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Evaluating Wifibroadcast for Long-Distance UAV-to-Ground Data Transmission

Jannis Mast, Thomas Hänel, Nikolas Wintering, Nils Aschenbruck
Institute of Computer Science, Osnabrück University, Friedrich-Janssen-Straße 1, 49076 Osnabrück, Germany
{jmast, haenel, nwintering, aschenbruck}@uos.de

***Abstract*—Using existing general purpose wireless technologies, it is difficult to transmit large amounts of data from Unmanned Aerial Vehicles (UAVs) to a ground station during flight. Thus, there is a demand for specialized solutions. Wifibroadcast proposes a solution for this use case, utilizing a unidirectional and connectionless design to transmit data using unmodified low-cost WiFi hardware. In this paper, we measure and evaluate the performance of Wifibroadcast for UAV to ground transmissions over large distances and provide a direct comparison against standard IEEE 802.11. We demonstrate that Wifibroadcast is able to outperform WiFi in all tested scenarios while identifying specific characteristics, limitations, and requirements of a long-distance transmission on both the 5 GHz and 2.4 GHz frequency bands.**

***Index Terms*—Wifibroadcast, Unmanned Aerial Vehicle**

I. Introduction

Unmanned Aerial Vehicles (UAVs) allow surveying large areas with relatively small effort. During a flight, various types of data can be collected, including images and video. Transmitting this data to another machine for evaluation requires sufficient bandwidth. While flying and collecting data, it may be desirable to receive the data as it is being recorded, either for real-time evaluation or simply as a live preview to monitor if the survey is progressing as planned.

A system for such a real-time transmission shall provide a high throughput while also operating at large distances. In this paper, we demonstrate a solution using *Wifibroadcast* [3], an existing open-source software project that implements unidirectional data transmission using off-the-shelf IEEE 802.11 hardware. Using this approach, we evaluate transmission from a UAV to a ground station with the ability to maintain a constant throughput over distances of several kilometers. We also show how this solution outperforms a regular WiFi network which suffers from delays and interruptions caused by link-layer retransmissions and the possibility of clients disassociating from their network due to packet loss at these distances.

We begin this paper with a discussion of related work on UAV communication and long-distance distance links using WiFi hardware in Sec. II. We then introduce Wifibroadcast, the main component of our implementation in Sec. III, followed by a description of our measurement setup in Sec. IV. In Sec. V, we present our results and discuss the data we collected. Finally, we conclude the study and discuss potential future research in Sec. VI.

II. Related work

The performance of WiFi for communication with a UAV and/or between UAVs during flight has been studied in several publications. For example, the authors of [2] present a measurement that analyzes the transmission of live telemetry, remote control, and video between a UAV and its controller on the ground. In [1], the authors measure the transfer of high resolution images between multiple UAVs using a high speed WiFi link. In both publications, the authors measure a decrease in connection performance starting at distances of about 50-200 m. This shows that standard WiFi is not suitable for transmission over large distances and an alternative approach is needed if a consistently high throughput without interruptions is demanded.

One such approach is demonstrated in [6]. The authors implement a customized variant of WiFi that can be used to transmit data over distances of several kilometers using unmodified WiFi hardware. They note that WiFi's built-in mechanisms for collision avoidance and loss detection and recovery cause problems for long-distance links. Thus, [6] mainly focuses on building alternative mechanisms to allow for a general purpose, bi-directional long-distance link. Instead, we intend to use a unidirectional link to bypass these mechanisms entirely since bidirectional communication is not required for our use case.

Using Wifibroadcast for this purpose has not yet been thoroughly evaluated in existing literature. The work shown in [7] employs Wifibroadcast to distribute software updates to Internet of Things (IoT) devices with

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evaluations investigating the reliability of receiving these updates over large transmission distances. However, current publications do not cover the performance of Wifibroadcast for repeated or continuous long-distance high-bandwidth unidirectional transmissions, such as images or video, with a comparison against standard WiFi, which is the focus of this research.

