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MAC Layer DATA/ACK Handshake in the Hybrid VLC-RF System

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ABSTRACT

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The hybrid VLC-RF system utilizes a uni-directional VLC link for downlink and the legacy Wi-Fi link for uplink transmission. However, simply integrating the two links without any modification in the MAC layer would cause problems for the MAC layer DATA/ACK handshake. The acknowledgements for VLC packets have to be transmitted via radio. Because of the Wi-Fi channel’s contention based random access, the transmission will be delayed and degrades the performance of the legacy Wi-Fi, especially when the Wi-Fi channel is heavily loaded. In my thesis, I design and analyze the Spoofed NAV Triggered Multi-client ACKs (STMA) scheme to transmit the delay-sensitive VLC ACK timely while keep the degradation of legacy Wi-Fi under-control. I implement the key components of STMA and evaluate its performance with a combination of over-the-air experiments and trace-driven simulations. The result shows that in a dense WLAN scenario, STMA reduces the response delay and legacy Wi-Fi degradation significantly in comparison to 802.11 contention-based approach.
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## Contents

Abstract

Acknowledgements

1 Introduction

2 Background
  2.1 VLC Uplink Design
  2.2 LiRa Architecture

3 Spoofed NAV-Triggered Multi-client ACKs
  3.1 Challenge
  3.2 STMA Overview
  3.3 STMA Analysis
  3.4 Degradation-Constrained Trigger Adaptation

4 VLC Implementation
  4.1 Small Scale Implementation Using WARP
  4.2 Multi-VLC Client Simulator
  4.3 VLC-RF Trace-Driven emulator

5 Experimental Evaluation
  5.1 STMA’s Adaptive Trigger Time Evaluation
  5.2 Performance Comparison with Per-client Contention
  5.3 STMA’s Performance with Lossy VLC Link

Abstract

Acknowledgements

1 Introduction

2 Background
  2.1 VLC Uplink Design
  2.2 LiRa Architecture

3 Spoofed NAV-Triggered Multi-client ACKs
  3.1 Challenge
  3.2 STMA Overview
  3.3 STMA Analysis
  3.4 Degradation-Constrained Trigger Adaptation

4 VLC Implementation
  4.1 Small Scale Implementation Using WARP
  4.2 Multi-VLC Client Simulator
  4.3 VLC-RF Trace-Driven emulator

5 Experimental Evaluation
  5.1 STMA’s Adaptive Trigger Time Evaluation
  5.2 Performance Comparison with Per-client Contention
  5.3 STMA’s Performance with Lossy VLC Link
6 Related Work
   6.1 Analytic Studies ............................................. 37
   6.2 System Implementations ...................................... 39
   6.3 VLC Services and Devices .................................... 40

7 Conclusion ......................................................... 42

References ............................................................ 43
List of Figures

2.1 Illustration of VLC system (a) with VLC uplink (b) with RF uplink .  
2.2 Protocol stack of the hybrid VLC-RF system (a) existing works before  
LiRa (b) LiRa . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 6  
3.1 Timeline for the scenario of two VLC clients and two legacy users in  
the network . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10  
3.2 STMA’s timeline for the scenario of two VLC clients and two legacy  
users in the network. STMA is the combination of STMA trigger to  
the AP, trigger message transmitted by the AP and uplink VLC ACK  
transmissions. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14  
3.3 Example of response delay. Ignore the VLC ACKs transmission time.  
The response delay of VLC Client 1’s packet 1 equals to the interval  
duration minus the packet transmission time, while the response delay  
of VLC Client 1’s packet 6 almost equals to 0. . . . . . . . . . . . . . . . 18  
4.1 Radio link Implementation Setup . . . . . . . . . . . . . . . . . . . . 23  
5.1 STMA’s trigger time evaluation for response delay. $T_w$ denotes the  
radio trigger time . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28  
5.2 STMA’s trigger time evaluation for legacy Wi-Fi throughput degrada-  
tion. $T_w$ denotes the radio trigger time . . . . . . . . . . . . . . . . . . . 30  
5.3 Response delay of STMA and PCC. $T_w$ denotes the radio trigger time.  
32  
5.4 Legacy Wi-Fi throughput degradation of STMA and PCC. $T_w$ denotes  
the radio trigger time . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
5.5 Response delay of STMA and PCC in realistic indoor environment. $T_w$ denotes the radio trigger time. ................................. 34
5.6 Acknowledgement delay of VLC with lossy VLC link. .................... 36
List of Tables

3.1 Notation table for STMA analysis. 15
Visible Light Communication (VLC) promises Gb/sec data rates [1, 2] while dual purposing LED-based lighting infrastructure for both illumination and communication [3]. In [4], a new hybrid VLC-RF system architecture, the Light-Radio WLAN is introduced. LiRa employs a simplex VLC link in which VLC transmissions are only possible from the lighting infrastructure, which is integrated with the Access Point (AP), to photodiodes on client devices. All uplink traffic, both control and data, is transmitted via radio using fully IEEE 802.11-compliant methods.

LiRa fuses light and radio links on a frame-by-frame basis at the MAC layer, thus provides the capability to transmit MAC layer acknowledgement (called VLC ACK) for the downlink VLC data packets. However, using the contention-based random access in the Wi-Fi MAC layer for the VLC ACK transmission will cause problems for both the VLC downlink and the Wi-Fi uplink. Because isolation between VLC and Wi-Fi channel, the legacy Wi-Fi users cannot detect the ongoing transmission on the VLC channel, thus cannot reserve the channel for the coming VLC ACK transmission. As a result, the VLC clients have to contend for the channel access to transmit the VLC ACK. On one hand, this channel access time overhead could delay the transmission of VLC ACK up to several mili-seconds long. Therefore, when packet
loss occurs, the retransmission will be delayed by the same amount of time. On the other hand, with fully backlogged VLC downlink traffic, the VLC ACK on the uplink will flood the Wi-Fi channel and greatly degrade the performance of legacy Wi-Fi users. In this thesis, I design, implement and evaluate a new VLC ACK transmission policy to solve the VLC ACK delay and legacy Wi-Fi degradation problem in dense traffic scenario and make the following contributions.

First, cooperate with the authors of [4], we design the structure, timing, and semantics of Spoofed NAV Triggered Multi-client ACKs (STMA). Instead of using contention based random access, STMA makes the AP to create a contention-free period and broadcast a trigger message to trigger VLC clients to transmit the VLC ACKs in order within that period. The transmission order is included in the trigger message so that VLC clients will not collide with each other. During the transmission, all legacy Wi-Fi users’ transmissions are deferred by the spoofed NAV duration included in the trigger message. Every radio trigger time, the same process is repeated. In this way, STMA prevents VLC ACKs from involving in contention or collisions and grants the AP capability to control the VLC ACK delay and legacy Wi-Fi degradation by adjusting the radio trigger time. In order to efficiently transmit the VLC ACKs during that period, STMA also makes each VLC client aggregate all existing VLC ACKs in its transmission queue into a single aggregated VLC ACK.

