Bridging Link Power Asymmetry in Mobile Whitespace Networks

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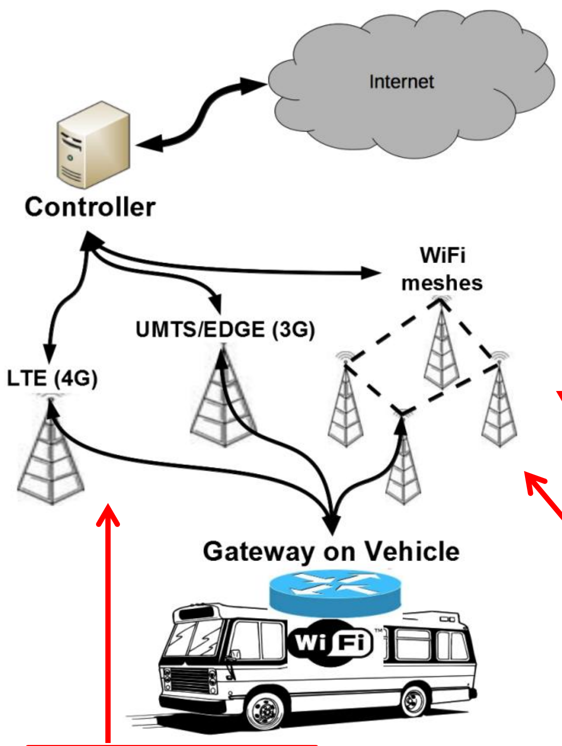
Wireless Access in Vehicles

- Wireless network in public vehicles use existing infrastructure (WiFi/3G/LTE) to enable internet access
- Single hop range is limited while delay in mesh network can be substantial



Limited range in single hop

Large delay in WiFi meshes

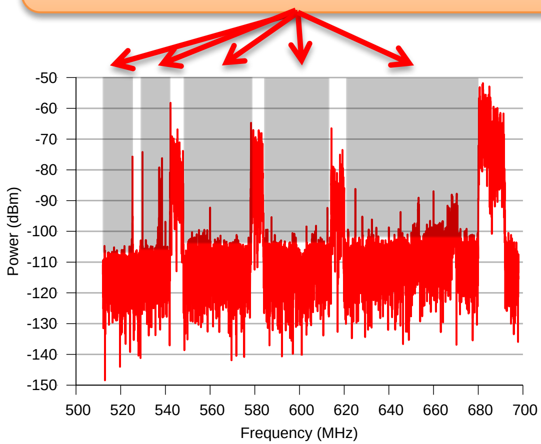
Licensed!

- 3G/LTE can provide good coverage but it is not free!

New Opportunity in TV Whitespaces

- Unlicensed access in TV Whitespaces

Vacant TV Channels



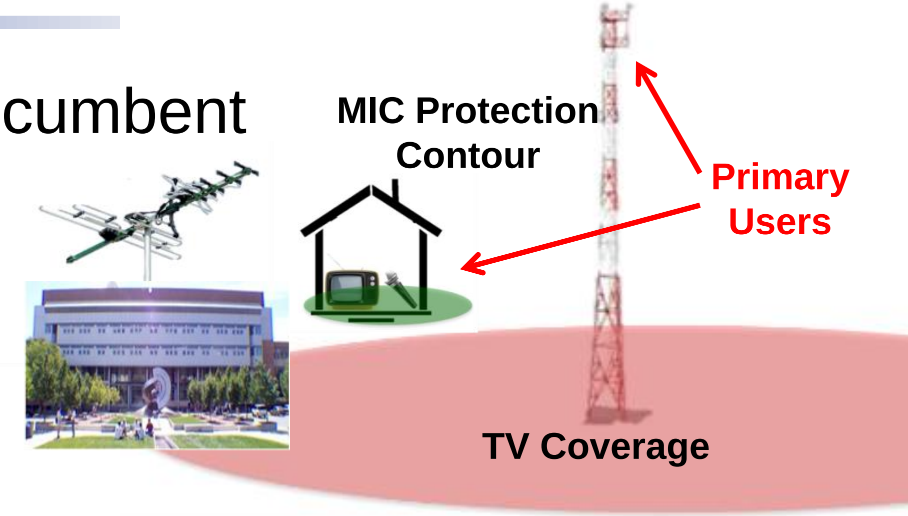
FCC OPENS TV WHITESPACES FOR UNLICENSED USE,

November 2008

- Advantages
  - Good propagation range in lower frequency (470 – 608 & 698 - 806 MHz)
  - Large unused spectrum resource after analog to digital TV broadcast transition
  - Zero license fee and low infrastructure cost

Unlicensed Access Rule of FCC

- No interference to primary incumbent
  - Whitespace devices can not transmit on the same & adjacent channels to primary users

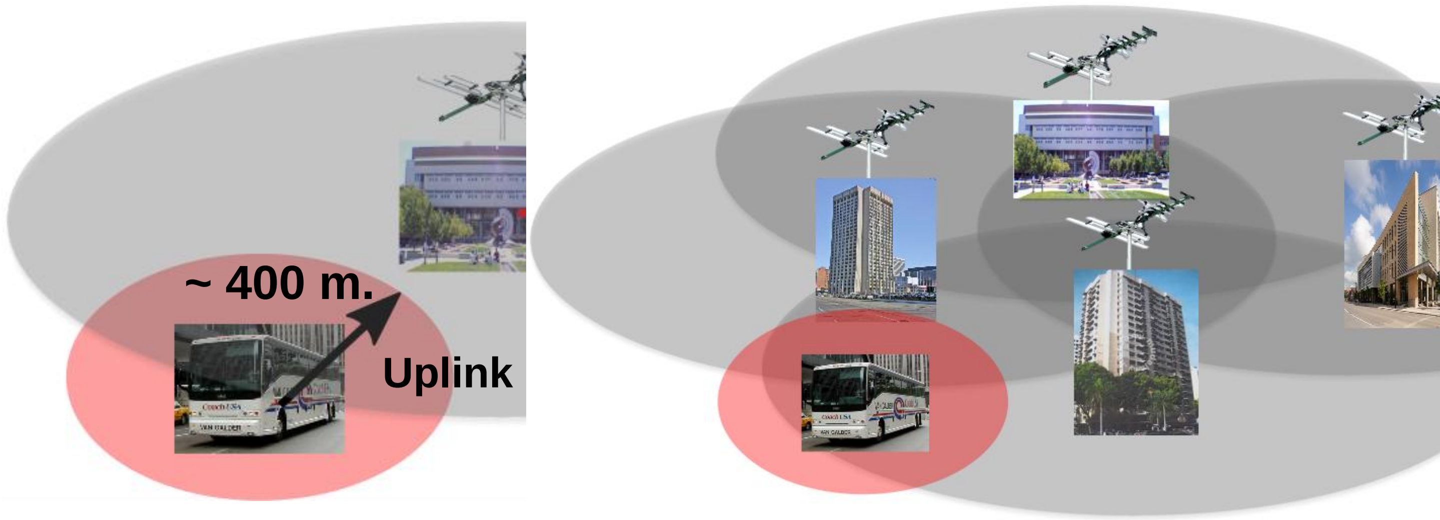


- Large power asymmetry for mobile clients
  - Static TV whitespace AP can transmit with max. 4 W power, mobile client are constrained to only 100 mW!
  - The conservative limit aims to prevent mobile devices to create excessive interference to primary users during roaming

Our work focuses on solving the issues due to power asymmetry

Challenges with 40x Power Asymmetry

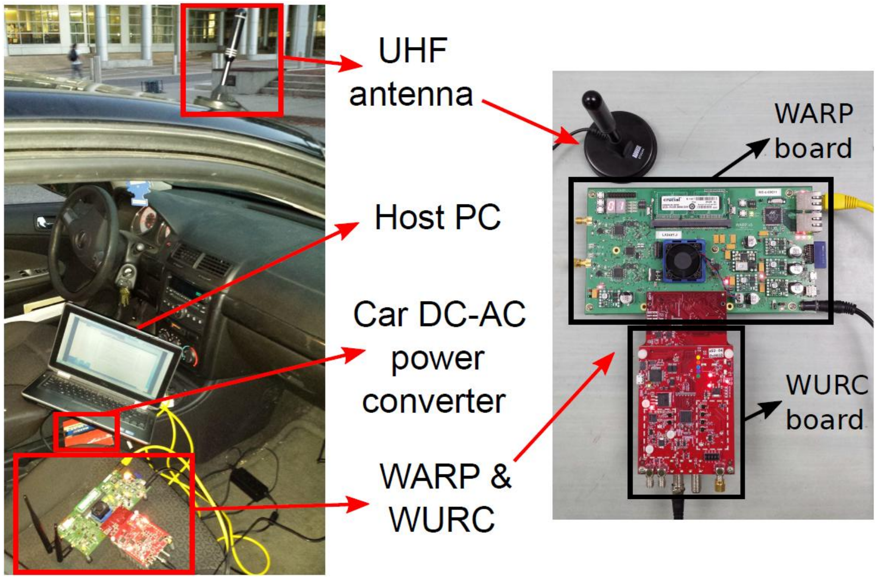
- Downlink and uplink range asymmetry
  - Power asymmetry creates ~5x range asymmetry, uplink becomes the connectivity bottleneck and often blacks out



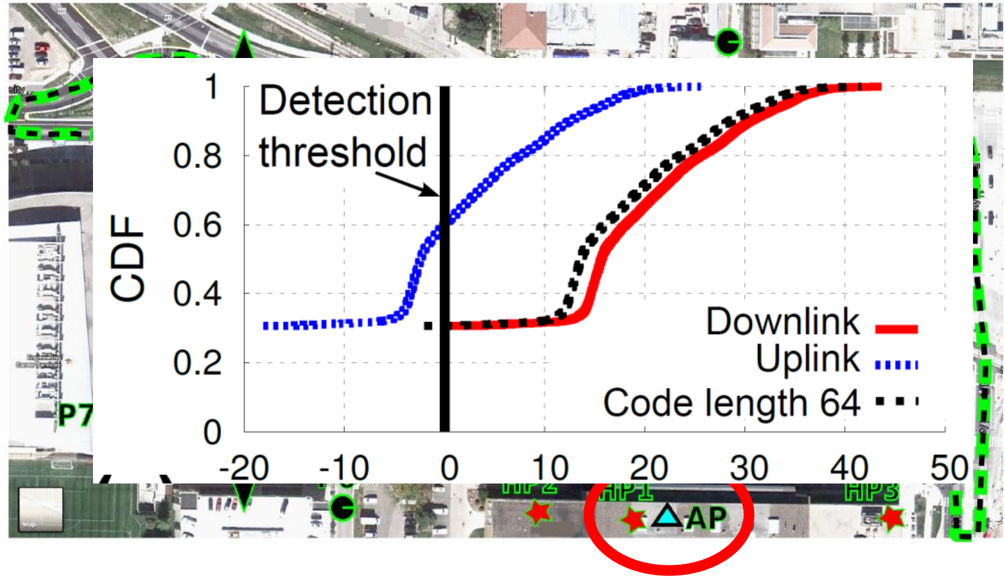
  - Increased infrastructure cost and reduced downlink range of each AP with multiple AP deployment

