Practical VLC to WiFi Handover Mechanisms

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Abstract

Visible light communication (VLC) is an emerging communication technology that perfectly integrates into crowded legacy radio frequency (RF) environments to increase bandwidth. Despite the fact that integrating these technologies would be beneficial for both of them, there is only little research on handover mechanisms, and most of it is simulation only. We design a software defined radio (SDR) based VLC+WiFi testbed in which both technologies can coexist, design handover mechanisms between VLC and WiFi, and evaluate them based on user-induced link blockage measurements in our testbed.

1 Introduction

Wireless networks rely on RF communication. With the emergence of light-emitting diodes (LEDs) for illumination, light can be modulated to transmit data, termed VLC. In contrast to RF spectrum, there are no regulations and usage does not require a license. VLC installations are beneficial in sensitive environments, such as airplanes and hospitals, as they do not introduce electromagnetic noise. Additionally, VLC offers a communication channel that does not interfere with existing RF in crowded environments.

However, VLC still faces problems such as portable mobile transmitters and coverage, as its physical properties make it way easier to interrupt the communication. Coexistence with ubiquitous WiFi is required to take full advantage of high VLC bandwidth, and a seamless handover between VLC and WiFi is needed for good user experience. There is little practice-oriented research on this topic, mostly simulations, as VLC itself is not established and off-the-shelf hardware capable of both technologies does not exist. Before hybrid networks can be adopted in commercial products, testbeds are required for development of standards.

In this paper, VLC hardware from prior works is optimized, simulated, and built. In a testbed measurements of link blockage are carried out. Multiple handover mechanisms from VLC to WiFi on media access control (MAC) layer are designed and simulated based on our link measurements to evaluate when to hand over and how. Handover decision algorithms are implemented for offline processing to compare their suitability. Our combined VLC+WiFi testbed is designed based on two SDR platforms, namely the wireless open-access research platform (WARP) and universal software radio peripheral (USRP).

This paper is structured as follows. Section 2 discusses related work. Section 3 describes hardware and software components of the VLC+WiFi testbed including a low-cost VLC transmitter circuit. In Section 4 a series of user movements is recorded and based on this, handover mechanisms are designed. These mechanisms are further evaluated in Section 5. Our results are concluded in Section 6.

2 Background and Related Work

This section discusses existing practical heterogeneous networks (HetNets). Moreover, we categorize hardware solutions in USRP-based and others.

Existing WiFi+VLC HetNets

In a HetNet, VLC is complemented with RF. Heterogeneous systems intend solving blockage and disqualification of VLC as uplink for mobile devices. Blockage is to be encountered with vertical handover (VHO) to RF, which is utilized for uplink as well. *Symmetric* refers to systems that use VLC in both link directions, while *asymmetric* networks use a non-VLC uplink. We assume all traffic passes the same access point (AP).

HetNets introduce new VLC research challenges, including optimal resource allocation, downlink aggregation, horizontal handover (HHO), and VHO. HetNets research is typically based on simulations. The most significant practical HetNet implementations are contributed by Shao et al. [12], Saud et al. [9], and Naribole et al. [7].

Shao et al. evaluate two approaches to integrate VLC and WiFi [12]. Their first asymmetric implementation uses WiFi as uplink and VLC as downlink channel, using MAC

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addresses on a relay to decide which technology to use in downlink direction. Their second implementation is symmetric, using WiFi and VLC in both directions, and a bonding driver on the host system combines both links.

Saud et al. [9] build a symmetric setup. Switching between WiFi and VLC is implemented with a Linux bonding driver, and switching times on VLC link failures are measured. On average a provoked VHO takes 900 ms to complete. Saud et al. argue the results depend on timing parameters in link monitoring and bonding drivers.

Naribole et al. [7] design light-radio (LiRa), which optimizes the MAC layer instead of bonding. VLC downlink acknowledgments (ACKs) are prioritized in the WiFi uplink. Measurements are conducted on a field-programmable gate array (FPGA)-based WARP WiFi implementation.