Second, I analyze the impact of STMA on the VLC downlink packet response delay (defined as the time between a packet is transmitted and the sender receives the feedback) and legacy Wi-Fi degradation. The frequency of STMA triggering the VLC ACK transmission is determined by the radio trigger time. Small radio trigger time leads to more frequent channel access acquisition, which results in small response delay but higher legacy Wi-Fi degradation. I deduce the function of the response delay and legacy Wi-Fi degradation with respect to the radio trigger time. The result
shows that the VLC ACK delay is upper-bounded by the radio trigger time, while the legacy Wi-Fi degradation is reverse proportional to the radio trigger time and is also affected by the VLC downlink transmission. In addition, both the response delay and the legacy Wi-Fi degradation are independent of the size of legacy users. Moreover, to constrain the legacy Wi-Fi degradation lower than a given threshold, I propose an algorithm to adaptively adjust the radio trigger time based on VLC downlink transmission. Every time a new downlink data packet is transmitted, the radio trigger time is adjusted accordingly. When the air-time passed since last VLC ACK transmission exceeds the current radio trigger time, the AP will be triggered.

Finally, I implement the key components of STMA and perform an extensive measurement and trace-driven simulation study. In particular, I implement the RF part of STMA in the ns-3 simulator and collect the VLC ACK transmission data in various scenarios. I also extend the reference design of WARP [5] to include the STMA mechanisms and collect over-the-air measurements of the VLC ACK transmission in both controlled environments and practical scenarios. Moreover, I create an emulator to evaluate the performance of the full LiRa system with STMA. The emulator simulates the downlink VLC transmission and take the VLC ACK transmission data as input. The result shows that in a dense WLAN scenario, STMA reduces the VLC link packet response delay by more than 5 times and reduces the legacy Wi-Fi throughput degradation from an excessive value of 0.45 to a pre-set constraint value of 0.1.

The remainder of the thesis is organized as follows. Chapter 2 introduces the background knowledge about the VLC uplink design and LiRa architecture. Chapter 3 introduces the design and analysis of the STMA scheme. Chapter 4 introduce how STMA is implemented on the WARP platform and ns-3 simulator. The evaluation of STMA is presented in Chapter 5. Chap. 6 discusses the related work. Finally,
Chapter 7 concludes the thesis.
In this chapter, I first discuss the uplink design in the indoor VLC system, and then introduce the LiRa \[4\] architecture which fuses the light and radio frame by frame on the MAC layer.

### 2.1 VLC Uplink Design

Although existing systems including \[3, 6\] and standards such as IEEE 802.15.7 \[7\] employ visible light for both the uplink and downlink, uplink VLC communication has several inherent limitations. First, while the illumination objective of the downlink ensures that the LED transmitters of the AP have a wide aperture, large field-of-view (FOV), and high transmit power, LEDs on the client device have none of these benefits. Figure 2.1a illustrates the FOV asymmetry encountered with a VLC or infrared uplink. As illustrated, the limited size, power, and aperture of the mobile client’s LED transmitter can severely constrain FOV, thereby limiting the rate or even breaking the uplink. Moreover, some researchers have suggested that visible light emitted by client devices might be irritable to human eyes \[3\].

Therefore, in order to provide the uplink service, the uni-directional VLC link
Figure 2.1: Illustration of VLC system (a) with VLC uplink (b) with RF uplink

Figure 2.2: Protocol stack of the hybrid VLC-RF system (a) existing works before LiRa (b) LiRa

is integrated with the bi-directional legacy Wi-Fi link to form the hybrid VLC-RF system structure, as illustrated in Figure 2.1b. The VLC clients are equipped with VLC receiver and Wi-Fi transceiver. It receives the downlink traffic from the VLC link and sends all uplink traffic, including data and control information, via the Wi-Fi link. To handle the coordination between the two different links, the Wi-Fi AP and VLC AP are also integrated into one device.
2.2 LiRa Architecture

Existing research systems that jointly employ light and radio, e.g., [8,9], treat the two mediums as independent, to be jointly managed by handoff and multi-network load balancing, analogous to the way that heterogenous technologies such as Wi-Fi and LTE can be integrated. In those systems, the VLC and Wi-Fi link are totally separated in the MAC layer, as shown in 2.2a. Because the VLC MAC has no access to the 802.11 PHY which is the only uplink channel, it is impossible for the client’s VLC MAC to transmit any feedback message to the AP. As a result, the MAC layer DATA/ACK handshake cannot be implemented in those systems. Therefore, when packet loss occurs, the retransmission can only be handled by the upper layer protocol such as TCP. The retransmission takes at least one round-trip time (RTT), which could be up to hundreds of milliseconds long in a multi-hop link. This greatly delayed the retransmission and may cause problem to the delay-sensitive applications such as video streaming or Voice over IP (VoIP). In addition, without the feedback information, the AP cannot do timely rate adaptation, which will cause sequential packet loss with over-selected MCS or link under-utilized with under-selected MCS.

In [4], a new hybrid VLC-RF architecture is introduced which fuses the light and radio in the MAC layer. As illustrated in 2.2b, LiRa inserts the ”LiRa Sublayer” between the MAC and PHY layer and grants the VLC MAC access to the Wi-Fi PHY. Consequently, with LiRa architecture, the client can transmit the MAC layer ACK for VLC data to the AP. The client’s VLC MAC generates the VLC ACK, forward it down to the LiRa sublayer, and the sublayer forwards it to the 802.11 PHY for transmission. At the AP’s side, the LiRa sublayer receives the VLC ACK and forward it up to the VLC MAC, thus the DATA/ACK handshake is completed. With LiRa, it is possible for the AP to complete the timely packet retransmission on MAC layer. The AP can also do rate adaptation based on the ACK reception or the
information included in the ACK packet such as current signal-to-interference-and-noise-ratio (SINR) using policy introduced in [10].
In this chapter, I first introduce the challenge for VLC ACK transmission existing in the hybrid VLC-RF systems. Then, I present the key strategy of STMA which is designed by me and the authors of [4]. After that, I propose theoretical performance analysis of STMA. Finally, based on the analysis, I introduce STMA’s degradation-constrained radio trigger time adaptation algorithm.

### 3.1 Challenge

In the hybrid VLC-RF system, the channel access scheme for the VLC ACK transmission is different from that for the MAC layer ACK transmission in the legacy Wi-Fi system. In 802.11 based Wi-Fi system, the ACK does not contend for the channel access separately. Instead, the ACK is protected by the save NAV that protects ACK’s associated data. The ACK transmission time is included in the duration field of the data MAC header and all other users set their own NAV accordingly. However, in LiRa, the transmission of VLC ACK cannot be protected by the same scheme. Due to the isolation between the Wi-Fi and VLC link, the legacy Wi-Fi users (called legacy users for short) cannot detect the transmission on the VLC link,
thus cannot defer their transmission for the coming VLC ACK. Therefore, the VLC clients need to obtain the transmission opportunity (TXOP) before transmitting the VLC ACKs.