Challenges with 40x Power Asymmetry

- Downlink and uplink range asymmetry
  - AP is mounted on top of Engineering Hall @ UW - Madison and client is placed inside a car, which we drive along the track



TV Whitespace software-radio platform

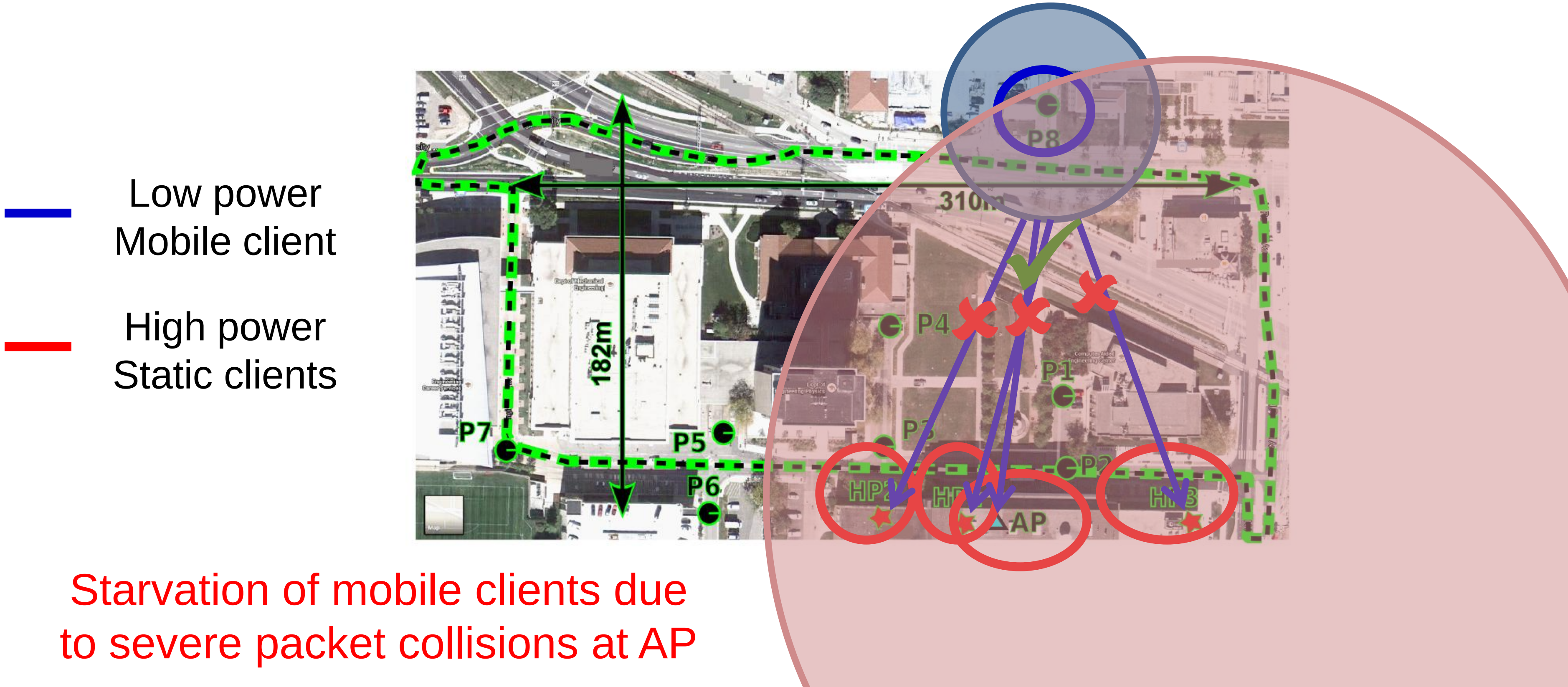


Outdoor driving region

  - Around 60% of uplink packets are not detected by AP with only 37% of the detected packets are successfully decoded

Challenges with 40x Power Asymmetry

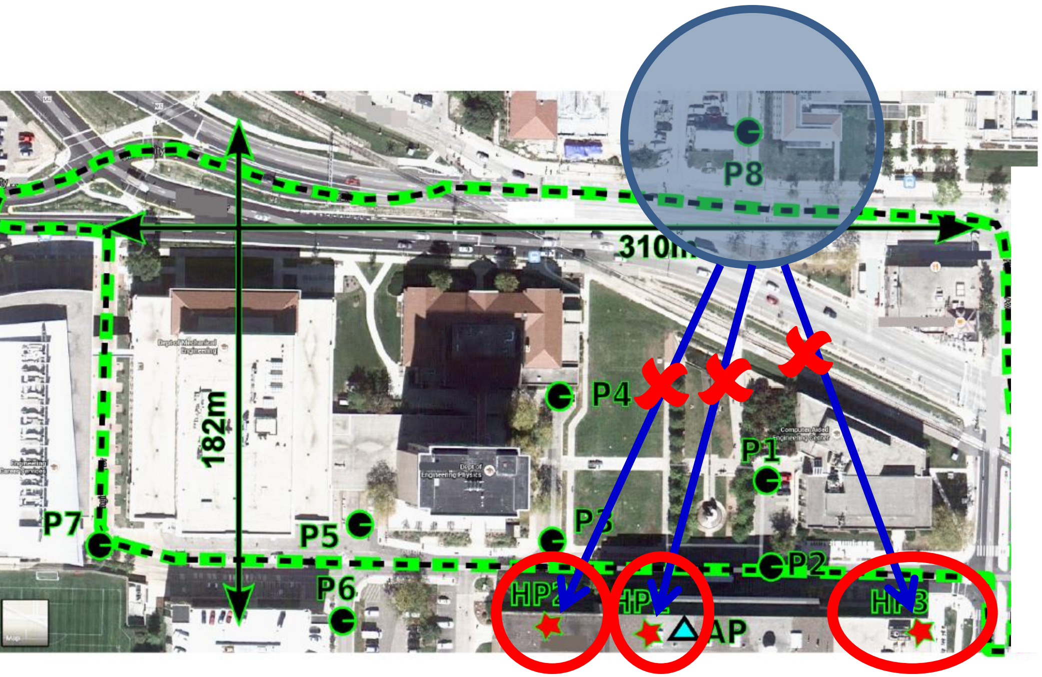
- Starvation of mobile clients
  - Power asymmetry rule is applicable to only mobile clients, a static client can have 4 W transmission power
  - Carrier sensing loss at high power clients for uplink packets of mobile clients may starve it from accessing channel

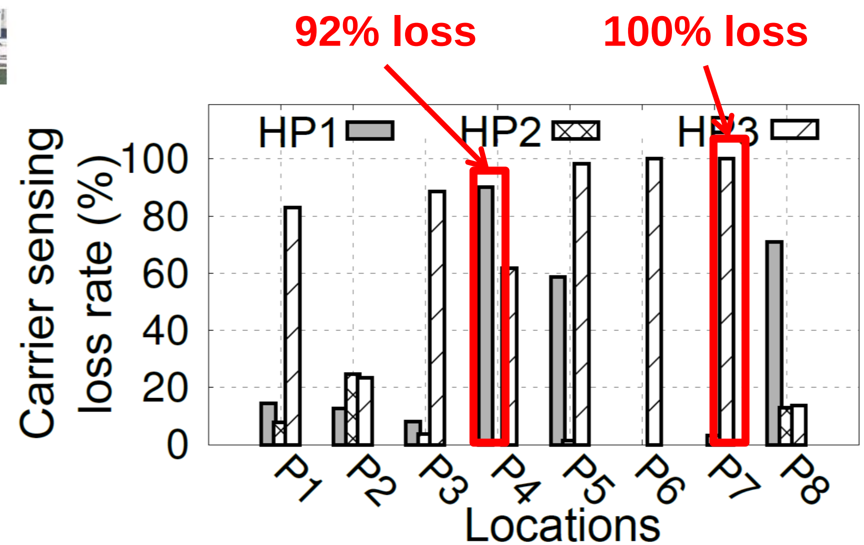


Starvation of mobile clients due to severe packet collisions at AP

Challenges with 40x Power Asymmetry

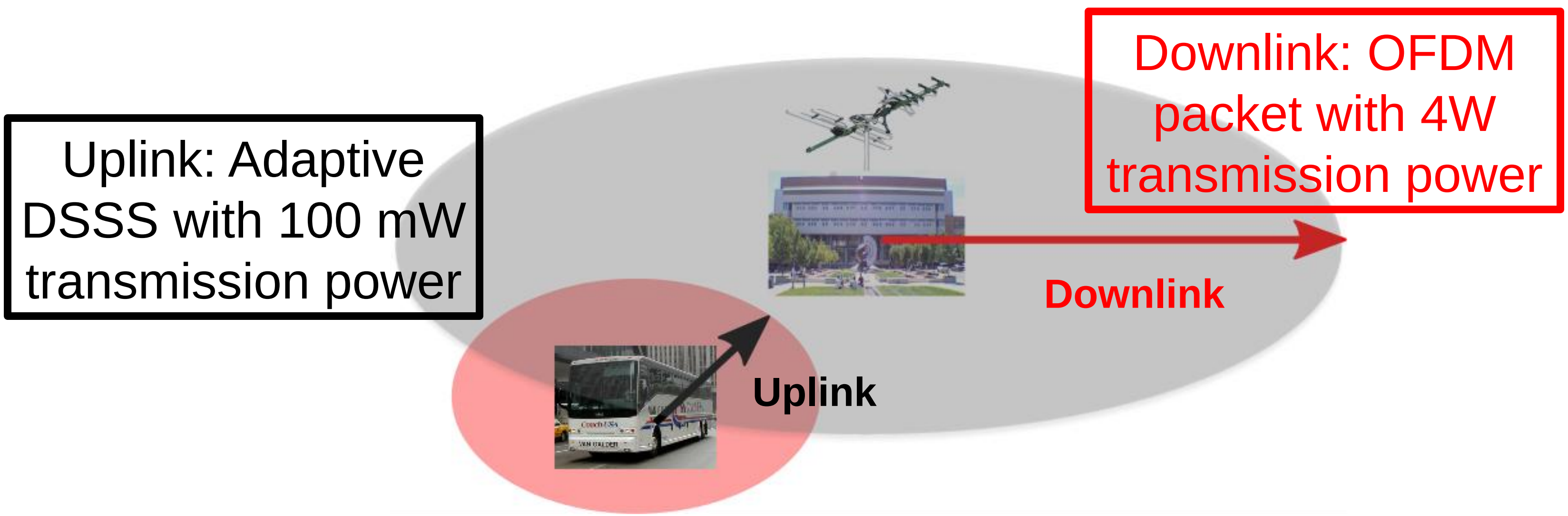
- Starvation of mobile clients
  - Severe carrier sensing loss at high power clients from the low power mobile clients