III. Wifibroadcast introduction

Wifibroadcast [3] is an open-source software project that implements broadcasting of data using conventional WiFi hardware with characteristics similar to an analog radio/television broadcast. The intended use case [3] is continuous live video streaming from a UAV, although with slight modifications to the software, it can be used to transmit arbitrary data packets. It uses a custom packet structure while retaining WiFi's physical layer and Medium Access Control (MAC) in order to maintain hardware compatibility. This is implemented by configuring the WiFi hardware in *monitor mode* which allows processing all packets received by the hardware, even while not associated with a network. Packets are transmitted using *packet injection*. This constitutes a possible limitation in compatibility with different WiFi hardware as not all drivers fully support these special modes of operation. Its design approach allows Wifibroadcast to be used on unlicensed frequency bands like a normal WiFi network without the need for potentially expensive custom hardware.

Wifibroadcast implements a unidirectional communication where transmitted data can be received by any number of clients within the sender's transmission range without having to associate with a network first. Packets are not acknowledged which avoids potential delays caused by retransmissions at the expense of risking occasional data loss if packets are not received. The reference implementation of Wifibroadcast[1] implements Forward Error Correction (FEC) to compensate for this risk by adding redundancy to the transmission. Furthermore, the modulation can be freely configured and remains fixed, allowing continuous high-speed transmission regardless of packet loss. As the receiver has no fixed association with a network, any number of devices can be used to receive a transmission, allowing for redundancy by placing multiple receivers in different locations to reduce the influence of effects such as multipath interference. Because receivers are entirely passive and don't transmit a response after receiving a packet, high-gain antennas that would otherwise violate regulations if used for transmitting can also be used to further improve reception.

IV. Measurement setup

To evaluate a Wifibroadcast connection, we transmit a stream of pseudorandom data between two points. We choose this to model compressed image or video data that we would be transmitting in a real-world deployment. The received data is stored as a raw trace for later evaluation. Based on the sequence numbers transmitted in each packet, we calculate the fraction of correctly received packets as a metric of connection quality.

We use *ALFA Network AWUS036ACH* WiFi adapters along with the included omnidirectional antennas connected to *Raspberry Pi 3 Model B+* single board computers to perform these measurements. A modified Linux driver[2] is used to enable support for packet injection. Additionally, we set up the Raspberry Pi's built-in WiFi as an additional access point for controlling the measurement software. To avoid interference, it is always configured to operate on a different frequency band (2.4 or 5 GHz) than the Wifibroadcast measurement. We use a slightly modified version of the original Wifibroadcast implementation[1]. To allow for a more detailed evaluation, we modified the software to save the raw received data as a trace before further processing is applied to the received packets. We also added support for setting the IEEE 802.11n Modulation Coding Scheme (MCS) index with this hardware using a fabricated *radiotap* header that gets passed to the driver with each injected packet since the hardware that Wifibroadcast was originally designed for uses a different mechanism.

During initial testing, we notice that Wifibroadcast appears to transmit data notably faster than the selected modulation allows, while only a small fraction of packets is received. We suspect that this is caused by the hardware or the driver not waiting until a packet is actually transmitted when using packet injection, causing a buffer to overflow and packets to be discarded. As a workaround, we implement a delay within the Wifibroadcast software that approximates the amount of time of a transmission before injecting the next packet. While this approach works for our measurements, it also results in lower throughput because we approximate the highest possible inter-frame spacing for WiFi's Distributed Coordination Function (DCF). This choice was made to avoid any risk of introducing additional packet loss as this is the metric we are primarily interested in.

[1] https://github.com/befinitiv/wifibroadcast

[2] https://github.com/aircrack-ng/rtl8812au

Table I
IEEE 802.11N MCS INDICES WITH CORRESPONDING MODULATION AND DATA RATES FOR BOTH POSSIBLE GUARD INTERVALS GI [5]

MCS index	Modulation	Data rate (Mb/s) $GI = 800\,\text{ns}$	Data rate (Mb/s) $GI = 400\,\text{ns}$
0	BPSK	6.5	7.2
1	QPSK	13.0	14.4
2	QPSK	19.5	21.7
3	16-QAM	26.0	28.9
4	16-QAM	39.0	43.3
5	64-QAM	52.0	57.8
6	64-QAM	58.5	65.0
7	64-QAM	65.0	72.2