A straight-forward way to obtain the channel access is to let the LiRa sublayer follow the Distributed Coordination Function (DCF) procedure defined in the 802.11 standard. However, this will cause extra delay for the VLC ACK transmission and degrade the legacy Wi-Fi performance, especially in a large scale network with a number of VLC clients and legacy users and dense traffic. Figure 3.1 shows an example timeline of VLC ACK transmission. There are two VLC clients and two legacy users in the figure. The AP keeps transmitting downlink data to the two VLC clients via the VLC link. On the Wi-Fi link, the two VLC clients contend individually for the TXOP using DCF. The first VLC ACK transmission attempt of VLC client 2 fails because of collision. The VLC ACK transmission of VLC client 1 succeeds after the collision ends.

From the figure it can bee seen that the delay of VLC ACK originates from the channel access overhead. The VLC client needs to wait the channel to be idle for
DIFS time, doing backoff, and then attempts to transmit. If collision occurs, the VLC client has to double its transmission window and repeat the backoff process. In the Figure 3.1, the ACK for VLC client2’s packet 1 is generated at time $t_1$ but not received by the AP until $t_2$.

On the other hand, the legacy users’ transmission is also impacted by the transmission of VLC ACK. Every VLC ACK transmission forces the legacy users to pause their backoff for DIFS plus VLC ACK transmission time. Although the VLC ACK packet is small, large number of VLC clients can still flood the Wi-Fi channel. Moreover, large number of VLC clients and legacy users also increase the probability of collisions between VLC clients and legacy users, which will further degrade the performance of legacy users.

### 3.2 STMA Overview

To remove the time overhead caused by backoff and avoid collisions between VLC ACKs and of VLC ACKs with regular Wi-Fi packets, STMA’s key strategy is to disable the 802.11-based contention procedure at the VLC clients to transmit the VLC ACKs and instead introduce a contention-free period to provide channel access. Specifically, STMA triggers the AP to acquire the Wi-Fi channel access after a pre-defined radio trigger time $T_w$, spoofs NAV to make legacy users and VLC clients defer from contention for their regular uplink packets and perform a scheduled transmission of VLC ACKs from multiple VLC clients. On the VLC clients’ side, the VLC ACKs are aggregated into one packet and transmitted after the AP triggers. I next discuss the key concepts in more details.

Given a pre-set radio trigger time $T_w$, after a duration of $T_w$ since the last VLC ACK transmission, STMA triggers the AP to acquire the Wi-Fi channel. However, there might be an ongoing transmission that prevents the AP to acquire the
channel immediately after being triggered. Note that based on the 802.11 standard, each user begins backoff only after the channel becomes idle for DIFS (= SIFS + 2*SLOT) duration. Here the SLOT refers to the length of one backoff slot duration. In order to guarantee that the AP acquires the channel before other users start backoff, STMA makes the AP send a trigger message after the channel becomes idle for PIFS (SIFS + SLOT) time. The trigger message has two key functions:

**Spoofed NAV for Deference.** To create a contention-free period, STMA spoofs the NAV setup with duration included in the trigger message. In 802.11 MAC, each frame has a duration field that indicates the amount of time the channel is reserved to the correspondents (the sender and the intended receiver of this packet) after this current frame. In contrast to this channel reservation for a specific pair of sender and intended receiver, STMA extends this concept by spoofing the NAV to reserve the Wi-Fi channel for VLC ACK transmissions from multiple VLC clients. For this purpose, the duration includes in the trigger message is long enough for all VLC clients who has a VLC ACK to transmit finish their VLC ACK transmission. Upon hearing the trigger message, any user on the Wi-Fi channel will adjust their NAV accordingly.

**Multi-Client Group VLC ACK.** To avoid collisions between the VLC ACK transmissions of multiple VLC clients, STMA includes in the trigger message the VLC ACK transmission order. Specifically, the trigger message includes a start time for each VLC client’s VLC ACK transmission. The starting time is essential because the VLC clients might be located out of range of each other such that they cannot listen to the beginning and ending of each other’s transmissions. Therefore, any de-centralized approach cannot fully avoid VLC ACK collisions at the AP. For computing the start times, STMA estimates each client’s VLC ACK transmission time by considering that each client will acknowledge all of its unacknowledged packets as
this represents the upper bound of the transmission time used by each client. The VLC ACK transmission is separated by SIFS time to compensate for potential oscillator deviation. On receiving the trigger message, the VLC clients transmit VLC ACKs following the time schedule.

In LiRa architecture, because the AP keeps transmitting downlink packets, when the AP triggers the VLC clients to transmit the VLC ACK, it is possible that each VLC client has generated multiple VLC ACKs waiting in the queue. To efficiently transmit those VLC ACKs, STMA makes the VLC clients aggregate all existing VLC ACKs into a single aggregated VLC ACK. The aggregation is done by using a bitmap, similar to Block ACK frame defined in the 802.11 standard. Note that this aggregation has no fixed length. Each VLC may have a different aggregation length depending on the number of packet it needs to acknowledge.

In order to facilitate retransmission of lost packets, every VLC client included in the AP’s trigger message transmits a VLC ACK even if it did not receive any data packets. This may happen when the VLC link is broken due to mobility or over-selection of downlink MCS by the AP. As there are no collisions with regular uplink packets or between VLC ACKs, the VLC ACK reception at AP will fail only because of Wi-Fi channel fading. To minimize the probability of VLC ACK reception failure, STMA makes the VLC clients transmit the VLC ACKs at Wi-Fi channel base rate. In LiRa architecture, on AP’s side, the VLC ACK frames are forwarded to the VLC MAC by the LiRa sub-layer without going through the Wi-Fi MAC. Therefore, the AP does not send any 802.11 MAC-layer ACK on receiving each VLC ACK. Instead, STMA broadcasts the confirmation of the VLC ACK reception via the VLC downlink after the spoofed NAV period ends. In case of VLC ACK transmission failure, VLC client will aggregate the content of the lost VLC ACK into the next VLC ACK.

Figure 3.2 illustrates STMA’s timeline. There are two VLC clients and two legacy
Figure 3.2: STMA’s timeline for the scenario of two VLC clients and two legacy users in the network. STMA is the combination of STMA trigger to the AP, trigger message transmitted by the AP and uplink VLC ACK transmissions.

users in the network. The AP transmits multiple data packets in a round-robin mechanism to each VLC client in spite of not receiving ACKs. Suppose the former VLC ACK transmission ends at time 0. After $T_w$ time, VLC triggers the AP to acquire the channel but there is an ongoing transmission of a legacy user. PIFS time after the transmission concludes, the AP transmits a trigger message followed by VLC ACK transmissions from each VLC client in the pre-assigned order. All users are deferred by their NAV during the VLC ACK transmissions.