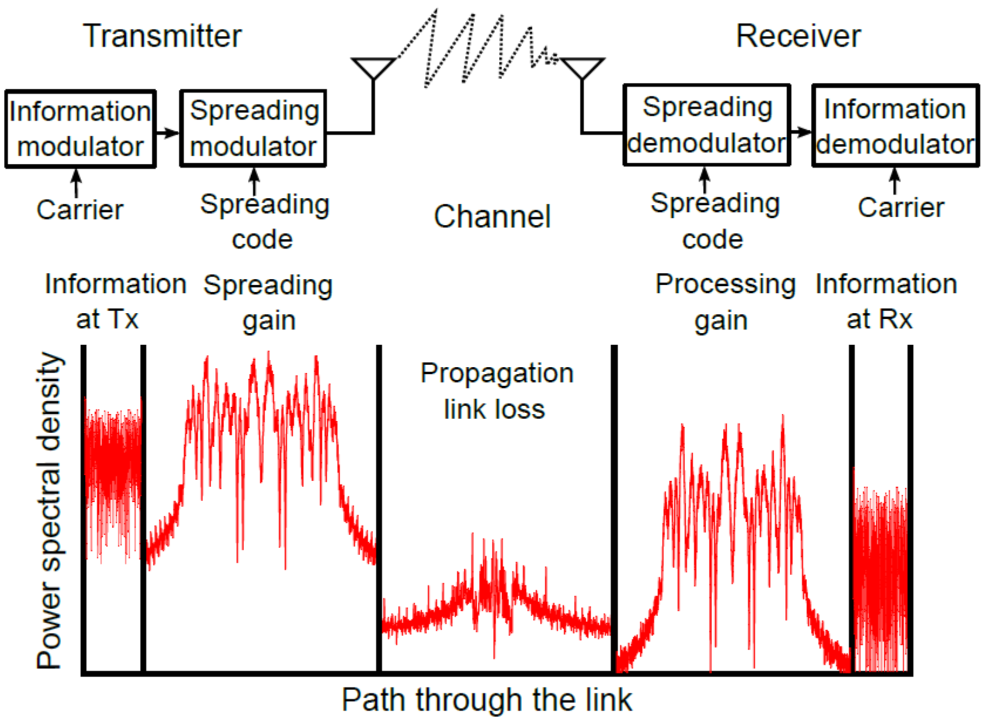
Our Design: Adaptive DSSS

- Extend uplink range through adaptive DSSS modulation
  - Modulate uplink packets with Direct-Sequence Spread Spectrum (DSSS) codes
  - Adapt packet-level DSSS code assignment to match the 40x asymmetry
- Downlink still uses traditional OFDM modulation
  - The access points are still compatible with TV Whitespace standard IEEE 802.11af



Why DSSS can extend uplink range?

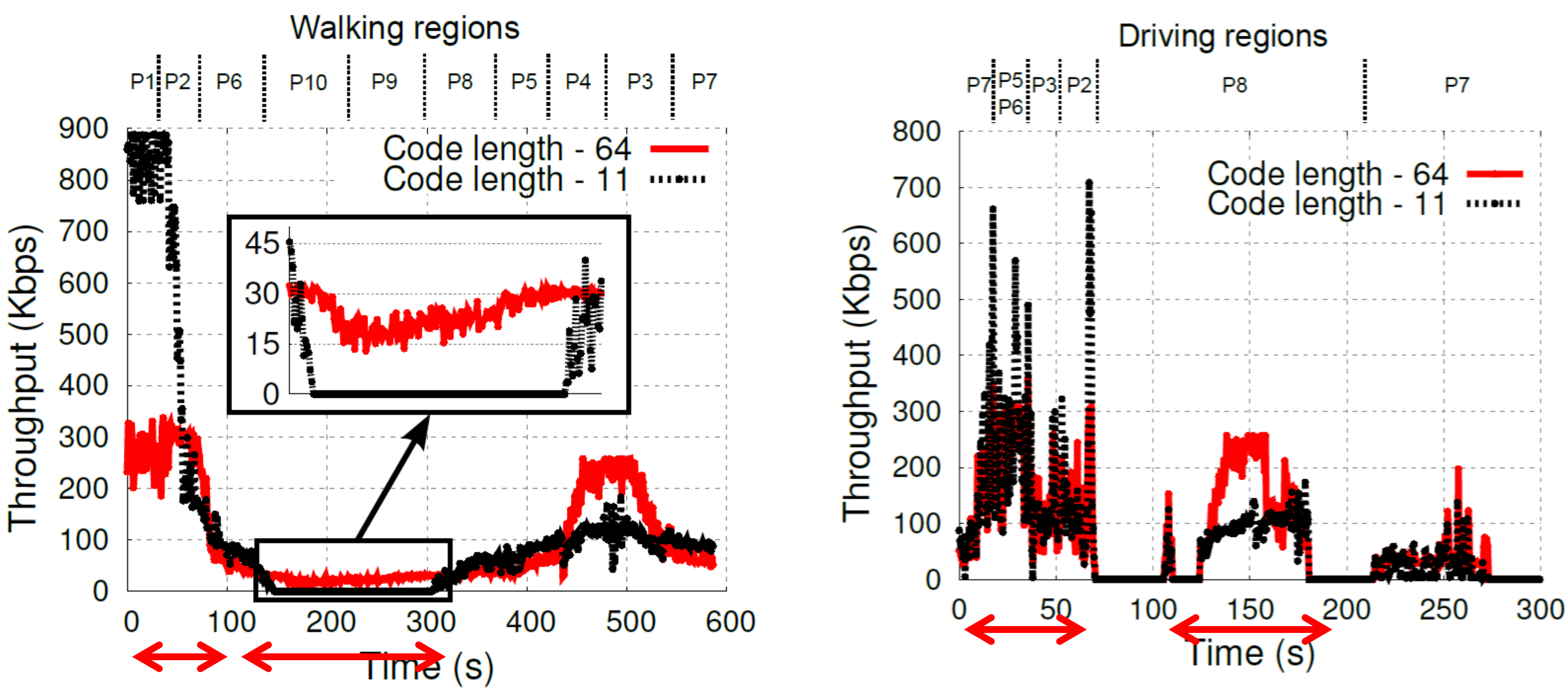
- DSSS communication primer
  - At transmitter, information symbols get *spread* over multiple chips that provides resistance from noise and multipath distortions



  - At receiver, a matched filter *de-spreads* received signals correlating with the spreading code. This provides an extra processing gain
  - Ideally, a spreading code of length *N* can provide processing gain of *N* times and boosts received SNR by 10*log10(*N*) dB

