Avoiding collisions at any (low) cost: ADS-B like position broadcast for UAVs

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ESAT-Telemic, KU Leuven, March 2020

Abstract

Unmanned Aerial Vehicles (UAVs), a.k.a. drones, are increasingly used for different tasks. With more drones in the sky, the risk of accidents rises, sparking the need for conflict management solutions. Aircraft use a system called Automatic Dependent System-Broadcast (ADS-B) to continuously broadcast their position and speed but this system is not suitable for small drones because of its cost, complexity and capacity limitations.

Broadband technologies such as Wi-Fi beacons are more suited for such dense scenarios, and they also offer the benefit of wide availability and low cost. The main challenges for Wi-Fi are (a) the multi-channel nature of the technology makes transmitter and receiver coordination difficult, and (b) standard chipsets are not designed for frequent broadcast transmission and reception. In this paper, we propose and analyze a multi-channel position broadcast solution that is robust against jamming and achieves a reliable location update within 125 ms. In addition, we implement the protocol on inexpensive embedded Wi-Fi modules and analyze the hardware limitations of such devices. Our conclusions are that even on the simplest Wi-Fi chipsets, our protocol can be implemented to achieve a realistic location broadcast solution that still perfectly mimics simulation and analytical results on the lab bench and still can achieve approximately 4 message/s throughput at a distance of 900 m on flying UAVs.

1 Background

This section introduces the background on the conflict management and the Wi-Fi technology.

1.1 Air conflict management

When two or more aircraft have to share a common air-space there is a possibility that their trajectories intersect causing accidents. These events are called conflicts and thus the act of foreseeing and preventing them is known as conflict management. The more aircrafts occupying the same volume of space, the
Figure 1: Relation between conflict management layers and collision timeline
higher the probability of conflicts. This is well known to the aviation industry which along the years put together a strict set of rules that pilots and ground personnel have to follow during each flight.

Conflict management, as explained in [11], can be either strategic, which means planning way-points and trajectories in advance; or tactical, which means dealing with possible conflicts arising during the flight itself by negotiating with the other aircraft in proximity and the control towers and maneuvering to prevent possible accidents. Figure 1 illustrates the different layers of conflict management. Beware that tactical and strategic management are complementary and both should be in place to guarantee safety.

Strategic conflict management consist of assigning flight plans to each airplane in order to minimize the number of air encounters. However, in some cases, aircraft can only pass close to each other. When this happens, they have to keep a safety distance between each other called well-clear separation. When it is not possible to keep well-clear separation, we enter the realm of collision avoidance, which means avoiding a collision at all costs.

Broadcasting UAVs positions is a prerequisite for both strategic and tactical conflict management because drones do not have a pilot on board which can look out of the windows and maneuver according to what he sees. Although camera based collision avoidance has been studied extensively [6,9], it has the drawback of limited range, high computational power and one or multiple cameras to be effective.

Broadcasting the position and speed of each UAV opens up the possibility to perform well-clear separation before the UAVs enter the area of collision avoidance by adopting specific algorithms like Optimal Reciprocal Collision Avoidance [10, 3].

1.2 Beacons

For the reasons described in the section??, Wi-Fi beacons seem to be a good candidate to absolve this task. Since beacons use the lowest bitrate allowed by
the selected Wi-Fi standard, they can propagate very far, even in the range of a kilometer. Beacons are normally sent every 102.5 ms giving enough margin to receive at least one beacon per second even if many are lost. They also do not require any acknowledgement nor any connection establishment to be received so there is no connection overhead in the communication. The positional information can be easily encoded and embedded in the SSID field (see Figure 2).

In principle, it is also possible to embed information in other fields of the beacon frame but then care must be taken to still keep the frame valid. Our analysis results does not depend on this implementation detail. Differently from the SSID, the other fields are interpreted by the WI-FI stack and not by default reported to the user. This means that if collision avoidance information is placed in another field than the SSID, it may render the beacon invalid. In this case, the receiving Wi-Fi hardware will discard the message without reporting its content even though it is successfully received.

2 System Model

In this section we first introduce the protocol. Afterwards, we propose a model for it and a simple analysis framework.