3.3 STMA Analysis

With STMA, if the AP employs a static radio trigger time $T_w$, the selection of $T_w$ represents a tradeoff between the VLC ACK delay and the legacy Wi-Fi throughput degradation. If $T_w$ is too low, then the AP acquires the Wi-Fi channel frequently for VLC ACK transmissions and this could lead to significant legacy Wi-Fi throughput degradation, especially when there are a large number of VLC clients. If $T_w$ is too
Table 3.1: Notation table for STMA analysis.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>VLC client size</td>
</tr>
<tr>
<td>$R_d$</td>
<td>VLC downlink data rate</td>
</tr>
<tr>
<td>$L$</td>
<td>downlink packet size</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Wi-Fi base rate</td>
</tr>
<tr>
<td>$C_1$</td>
<td>constant coefficient, equals to $\frac{R_d}{L}$</td>
</tr>
<tr>
<td>$T_w$</td>
<td>radio trigger time</td>
</tr>
<tr>
<td>$T_u$</td>
<td>time utilized by STMA for VLC ACK transmission</td>
</tr>
<tr>
<td>$T_{off}$</td>
<td>duration of ongoing transmission</td>
</tr>
<tr>
<td>$T_{ov}$</td>
<td>VLC control overhead</td>
</tr>
<tr>
<td>$T_{trigg}$</td>
<td>trigger message transmission time</td>
</tr>
<tr>
<td>$T_{header}$</td>
<td>VLC ACK header transmission time</td>
</tr>
<tr>
<td>$D_r$</td>
<td>Response Delay</td>
</tr>
<tr>
<td>$T_{w, adaptive}(x)$</td>
<td>Adaptive radio trigger time after $x$ downlink packet transmissions</td>
</tr>
<tr>
<td>$T_{timer}$</td>
<td>radio trigger timer that begins on completion of VLC ACK transmissions</td>
</tr>
<tr>
<td>$\delta$</td>
<td>legacy Wi-Fi throughput degradation constraint</td>
</tr>
<tr>
<td>$U$</td>
<td>legacy Wi-Fi throughput degradation</td>
</tr>
</tbody>
</table>

If the channel is idle for PIFS time, the AP can acquire the channel immediately by sending the trigger message. Otherwise, an ongoing transmission can take up to the transmission opportunity time limit to complete and only then the AP can acquire the Wi-Fi channel. I denote $T_{off}$ as the time between STMA triggering the AP and the time when the ongoing transmission ends. We consider the Wi-Fi base rate as $R_b$. The complete list of notation is provided in Table 3.1.
3.3.1 Legacy Wi-Fi Degradation

I define \textit{legacy Wi-Fi throughput degradation} of any VLC ACK transmission mechanism as the throughput degradation of the legacy Wi-Fi traffic caused by the VLC ACK transmissions, expressed as

\[
1 - \frac{\text{throughput (with VLC ACK transmissions)}}{\text{throughput (without VLC ACK transmissions)}}.
\]  

(3.1)

In the following analysis, I consider that \( T_w \) is large enough such that every VLC client has a VLC ACK to transmit when the AP triggers the VLC ACK transmission. As a result, the total control overhead \( T_{ov} \) is

\[
T_{ov} = PIFS + T_{trigg} + N(T_{header} + SIFS),
\]  

(3.2)

where \( T_{header} \) is the VLC ACK header and \( T_{trigg} \) is the trigger message transmission time. Based on the ACK aggregation methodology discussed above, each packet will have a corresponding single bit in a VLC ACK packet indicating the success or failure of reception. The transmitting time of these bits can be estimated as \((T_w + T_{off}) \frac{R_{d}}{LR_{d}}\). Let \( C_1 = \frac{R_{d}}{LR_{d}} \) which is a constant. The total Wi-Fi channel time utilized by STMA can be expressed as

\[
T_u = T_{ov} + C_1(T_w + T_{off}).
\]  

(3.3)

Note that STMA does not change the contention status of legacy users. As a result, the only impact of STMA on the legacy Wi-Fi channel is to occupy the channel for some time. Therefore, the legacy Wi-Fi throughput degradation \( U \) should equal to the ratio of STMA occupying time over the total time of this single VLC ACK interval.
\[ U = \frac{T_u}{T_u + T_w + T_{off}} = \frac{T_{ov} + C_1(T_w + T_{off})}{T_w + T_{off} + T_{ov} + C_1(T_w + T_{off})} \]  

(3.4)

Note the only random variable in the analysis is \( T_{off} \). For each VLC ACK interval, the particular value of \( T_{off} \) is determined by the Wi-Fi channel data transmission which is independent of the VLC ACK transmission trigger. Over a large number of VLC ACK intervals, \( T_{off} \) can be treated as an independent and identical distributed random variable. As a result, considering the start of each VLC ACK interval as the renewal point, the VLC ACK transmission becomes a renewal process and the reward is the time of STMA VLC ACK transmission. As a result, the expectation of legacy Wi-Fi throughput degradation \( U \) results in

\[
E\{U\} = \frac{E\{T_{ov} + C_1(T_w + T_{off})\}}{E\{T_w + T_{off} + T_{ov} + C_1(T_w + T_{off})\}} = \frac{T_{ov} + C_1T_w + C_1E\{T_{off}\}}{T_{ov} + (1 + C_1)T_w + (1 + C_1)E\{T_{off}\}} = \frac{1}{1 + C_1} \left[ C_1 + \frac{T_{ov}}{T_{ov} + (1 + C_1) \cdot (T_w + E\{T_{off}\})} \right],
\]

(3.5)

where \( E\{\} \) represents the expectation operation. According to Equation (3.5), the legacy Wi-Fi throughput degradation is inversely proportional to the radio trigger time \( T_w \). On the other hand, \( T_{off} \) is determined by the current ongoing Wi-Fi transmission. Therefore, it is related to the single packet transmission time but independent of the number of legacy users in the network.
3.3.2 STMA’s Response Delay

After sending a downlink data packet, the AP receives the feedback (response) when the corresponding VLC ACK is received. The AP react based on the response, re-transmit the packet if the packet is lost, or change the MCS if that VLC ACK triggers the rate adaptation mechanism. I define response delay as the duration between a packet transmitted by the AP and the corresponding VLC ACK received by the AP. Note the VLC ACK may acknowledge the packet or un-acknowledge the packet. The shorter the response delay is, the quicker the AP can react with retransmission or MCS change.

Figure 3.3: Example of response delay. Ignore the VLC ACKs transmission time. The response delay of VLC Client 1’s packet 1 equals to the interval duration minus the packet transmission time, while the response delay of VLC Client 1’s packet 6 almost equals to 0.

According to the definition, in a VLC ACK interval each packet will have different response delay. Ignoring the VLC ACK transmission time that is relatively small comparing to $T_w$, the response delay of the first packet transmitted in this VLC ACK interval equals to this interval duration minus the packet transmission time, while
the response delay of the last packet transmitted in the VLC ACK interval almost equals to 0. The response delay of other packets are evenly distributed, as shown in Figure 3.3. Therefore, the response delay is always less than the VLC ACK interval duration and the average response delay of all packets in a single VLC ACK interval is proportional to this VLC ACK interval duration.

\[
E\{D_r\} = C_2 \times (T_w + T_{off} + T_{ov}),
\]

\[
\max\{D_r\} < (1 + C_1)(T_w + \max\{T_{off}\}) + T_{ov}
\]  

(3.6)

where \(C_2\) is a constant. Because both \(T_{ov}\) and \(T_{off}\) are independent of \(T_w\), I observe that the expectation of \(D_r\) in a single VLC ACK interval is linearly related to \(T_w\). Considering the average over multiple VLC ACK interval, the linear relationship is still valid. In addition, the \(T_{off}\) is always less than the maximum legacy user’s packet transmission time. Therefore, given \(T_w\), the response delay is upper-bounded.