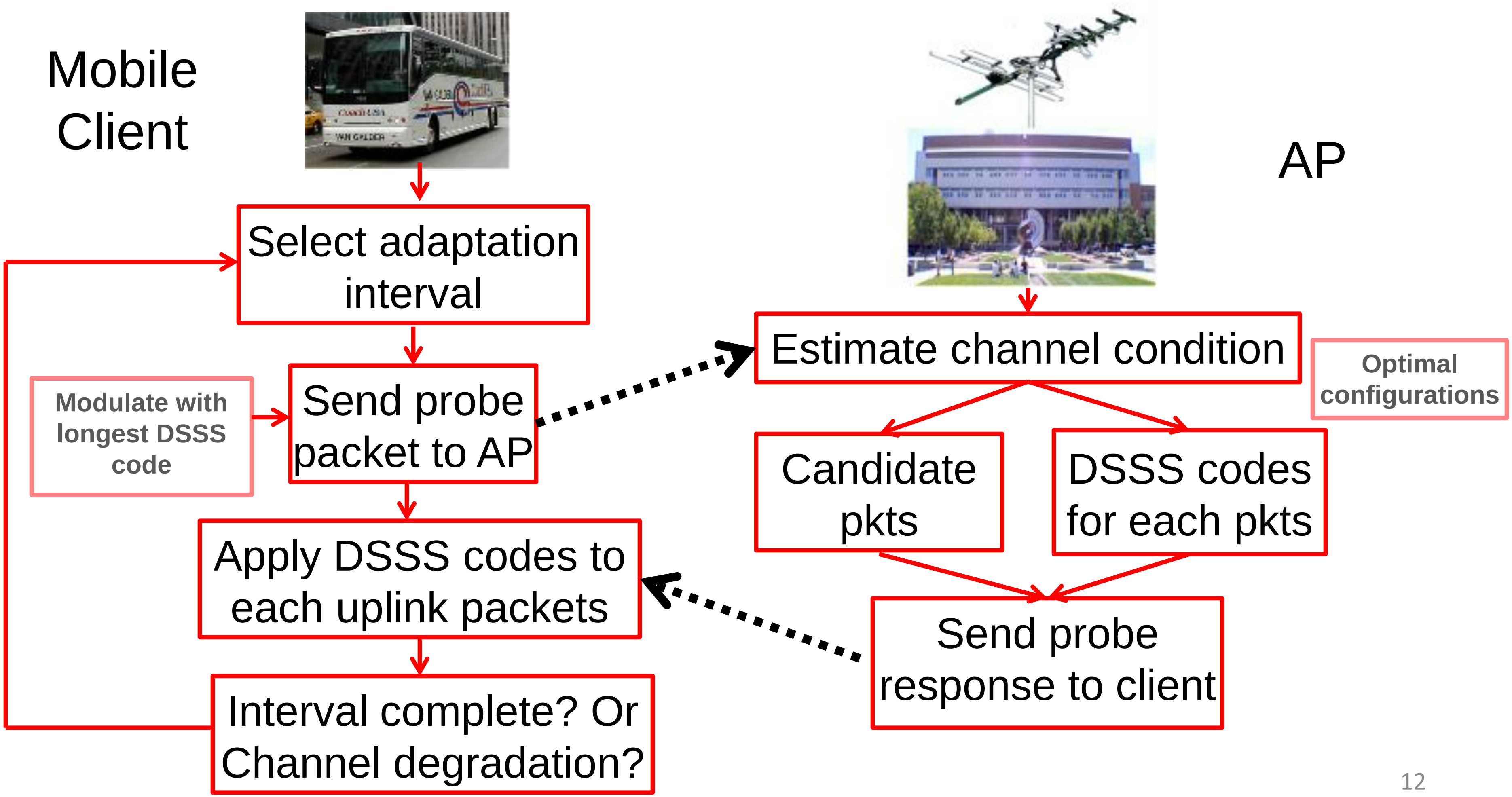
The Need for Adapting Code Length

- Balancing coverage and throughput
  - Long DSSS codes increases channel time for useful information symbol and thus reducing throughput
  - Different choice of code length can result in higher performance, depending on the channel condition



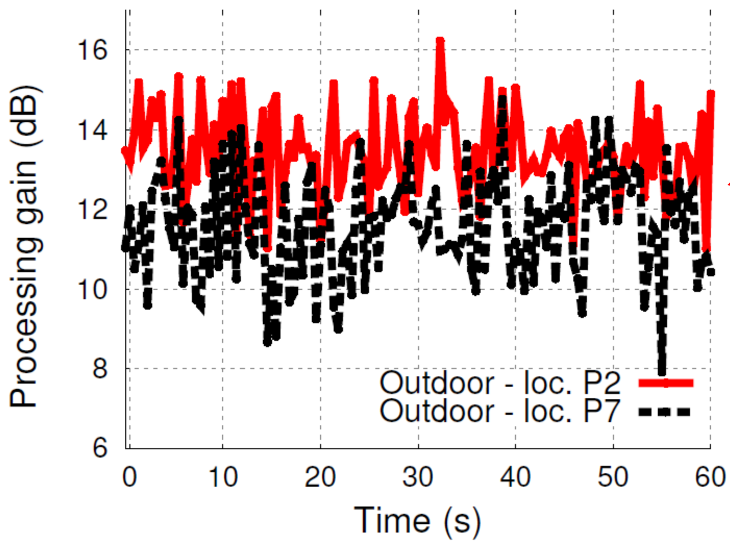
Our Design: Adaptive DSSS

- Extend uplink range through adaptive DSSS modulation
  - Adapt packet-level DSSS code assignment on basis of intervals



Adaptive DSSS design: Estimating Processing Gain under Channel Condition

- Processing gain from a DSSS code depends on the channel condition

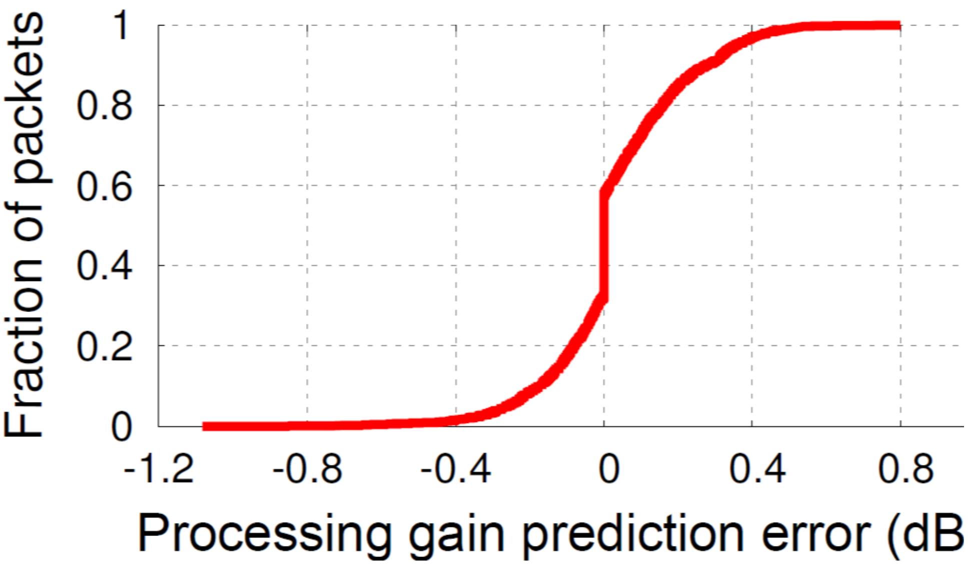


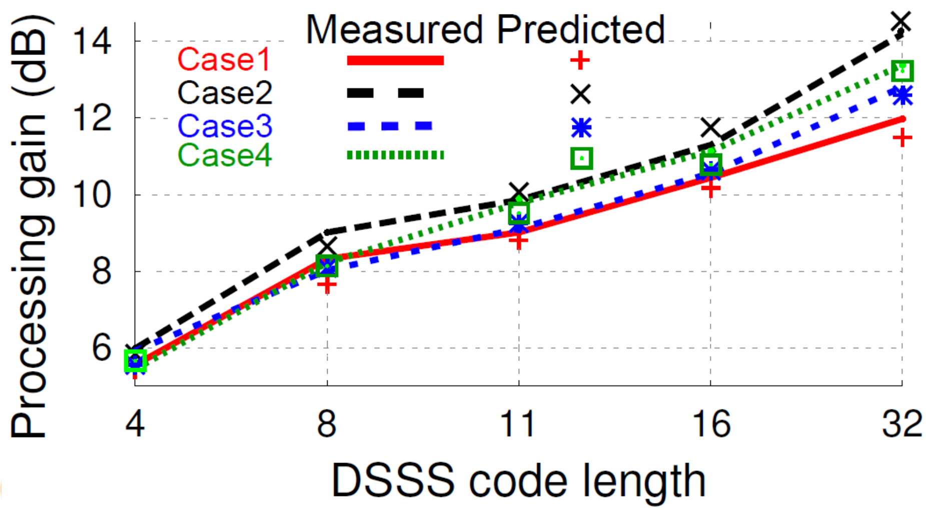
64-bit spreading, ideal processing gain = 18 dB

- How does AP know the best DSSS code at certain channel condition?
  - Observation: Channel condition affects processing gain of all DSSS codes similarly
  - Extract feature of channel condition from a few DSSS codes and use it to predict the processing gain of other DSSS codes

Adaptive DSSS design: Estimating Processing Gain under Channel Condition

- Processing gain prediction accuracy
  - Measurement and estimation across 8 fixed locations in outdoor with 10K packets in each locations





95th percentile prediction error is within ±0.8 dB

High consistency of prediction across multiple locations

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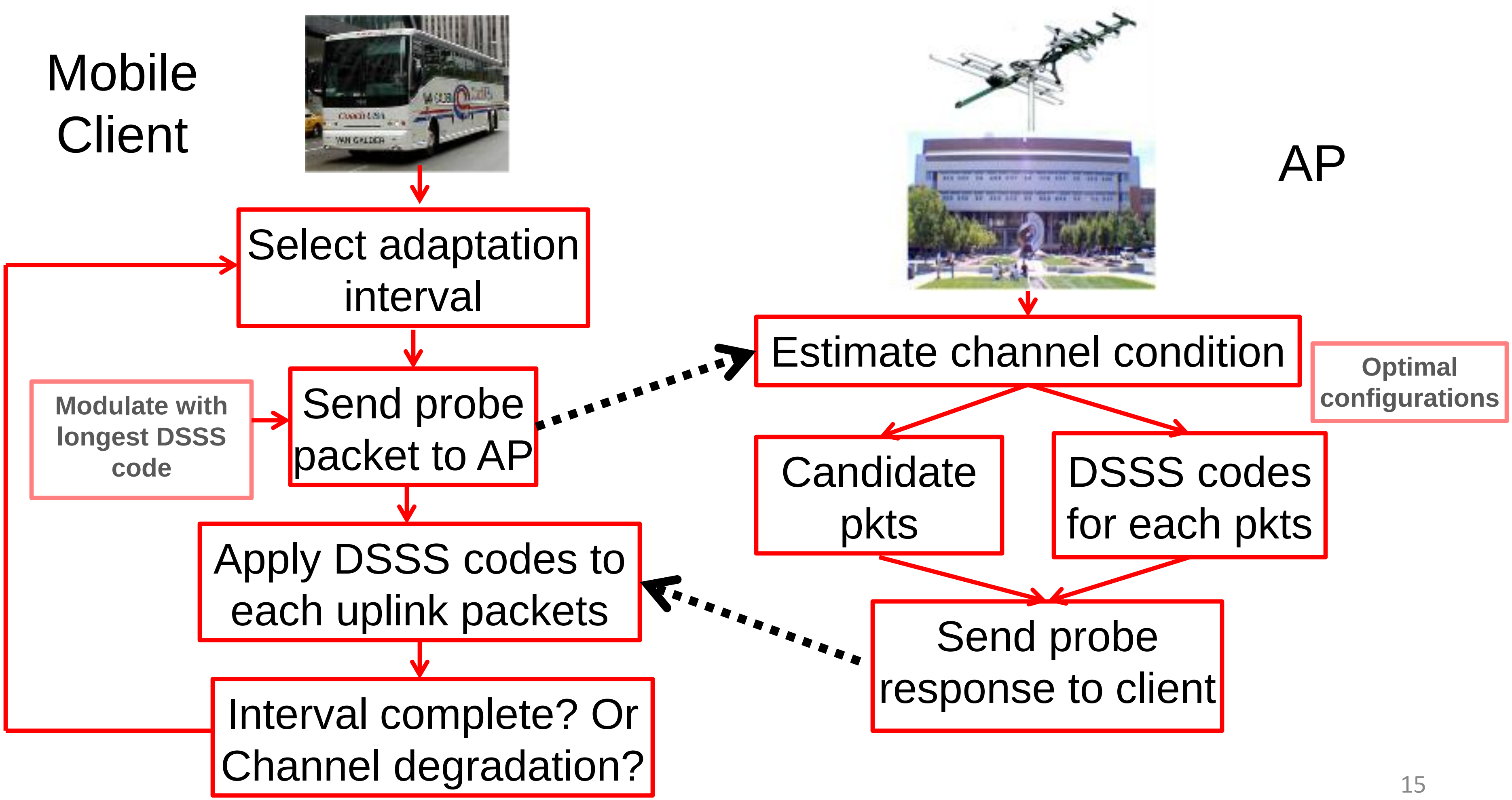

