LiRa: a WLAN architecture for Visible Light Communication with a Wi-Fi uplink

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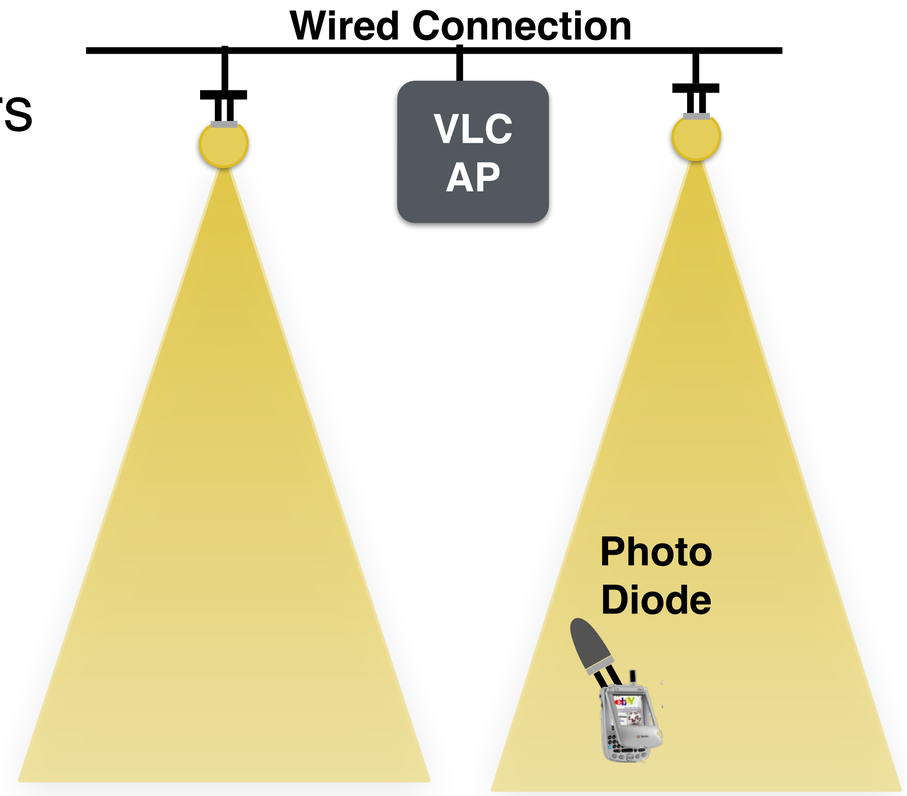
Visible Light Communication System (VLC)

- **Dual-purposing lighting**
  - Exploits the illumination energy by LED transmitters
- **Downlink**
  - Distributed LED bulb luminaries for coverage
- **Flicker-free Modulation**
  - Unnoticeable to the human eyes [1]
  - Low-cost photodiodes on end-user devices
- **Applications**
  - IoT applications [2] to Gigabit rate wireless [3]
  - High-resolution localization [4]



[1] Z. Tian et al.,"The DarkLight Rises: Visible Light Communication in the Dark," *Proc of ACM MobiCom*, 2016.

[2] S. Schmid et al., "Using consumer LED light bulbs for low-cost VLC systems" *Proc. of ACM MobiCom VLCS*, 2014.

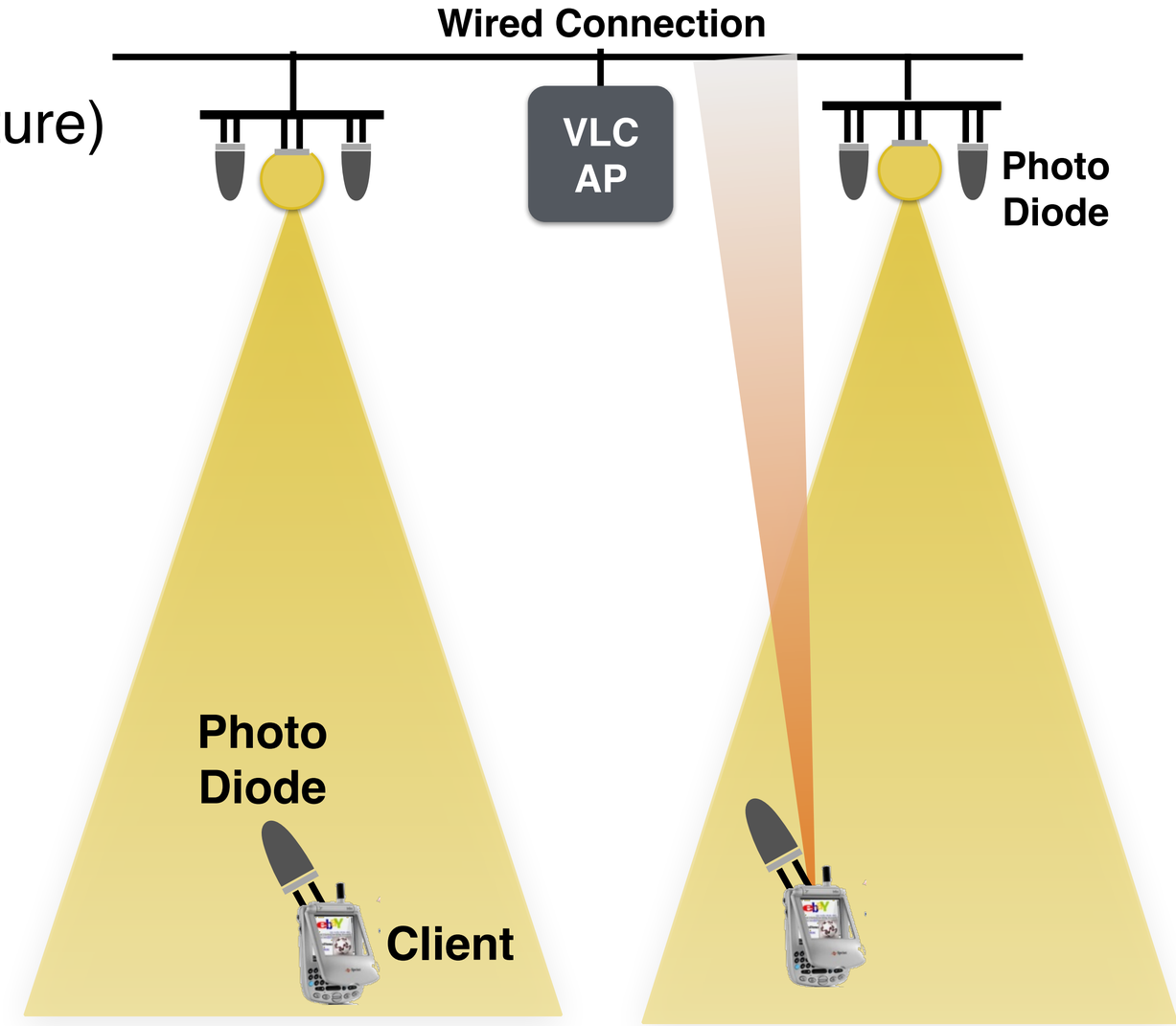
[3] D.Tsonev et al., "Towards a 100 GB/s visible light wireless access network" *OSA Optics Express*, 2015.