### 3.4 Degradation-Constrained Trigger Adaptation

Although selecting a fixed radio trigger time would ensure the response delay is upper-bounded, the legacy Wi-Fi degradation is also affected by the number of VLC clients based on Equation (3.2) and Equation (3.5). When the number of VLC clients change, to keep the legacy Wi-Fi degradation throughput always below a given limit \(\delta\), I present a frame-by-frame adaptation algorithm of the radio trigger time.

Because \(T_{off} > 0\), according to Equation (3.5),

\[
E\{U\} < \frac{T_w}{T_u + T_w}.
\]  

(3.7)
As a result, given the constraint \( E\{U\} < \delta \), the expected \( T_w \) with respect to \( T_u \) is

\[
T_w = \left( \frac{1}{\delta} - 1 \right) T_u \tag{3.8}
\]

For the trigger time adaptation, the key strategy is to adjust \( T_w \) whenever \( T_u \) changes and trigger the AP to acquire the Wi-Fi channel access after airtime passed since last VLC ACK transmissions (\( T_{timer} \)) is just greater than \( T_u \). I next discuss the mechanism in more detail.

(i) Trigger Time Initialization: The AP needs to acquire the channel after transmitting at least one VLC data packet to the VLC client. Therefore, I initialize the initial radio trigger time to be

\[
T_{w,\text{adaptive}}(0) = \left( \frac{1}{\delta} - 1 \right) (T_{ov} |_{N=1} + \frac{1}{R_b}). \tag{3.9}
\]

where \( \frac{1}{R_b} \) corresponds to the transmission time of a single bit in the bitmap of corresponding VLC client’s VLC ACK. At this initial point, VLC starts the timer \( T_{timer} \) at 0. Initially, \( T_{timer} < T_{w,\text{adaptive}}(0) \).

(ii) Trigger Update: As discussed before, the trigger time \( T_w \) should be adjusted whenever the \( T_u \) changes, i.e. whenever the AP sends a new VLC downlink data packet. There exist two different cases. If the new data packet is destined to a VLC client who has not received any data packet, then \( T_{ov} \) should be adjusted to include transmission overhead of the new aggregated VLC ACK from this client. Therefore, the \( T_w \) should be updated as,

\[
T_{w,\text{adaptive}}(n) = T_{w,\text{adaptive}}(n-1) + \left( \frac{1}{\delta} - 1 \right) (T_{\text{header}} + SIFS + \frac{1}{R_b}), \tag{3.10}
\]
On the other hand, if the new data packet is destined to a VLC client who has already received some data packets, then $T_u$ only adds the transmission time of corresponding bit in the aggregated ACK. Consequently,

$$T_{w,\text{adaptive}}(n) = T_{w,\text{adaptive}}(n - 1) + (\frac{1}{\delta} - 1)(\frac{1}{R_b}),$$  \hspace{1cm} (3.11)

STMA keeps checking if $T_{\text{timer}} \geq T_{w,\text{adaptive}}$. If the condition is satisfied, then, STMA triggers the AP to acquire the Wi-Fi channel. Otherwise, the VLC ACK trigger time update process continues.

The update process above is described as a continuous process. However, in a practical system, the update of $T_w$ is discrete because the transmission time should be computed based on the number of PHY layer symbols instead of based on the number of bits. The number of bits contained in a symbol is determined by the MCS. For example, for 802.11g 6Mbps MCS, each symbol takes $4\mu s$ to transmit and contains 24 bits. Therefore, in the practical system with 6Mbps data rate, even a packet only contains 1 bit payload, it still takes $4\mu s$ (1 symbol) to transmit that payload. As a result, with 6Mbps control rate, in the update process the first bit of payload in the VLC ACK counts for $4\mu s$ augment of $T_u$, which corresponds to $4(\frac{1}{\delta} - 1)$ augment of $T_w$. $T_w$ will be adjusted because of this VLC client again only after the AP sends the 25 new data packets to this VLC client, which will add the 25th bit to the VLC ACK payload and another symbol is needed to transmit the VLC ACK.
In this chapter, I discuss the implementation of the key components of STMA. The implementation includes two parts. First, we emulate STMA on the WARP board platform [5] with small number of legacy users and VLC clients and collect the VLC ACK transmission trace. Second, we implement an STMA simulator using ns-3 discrete-event network simulation framework and collect VLC ACK transmission data for dense WLAN scenarios. Taking the collected VLC ACK transmission data as input data, I simulate the VLC downlink in MATLAB and emulate the whole LiRa system.

4.1 Small Scale Implementation Using WARP

4.1.1 VLC Downlink Implementation

The VLC equipment we have employs DCO-OFDM [11] modulation and has a the limited modulation bandwidth of 2 MHz. Upon using DCO-OFDM, positive and real-valued symbol representations are generated, which can be transmitted via the Intensity Modulation/Direct Detection (IM/DD) VLC PHY. A VLC testbed is con-
constructed for the VLC link based on WARP v1.2 software-defined platform [12]. An array of white LEDs (Bridgelux BXRA-40E0950-B-03) serves as the LED transmitters at the AP and a photo diode (LEC-RP0508) serves as the receiver at the VLC client. The WARP boards, which typically outputs legacy WiFi carrier signals, are extended with an analog boards interfacing arbitrary baseband signals as required for DCO-OFDM. This setup provides a sampling rate of 40 MHz. The modulation utilizes 128 subcarriers, but only 64 of them carry the data to obtain a real-valued OFDM output from the analog boards. A DC offset is added by another circuit, whose voltage can be adjusted to enhance the optical power. The driver circuit converts voltage to a current, changing LED brightness, thus modulating the signal onto the LEDs brightness. At the VLC client, the photodiode converts light to current, which the VLC receiver amplifies and the driver circuit converts to voltage.

![Figure 4.1: Radio link Implementation Setup](image-url)
4.1.2 Radio Link Implementation

With STMA, the AP attempts to obtain the channel access after radio trigger time since the last VLC ACK transmission. During this period of time, as long as all other transmissions are deferred, whether the VLC ACKs are transmitted or not has no impact on the legacy Wi-Fi channel. In addition, the VLC ACK transmissions are contention-free. As a consequence, the VLC ACK transmission would only fail due to channel fading. Considering the short distance between the VLC client and the AP in the indoor environment and the fact that VLC ACKs are transmitted at base rate, we can assume that the VLC ACK transmissions are always successful. Therefore, in the implementation, we do not make VLC clients transmit VLC ACKs. Instead, I make the AP acquire the Wi-Fi channel for controlled duration and assume that all VLC ACKs are successfully transmitted during this period.

The hardware setup of my implementation is illustrated in Figure 4.1. The WARP v3 [5] platform is utilized. The WARP board exchanges data with a computer via the Ethernet interface and can perform real-time wireless transmission with its WARPNet module. I use the 802.11 Reference Design for WARP v3 as the MAC layer design, which is 802.11g compatible. I utilize at most 4 WARP board nodes, including 1 AP, 1 VLC client, and at most two legacy users. In order to make the AP able to obtain the channel access immediately after the channel becomes idle once requested, I adjust the DIFS of the AP node to PIFS time and set the contention window size to 0. Because the VLC clients are not required to transmit the VLC ACK, although we only have one VLC client node, we can emulate the behavior for multiple VLC clients scenario.