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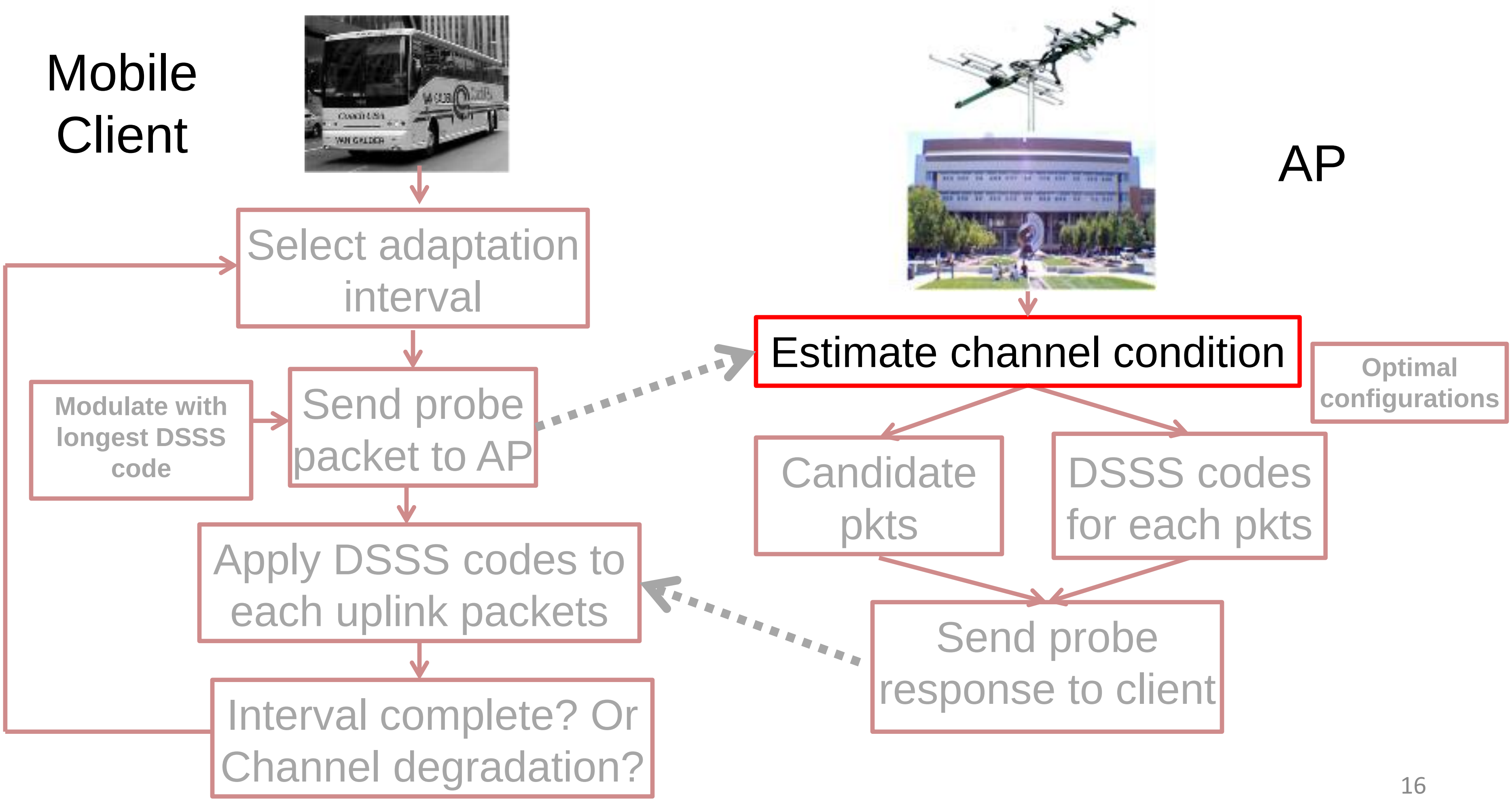

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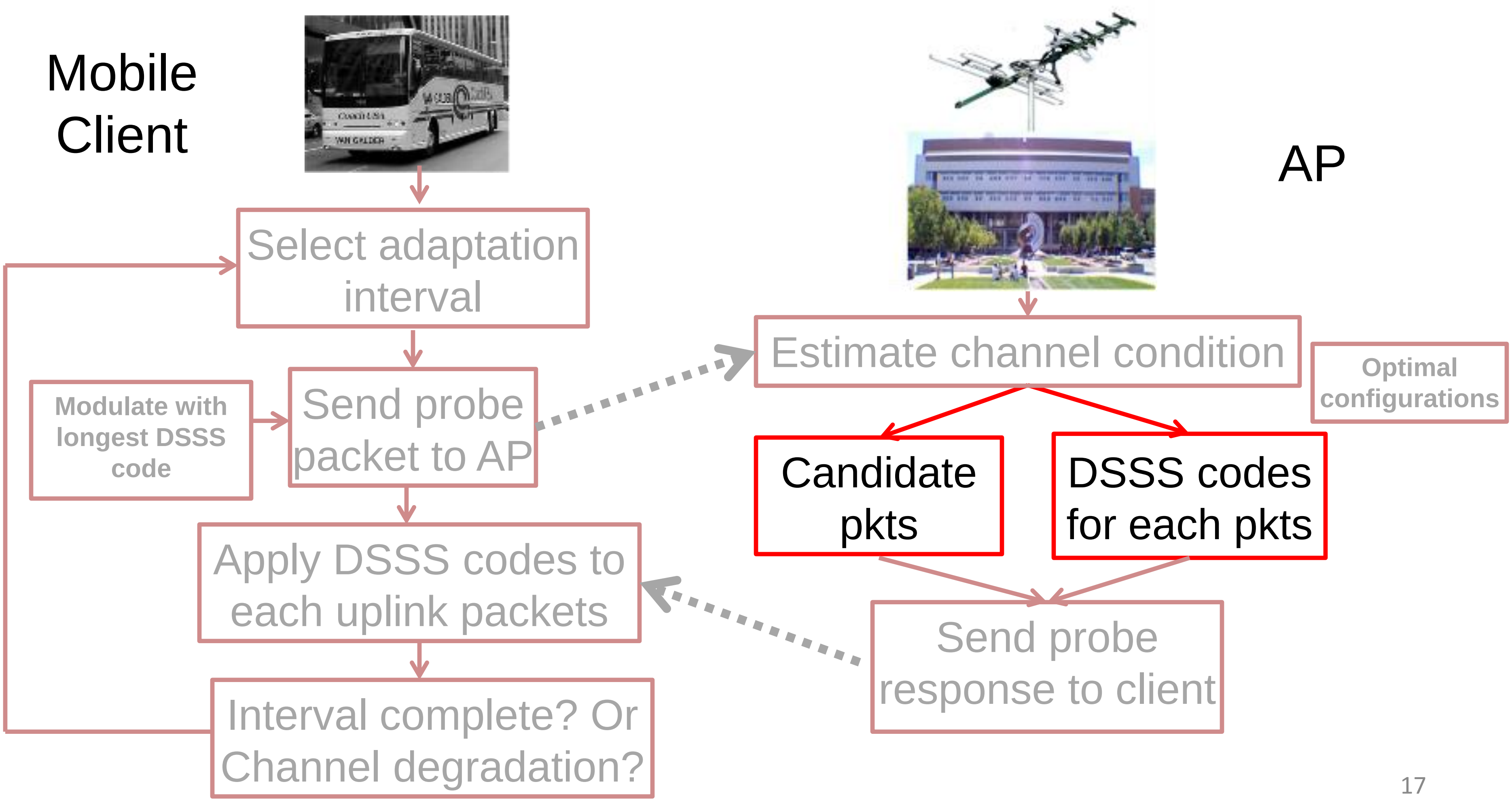
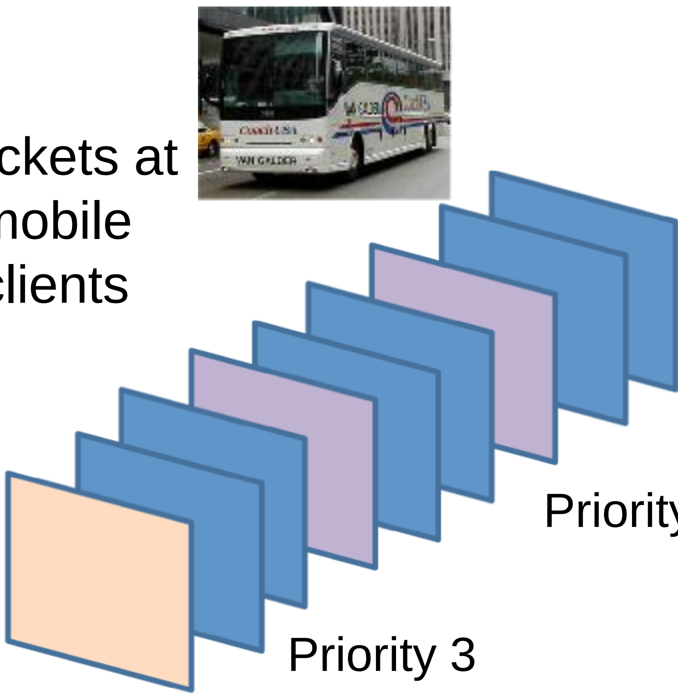