2.1 Protocol

2.1.1 Channel selection

One key challenge for Wi-Fi is the rendezvous protocol to ensure that the transmitter and receiver are working on the same channel at the same time with as little coordination as possible. This requires state transitions between scan, broadcast and data communication modes which might take a long time, especially on low cost hardware. In our previous work [7], we investigated multiple strategies to exploit the Wi-Fi hardware for location broadcasting. In particular, we identified four possible modes of operation (See Figure 3):

A broadcasting and scanning on the same channel;
B broadcasting on all the channels and scanning a single channel;
C broadcasting on a single channel but scanning all the channels;
D broadcasting on and scanning all the channels.

The most effective strategy among the four resulted being Strategy B. While strategy A is the fastest, it requires both transmitter and receiver to know in advance which channel is used for the collision avoidance broadcast. If the channel is congested, both need coordination to change it. The main drawback of strategies C and D is that, scanning all channels is a long operation which can take more than two seconds and the received messages are only available at the end of it.
Figure 3: Broadcast/scan strategies: (A): broadcasts and scans use a single channel; (B) broadcasts are on all channels, scans on a single channel, (C) broadcasts are on a single channel, scans are on all channels, (D) broadcasts and scans span all channels. Transmissions are indicated by vertical bars, scans by rectangles. The white part of scans is where the receiver is actually listening and the remaining part is the time used to process the incoming transmission.

Strategy B does not require any particular rendezvous algorithm and allows for continuous scanning of a single channel which can be chosen depending on traffic or propagation conditions. Strategy B can also be modified to use only a subset of the available channels to reduce the impact on other Wi-Fi networks.

2.1.2 Timing

The vast majority of inexpensive Wi-Fi modules have only one RF chain. This implies that the operations of transmitting and receiving messages cannot be performed simultaneously. In this light, the understanding of timing is vital for the protocol design.

The duration of a beacon is indicated as $T_{\text{beacon}}$ but the duration of a multi-channel broadcast event is $T_B$. During $T_B$, multiple transmissions take place with a small interval in between in order to change channel. This means that, while the radio stays in broadcast state for a period of time $T_B$, it actually occupies each channel only for $T_{\text{beacon}} \times N_{ch}$. However, some time ($T_{\text{switch}}$ in Figure 3) is also required to jump from one transmit channel to the next one. The relation between $T_B$ and $T_{\text{beacon}}$ is $T_B = N_{ch} \cdot (T_{\text{beacon}} + T_{\text{switch}})$ (see Fig. 3).

The duration of a scan operation by a radio in receive mode is indicated as $T_S$. $T_S$ incorporates both the time in which the module is actively listening to the channel $T_{Rx}$ and the time spent to process the received transmissions and extract the packets $T_{\text{comp}}$. Thus $T_S = T_{Rx} + T_{\text{comp}}$. This is illustrated in the timing diagram in Fig. 3. It is worth noting that the $T_S$ may increase significantly when beacon traffic increases. However, when the number of received transmissions is low $T_{\text{comp}} \approx 0$ and $T_S \approx T_{Rx}$.

The increased duration of $T_S$ may effectively reduce the success rate since the additional time spent for processing is time in which the radio module is
not listening for incoming transmissions. For low traffic, the processing time is so small that it can be effectively neglected. A more in depth analysis of this phenomenon is presented in Section 4.1.

With $T_N$, we then indicate the time dedicated to traditional Wi-Fi networking operations. A networking operation is time allocated to exchange telemetry or other data via Wi-Fi (e.g. video streaming or sensor readings).

2.2 Behavioral model

Consider a set of drones, each one equipped with a radio transceiver which can be in three possible states:

- Broadcast with duration $T_B$: the node broadcasts positional information in beacon frames an all the Wi-Fi channels;

- Networking with duration $T_N$: the node is blind to beacons and is using the radio for other tasks like telemetry or video streaming on a single channel;

- Scan with duration $T_S$: the node listens for incoming beacons on the same channel used for telemetry.
At each instant in time, each module can be in any of the three mentioned states independently from the state of any other node composing the group of UAVs.

When a node is in scan state, it scans a single Wi-Fi channel for beacons and filters only the ones that contain positional information. Different channels offer different performance and thus it is wise to implement different scan channel selection strategies depending on the UAV mission or environment. The design of those strategies is out of scope for this work.