USRP-based VLC Testbeds

In the following, USRP-based testbeds that introduced interesting features are described. Rahaim et al. [8] are the first to use an USRP for VLC, achieving up to 2 Mbit/s with orthogonal frequency-division multiplexing (OFDM), but without measuring bit error rate (BER). Ball and Tien [4] improve that setup, achieving a data rate of 1 Mbit/s with zero BER and a throughput of 3 Mbit/s at 1 m distance. Mirvakili et al. [6] program reverse polarity optical OFDM in FPGA with Simulink, thereby building a real-time transmission system. Hussain et al. [5] implement all modes of IEEE 802.15.7 PHY I and transmit live audio at a distance of 2 m.

Miscellaneous VLC Testbeds

These testbeds are built upon development that are not intended for use as SDR. OpenVLC [13] is an embedded low-cost platform, but due to hardware limitations only allows for low-throughput on-off-keying (OOK). Other testbeds to mention are [3, 14, 10] which focus on the exploration of modulation schemes and other physical layer aspects. Disney Research achieves 800 B/s single link throughput [11].

3 Setup

The setup consists of a low-cost VLC transmitter connected to a USRP to build a software-defined VLC transceiver that is integrated in a network setup consisting of two VLC transceivers and two WARP-based WiFi transceivers.

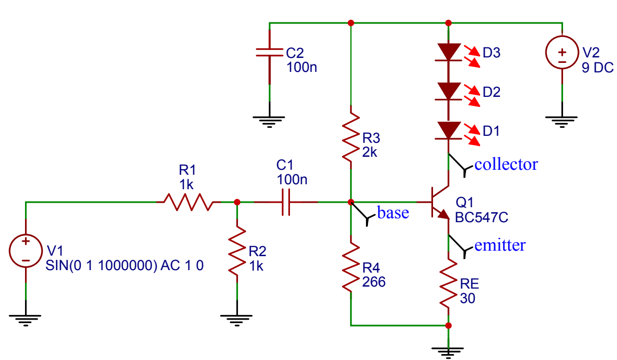


Figure 1. Schematic of our low-cost transmitter front-end.

Low-cost VLC Transmitter

We simulate and test a transmitter based on cheap standard components, which is depicted in Figure 1.

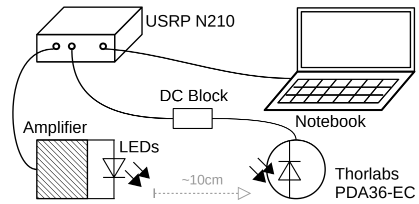


Figure 2. Measurement lab setup.

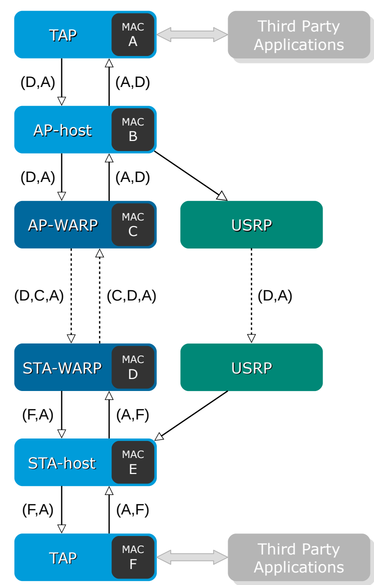


Figure 3. Flow of MAC layer frames. Wired connections: continues lines, wireless connections: dashed lines. Edge annotations: (destination, source) for Ethernet and VLC, (receiver, transmitter, destination) for WiFi.