We test several different MCS indices during our measurements. For reference, table I lists all possible MCS indices using a single spatial stream and the corresponding modulation and possible data rates for each index taken from the 802.11 standard [5]. We find that due to a bottleneck caused by this hardware/driver combination when using packet injection, setting the MCS index higher than 5 does not increase throughput. Because of this, we do not run measurements using the highest MCS indices 6 and 7. We also do not attempt to use other settings to further increase the possible data rate such as using the optional 400 ns guard interval or using more than one spatial stream as this would not result in a positive effect on the transmission. We evaluate both the 2.4 GHz and 5 GHz frequency bands. The transmission power is set to the driver's default value of 20 dBm which is the highest setting permitted by local regulations for the 2.4 GHz band. This power level is used for both frequency bands because attempting to change it did not show any effect while using this hardware/driver combination.

For comparison, we repeat our measurements using a regular WiFi network on the same hardware. In this case, data is transmitted using User Datagram Protocol (UDP) packets to avoid adding corrections on the transport layer into the measurement.

V. Evaluation

We evaluate Wifibroadcast transmissions in two different scenarios. The initial set of measurements is performed in a residential area, showing Wifibroadcast's behavior in an interference-heavy urban environment with wireless activity from other networks. The second set is done using a UAV with an attached transmitter flying over a agricultural field to measure performance over larger distances. This configuration reflects a realistic use case when using a UAV for area survey.

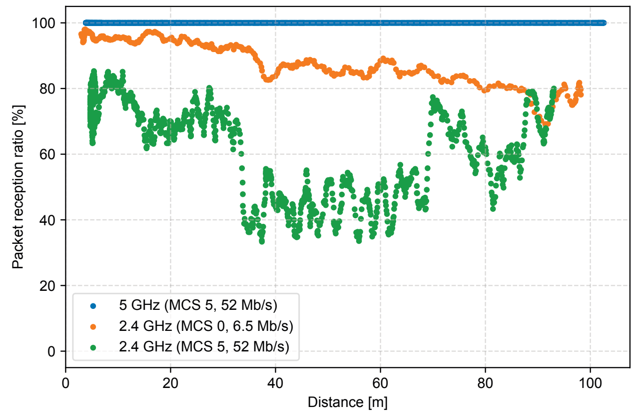

Figure 1. PRR measured using Wifibroadcast in a residential area

A. Residential environment

To evaluate Wifibroadcast in a residential environment, we position one WiFi adapter in a window on the second floor of a building, giving an elevated position that we would also have when attaching it to a UAV. We then walk along the street while carrying the second adapter and using a Global Positioning System (GPS) module to continuously record its position. To minimize interference from other WiFi networks, we select channel 136 on the 5 GHz band because we did not detect any other networks using the same or overlapping channels within the area. On the 2.4 GHz band, we did not find a completely unused channel. Instead, we choose channel 11 as it was found to have the lowest number of active networks.

The measured Packet Reception Ratio (PRR) over distance for this scenario is shown in figure 1. Using a free channel on the 5 GHz band, no packet loss is detected for the entire measured distance up to about 100 m. On 2.4 GHz however, we observe a significantly lower connection quality with a reception rate of less than 40 % at several points during the measurement, likely caused by interference from other WiFi networks. While decreasing the MCS index allows for better reception rates at the expense of lower throughput, even the lowest possible setting is not able to deliver the connection quality that we observe on 5 GHz.

The results of the measurement using a regular WiFi network are shown in figure 2. These measurements start without packet loss as WiFi uses link layer retransmissions to correct missing packets. The exact MCS index during these measurements is not known as it is automatically selected by the WiFi driver and not reported to the application. The results also show several