[4] C. Zhang et al., "LiTell: Robust Indoor Localization Using Unmodified Light Fixtures", *Proc. of ACM MobiCom*, 2016.

Infeasible VLC Uplink

- **Constraints**
  - Form Factor (> 100 times smaller aperture)
  - Transmission power
- **Impact**
  - Narrow field-of-view
  - Rotational misalignment [5]

- **RF-based uplink**
  - Wider coverage
  - Robustness to rotation/mobility



[5] S. Naribole and E. Knightly, “Scalable Multicast in Highly-Directional 60 GHz WLANs,” *Proc. of IEEE SECON*, 2016.

Objective

To design, implement and evaluate a high performance WLAN system with:

a) VLC simplex downlink and RF uplink;

b) inter-operability with legacy Wi-Fi and

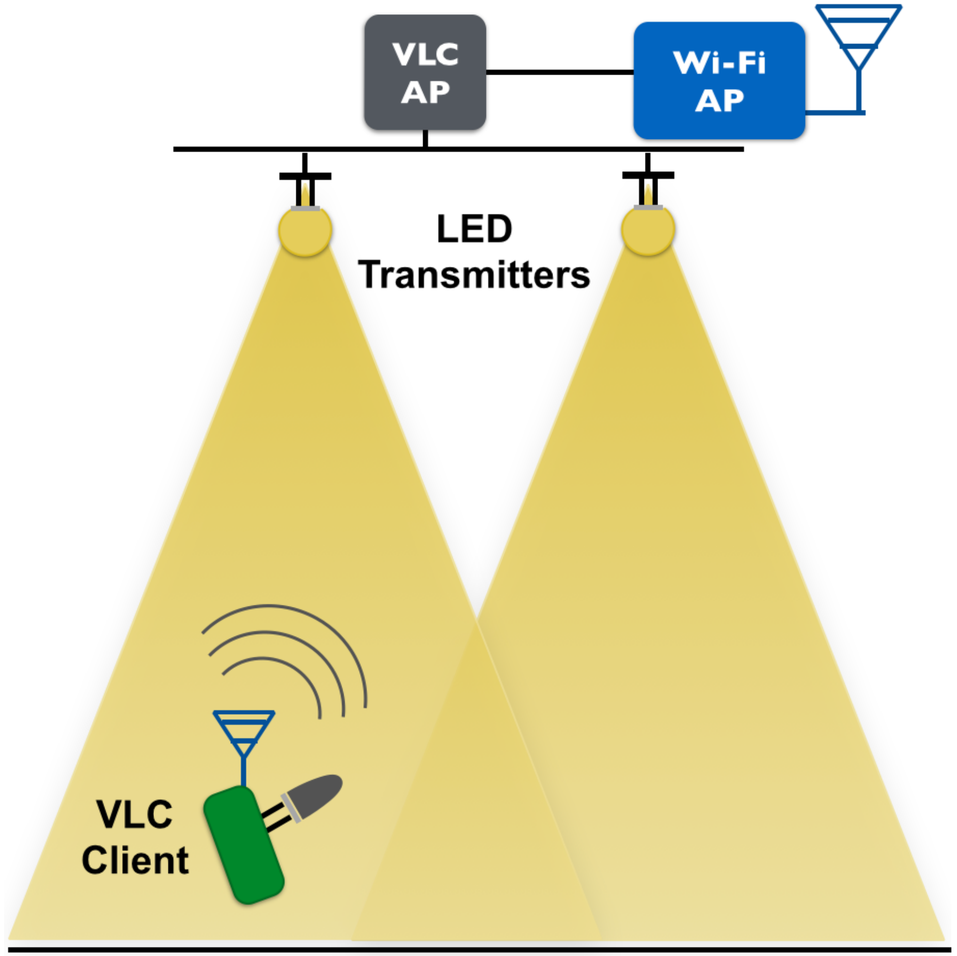
c) a controlled impact on legacy Wi-Fi performance

Prior Work

- **Layer-3 Integration**
  - Separate VLC AP and Wi-Fi AP devices

- **Prior Work Focus**
  - Load balancing [6] [7]
  - Wi-Fi contention for VLC downlink traffic [8]

VLC Feedback via RF for error control not addressed



[6] Rahaim et al., “A Hybrid Radio Frequency and Broadcast Visible Light Communication System”, *Proc. of IEEE GLOBECOM*, 2011.