Adaptive DSSS design: Code assignment

- Traffic-aware code length adaptation



  - Not all packets are created equal
  - Critical packets (e.g. safety info, GPS update) have higher priority in receiver than throughput-sensitive (e.g. download requests, web browsing, video streaming)
  - Certain loss-tolerant packets, may prefer less reliable short code in order to meet their own requirements, while making room for other critical packets

Adaptive DSSS design: Code assignment

- Traffic-aware code length adaptation

Pac

mobil

Guarantee the delivery of important packets, while maximizing the channel utilization

receiver than throughput sensitive

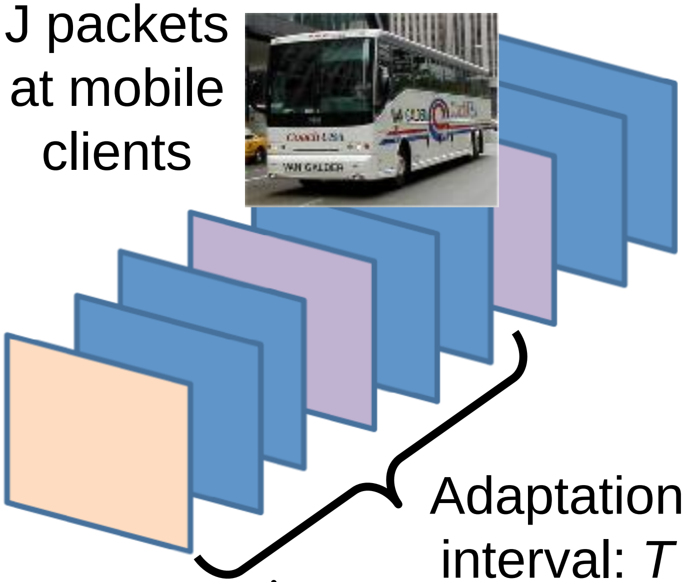
(e.g. download requests, web browsing, video streaming)

1. What packets to allow within an adaptation interval?
2. What DSSS codes to use for each packet?

for other critical packets

Adaptive DSSS design: Code assignment

- Problem formulation



Available DSSS code length: $\{n_1, n_2, \ldots, n_M\}$

Adaptation interval: $T \geq \Sigma$ Packet size/Throughput

Adaptation interval T with long DSSS codes for all packets are not enough!

↓

Apply long DSSS codes to selected packets and schedule based on priority

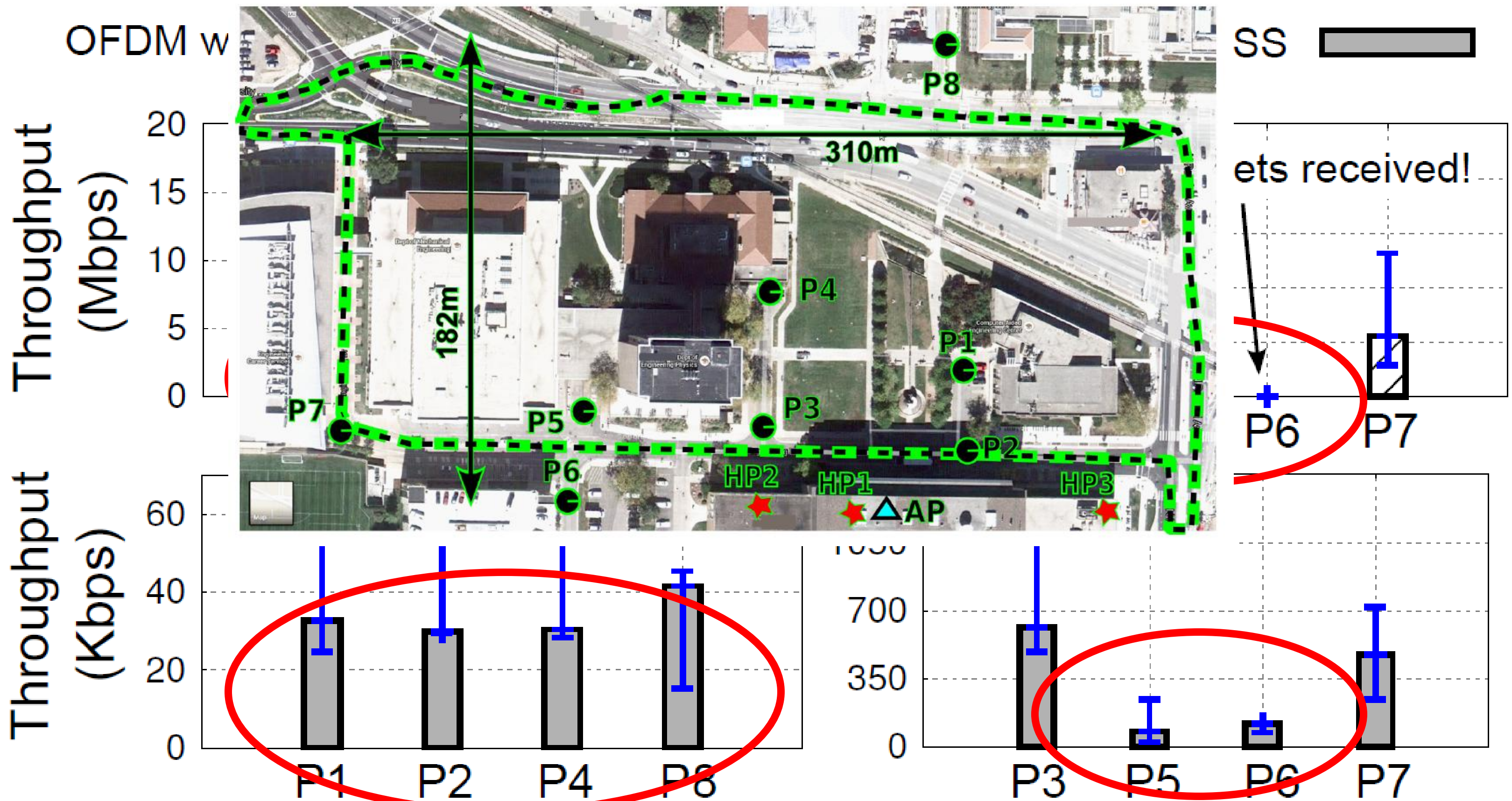
Utility: u_j^i of receiving packet j at AP using DSSS code of length n_i

Goal: Maximize the total utility received by AP, subjected to the total adaptation interval constrain

$$\max \sum_{j=1}^{J}\sum_{i=1}^{M} x_j^i u_j^i \quad \text{s.t.} \quad \sum_{j=1}^{J}\sum_{i=1}^{M} x_j^i n_i t_j \leq T \qquad x_j^i \in \{0,1\}$$

Adaptive DSSS Performance

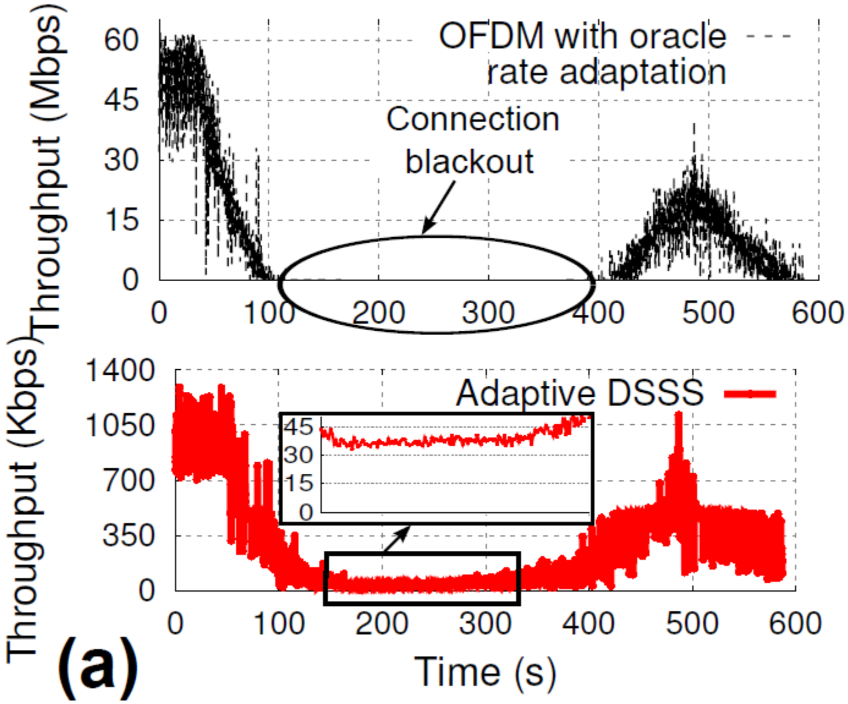
- Maintaining uplink connectivity
  - Without adaptive DSSS, from 6 out of 8 locations, the AP did not receive any packets



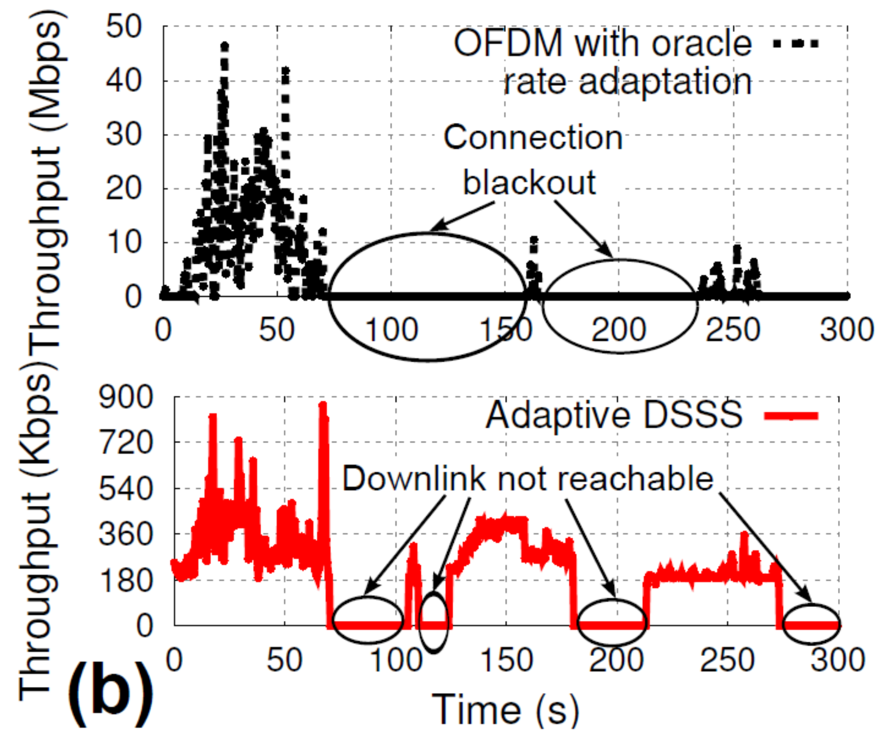
Throughput in 8 static locations in outdoor

