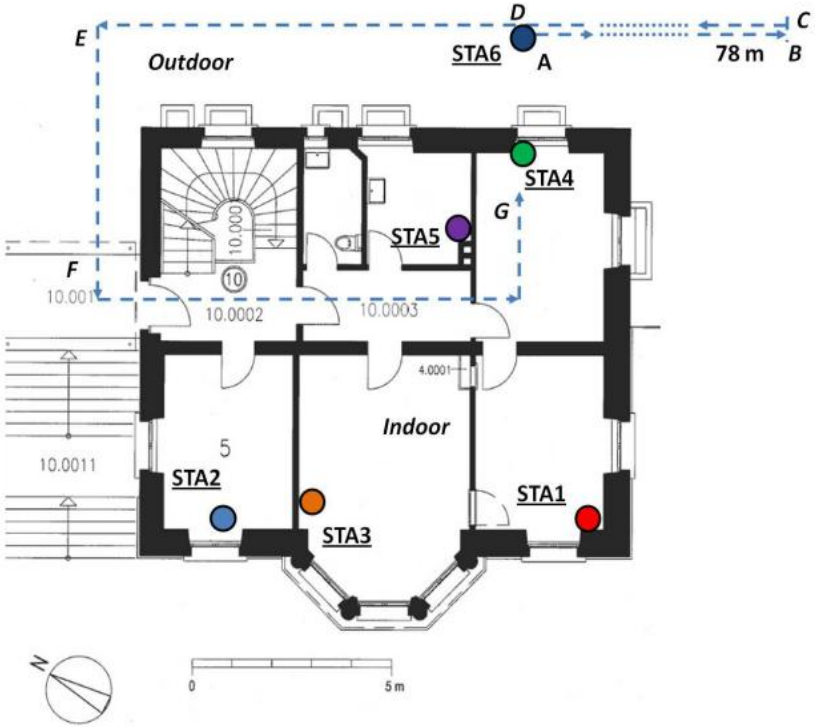
Map of evaluation



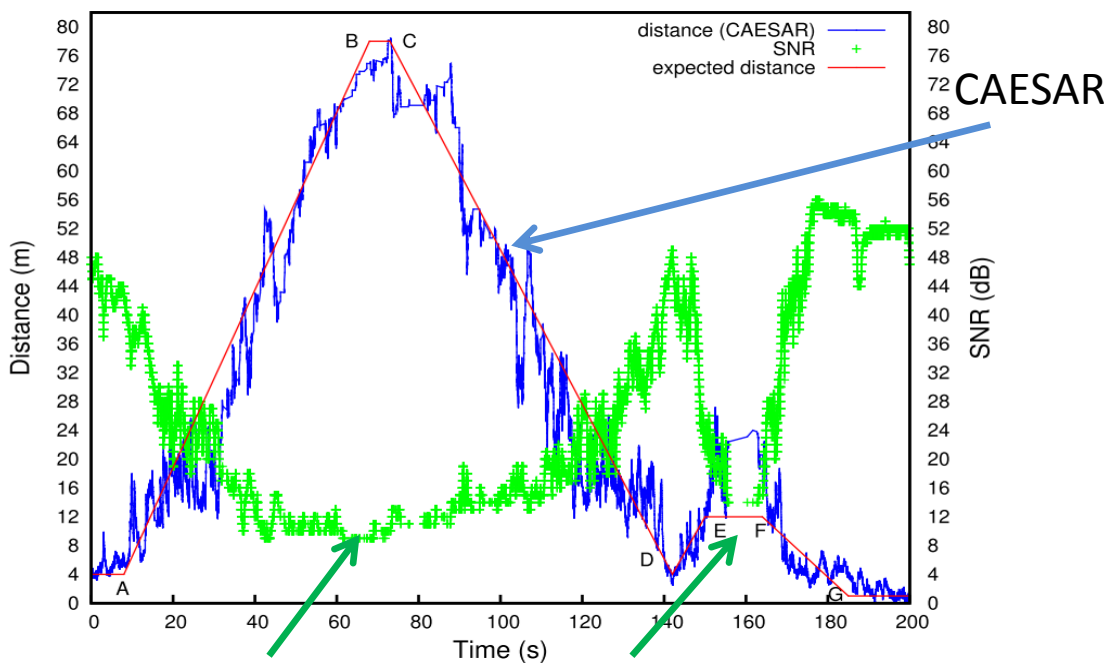
- STA1-STA5, WLAN Atheros chipset
- STA6, “HTC magic” smartphone

Indoors

- Average errors of < 1 m
  - in 8 links out of 10
- Absolute error of < 2 m after fewer than 25 samples
  - in 9 links out of 10

Tracking

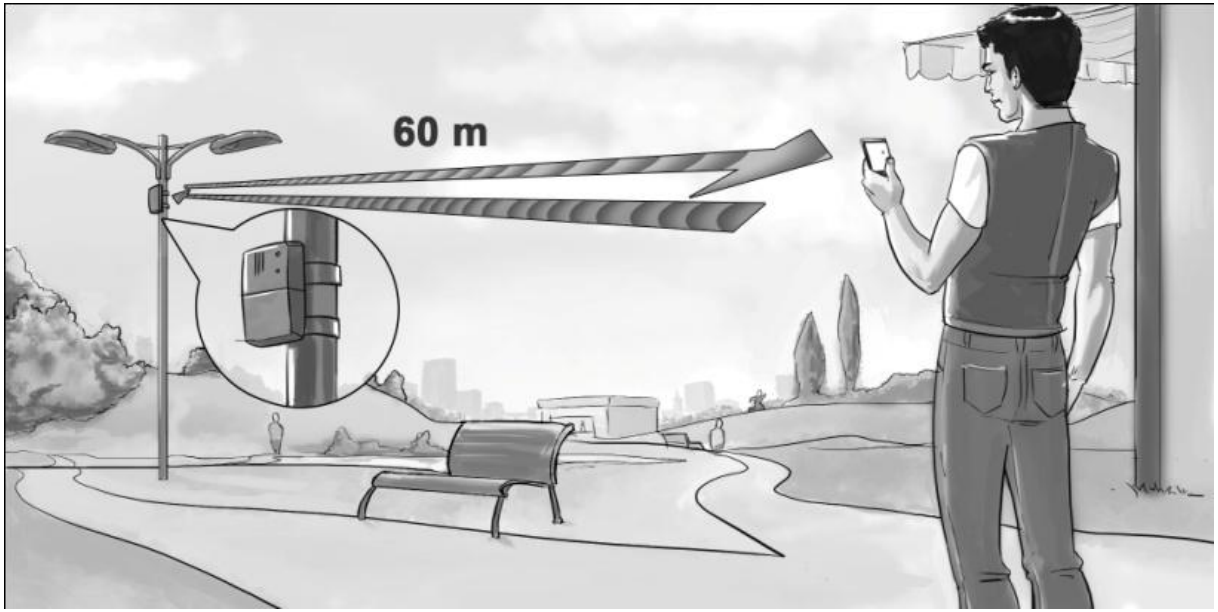
- 7 positions: A,B,…G
- CAESAR tracks the distance to a moving smartphone
- SNR is not a reliable indicator of distance



SNR= (similar values for different distances)

Conclusion

- Ranging technique is crucial in navigation system
- CAESAR measures the distance to remote WLAN devices
  - Key ideas based on MAC protocol operations for communication
  - high accuracy, high convergence, no changes in the network protocol, no offline calibration,…
- Effective technique to use in off-the-shelf devices



thank you for your attention !