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**
  - High-resolution localization [4]

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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

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

• MAC DATA/ACK handshake
  ○ Error control method for reliable transmission

• Legacy WiFi:

  - DL: DATA
  - UL: ACK

• VLC-WiFi:

  - DL: VLC DATA
  - UL: VLC on Wi-Fi

• Wi-Fi Encapsulation of VLC ACK
  ○ Wi-Fi compatibility
• Uncontrolled Access Delay degrades VLC downlink
• Uncontrolled Wi-Fi throughput degradation
LiRa: Light-Radio WLAN

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

AP VLC DL

LEGACY Wi-Fi

DATA ACK ACK

1 2 4 1 4
• **Aggressive Channel Access**
  ○ AP transmits Trigger message PIFS (= SIFS + 1 SLOT) after sensing idle
  ○ Similar to Beacon for contention-Free PCF
Goals of AP Trigger Message:

• Defer legacy Wi-Fi contention

• VLC ARQ feedback from multiple LiRa clients
• Spooled 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 resets after the VLC ARQ Transmission
• Adaptive timer to handle mobility, traffic bursts etc.
• 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
• **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
• **Per-client Contention (PCC) - Baseline**
  - Each client takes part in 802.11 contention independently
  - Opportunistic aggregation of VLC ACK
Feedback with Baseline Strategy

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

- **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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Evaluation
- Feedback access delay reduction by 15x
- Legacy Wi-Fi degradation reduced to < 3% from 74%
BACKUP
Wi-Fi Throughput Degradation

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

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

• **Goal**
  ○ Compare LiRa’s Wi-Fi throughput degradation vs baseline

• **Per-client Contention (PCC) - Baseline**
  ○ Each client takes part in 802.11 contention independently
  ○ Opportunistic aggregation of VLC ACK
Wi-Fi Throughput Degradation

![Wi-Fi Throughput Degradation Chart]

- **Wi-Fi Throughput Degradation (%)**
- **Number of VLC Clients**
  - 1
  - 2
  - 3
  - 4

**Legend**:
- **LiRa - 1 ms trigger**
- **LiRa - 5 ms trigger**
- **LiRa - 10 ms trigger**
- **802.11 Per-Client Contention**