Adaptive DSSS Performance

- Performance of code length adaptation
  - With adaptive DSSS, uplink is sustained whenever downlink is reachable
  - In contrast, OFDM can sustain the connection only for 43% of time



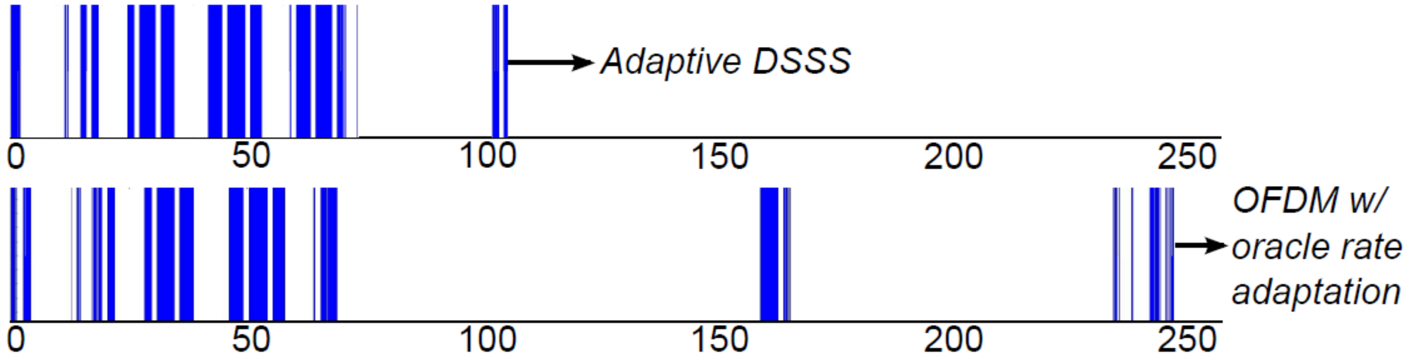
Indoor walking



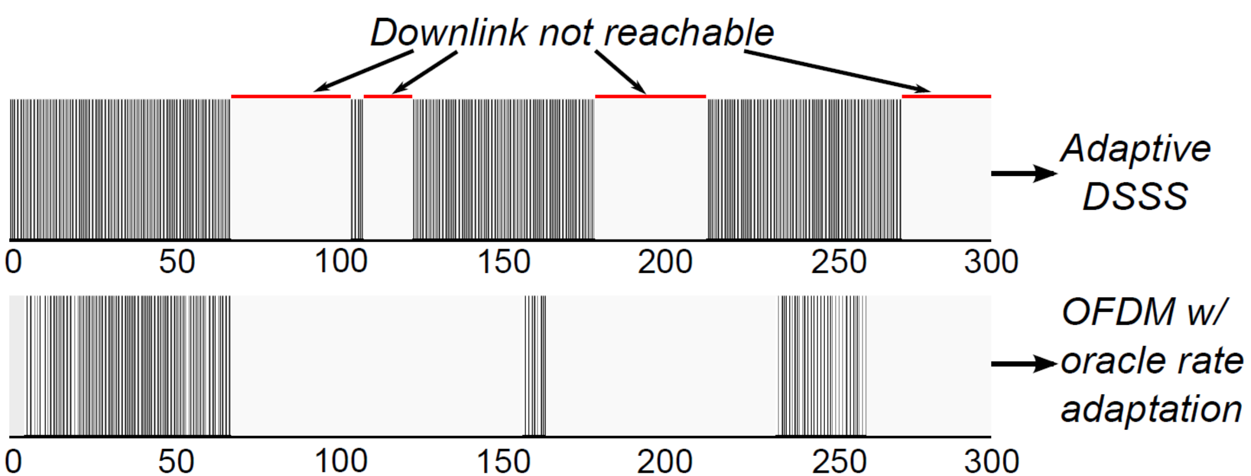
Outdoor driving

Adaptive DSSS Performance

- Traffic-aware multi-packet code assignment
  - Coexistence of real-time and non-real-time traffics



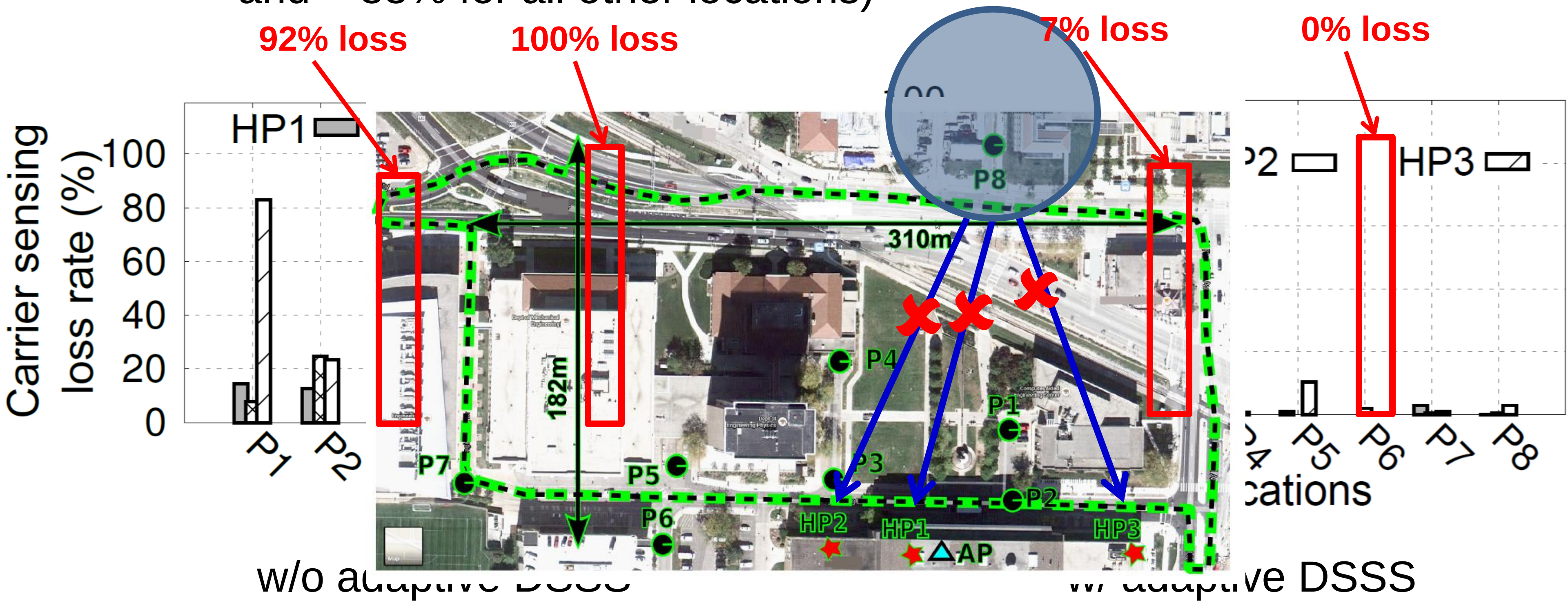
Video downloading with and without adaptive DSSS



300 s. of GPS update for outdoor driving with and without using adaptive DSSS

Adaptive DSSS Performance

- Performance in presence of high power fixed clients
  - Carrier sensing loss rate is reduced on average 85% (67% for P1 and > 88% for all other locations)



Reduction in carrier sensing loss rate at high power client nodes reduces the starvation of mobile clients as it gives more fair access to channel usage

Conclusion

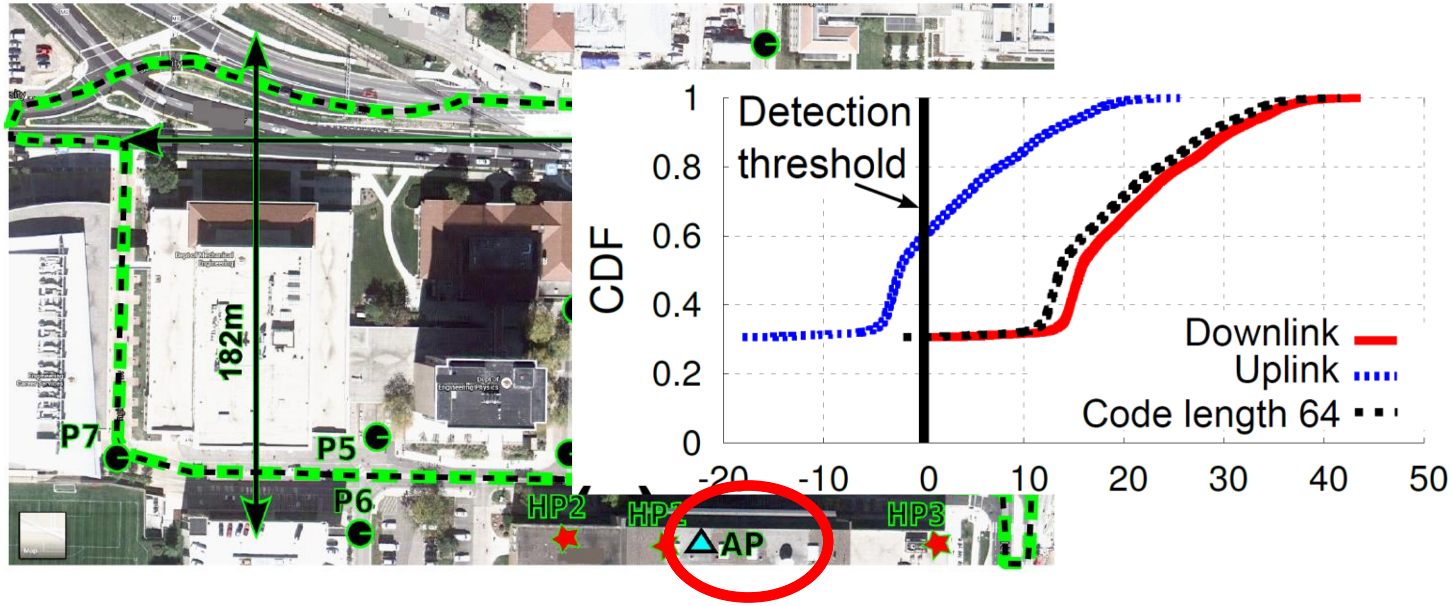
- TV whitespaces provide good opportunity in enabling long range unlicensed communication in unused TV bands
- 40x power asymmetry rule from FCC causes severe uplink blackouts and starvation in mobile clients
- Our adaptive DSSS design rethinks existing spread spectrum based system to bridge the power asymmetry

Thank you!