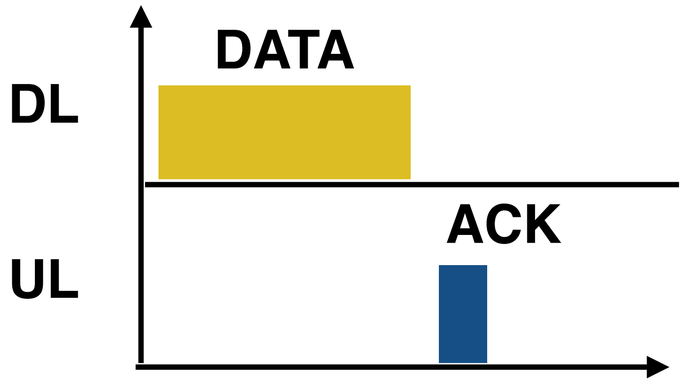
[7] Li et al., “Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi”, *IEEE Transactions on Communications*, Apr 2015.

[8] W. Guo et al., “A parallel transmission MAC protocol in hybrid VLC-RF network.”, *Journal of Communications*, Jan 2015

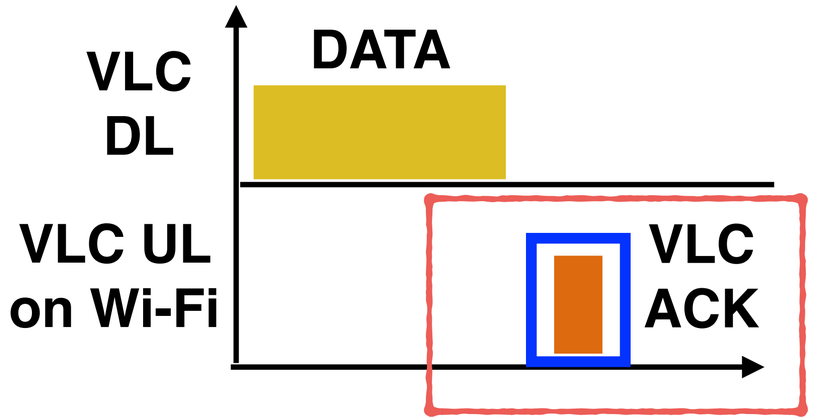
Encapsulated Handshake

- **MAC DATA/ACK handshake**
  - Error control method for reliable transmission

- **Legacy WiFi:**

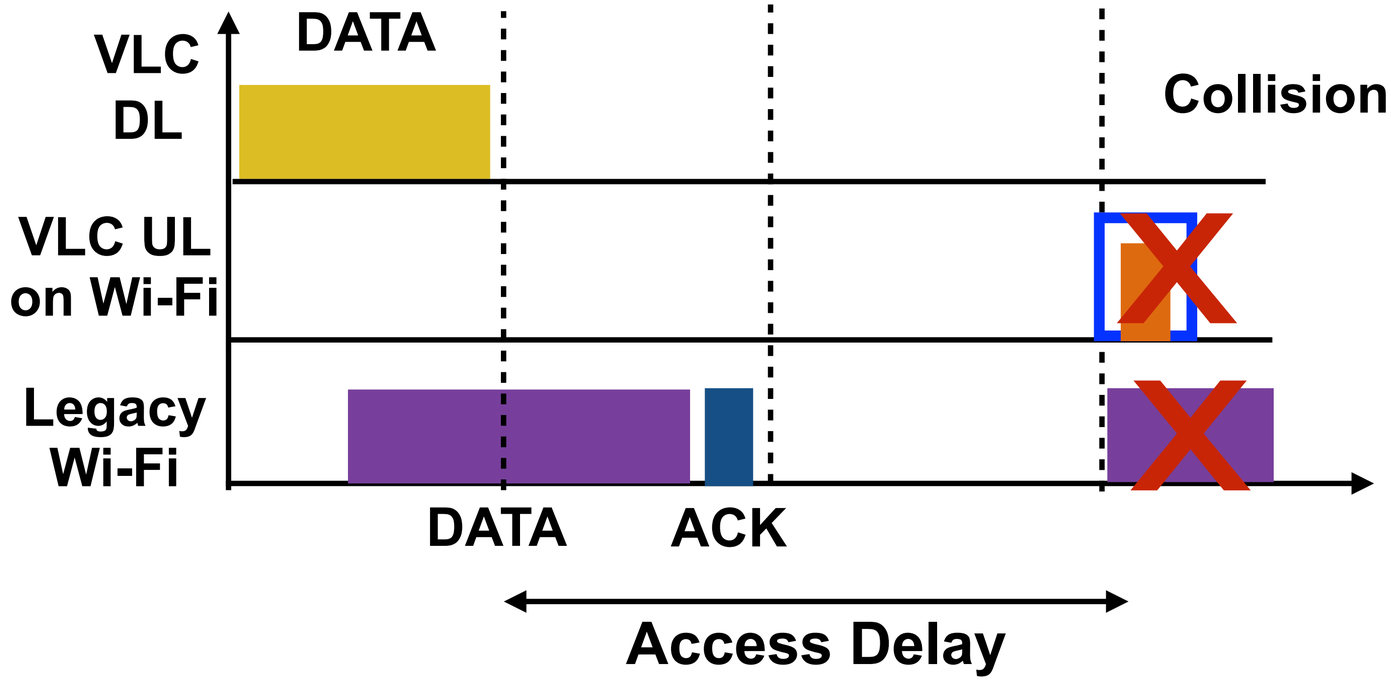


- **VLC-WiFi:**



- **Wi-Fi Encapsulation of VLC ACK**
  - Wi-Fi compatibility

Encapsulated Handshake



- Uncontrolled Access Delay degrades VLC downlink
- Uncontrolled Wi-Fi throughput degradation