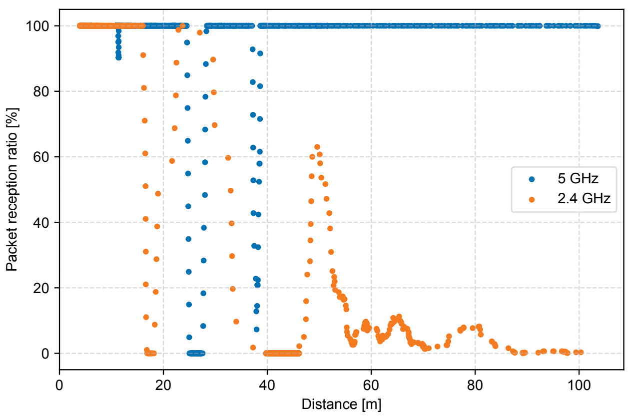

Figure 2. PRR measured using WiFi in a residential area

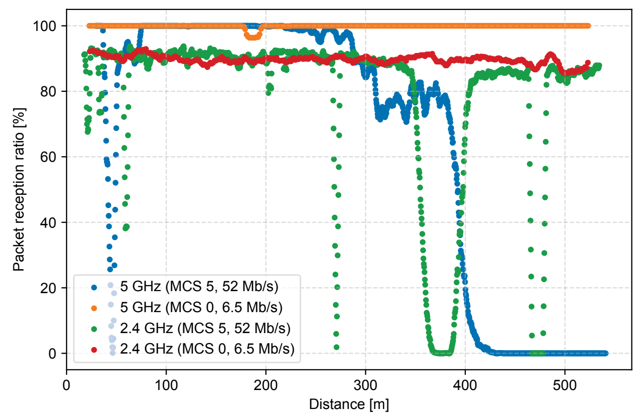

Figure 4. PRR measured using Wifibroadcast during UAV flights

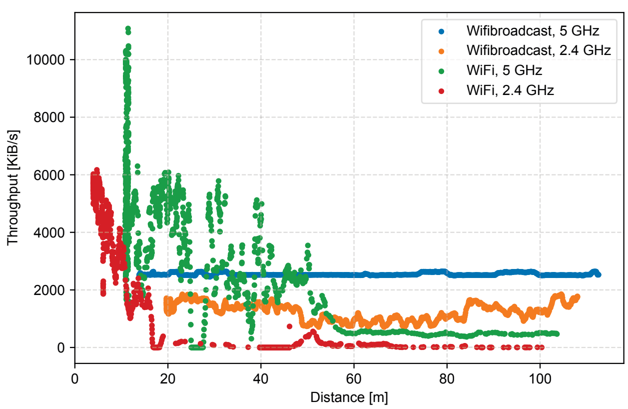

Figure 3. Throughput measured in a residential area (Wifibroadcast at MCS 5)

connection losses where the client disassociates from the network, causing all transmitted data to be lost until the connection is re-established. The gradual transition from 100% to 0% in figure 2 is an artifact caused by calculating the PRR using a moving window. Due to the higher interference, the client is not able to re-establish a reliable connection on 2.4 GHz after about 50 m.

Figure 3 shows the throughput that was achieved during these measurements. This data shows how Wifibroadcast is able to maintain an essentially constant throughput when not impacted by packet loss on the 5 GHz band while the throughput using 2.4 GHz shows a lot more variation that closely follows the packet loss shown in figure 1. It should be noted that the observed throughput for Wifibroadcast is significantly lower than the theoretical maximum achievable with this modulation. This is caused by the previously mentioned workaround (see Sec. IV) that adds a conservatively chosen delay to avoid any risk of introducing additional packet loss. With regular WiFi, the initial throughput at low distances exceeds what we are able to achieve with Wifibroadcast as regular WiFi operation does not suffer the same bottleneck as packet injection. Additionally, a lot of variation in throughput can be seen as the WiFi network automatically adjusts its modulation depending on the connection quality. Although the 5 GHz network is able to achieve a perfect reception ratio for the same distance as Wifibroadcast, the throughput drops to a very poor 500 KiB/s after about 60 m. On 2.4 GHz, this happens much faster at only about 20 m. In both cases, Wifibroadcast's throughput exceeds that of WiFi, even when suffering from high packet loss on the 2.4 GHz band. This shows how Wifibroadcast's unidirectional approach enables it to maintain a mostly constant throughput over larger distances because it does not have to wait for acknowledgments and/or retransmissions from the receiver and it is able to use the same modulation at all times.

B. Farm measurements using a UAV

The second set of measurements is performed in an agricultural environment using a UAV flying over farmland with the wireless transmitter attached to one of its legs. Because this environment is located a significant distance away from any residential or commercial buildings, we expect significantly less interference compared to the measurements discussed in Sec. V-A.