VLC Link

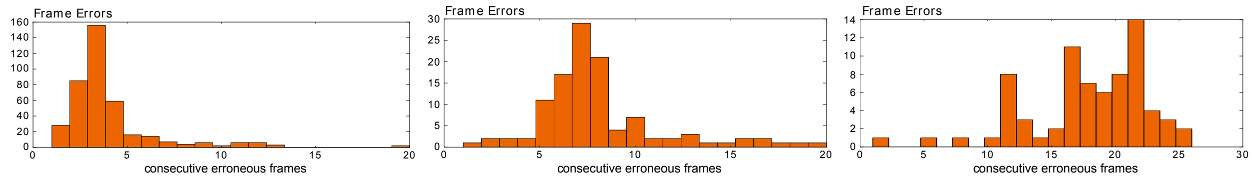
The VLC link in this setup is based on [9], a recent USRP-based testbed, which can be programmed using GNU Radio. Figure 2 shows all components of one VLC transceiver, with a host controlling a USRP which controls LEDs for transmission and a photodiode for reception.

WiFi Integration

In the HetNet setup, each host controls a VLC link and additionally a WiFi link. The WiFi implementation needs to be software-defined to change the MAC layer for smooth VLC+WiFi handover, a requirement met by WARP [1].

4 Handover Mechanisms

The handover environment is described in Section 4.1, errors characteristics in VLC links to determine when to do vertical handover (VHO) in Section 4.2, and VHO mechanisms that optimize the MAC layer in Section 4.3.



(a) fast **(b)** moderate **(c)** slow

Figure 4. Histogram of frame error length (corrupt and missing frames combined).

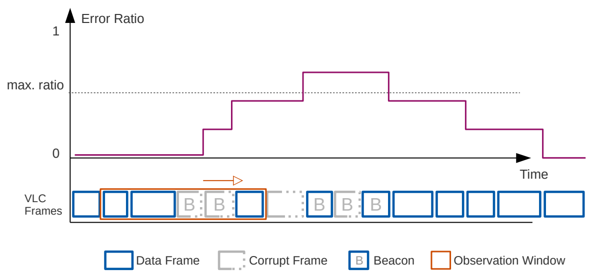


Figure 5. Simplified example of the error ratio method.

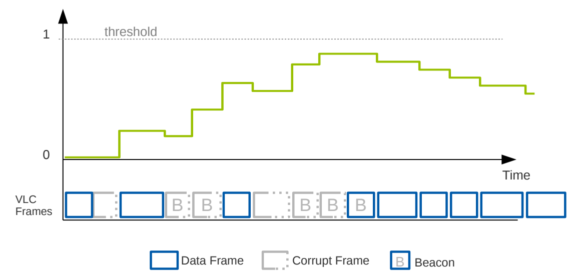


Figure 6. Example of a simple threshold decision algorithm.

4.1 Handover Assumptions

We assume VLC links are unidirectional downlinks, with an AP transmitter and a station (STA) receiver. Using mobile stations as VLC transmitters is impractical, because power constraints result in narrow beams and are easily blocked by users or the mobile station itself, while stationary downlinks can be high-power at a larger reception range.

VLC APs are always on as they are an illumination source and sending beacons. In this paper, beacons decrease handover delay. Beacons are sent continuously during data stream pauses, thus STAs expect to receive frames all the time. As VLC offers higher bandwidth than WiFi, we prioritize VLC connections over WiFi if they are available.

4.2 Link Measurements for Device Handover

Handover mechanism design questions are how the VLC channel behaves during transition to blockage and which parameters are suitable to observe blockage. To answer these questions, we generate data for the transmitter, obtain the receiver's signal, and store it for further analysis. Two reasons of link failure are to be regarded:

1. permanent failure, e.g. switching off the light, and
2. intermittent failure, e.g. a person walking through the signal path or weak signal strength.

Measurements of different movement scenarios are given in Section 4.2 to implement handover decisions. Moreover, Received signal strength (RSS) values in the evaluation in Figure 9a were measured in our lab with natural movements of a person, while Figure 9b represents a transition to permanent blockage. Based on link measurements, we design frame-based and RSS-based VHO algorithms.

4.2.1 Frame-based VHO

Frame-based statistics are easy to compare amongst MAC layers and can be accessed without hardware access.