We assume that networking operations do not collide with broadcasting because Wi-Fi uses Carrier Sense Multiple Access/Collision Avoidance which employs a listen-before-transmit mechanism \[1\]. We do study collisions between beacon frames.

Some Wi-Fi modules can work in monitor mode and can receive multiple kind of packets at the same time (beacons, association, IP packets, etc...). However, monitor mode is not standard in Wi-Fi adapters and therefore, it is not taken into account by our model.

2.2.1 Probabilistic model

We now model the protocol statistically, assuming the radio randomly selects one of the three states after completing the previous event with duration \( T_{B,S,N} \). The probabilities of being the broadcast state, scan state or network state are defined respectively as \( P_B \), \( P_S \) and \( P_N \), respectively. In other words, they describe the share of time spent in the corresponding state.

The state selection probabilities are indicated as \( \rho_B \), \( \rho_S \) and \( \rho_N \). The model assumes that the probability of selecting a state is independent from the previous state.

Since the duration of each state once it starts is different, \( P_{B,S,N} \) are different from their selection probabilities \( \rho_{B,S,N} \). To clarify, let us consider as an example a case in which no networking is involved: if \( P_B = 0.5 \), \( T_B = 30 \text{ ms} \), \( P_S = 0.5 \) and \( T_S = 60 \text{ ms} \), then for each scan operation there will be two broadcasts, which means that the selection probability for the broadcast state \( \rho_B \) is twice as much as the transition probability for the scan state. The selection probabilities are linked to the steady state probabilities as in:

\[
P_B = \frac{\rho_B \cdot T_B}{\rho_B \cdot T_B + \rho_S \cdot T_S + \rho_N \cdot T_N}
\]

\[
P_S = \frac{\rho_S \cdot T_B}{\rho_B \cdot T_B + \rho_S \cdot T_S + \rho_N \cdot T_N}
\]

\[
P_N = \frac{\rho_N \cdot T_B}{\rho_B \cdot T_B + \rho_S \cdot T_S + \rho_N \cdot T_N}
\]

Solving these equations for \( \rho_B \), \( \rho_S \) and \( \rho_N \) gives the selection probabilities.

The probability of observing the device actually broadcasting a beacon is:

\[
P_{\text{beacon}} = \frac{P_B \cdot T_{\text{beacon}}}{T_B}
\]
When \( k \) drones are in the system, which means more drones are close enough to be in range of the broadcasting drone and all can transmit, the probability of a successful reception is:

\[
P_{\text{success}}(k) = P_S \cdot P_B \cdot (1 - P_{\text{collision}}(k)).
\]  \( (5) \)

\( k \) is the number of potential transmitters. The meaning of this equation is that the probability of success is defined as the probability that one drone is listening, another drone is broadcasting and the others are not broadcasting but rather scanning or networking.

The probability that, in a scenario with \( k \) drones, given one drone is transmitting a beacon, at least another one tries to transmit is:

\[
P_{\text{collision}}(k) = 1 - (1 - P_{\text{beacon}})^{k-1}.
\]  \( (6) \)

In our analysis, we are interested in the probability to get a position update in a given window, and we assume here that \( T_W = 1 \text{ s} \) is a meaningful value. Given \( T_W \),

we can derive the average amount of events within an observation window as:

\[
N_x = P_x \cdot \frac{T_W}{T_x},
\]

where \( x \) can be \( S, N \) or \( B \) which stand for Scan, Networking and Broadcast, respectively.

From the number of broadcasts we can derive the average number of successful broadcasts during the observation window \( T_W \):

\[
N_{\text{success}}(k) = P_S P_B (1 - P_{\text{collision}}(k)) \cdot \frac{T_W}{T_B}.
\]  \( (8) \)

### 3 Protocol Analysis

#### 3.1 Behavioral Simulation

In order to validate our system, we designed a behavioral simulation in which each node is modeled as a state machine. At each step of the simulation, a random number generator provides the input to determine which transition will be performed next.

Success probability, collision probability, and other statistical metrics are analyzed based on the simulation results. The time step resolution for the simulation is 1 ms which is also the minimum time resolution reliably measurable on the physical device used for the experiments.