For the software setup, I write the packet transmission and reception program in Linux using the raw socket API. To implement STMA, after radio trigger time since last VLC ACK transmission, I make the AP attempt to transmit to the VLC client a
data packet whose transmission time would equal to the computed VLC ACK trans-
mmission time. In this manner, I emulate the procedure of VLC clients transmitting
VLC ACKs to the AP. To emulate the multiple VLC clients scenario, we only need to
adjust the packet size so the transmission time matches the VLC ACK transmitting
time for multiple VLC clients.

For legacy users, I consider a dense traffic scenario and let them have fully back-
logged uplink traffic. On the other hand, the VLC clients have no regular uplink data
traffic. In practice, the VLC clients will have their own regular uplink traffic while
the AP will have regular downlink traffic for legacy users. However, regarding the
VLC ACK transmission trace collection, a VLC clients’ uplink traffic and AP’s down-
link traffic can each be separately considered as another legacy user in the network
with uplink traffic to transmit. Therefore, I do not implement Wi-Fi traffic on the
AP or the VLC client.

4.2 Multi-VLC Client Simulator

I also implement a STMA simulator using ns-3 to analyze the performance for dense
WLAN scenarios. In this simulator, I utilize the same transmission methodology as
that of the hardware implementation for implementing STMA. That is, instead of
every VLC client transmitting the VLC ACK, the AP transmits a data packet whose
transmitting time equals to the transmitting time of all VLC ACKs to emulate the
VLC ACK transmission. Similarly, for the AP node, we also set the DIFS time to
PIFS time and the contention window size to 0.

In the simulation, all the nodes are set to be static and within the signal range of
each other to eliminate hidden terminals. I consider the SNR from the AP node to
other nodes is sufficient to utilize the highest MCS. I utilize the same traffic setup as
that of hardware implementation. I record the throughput of legacy user nodes
and the time each VLC client receives the data packet from the AP as the VLC ACK transmission data.

4.3 VLC-RF Trace-Driven emulator

I implement a VLC-RF system trace-driven emulator in MATLAB that can take the VLC ACK transmission data from both the hardware implementation and ns-3 simulator as input to evaluate the performance of the whole VLC-RF system. I incorporate the LiRa architecture into this emulator. I assume the VLC downlink has an AWGN channel and the data rate selection is up to 1 Gbps. For the uplink, each VLC client will transmit the VLC ACK based on the time provided in the input. Currently there is no standard defining the MAC and PHY layer for the Gbps VLC link. In order to properly emulate the transmission overhead caused by the MAC layer and PHY layer, I refer the parameters used in IEEE 802.11ad standard [13] for multi-Gbps 60 GHz communication. Specifically, the SIFS time is set to 3 µs and the transmission time for PHY preamble and header is set to 2.36 µs. I also assume that the maximum length of the MPDU (MAC Protocol Data Unit) is 32KB.
In this chapter, we evaluate the performance of STMA with the help of our collected VLC ACK transmission data in various scenarios. The two evaluation metrics are the response delay and the legacy Wi-Fi throughput degradation. Firstly, we compare the performance of STMA’s trigger time adaptation versus a fixed radio trigger time approach. Secondly, we compare STMA’s performance versus the baseline system of per-client contention.

For each combination of parameters analyzed in this section and for both our hardware implementation and STMA simulator, we obtain a data set corresponding to 10 independent runs. A single run consists of a running time of 30 seconds in which thousands of legacy users’ data packets and VLC ACKs are transmitted. We consider all legacy user data packets have the same length of 1464 Bytes and the MCS selected corresponds to the data rate of 54 Mbps. The legacy users follow the standard IEEE 802.11g operation. We also consider that the AP has fully backlogged data for the VLC clients. Each VLC ACK has the header identical to that of an ACK in the 802.11 standard, along with extra length determined by the number of aggregated VLC ACKs. Unless otherwise stated, the VLC link is loss-free with 1 Gbps date rate, and the MPDU on the VLC links have a fixed length of 32 KB.
5.1 STMA’s Adaptive Trigger Time Evaluation

As discussed in Section 3.3.1, the legacy Wi-Fi throughput degradation is inversely proportional to the radio trigger time and is independent of the number of legacy users in the network due to the contention-free VLC ACK transmissions. On the other hand, as discussed in Section 3.3.2, the response delay increases linearly with the radio trigger time. I next show the impact of the VLC client size on STMA’s trigger time adaptation.

For this purpose, utilizing VLC ACK transmission data collected from our STMA simulator, I compare STMA’s adaptive trigger mechanism with a fixed radio trigger time approach. For the adaptive trigger mechanism, the degradation constraint is set to 0.1. For the fixed trigger time approach, I consider the cases of low trigger time of 1ms that leads to frequent VLC ACK transmissions and a relatively high trigger time of 10ms that leads to higher response delay.

![Figure 5.1: STMA’s trigger time evaluation for response delay. $T_w$ denotes the radio trigger time.](image-url)
In Figure 5.1, the x-axis is the number of VLC clients and the y-axis is the mean response delay. First, for each of the fixed trigger time curves, the mean response delay is lower than the corresponding trigger time value. This is because the average is computed over the response delay of every downlink packet transmitted. According to Equation (3.6), the maximum response delay is upper-bounded by a value slightly greater than the radio trigger time. Second, for the fixed trigger time approaches, the response delay slightly increases with the number of VLC clients because of the increase in total VLC ACK transmission time. Third, for the adaptive trigger mechanism, the response delay increases with VLC client size but with a greater slope than that of the curves for fixed trigger time approach. This is because for the adaptive trigger time approach, in order to maintain the legacy Wi-Fi throughput degradation below the given constraint, the trigger time selected increases with VLC client size to compensate for the additional VLC ACK transmission time per VLC ACK interval, and that compensation is much larger than the additional VLC ACK transmission time itself.

In Figure 5.2, the x-axis is the number of VLC clients and the y-axis is the legacy Wi-Fi throughput degradation. First, for the fixed trigger time approaches, the legacy Wi-Fi throughput degradation increases with the number of VLC clients due to the increase in VLC ACK transmission time per VLC ACK interval, which makes the VLC ACKs occupy the channel more. In contrast, the adaptive radio trigger time approach increases the radio trigger time with the VLC ACK transmission time to keep the legacy Wi-Fi degradation steady. Second, for the adaptive radio trigger time scheme, the throughput degradation is slightly higher than 0.1 at some data points, indicating that STMA causes more degradation than Equation (3.5) estimates, but the drift is limited. In DCF, if a user detects the channel to be idle for DIFS time, it will transmit its packet immediately. Otherwise, it waits the channel to be idle
Figure 5.2: STMA’s trigger time evaluation for legacy Wi-Fi throughput degradation. $T_w$ denotes the radio trigger time.

for DIFS time, completes the backoff, and then transmits the packet. Therefore, users attempt to acquire the channel during the VLC ACK transmission has to do backoff before it transmits the packet, which may not be necessary without VLC ACK transmission. This part of degradation is not considered in Equation (3.5).