Table 1. Parameters for consecutive frame error lengths.

Parameter	Value
distance	10 cm
frequency	3.125 MHz
bit rate	3.125 Mbit/s
total frame length	1500 B

4.2.1.1 Dwell Counter

Handover can be decided based on frame checksums by counting consecutive failed checks and initiating VHO when a limit is exceeded. This represents a *dwell counter*, which differentiates between incorrectly received frames and never received frames. The counter's threshold defines the amount of tolerated frame errors. This threshold is determined experimentally with a reduced VLC single link setup with only one USRP being connected to a photodiode and LED. The receiver process chain is adapted to log the outcome of the checksum verification. Frames are missing if time of arrival of two frames deviates significantly. The VLC link is disrupted manually by moving an object, e.g. a hand, back and forth to block the transmission path. This procedure is repeated with different speeds, categorized as slow, moderate, and fast, whereby fast means as fast as possible the executing person can move his hand.

Measurement parameters are shown in Table 1. With 3.125 Mbit/s a frame's airtime is 3.84 ms. Histograms in Figure 4 indicate error bursts of up to 25 frames occur frequently, while bursts of ≥ 30 errors occur infrequently. As a result, a dwell counter threshold should be ≥ 30 frame errors.

4.2.1.2 Error Ratio

The dwell counter fails on short error bursts. An improvement is to consider an error ratio $R = \frac{\text{Frame Errors}}{\text{Total Frames}}$ within a limited period instead of strictly observing consecutive errors, i.e. exceeding of a ratio of 30 errors within 100 frames. An example is illustrated in Figure 5. In wireless transmissions a BER of 10^{-5} to 10^{-6} is typical [4]. Assumed the BER is still in the magnitude of 10^{-5} after application of forward error correction (FEC), for 1500 bytes frame length we can approximate the frame error rate (FER) to:

$$\mathrm{FER} = \mathrm{BER} \cdot \text{frame length} = 10^{-5} \cdot 1500 \cdot 8 = \frac{12}{100}. \quad (1)$$

Regarding frame corruption as random event, the standard deviation σ can be estimated by taking the square root of the mean FER. An upper limit of statistically possible frame errors is estimated by adding a confidence interval of 3σ:

$$12 + 3 \cdot \sigma = 12 + 3 \cdot \sqrt{12} \approx 23 \quad (2)$$

Hence, the error ratio is defined as $R = {}^{23}/_{100}$. If the error ratio method should initiate handover earliest on 30 consecutive frame errors, the amount of past frames to observe is $100 \cdot {}^{30}/_{23} \approx 131$. With a 3.125 Mbit/s VLC link setup, maximum delay for detection of an error ratio ≥ 30 errors per 131 frames is

$$\frac{131 \cdot 8 \cdot 1500\,\text{byte}}{3.125\,\text{Mbit/s}} \approx 0.5\,\text{s}. \quad (3)$$

4.2.1.3 Threshold Method

In this method, failed checksum verification and missing frames increase a threshold value until its limit triggers handover. The counting variable is decreased by valid frames as depicted in Figure 6, with the threshold normalized to 1. An asymmetry between increase and decrease steps is necessary for situations where intermittent errors persist. Step sizes are estimated based on previous parameters and scenarios: 1) permanent signal loss, and 2) intermittent blockage. For 1) the decision variable must rise to the threshold after 30 consecutive failures, resulting in an increase i of ${}^{1}/_{30}$. To decrease d in 2) the previously stated error ratio of ${}^{30}/_{131}$ is considered. The 31st erroneous frame must exceed the threshold, thus d yields in:

$$31 \cdot i + (131 - 30) \cdot d \geq 1 \quad (4)$$

$$d \geq \frac{1 - 31 \cdot i}{101} = \frac{1 - \frac{31}{30}}{101} = \frac{-\frac{1}{30}}{101} \quad (5)$$

This implies decrement steps are 101 times smaller than increment steps. On intermittent blockage the variable will rise fast and take long to recover. The decision variable is reset after making the handover from WiFi back to VLC to assume an initially stable connection.