#### 3.2 Parameters Tuning

Analyzing the results obtained with different parameters combinations allows for a much quicker evaluation of the multiple trade offs involved in designing
such a system. Moreover, it helps to test the protocol in conditions that are difficult to achieve with the hardware itself (e.g. collisions). The timing values used for the simulations are listed in Table 1. All the source code used to conduct all the experiments and simulations is available at the URL in [5].

Table 1: Simulation Parameters. The timing values are chosen according to our measurements on the low-cost embedded Wi-Fi modules. These values are device dependent and can be changed if different Wi-Fi modules are used. Using these values is important to compare simulation results with the experimental results.

| Parameter       | Value |
|-----------------|-------|
| $T_{\text{beacon}}$ | 1 ms  |
| $T_B$           | 30 ms |
| $T_S$           | 60 ms |
| $T_N$           | 100 ms|
| Time resolution | 1 ms  |
| Number of drones | $\geq 10$ |
| Number of state transitions | $10^6$ |

Figure 5 illustrates how the Broadcast - Scan throughput is affected by changing the duration of a scan operation. Shorter and more frequent scans result in a narrower distribution and a higher probability of keeping the average throughput. However, increasing $T_S$ does not produce any important change in the protocol performance. Because of our hardware, we have decided to chose $T_S = 60$ ms. A more detailed explanation about the hardware limitations on $T_S$ is given in section 4.1.

As shown in Figure 6, the value of $T_B$ has a larger impact on the broadcast - scan throughput. Minimizing $T_B$ is important to increase the throughput but the limitation of the real hardware must be taken into account when deciding a value. The lower limit to $T_B$ is given by the duration of a beacon plus the setup time of the hardware itself.

In Figure 7, the broadcast - scan throughput is computed for different values of $P_N$. The trade-off between telemetry and broadcast-scan is very important because the primary function of drone’s Wi-Fi is telemetry. The choice of $T_N$ is very hardware dependent: very small values might cause memory errors, like buffer overflows but large values result in long periods of time when the location update is not possible. $T_N = 100$ ms is the best trade-off that could be found for the ESP32 hardware used for this research. Using the same values for simulations and experiments allows to compare the results and understand other constraints not included in the behavioral model.

4 Experimental results

In this section, we describe the used hardware and its constraints as well as the experimental campaigns in the laboratory and on the field with real drones.
Laboratory experiments are quite important to understand how the real hardware behaves compared to the simulation model. After the hardware has been validated in the lab, drone experiments could be performed to evaluate how the protocol behaves versus distance in a more realistic scenario as what could be obtained only in ideal conditions.

4.1 Hardware

The Wi-Fi modules used for the experiments are wipy 3.0 by Pycom [8] and are based upon the ESP32 [2]. They are some of the lowest cost Wi-Fi solutions we could find at the time of starting this research, and we have selected them because of their low weight and cost. As a result, we can imagine using them for every drone. Each module is equipped with an external antenna to improve the RF performance which otherwise may be hindered by the ceramic chip antenna mounted on the PCB. The behavioral model is implemented with Arduino (C++) which substitutes the default Micropython environment.

The physical nodes are programmed to behave like the simulated nodes with some small differences dictated by the nature of the device.

Each module is controlled by its own thread on the PC. Since transitions are much less frequent than the period of the system clock, the time accuracy is not a concern and does not invalidate the statistical analysis of the results. The interface between the Wi-Fi modules and the PC is a Serial-to-USB converter (Silabs CP2102) operating at 115200 kbps.
4.1.1 Limitations of the setup

During our experimental campaign we could observe the presence of jitter on the broadcast interval duration $T_B$. This is because the UART communication is asynchronous and the read operation on the embedded module is blocking with timeout. To mitigate this, it is advisable to enable flow control, depending on the selected serial speed. Up to 230400bps, the so called software flow control (XON/XOFF) is sufficient to ensure correct operation, for faster speeds, hardware flow control (RTS/CTS) needs to be implemented. The effect of this jitter, whose distribution is shown in Figure 8, is noticeable in the results.

It is important to keep in mind the limited amount of memory of these embedded devices. When the required broadcast rate is too high, it is easy to completely fill in the Wi-Fi memory buffer and to prevent any transmission. The two possible countermeasures are to slow down the transmission rate (e.g. by extending the broadcast time with a short delay() call), or by ensuring that more time is spent scanning than broadcasting.