Moreover, for the scenario of radio trigger time equal to 1ms, the throughput degradation stops increasing after the number of VLC clients exceeds 4. This is because, with 32 KB MPDU and 1Gbps VLC link, each VLC data packet takes around $262\mu s$ to transmit. In 1ms radio trigger time scenario, at most 4 VLC clients can get new data packets from the AP (it is possible that a downlink packet is transmitted during the VLC ACK transmission, which will be acknowledged in the next set of group VLC ACK transmissions). Therefore, regardless of the number of VLC clients, at most 4 VLC ACKs will be transmitted every VLC ACK interval. As a result, the throughput degradation stays almost the same after the number of VLC clients exceeds 4. In fact, in Figure 5.1, the response delay also stops increasing.
after the number of VLC clients exceeds 4. *Finding: The fixed trigger time approach is a response delay-control policy while the adaptive trigger time operation is a degradation-control policy.* The adaptive approach is utilized for the remainder of the performance evaluation.

### 5.2 Performance Comparison with Per-client Contention

**Per-client Contention (PCC) Baseline.** For evaluation, I create a baseline system in which every VLC client *independently* contends via 802.11 to transmit the VLC ACKs. Because there is no scheduled VLC ACK transmission in this baseline, each VLC client relies on acknowledgement from the AP after transmitting a VLC ACK to find out if a retransmission of VLC ACK is necessary. The retransmission follows the procedure defined in the 802.11 standard. For this purpose, we assume the AP provides an instantaneous acknowledgement using the VLC channel for every VLC ACK received over the Wi-Fi channel. Because the evaluation focuses on STMA’s channel access mechanism, in the baseline model I assume the ACK aggregation is still utilized. That is, when the VLC client obtains the TXOP, it aggregates all the VLC ACKs into one packet and transmit. We consider the VLC clients use the base rate for VLC ACK transmission and that the Wi-Fi channel is loss free so the VLC ACK transmission failures are only due to collisions.

Using VLC ACK transmission data collected from our STMA simulator, we compare STMA’s performance with the baseline of per-client contention. For STMA, we consider the trigger time adaptation with degradation constraint of 0.1 and 10 legacy users in the network. For the baseline, we consider a scenario of just 1 legacy user and a dense scenario of 10 legacy users.
In Figure 5.3, the x-axis is the number of VLC clients and the y-axis is the average response delay. First, the response delay of STMA is below that of PCC with 1 legacy user, independent of the VLC client size. This is because with just one legacy user, the probability of VLC clients winning contention for VLC ACK transmissions is high. Therefore, the VLC ACK can be transmitted more frequently than STMA. Second, the response delay of PCC with 10 legacy users in the network is over 5 times (> 20 ms) that of STMA. This excessive delay results from the airtime lost in doing backoff and collisions between the VLC ACKs and the uplink data packets of legacy users. Third, the response delay monotonically increases with VLC client size for STMA and PCC with 1 legacy user. In contrast, for the case of PCC with 10 legacy users, we observe an initial decrease with increase in VLC client size. This is because the increase in VLC client size leads to higher probability of a VLC client winning contention and more frequent VLC ACK transmission. However, for larger VLC client sizes, collisions have a bigger impact leading to the increase in the response
delay.

In Figure 5.4, the x-axis is the number of VLC clients and the y-axis is the legacy Wi-Fi throughput degradation. First, the per-client contention baseline has lower Wi-Fi throughput degradation only at one data point with 1 VLC client and 10 legacy users. At this point, the legacy users outnumber the single VLC client, making it difficult for the VLC client to win contention. As a result, the single VLC client transmits VLC ACK much less frequent, result in low legacy Wi-Fi degradation but high response delay as shown in Figure 5.3. Second, using STMA with adaptive trigger time approach, the throughput degradation remains constant with the increasing VLC client size while the legay Wi-Fi degradation keeps increasing due to more severe contention on the Wi-Fi channel. Third, the legacy Wi-Fi throughput degradation is higher for PCC with one legacy user in comparison to 10 legacy users because of the higher probability of VLC clients winning the Wi-Fi channel contention and more frequent VLC ACK transmission in the former case. Finding: In a dense WLAN sce-
nario, STMA can maintain both low response delay and low legacy Wi-Fi degradation while PCC can achieve only one of them with the other one much higher than STMA. Specifically, STMA reduces the VLC ACK response delay by more than 90% in the case of 10 legacy user and reduces the legacy Wi-Fi throughput degradation from an excessive value of 0.62 to the targeted limit of 0.1 in the case of 1 legacy user.

Figure 5.5: Response delay of STMA and PCC in realistic indoor environment. $T_w$ denotes the radio trigger time.

I next analyze STMA’s performance in a realistic indoor environment by feeding the VLC ACK transmission trace data collected using the WARP-based implementation to the VLC emulator. In Figure 5.5, the x-axis is the number of VLC clients and the y axis is the mean response delay using STMA’s adaptive trigger mechanism. For the practical scenario, we run the experiment in the day time in typical office environment, where the legacy users are all users using Wi-Fi in the same channel. For other cases, we run the experiment in a controlled environment such that the only legacy users in the network are our legacy user nodes. First, expectedly, across all scenarios, the response delay increases almost linearly with the number of VLC clients. Second,
the mean response delay is independent of the number of legacy users, but is in the practical scenario the response delay is higher than the controlled environment case. This is because in Equation (3.6), the response delay is also affected by the ongoing transmission time, which is upper-bounded by the legacy user’s data packet transmission time. In the practical scenario, the data packet transmission time is flexible and probably higher than the value in the controlled experiment. This leads to an increase in the mean response time and the deviation.

5.3 STMA’s Performance with Lossy VLC Link

In the evaluation so far, the VLC link is assumed to be loss-free perfect. I next analyze how the retransmission is impacted by STMA with a lossy link. As discussed in Section 3.3.2, lower response delay result in more timely packet retransmission. I define the acknowledgement delay as the interval between the time a packet is firstly transmitted and the time this packet is acknowledged. If the packet is lost, the time cost by retransmission is also included in the acknowledgement delay. If a packet transmission succeeds without any retransmission, the acknowledgement delay equals to the response delay. Otherwise, the acknowledgement delay will be larger.

I considering the VLC channel as an AWGN channel, so the packet loss occurs independently with a fixed probability. In the practical system, a rate adaptation algorithm should lower the MCS when massive packet loss happens. However, in this evaluation, I consider the VLC link MCS does not change regardless of packet loss.

In Figure 5.6, the x-axis is the VLC link packet loss ratio and the y-axis is the mean acknowledgement delay, respectively. The acknowledgement delay increases significantly with the packet loss ratio because of the packet retransmission. Note that with more VLC clients, the acknowledgement delay increases faster with packet loss ratio. This is because we use the round-robin scheduling which may delay the
retransmission of lost packets. For example, with 2 VLC clients, if VLC client A has two lost packets while VLC client B has no lost packets, before the AP retransmits the second lost packet of VLC client A, the AP transmits a normal data packet to VLC client B. Therefore, the retransmission of the second lost packet is delayed by one data packet transmission time. **Finding:** With AWGN channel model, when the link is lossy, the acknowledgement delay increases rapidly with the packet loss ratio, and the increase rate monotonically increases with the VLC client size.
This thesis presents the first MAC layer DATA/ACK handshake design in the hybrid VLC-RF system. The handshake problem is not addressed in the related work below, and STMA design is complementary to the following related works.