LiRa: Light-Radio WLAN

RICE

Architecture

- VLC and Wi-Fi integrated at the MAC layer
- Single Layer-2 interface

ASMA

- AP-Spoofed Multi-Client ARQ Protocol
- Wi-Fi compliant scalable feedback channel

Evaluation

- Implemented LiRa and ASMA in hardware
- LiRa reduces feedback access delay and Wi-Fi degradation

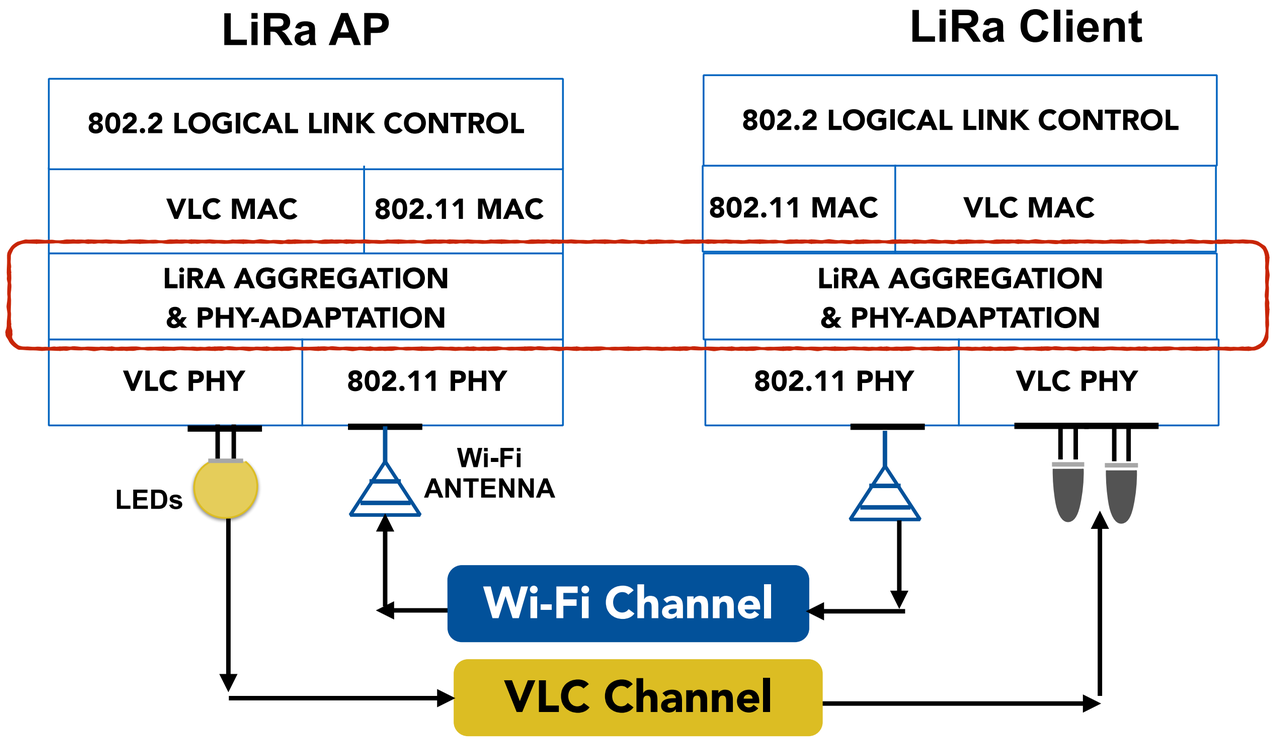
LiRa Architecture

- **Goals**
  - AP-controlled feedback access to eliminate the per-client contention
  - Retain the 802.11 MAC for legacy Wi-Fi operation