The scan time $T_S$, which is the time spent listening for incoming transmissions and decoding the messages within them, can be broken into two components: $T_{Rx}$ which is the time spent actually listening to the channel and $T_{comp}$ which is the time spent to extract the received messages from the incoming transmissions and put them in memory in a readable form. Thus $T_S = T_{comp} + T_{Rx}$. The amount of messages arriving at the receiver has a considerable impact on $T_{comp}$. This translates into a stretch of $T_S$ which is not accompanied by an increase in listening time $T_{Rx}$ but rather into a blind period of duration $T_{comp}$. While for very low traffic, the approximation $T_S \approx T_{Rx}$ is valid, for higher traf-
Figure 7: Probability density of receiving k messages in a second. The peak is the average throughput. With $P_S = P_B$ and $T_N = 100$ ms, multiple values of $P_N$ have been studied. Increasing $P_N$ reduces the broadcast/scan throughput.

fic, $T_{comp}$ must be taken into account. In simpler words, the scan function takes much longer to execute when more messages are received. The additional time seems to be used for processing packets and moving data in memory.

The extra processing time is due to the fact that the ESP32 is used for something it is not designed for. Our educated guess is that, if we could access the low level firmware, the performance can be greatly improved. Espressif provides a proprietary mesh protocol which works up to 32 devices in the same network and its MAC protocol is not very different from beacon exchange. We are thus reasonably sure that the hardware is far more capable than what is possible to do just by using its public API.

Figures 9 and 10 show the impact of the transmission rate on the receive time and the reception rate respectively. It is clear that the more messages are transmitted, the longer it takes to the wi-fi chip to process them impacting negatively the reception rate. While the transmission rate has barely any impact below 50 msg/s, the receiver struggles progressively with the increase of incoming messages to be processed. With two transmitters, the turning point happens even earlier because the rate of incoming messages is the double. Figure 10 shows how the reception rate does not follow a linear trend and its slope reduces more and more with the amount of transmitted messages.

4.2 Laboratory experiments setup

In order to get a baseline for the real-world experiments performed with the drones, a complete measurement campaign has been performed in our labs. The measurements have been performed both in an office environment and in a Faraday cage. The modules have been programmed to operate according to our behavioral simulation so that results could be compared between simulation
Figure 8: Distribution of $T_B$. Although the average is close to 30ms, there is some jitter on $T_B$ which can make it vary between 24 ms and 39 ms.

Figure 9: $T_S$ vs Transmission rate. An increase in the message transmission rate has a big impact on the processing time. This behavior is dominant over radio collisions. In fact, the time spent processing the incoming messages becomes higher than the time spent receiving them.
and experiments. The real modules, programmed with the same parameters as in Table 1, give very similar results as our simulation model but also show how perfection does not belong to our world. The physical limitations and constraints of the ESP32 are discussed in detail in Section 4.1.

The modules have been placed approximately 50 cm away from each other to minimise propagation effects.

The time spent for each operation has been measured on the ESP32 Wi-Fi chip both with an oscilloscope, by toggling some of the pins at the beginning and end of the timed functions, and with the internal timer of the ESP32.

Each device is connected via serial port to a Raspberry pi which saves all the incoming beacons together with its timestamp. The time is measured from the beginning of the logging program. In the simulations, we assume that all the drones broadcast beacons, scan for beacons and do networking operations with the same probability as any other drone. In other words, every drone uses the same protocol parameters.

From the probabilistic model, we can derive the fact that $P_S$ is the limiting factor in the amount of messages that can be received.

The higher $P_S$, the more more messages get received in proportion to the transmitted ones. However, a higher $P_S$ means a lower $P_B$ which implies that less messages are transmitted. The maximum throughput is only obtainable when $P_S = P_B$ and, when no networking is present, at most a half of the transmitted messages can be received by a single drone.

Both experiments and analysis show that, as expected, the delay between successfully received packets follows an exponential distribution (see Figure 11).