### 6.1 Analytic Studies

Most prior works in the field of VLC are based on theoretical analysis and simulations. Some of them focus on the scheduling and resource allocation in the VLC only system, where a multi-cell model is usually considered. Others consider the hybrid VLC-RF system and study the load balancing and handover between the VLC and RF channels.

#### 6.1.1 VLC Only Networks

Fractional frequency reuse (FFR) was proposed in [14] to manage the trade-off between spectral efficiency and cell-edge user throughput. In the multi-cell model, each LED cluster covers a small area to form a cell and multiple cells is usually needed to fully cover a room. Each cell can transmit different data to different receivers simultaneously. Full frequency reuse among cells maximizes the throughput, but cell-edge
users will suffer from co-channel interference. Partitioning the spectrum for different cells eliminate the co-channel interference at the cost of throughput lost. By introducing FFR, the authors divided each cell into several sub-cells and only sub-cells without cell-edge users are permitted to use the entire bandwidth. The simulation result showed that FFR improves the system in terms of cell-edge users throughput and overall system throughput in comparison to the full frequency reuse and cluster-based resource partitioning.

Scheduling algorithms to determine the serving cell and serving time for each client were presented in [15]. The authors introduced two different perspectives of cell formation, the Cell-Centric, in which cells have fixed boundaries, and User-Centric, in which amorphous cells are formed based on users’ locations. A Multi-User Scheduling optimization problem relying on the users’ Proportional Fairness as a measure was formed to schedule the serving cell and serving time for clients. To solve the optimization problem, a heuristic algorithm was proposed. The authors evaluated the throughput and fairness of the scheduling algorithm in various cell formations.

6.1.2 Integrated VLC-RF Networks

The structure of the hybrid VLC-RF system was exploited for broadcast service in [16]. In the proposed system, both the VLC and RF links are utilized for downlink transmission. Traffic is off-loaded to the VLC link when the Wi-Fi channel is congested. The authors studied the allocation and vertical handover scheme between VLC and RF links and proposed the theoretical performance analysis of the hybrid VLC-RF system.

Load balancing between VLC and RF links was further studied in [17] as an optimization problem. The proportional fairness was selected as the optimization objective. The optimization problems represented an Mixed-Integer Non-Linear Pro-
gramming (MINLP) problem and the authors proposed an approximated solution by utilizing discretized linear programming. Based on the solution, the authors introduced the implementation algorithm and evaluated the performance in various cell formations via simulation.

In [18], the authors consider the hybrid VLC-RF system in which the RF system utilizes OFDMA. Horizontal and vertical handover mechanisms were devised, which aim at maintaining the VLC connection while users are moving. The authors defined the spatial density as the request interarrival time in $s^{-1}m^{-2}$ to measure the capacity of the hybrid system and analyzed the maximum spatial density the system can support. The VLC accessing time and handover delay were also discussed. Through simulations, the authors showed the impact of various system parameters on the maximum spatial density.

6.2 System Implementations

Besides analysis and simulations, researchers also dedicate to implement the VLC system in practice. Both the VLC only and hybrid VLC-RF system prototypes have been implemented, showing the promising future of the VLC systems.

6.2.1 VLC only systems

A software-defined VLC system including a bi-directional VLC link with On-Off keying (OOK) modulation, openVLC, is presented in [19]. Based on the embedded Linux platform BeagleBone board, openVLC has a programmable PHY and MAC layer. Although the data rate of openVLC is limited by the OOK modulation, openVLC shows the potential of software-defined VLC system.

On the other hand, Li-Flame is a commercial VLC system product that provides
10Mbps downlink over a range up to 3 meters with VLC and 10 Mbps uplink with infrared [20]. With Li-Flame, the Ceiling Unit which works as the VLC AP and infrared receiver is connected to the backhaul network via a standard Ethernet cable. The Desktop Unit which works as the VLC receiver and infrared transmitter can connect to users’ device via USB port. The producers also claim that seamless handover protocol between different Ceiling Units is implemented, therefore users’ mobility is supported.

6.2.2 Integrated VLC-RF systems

Two integrated VLC-RF systems are implemented in [8]: one utilizes a simplex VLC link for the downlink channel and Wi-Fi link as the uplink; the other aggregates bi-directional VLC and bi-directional Wi-Fi. The VLC system used in [8] provides up to 70Mbps data rate in 2m distance. Experiment results showed that the aggregated system increases the average throughput by more than 35 times in 6 users case comparing with the Wi-Fi only system. The authors also showed that without aggregation, the hybrid VLC-RF system has worse performance than the Wi-Fi when the distance between the AP and the user exceeds 4m. This paper focus on design mechanisms for routing and address spoofing at the IP layer. The RF and VLC MAC layers are separate therefore no MAC layer DATA/ACK handshake is implemented.

6.3 VLC Services and Devices

Lastly, there is an emerging body of research on employing VLC for sensing or localization and employing cameras as receivers. A VLC module, Okuli, was designed to locate a user’s finger within a workspace with one-centimeter precision [21]. Utilizing a single LED and two photodiodes together with a shroud which reshapes
LED/photodiode’s field of view, Okuli executes a 3-point initial calibration to locate the finger. Okuli also takes advantage of flickering to distinguish the light signal from the ambient noise and reduce power consumption at the same time. The prototype of Okuli was implemented as a peripheral module to an Android device. The experiment result showed that one-centimeter lever precision is achieved.

Likewise, a VLC sensing system can reconstruct the 3D human skeleton postures from the 2D shadow information, LiSense, is presented in [22]. In LiSense, the photodiodes monitor the light intensity change to acquire the shadow mapper which is utilized to reconstruct the 3D posture. In order to eliminate the ambient light interference, the authors designed special light beacons to separate light rays from individual LEDs and ambient light. An algorithm was also presented to precisely reconstruct the posture from low-resolution shadow maps. LiSensed was implemented with off-the-shelf LED, photodiodes and micro-controllers. The experiment result showed that LiSense can reconstruct the posture in less than 16ms with average angular error of 10°.
In this thesis, I present the design of STMA, a MAC layer DATA/ACK handshake scheme for the hybrid VLC-RF system. In order for clients to transmit VLC ACKs via Wi-Fi channel without excessive channel access delay and legacy Wi-Fi degradation, STMA disables the DCF contention-based channel access and provides a central-controlled access scheme. Using over-the-air measurements and trace driven simulations, I evaluated the performance of my designs in different WLAN scenarios. I showed that STMA is able to reduce the response delay by more than 10 times in comparison to 802.11 contention-based approach and meanwhile constrains the legacy Wi-Fi throughput degradation to a pre-determined level.
References


[20] pureLiFi, “Li-Flame high-speed wireless network solution using VLC.” 6.2.1