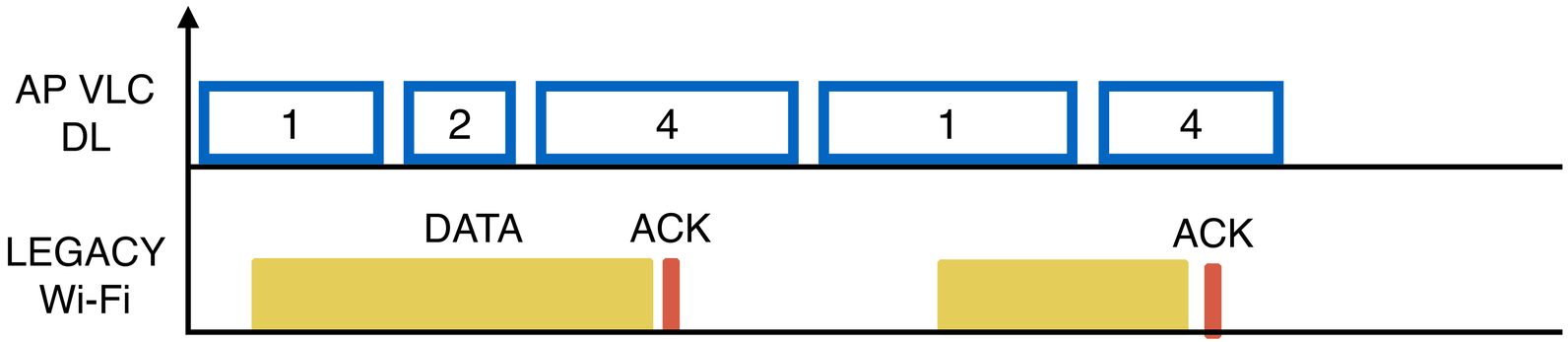
- **LiRa's Layer 2 Abstraction**

- **AP**
  - PHY Adaptation

- **Client**
  - Opportunistic ACK aggregation
  - No negotiation overhead



AP-controlled Feedback



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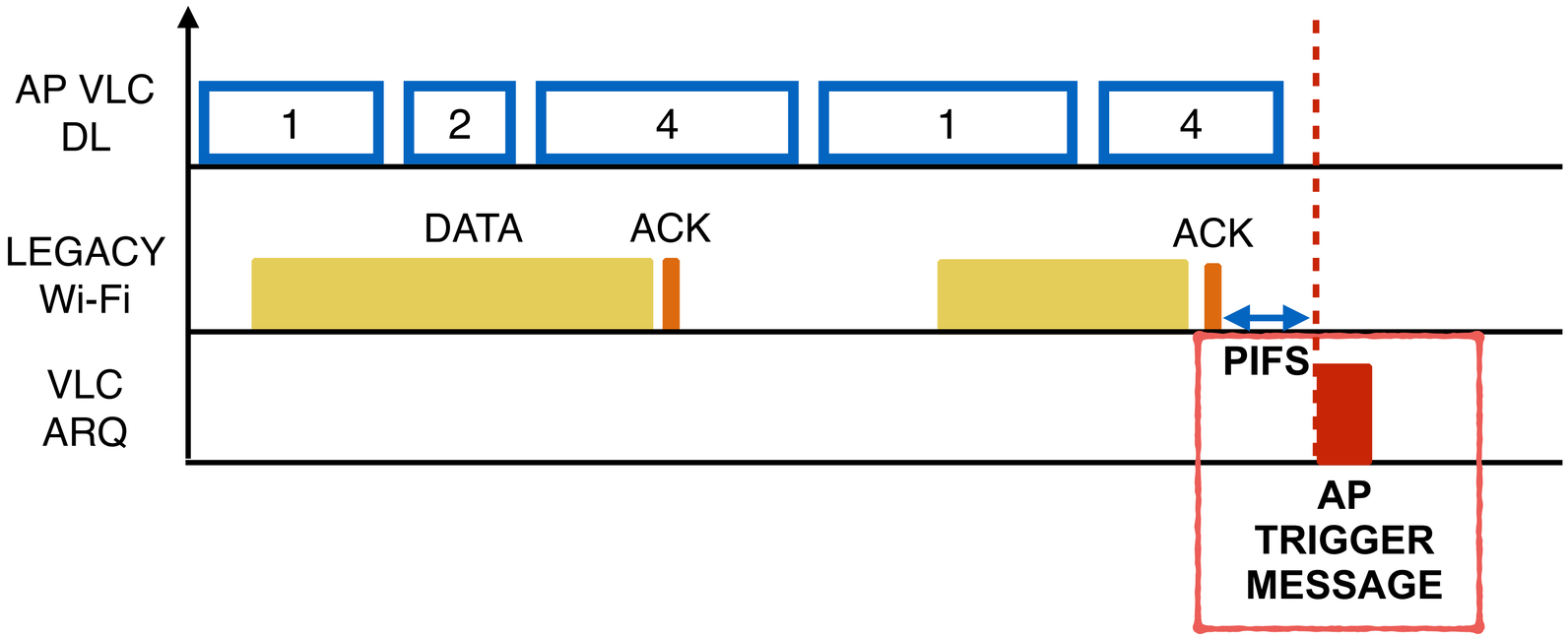


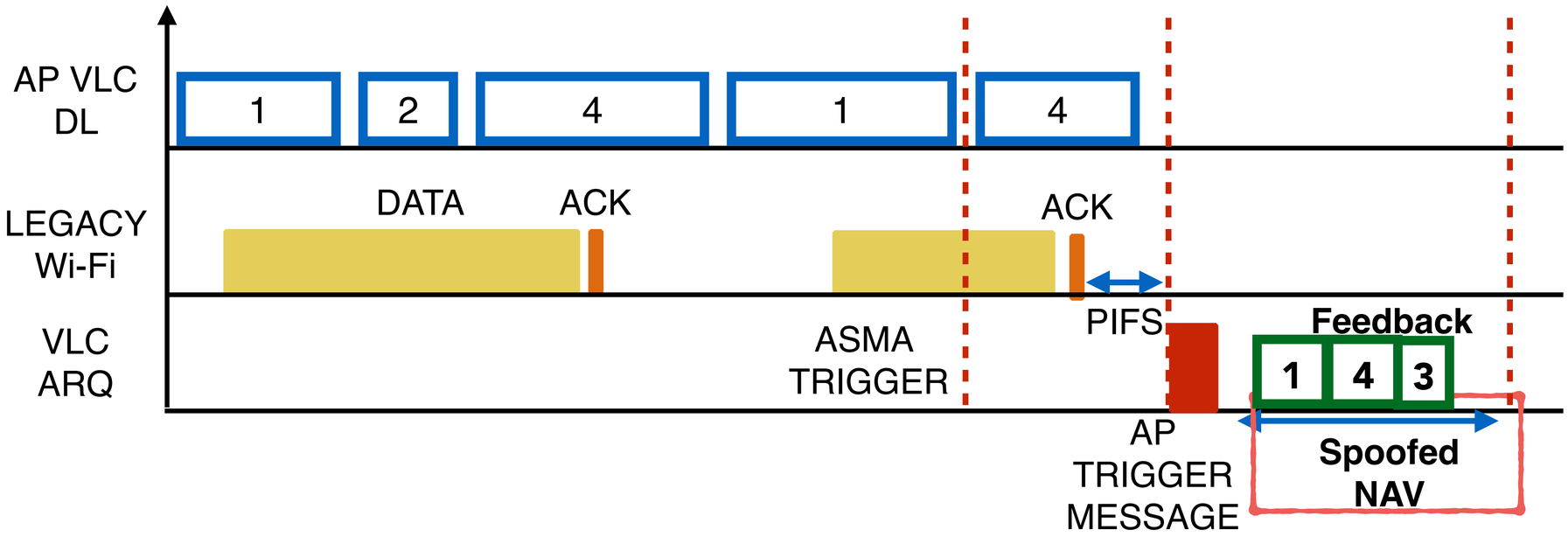
- **Aggressive Channel Access**
  - AP transmits Trigger message PIFS (= SIFS + 1 SLOT) after sensing idle
  - Similar to Beacon for contention-Free PCF