Since messages can be lost due to many causes (e.g. congestion, multipath fading, bad antenna alignment), it is important to maximize the throughput to share always the most updated position available. The maximum throughput
4.3 Laboratory experiments results

4.3.1 Broadcast - Scan

The simplest implementation of the communication protocol involves only broadcast and scan, without networking. The behavior of each module can then be modeled as a Poisson process. The time of arrival follows an exponential distribution (see Figure 11) which validates this assumption.

The experimental results are in agreement with the simulations results. However, the physical device shows some limitations and constraints which were not considered in the simulations. Despite the device limitations, the results are very close to what could be observed by simulating the behavioral model.

With $P_B = P_S = 0.5$ and the settings of Table 1, the average throughput is slightly higher than 8 msg/s which is half the broadcast rate. This has been confirmed by both simulations and experiments in the laboratory (see Figure 12) and it is in accordance with our mathematical model. For example, the number of successful receptions in a 1 s window follows (8), resulting in $N_{success} = 8$. As shown in Figures 11 and 12, the results match very well both simulations and experiments with the real devices.
Figure 12: Probability density of receiving k messages in a second: Simulation vs Experimental results for $P_B = P_S = 0.5$.

Figure 13: Cumulative distribution function of the probability of collisions depending on the amount of drones (0 to 100) and the probability of broadcasting (0 to 1). The bottom image is the theoretical result (see [6]), the top image is the simulation result.
Throughput [msg/s] 0.0 0.1 0.2 0.3 0.4 0.5
Probability Density
TB = 30 ms, TS = 60 ms, TN = 100 ms
PN = 0.1
PN = 0.2
PN = 0.3
PN = 0.4
PN = 0.5

Figure 14: Probability density (experimental results) of receiving k messages in a second for different networking rates. A trade off must be chosen between telemetry and broadcast-scan in order to guarantee a minimum throughput of 1 msg/s.

4.3.2 Radio Collisions

The amount of information needed to avoid accidents when multiple drones are close to each other is much higher than when the drones are far apart. Thus, the effect of radio collisions needs to be carefully evaluated in order to predict the amount of drones that can safely fly in the same area. Moreover, it is important to consider the effect of hardware "saturation" explained in Section 4.1.

Figure 13 shows the probability of collision between transmissions depending on the amount of active drones and the probability that they are in the broadcast mode. The simulation result matches closely the theoretical model of equation (6). In theory, the effect of radio collisions is small on the system performance because the message length is very short compared to the time between consecutive transmissions (less than 1 ms vs tens or hundreds of ms).

However, experiments with the real devices show that the limiting factor is the hardware. As mentioned in Section 4.1, the processing time of received packets increases proportionally to the number of incoming messages to the point where it is not negligible anymore.

However, this is somehow a device specific behavior which can be mitigated by both hardware and firmware adjustments (e.g. faster hardware, bigger receive buffer, algorithmic optimizations, faster communication interface).

Summarizing, we observed from our experiments that processing time increase is dominant over radio collisions.
4.3.3 Broadcast, Scan, Networking

Introducing networking periods is going to impact the performance of the broadcast - scan mechanism. In particular, we noticed how the broadcast and scan rates must be reduced to accommodate for the processing of network packets. From a conflict management perspective, the parameters should be set in order to move the curve of Figure 14 to the right until the probability of getting 0 msg/s is 0 but this would greatly reduce the network throughput. It is important at the design stage to find a proper trade-off between network/telemetry and broadcast-scan such that at least 1 msg/s can be successfully exchanged without disrupting the telemetry link. According to Table 14 in [4], the requirement for control and navigation aid data rate can go to approximately 12.2 kbps, which poses a minimum requirement for the network throughput of at least 1 packet/s, since Wi-Fi packets can be up to approximately 12 kbit in length. The experimental results are shown in Figures 14 and 15. As expected, the more time is allocated to the beacon broadcasting, the higher the probability that messages get received at the expense of the network throughput.