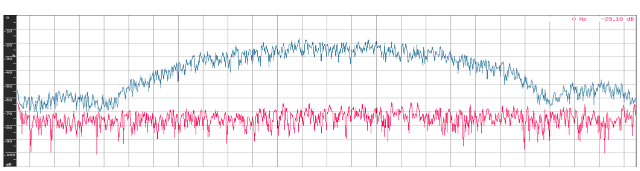


Figure 7. Frequency spectrum: signals (blue), noise (red).

4.2.2 RSS-based VHO

Normally RSS is not suitable for direct comparison of WiFi and VLC link quality since this value would have different interpretations on different physical layers, yet handover decisions can be made in our scenario due to the assumption that the VLC link is prioritized. Intermittent blockage causes frequently alternating RSS, thus a *dwell timer* is utilized, which can send handover requests only if blockage lasts. In contrast to a dwell counter, a dwell timer only recognizes the two states of sufficient and insufficient signal intensity. RSS is a measure for received signal power. Power is the amount of energy per time and can be calculated by the root mean square (RMS) of the voltage applied to the USRP's input and its resistance:

$$P = \frac{(U_{RMS})^2}{R} \quad (6)$$

We dimension the dwell timer similar to the frame-based method. Regarding the link setup with 3.125 Mbit/s, a span of 15 frames translates into a duration of 57.6 ms. The timer is started if RSS falls below a certain value and is stopped if this value is exceeded, or if the time limit is hit. Spectrum analysis of idle passages in the captured signal gives a noise floor -70 dB, depicted in Figure 7. In areas of distinct signal waveform the level is estimated to -30 dB. Considering a noise margin of 20 dB, which equals a factor of 100, the threshold is -50 dB. To evaluate the RSS-based decision algorithm on basis of link measurement (with parameters of Table 1) the threshold is set to ${}^{1}/_{100}$ of the average amplitude, which yields in 0.035 for the reference measurement.

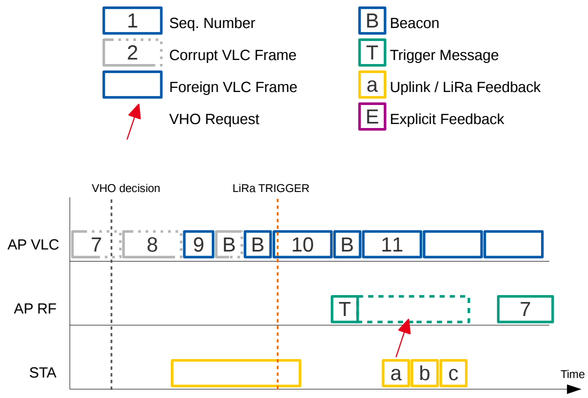
4.3 Handover Execution Strategies

Measurements capturing VLC behavior are used to design three handover algorithms that can be integrated into a VLC+WiFi setup as described in Section 3. We aimed at utilizing LiRa [7], but it was not suitable for our handover experiments without tremendous modifications, because they did VLC and WiFi measurements separately and simulated VLC transmission within WARP with a local traffic generator (LTG).

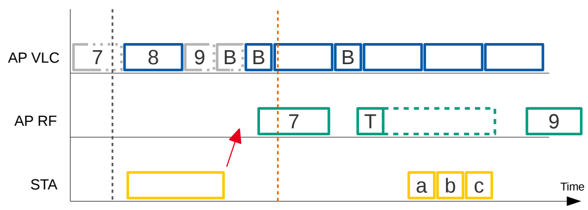
Figure 8 shows our LiRa-based handover execution strategies. The first row illustrates VLC frames. Frames addressed to the same STA are indicated by sequence numbers, unnumbered *foreign* frames are addressed to other STAs. The second row marks WiFi frames transmitted by the AP. Dotted lines of the trigger message are its virtual length spanning the contention-free period. A trigger message is sent after expiration of the LiRa *TRIGGER* timer, shown in the figure as dotted red line. The third row of each chart depicts transmission of WiFi frames from STA to AP. Feedback from different STAs is indicated by lowercase letters.