AP-controlled Feedback

Goals of AP Trigger Message:

- Defer legacy Wi-Fi contention
- VLC ARQ feedback from multiple LiRa clients

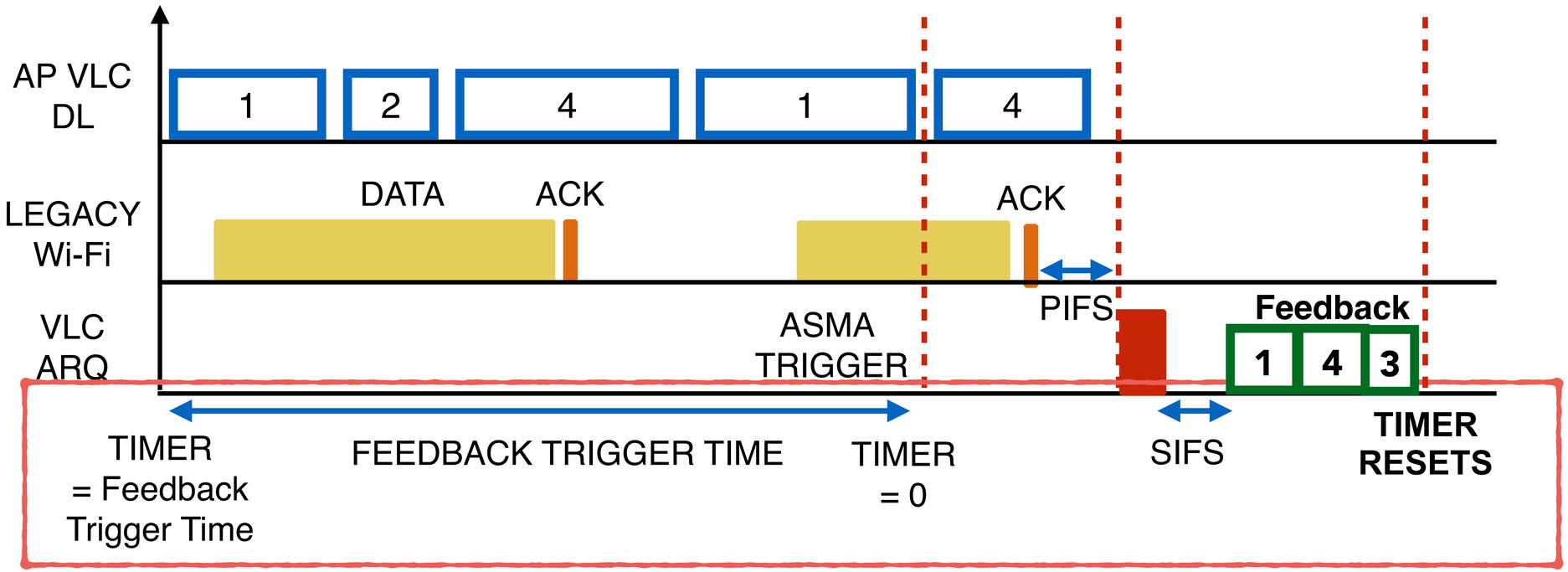
AP Trigger



- **Spoofed Network Allocation Vector (NAV)**
  - Downlink Schedule known by AP
  - NAV Duration set using VLC ARQ transmission time from scheduled clients

- **Multi-client scheduled Feedback**
  - Identifier and start time for each scheduled client

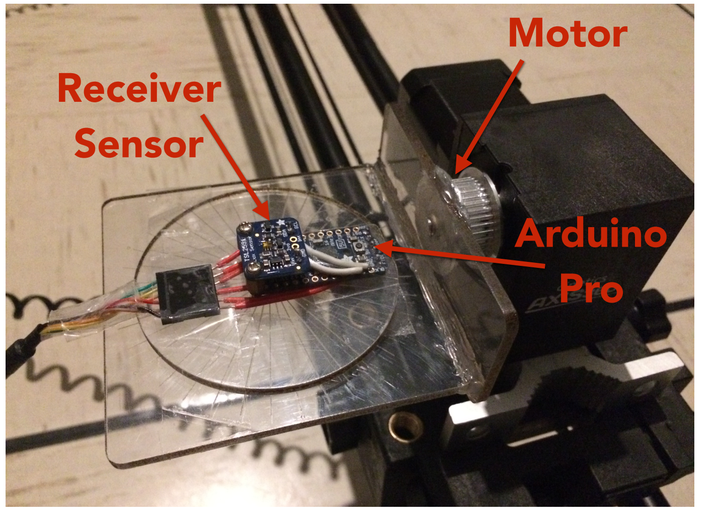
Trigger Timer for controlled Wi-Fi impact