4.4 Drone experiments

We also study Wi-Fi coverage on a drone. The system performance has been tested at different distances to verify up to which point the Wi-Fi is still useful for conflict management. The experiments have been conducted using two identical devices called Collision Avoidance Packages (CAPs). Each CAP includes a
Figure 16: Setup for the drone experiments. Top: fully assembled drone (3DR Iris+) with attached the CAP box. Bottom: the open box containing a Raspberry pi, the ESP32 module and a small power board to convert the 12 V from the battery to 5 V.
Raspberry Pi 3B+, a GPS module and a ESP32 equipped with a stylus antenna. The setup is shown in Figure 16. The Raspberry Pi is responsible for reading the GPS coordinates, encoding them and passing them to the ESP32 via serial port. The Pi also collects the incoming data from the ESP32 and saves them on a text file. When the CAP is connected to a drone, it acts as companion computer for the flight computer, giving high level commands such as take off, land or go to a way-point, and it is responsible for running the physical collision avoidance algorithm. For this research work, though, no physical collision avoidance has been activated since the purpose has been to characterize the communication system.

One of the CAPs was on the highest tower of our department, in order to simulate a drone deployment. A second CAP was connected to a drone hovering at the same altitude as the tower but at different positions in the Arenberg Campus (See Figure 4.5). This setup was used to characterize the communication performance vs distance. The node positioned on top of our department tower is composed by the exact same hardware and software as the package mounted on the UAV.

4.5 Drone results

The drone experiments have been performed in the Arenberg campus in Heverlee, Belgium (see Figure 4.5). The environment can be considered sub-urban with high vegetation and trees surrounding sparse tall buildings. The furthest measurement point from the tower is approximately 900 m far.
Figure 18: Throughput vs distance. The area between 400m and 600m is covered in vegetation and trees and next to a set of tall buildings. This affects negatively the RSSI performance. The last two points, although not line of sight, are taken in the middle of an open field with almost no obstacles in the Fresnel zone.

Figure 19: This figure shows the time between consecutive messages at different distances. Where vegetation and buildings are more dense, the recorded time values have a higher dispersion as it is also reflected by the average throughput.
Figure 20: The RSSI, follows pretty well the free space path loss, even though a few points are not in line of sight. The path loss parameters are: $P_t = 19.5$ dBm, $K = \lambda/(4\pi d_0) = -3.55$, $d_0 = 2D/\lambda = 0.0147$, $\gamma = 2.118$. Towards the end, there is a slight increase in the average RSSI which depends from receiving only the messages with better RSSI and losing the messages with lower RSSI due to low SNR.

Even at the furthest location, it was possible to receive approximately 4 msg/s with low Received Signal Strength Indicator (RSSI, -85 dBm on average).

4.5.1 RSSI vs Distance

As shown in Figure 20, our RSSI measurements follow pretty well the log distance path loss model $P_r = P_t - K - 10\gamma\log_{10}(d/d_0)$, where:

- $P_r$ is the received power;
- $P_t = 19.5$ dBm is the transmit power;
- $d_0 = 2D/\lambda = 0.0147$ is the far field distance for the Wi-Fi middle frequency of 2.45 GHz;
- $K = \lambda/(4\pi d_0) = 3.55$ is the path loss factor;
- $\gamma = 2.118$ is the path loss exponent extrapolated from the measurements.
At close distance, it still possible to receive beacons arriving with lower power, that is why the bottom part of the plot is more populated at distances lower than 500 m than it is for further distances. This result is encouraging as it shows that messages can still be received at 900 m distance. However, signal strengths below -80 dBm indicate the need for a different radio system for distances greater than 1 km.

4.5.2 Throughput vs Distance

The throughput suffered for the presence of buildings and vegetation (see Figures 18 and 19) dropping to 2.5 msg/s but the system overall remained functional. This might be an important factor to keep into account for missions in dense urban or forest environments. Another important lesson to bring home is that correctly positioning the antennas is very important. The UAV frame itself can cause shadowing to the antennas and reduce the communication performance.

5 Conclusions

In this paper, we propose a method for exploiting the Wi-Fi modules already present in many small UAVs as a tool for sense and avoid. The main concept is to use Wi-Fi beacons as a mechanism to broadcast positional information of the UAVs.

Our simulation results show that the system can be tuned to have good reliability and it is able to deliver more than one message per second, even when a considerable number of drones share the same radio channel.

The experimental results obtained with low cost Wi-Fi devices agree perfectly with the simulation results.

Measurements performed with drones also show that the system works reliably even at distances close to 900 m, leaving enough room to the UAV to safely perform an avoidance maneuver.

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