4.3.1 Handover Execution with LiRa

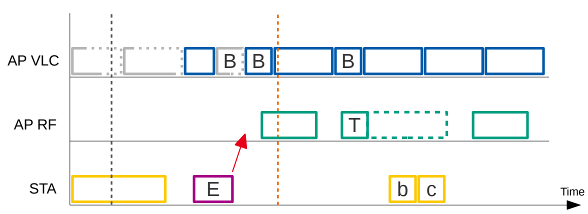
The first strategy, displayed in Figure 8a, utilizes the feedback mechanism known from LiRa. When a station decides for handover, the feedback following the next trigger message contains a VHO request. An AP receiving a VHO request is supposed to switch the currently active network. Maximum latency between decision and finished handover execution is equal to LiRa trigger timeout.



(a) Handover execution with LiRa.



(b) Handover execution with piggybacking.



(c) Handover execution with explicit feedback.

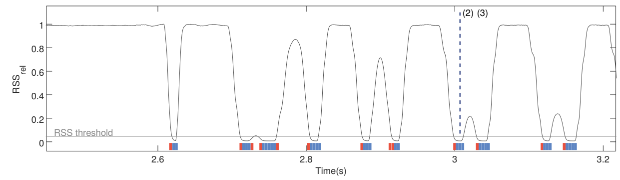
Figure 8. Station-based handover execution strategies.

4.3.2 Handover Execution with Piggybacking

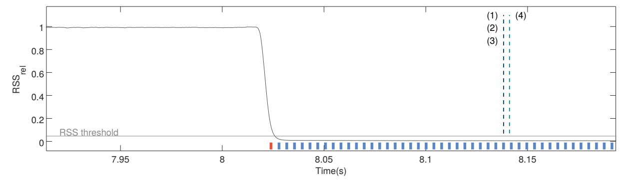
Piggybacking is used to potentially shorten delays in transmitting VHO requests as shown in Figure 8b. With piggybacking a STA uses existing uplink traffic to transport request messages. In the best case, execution delay is one uplink data frame. Assuming VLC is faster, it may happen that multiple VLC frames are transmitted during the uplink frame containing the VHO request. The VLC-AP keeps the STA for one more cycle in the feedback schedule to ensure to get the STA's complete feedback.

4.3.3 Handover Execution with Explicit Messaging

The explicit messaging strategy is shown in Figure 8c. After handover decision a STA generates and transmits an explicit message including feedback to notify the AP of signal loss. After receipt of the explicit message the AP immediately switches to WiFi. Because the VLC link is detected as corrupt, it is less likely that VLC frames are received by the STA until the next trigger message. The ideal latency of this strategy is the control frame transmission duration. As for piggybacking, the RF channel may be blocked by contending stations and handover execution can be delayed.



(a) Intermittent blockage.



(b) Permanent blockage.

Figure 9. Marks on the bottom illustrate corrupt (red) and undetected (blue) frames. Figure 9a shows intermittent blockage and Figure 9b shows a transition to permanent blockage. Dotted lines depict handover decisions by (1) dwell counter, (2) error ratio, (3) threshold, and (4) dwell timer.

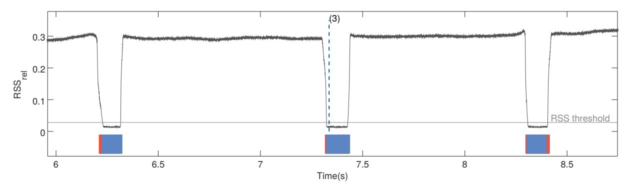


Figure 10. Positive detection by the threshold method.