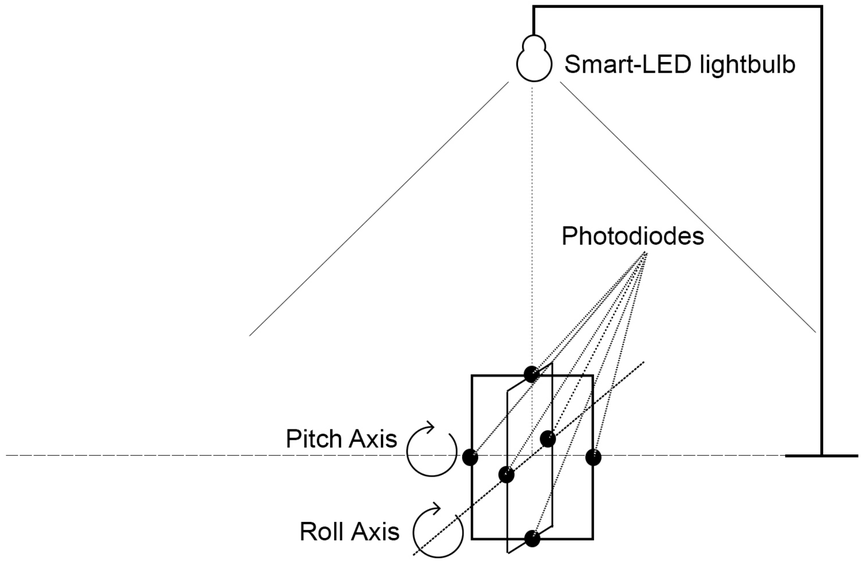


- Trigger timer resets after the VLC ARQ Transmission
- Adaptive timer to handle mobility, traffic bursts etc.

Implementation

- **VLC Link Implementation**
  - Philips Smart Hue Light bulbs
  - Adafruit High dynamic range light sensor
- **VLC Measures**
  - Over 150 cm range in roll and pitch axes
  - Determines the per-client MCS
- **Radio Link Implementation**
  - Extended 802.11g reference design for WARP v3
- **Radio Measures**
  - VLC client size, Feedback trigger time
  - Legacy Wi-Fi uplink MCS, operating channel





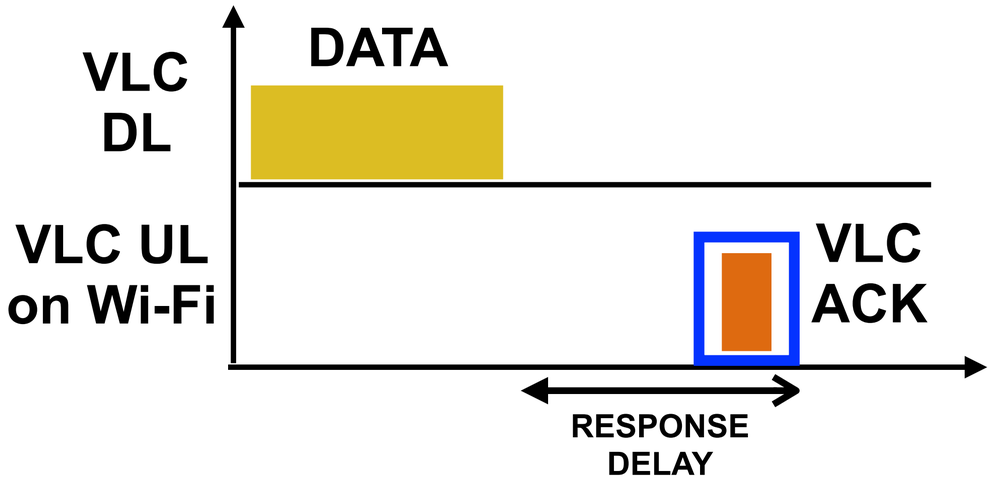
System Configuration

- **Timing and MCS**
  - VLC Downlink MPDU is 1 kB
  - Sizes and timings using IEEE 802.11 and 802.15.7 standards
- **Traffic**
  - Fully-backlogged downlink VLC traffic
  - Fully-backlogged legacy Wi-Fi users
  - No uplink data traffic for LiRa clients
- **Downlink Scheduling**
  - Round-robin scheduling of LiRa clients
- **Evaluation**
  - Running time of 30 seconds with thousands of VLC data packets
  - Each data point is averaged over 100 distributions of client locations and orientations

LiRa: Congested Channel Feedback Delay

- **Goal**
  - Analyze the impact of legacy Wi-Fi traffic on LiRa's feedback access delay

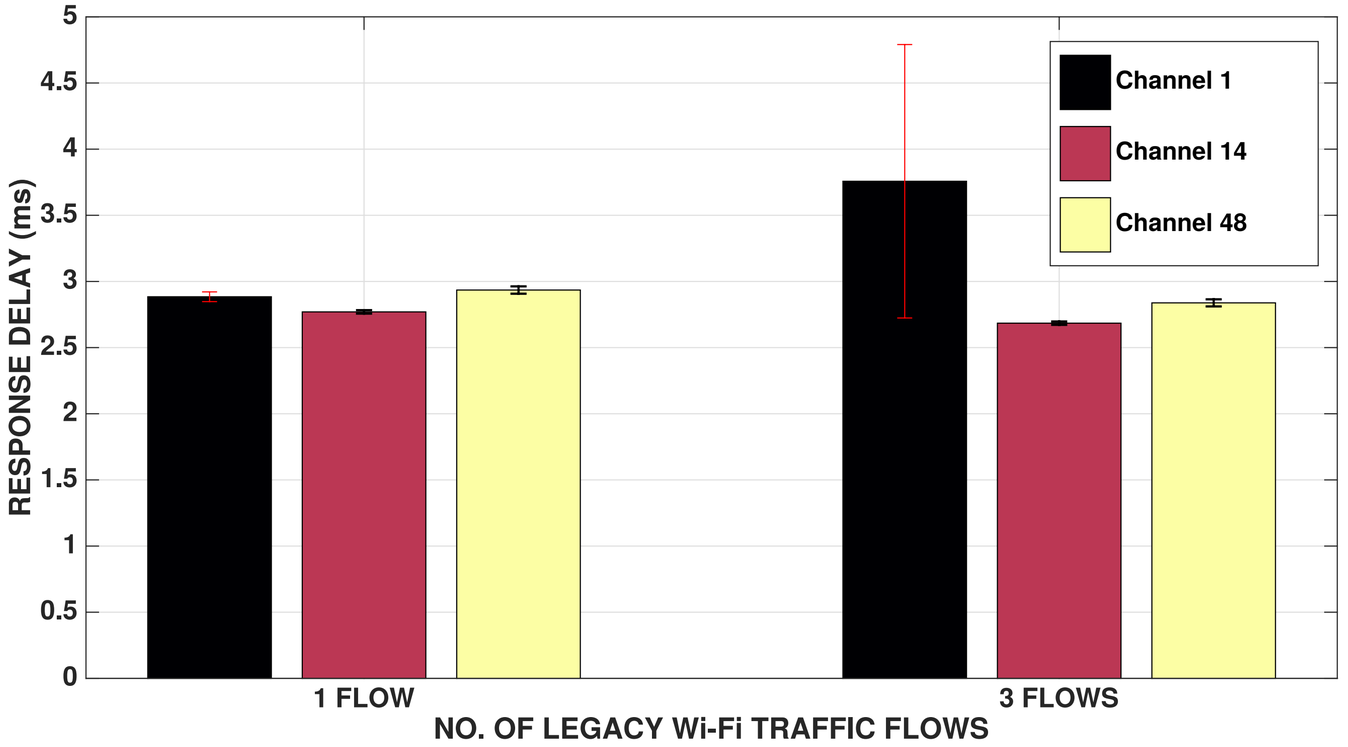
- **Metric**
  - Response Delay
  - Computed per VLC downlink packet