We attach the transmitter to a *DJI Matrice 210 RTK* [4] UAV while the receiver is positioned on the ground. The UAV is configured to fly a straight path away from the receiver at an altitude of 70 m with a speed of 25 km/h while the receiver remains stationary. Data is transmitted during the entire flight.

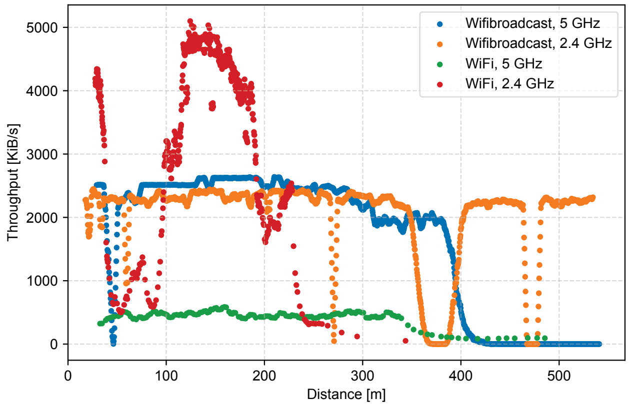

Figure 5. Throughput measured during UAV flights (Wifibroadcast at MCS 5)

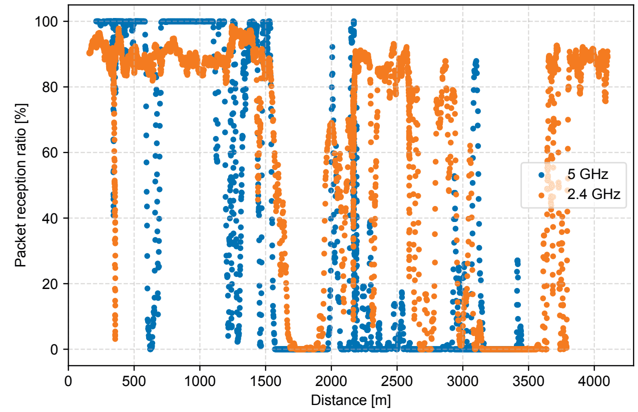

Figure 6. PRR measured using Wifibroadcast with the receiver attached to a car

The observed PRR during these measurements is shown in figure 4. Similar to the previous results in Sec. V-A, we observe a nearly perfect transmission when using the 5 GHz band up to a ground distance of about 300 m when using MCS 5. After that, the PRR starts to drop significantly and reception stops entirely after 400 m. Using a slower modulation (MCS 0 is shown in figure 4), we are able to observe data transmission without any packet loss over the entire flight distance. The performance on the 2.4 GHz band also improves significantly compared to the residential environment due to less interference from other wireless networks. But a constant packet loss of about 10-15% can be observed throughout the entire flight. This can be explained with the UAV also using the 2.4 GHz band to communicate with its remote controller and the Real-Time Kinematic (RTK) ground station [4], causing interference during the measurement. A number of interruptions in the transmission can be observed where no data was received for a period of time. We attribute this effect to multipath interference caused by ground reflections because these interruptions happened at the same positions in every flight, including several additional flights that are not shown in figure 4.

Results for comparison with a regular WiFi network are shown in figure 5. Unlike the residential measurements in Sec. V-A, no packet loss or temporary connection losses are observed during these flights. Because of this, we only use the measured throughput to evaluate the connection's quality. Using 2.4 GHz, WiFi achieves a relatively high throughput between 100-200 m after an initial period with low throughput below 100 m. This is likely caused by increased packet loss which is also seen with Wifibroadcast around the same distance (see figure 4). After 200 m, the throughput decreases sharply until no significant amount of data can be transferred after around 250 m. This matches the observations made in [1] using a similar configuration, confirming the validity of our results. Later during the measurement, a connection loss is observed where the client disassociates from the WiFi network. This happens shortly after the UAV reaches the maximum distance and starts its return flight towards the ground station. This is why it is not visible in the graph. It might be possible that this loss of connection occurs earlier without being detected by the access point initially since no data is received from the UAV after around 350 m. Using a network on the 5 GHz band, the throughput drops to around 500 KiB/s even before the UAV reaches its configured altitude. This low throughput is seen until a distance of around 350 m which is similar to the maximum transmission distance observed with Wifibroadcast using MCS 5, although Wifibroadcast achieves a significantly higher throughput at this distance. Unlike the measurement using 2.4 GHz, the connection remains active the entire flight. But considering the extremely low throughput after 400 m, the connection can be considered unusable for any practical deployment after that point. The throughput using Wifibroadcast matches what we observed during the residential area measurements in Sec. 2, with the throughput being mostly constant and the only major influence being packet loss, causing the throughput to mostly follow the graphs in figure 4.