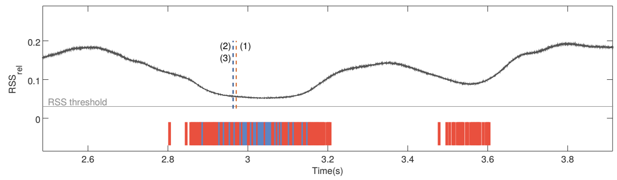
In the worst case handover execution takes as long as the period between trigger messages, for which Naribole et al. [7] recommend a value of 5 ms. However, trigger messages are not acknowledged and if they are corrupted frames handover execution will be multiple times the trigger period. In the best case, execution of handover takes as long as the time for construction, transmission and reception of an explicit feedback message. This is considered faster than the piggybacking method, because the frame length of the explicit message is shorter than frames that contain upload data. The time required for transmission and reception of an explicit message, which does not contain any ACKs, is approximately 100 µs [2].

5 Evaluation

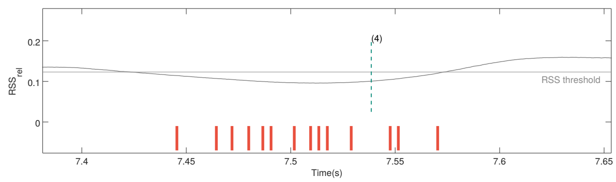
Decision algorithms are evaluated based on a series of five measurements. The first two measurements are carried out with a fixed distance between transmitter and receiver, and the link was blocked by temporarily casting a shadow on the photodiode. Then several measurements are taken holding the receiver in one hand while moving and tilting it occasionally to imitate mobile phone movement.

5.1 Stationary Scenario

Figure 9a depicts the beginning of intermittent blockage obtained from the first experiment. As the RSS alternates frequently between its maximum and nearly zero it crosses the threshold that was determined in Section 4.2.2 to be the minimum recoverable signal strength. Corrupt frames are marked



(a) False non-detection.



(b) False detection.

Figure 11. False decisions by the dwell timer (4).

by red lines on the bottom of each figure. Blue marks the interpolated time of arrival of frames that were not received. Dotted lines depict initiation of handover by the decision algorithms. In Figure 9a, the frame-based error ratio (2) and threshold method (3) trigger handover. Both trigger at once, since the threshold method was designed with parameters of the error ratio. The dwell counter (1) and dwell timer (4) do not trigger because the frequency of the intermittent blockage is high. Since intermittent blockage duration is large (> 2 s) not initiating handover means the dwell methods' performance in this situation is poor.

Handover at permanent blockage is illustrated in Figure 9b. This time the dwell counter (1) performs exactly as the two other frame-based methods. The dwell timer's (4) result is similar, being approximately one frame behind. Theoretically the dwell timer is expected to trigger handover before the other methods. But due to inaccuracies in RSS threshold determination, statistical errors, or random noise the arrival of valid frames stopped before the RSS threshold exceeded. In summary, all four methods perform at permanent blockage similarly and in line with expectations.

5.2 Portable Scenario

Regarding portable devices, measurements with a moving photodiode module are carried out.

The first recording of this scenario reveals a dwell timer issue. RSS is weak for a period of approximately 300 ms and the frame-based methods correctly indicate handover in Figure 11a, but the dwell timer does not. This adheres from an underestimation of the RSS threshold that prevents the dwell timer from starting to count.

After increasing the RSS threshold, another recording was taken. As shown in Figure 11b the threshold is overestimated, thus initiating handover too early at 11 corrupted frames. The frame-based decision methods perform well.

6 Conclusion

A custom VLC testbed was built that uses standard SDRs and a low-cost VLC transmitter, which is easy to reproduce for other researchers. The WiFi+VLC testbed design shows that a testbed can be realized at reasonable effort, and it underlines the wide design space of heterogeneous networks. Measurements on blockage effects by users in a practical setup were used to design multiple decision algorithms for a perfect handover timing. Handover mechanisms that optimize management and acknowledgment frames on the MAC layer were designed.

7 Acknowledgments

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