Backup slides

Challenges with 40x Power Asymmetry

- Downlink and uplink range asymmetry
  - The transmission power of AP and client is calibrated as per the FCC rule
  - Measured downlink and uplink packet detection & decoding distribution around the track



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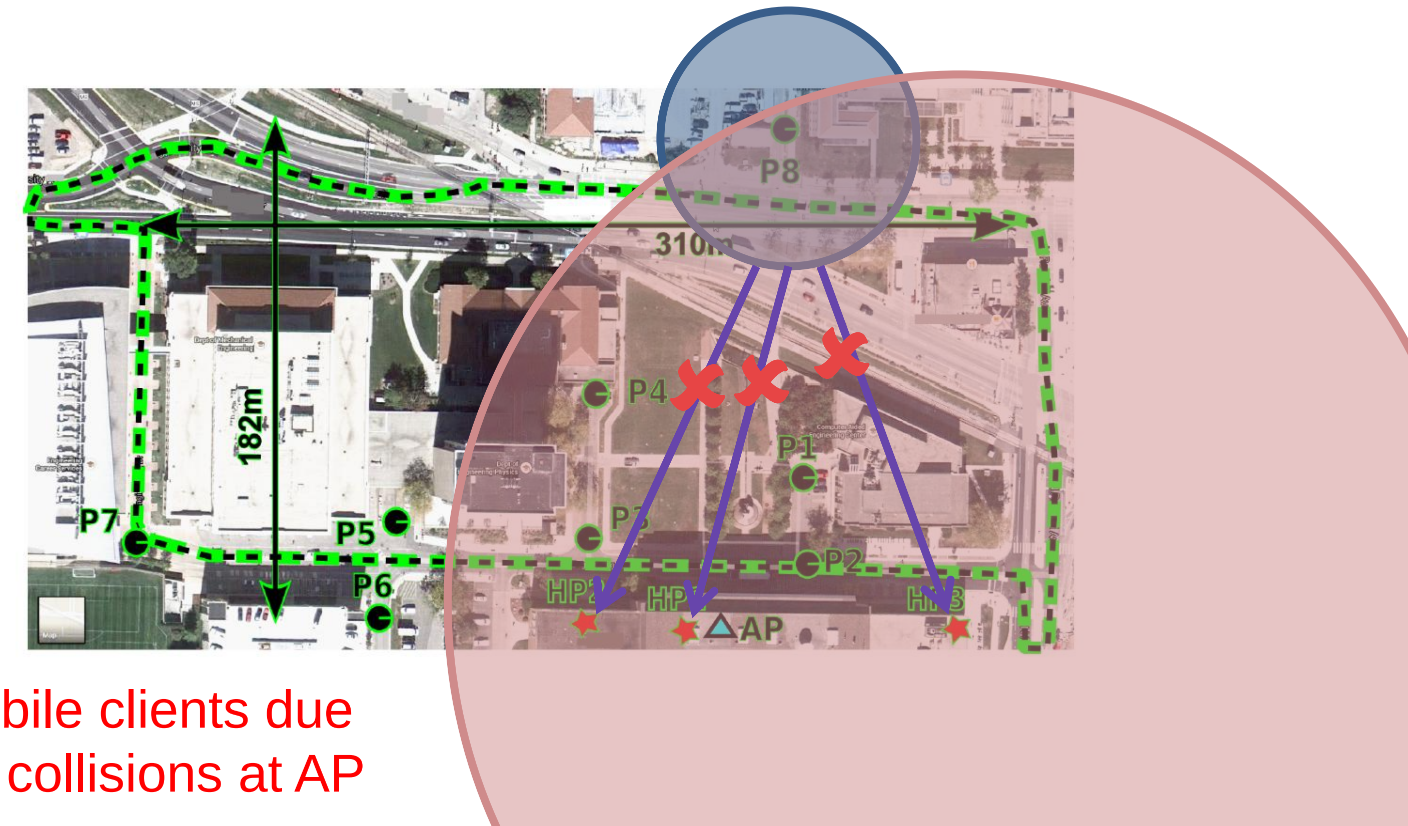
- Starvation of mobile clients
  - Power asymmetry rule is applicable to only mobile clients, a static client can have 4 W transmission power
  - Failure of carrier sensing at high power clients for uplink packets from mobile clients may starve it from accessing channel

Low power Mobile client

High power Static clients



Starvation of mobile clients due to severe packet collisions at AP

Adaptive DSSS design: Estimating Processing Gain under Channel Condition

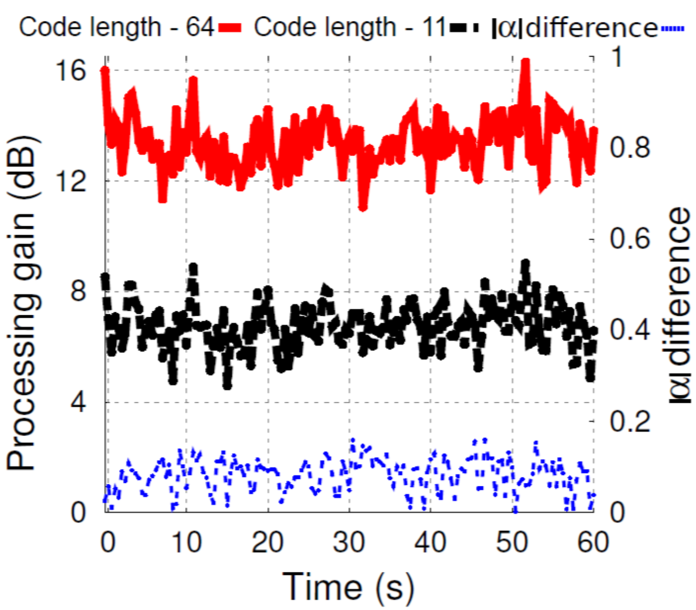
- Observation: Channel condition affects processing gain for all DSSS codes similarly
  - Ideal processing gain is affected by the current channel condition

Ideal processing gain

$$10\log_{10}(N)$$

Channel conditioned processing gain

$$10\log_{10}(\alpha N) \quad 0 < \alpha \leq 1$$

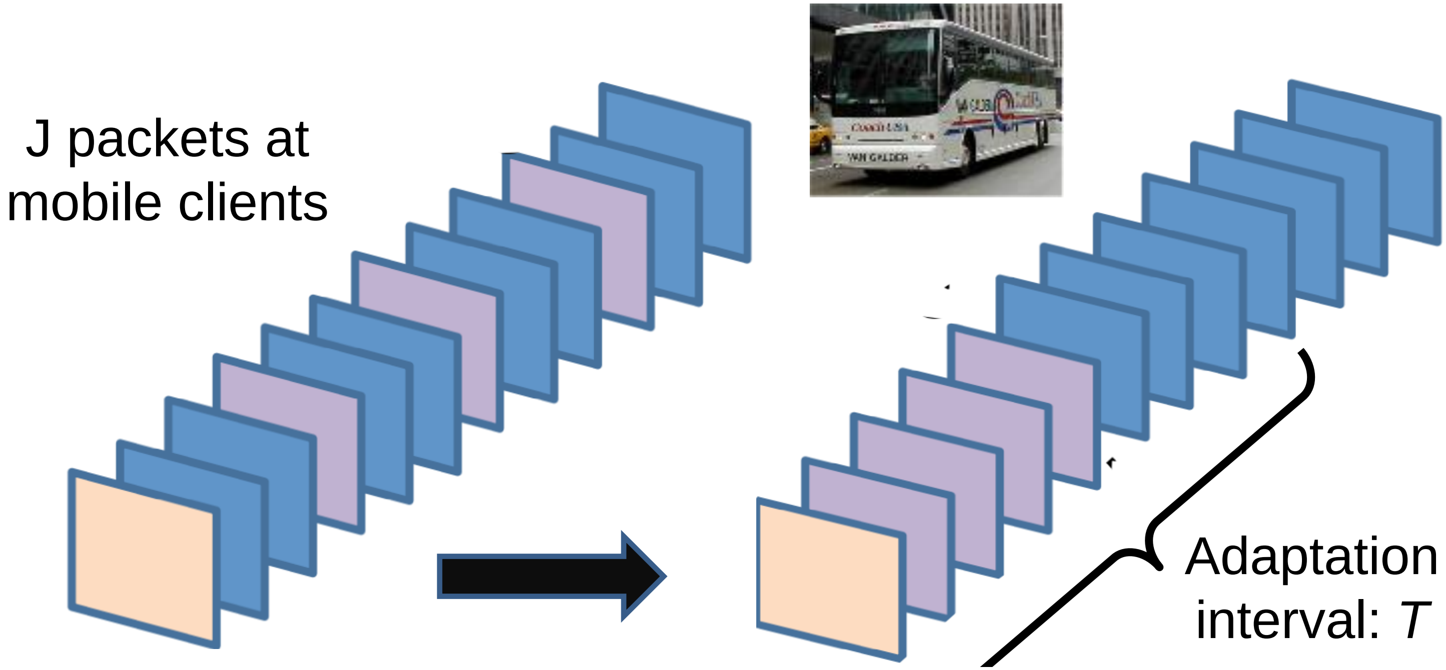


- Solution: Send probe packet containing longest and shortest DSSS codes. Estimate α using the difference of the measured gains
- Use the same α to predict the processing gain of other spreading codes

Adaptive DSSS design: Code assignment

- Problem formulation

Goal: Maximize the total utility received by AP, subjected to the total adaptation interval constrain



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