Finally, to examine the maximum possible distance for data transmission using Wifibroadcast without being limited by the UAV's flight range, we attached the receiver to a car while leaving the UAV with the attached transmitter hovering on a fixed position. Using MCS 0, we were able to receive data over a distance of about 3.1 km using 5 GHz and 4.25 km using 2.4 GHz. The PRR observed during these measurements is shown in figure 6. The measurement on the 2.4 GHz band was stopped before observing a complete loss of connection because the UAV ran out of battery charge while hovering. This means that even higher distances might be possible. However, given the UAV's limited flight range, we believe that transmitting over up to 4 km sufficiently covers any realistic use case. After landing, no more data is received, showing that the transmitter's elevated position contributes to the achievable transmission range. We also notice that a clear line of sight is important for successful transmission, especially when using the 5 GHz band. Over larger distances, even small obstacles such as trees, buildings, or terrain result in reception stopping entirely until a line of sight is restored. This makes continuous measurements impossible. At larger distances, less locations allow for a clear line of sight. This effect is clearly visible in figure 6, indicated by frequent periods where little or no data is received. While the transmitter is in sight however, we measure no packet loss at any distance. Using 2.4 GHz, this effect is less significant and reception continues even with obstacles between the transmitter and receiver. However, the previously observed 10-15% packet loss from the UAV's wireless interference is also measured in this scenario.

VI. Conclusion and Future Work

In this paper, we evaluated data transmission from a UAV to a ground station over distances up to several kilometers using Wifibroadcast and low-cost off-the-shelf WiFi hardware. In our evaluation, we measured a consistently high throughput suitable for transmitting media such as video or individual high-resolution images. Because of Wifibroadcast's unidirectional design, the transmission is not interrupted or slowed down by having to wait for acknowledgments or retransmissions at the expense of packet loss in some cases. In comparison, we evaluated the same transmission using a regular WiFi network. The latter suffers from extremely low throughput and occasional connection losses after distances of a few hundred meters, making the connection effectively unusable after that point.

We compared the performance on the 2.4 GHz and 5 GHz frequency bands. Using 2.4 GHz, we observed a constant amount of packet loss caused by the communication between the UAV and its remote controller, although the amount was low enough to be corrected by including redundancy in the transmission for error correction. This was not the case when using the 5 GHz band. However, using the 5 GHz band reduced the maximum transmission range that we were able to achieve. In an environment with strong interference such as a residential area, the 2.4 GHz band is completely unusable as too much interference causes extremely high packet loss. This makes use of the the less congested 5 GHz band mandatory for our use case. Finally, we found that a clear line of sight is critical when transmitting on 5 GHz while a transmission on 2.4 GHz was able to cope with smaller obstacles such as trees between the UAV and the ground station.

Regarding potential future research, we believe that there are several opportunities to possibly improve the reception quality that should still be evaluated in future work. While discussing the measurements in Sec. V-B, we noted packet loss caused by multipath interference due to ground reflections. This could potentially be corrected by using multiple receivers as described in Sec. III. Additionally, as already mentioned, antennas with a higher gain could be used for reception. By doing so, a larger range could be achieved. Finally, when using the stock antennas that were included with the WiFi adapters we were using (see Sec. IV), we noticed that the transmitting antenna's orientation could make a significant difference in connection quality. Since UAVs usually tilt towards their direction of flight, this can be important if data is being transmitted while the UAV is moving. This makes this effect a candidate for further evaluation and optimization, potentially by also studying the use of different antennas on the UAV.

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