- **Experiment**
  - Single LiRa client with feedback trigger time of 4 ms
  - No. of Wi-Fi traffic flows, Wi-Fi channel

- **Hypothesis**
  - Response delay increases with number of traffic flows

LiRa: Congested Channel Feedback Delay



- **Mean response delay < Trigger Time**
  - Frames transmitted in the latter part have delay lower than feedback trigger time
- **Traffic flows**
  - Response delay increases with increase in no. of flows

Feedback with Baseline Strategy

- **Per-client Contention (PCC) - Baseline**
  - Each client takes part in 802.11 contention independently
  - Opportunistic aggregation of VLC ACK

Feedback with Baseline Strategy

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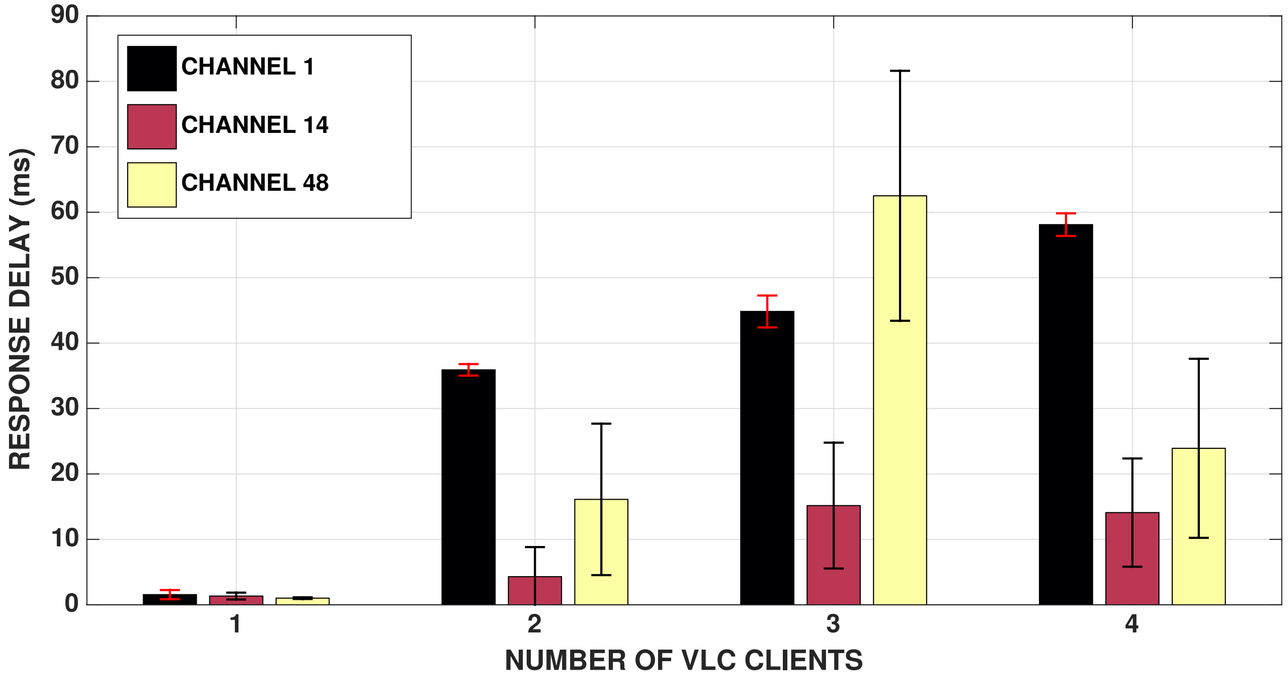
- **2 Clients**
  - Channel 1 delay > 35 ms
  - Co-channel interference

- **3 clients**
  - VLC ARQ and legacy data collide

- **4 clients**
  - Increased probability for VLC clients to win contention



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ASMA

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Evaluation

- Feedback access delay reduction by 15x
- Legacy Wi-Fi degradation reduced to < 3% from 74%

BACKUP

Wi-Fi Throughput Degradation

- **Per-client Contention (PCC) - Baseline**
  - Each client takes part in 802.11 contention independently
  - Opportunistic aggregation of VLC ACK

- **Goal**
  - Compare LiRa's Wi-Fi throughput degradation vs baseline

- **Experiment**
  - Single legacy user with fully backlogged traffic
  - Varying VLC client size and LiRa feedback trigger time

- **Hypothesis**
  - Wi-Fi throughput degradation increases with client size for both the strategies

Wi-Fi Throughput Degradation