DroneCAST – Physical Layer Design and Measurement-based Simulation Analysis for Urban Drone-to-Drone Communication Scenarios

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***Abstract*—In order to mitigate midair collisions, a reliable and fast information exchange based on direct Drone-to-Drone (D2D) communication will be one key factor for the realization of Urban Air Mobility (UAM). However, the expected high-density traffic scenarios with highly mobile airspace users, combined with the fast-changing and rich multipath propagation channel characteristics of urban environments pose unique challenges for communication systems. Therefore, in previous work we proposed DroneCAST (Drone Communications and Surveillance Technology) as a first step towards a novel D2D communications and surveillance system tailored to the specific requirements of a future urban airspace. In this work, we present and discuss our design decisions on the physical layer of DroneCAST, which is based on considerations on the specific propagation characteristics of urban D2D channels. Furthermore, we evaluate the design by analyzing the impact of several transmission parameter with different communication channels from three different measured D2D scenarios within software simulations. Our simulation framework implements the physical layer of DroneCAST and simulates transmitting the physical waveform over different communication channels as well as considers non-ideal real world effects of a transmission system.**

***Index Terms*—unmanned aviation, urban air mobility, drone-to-drone communication, air-to-air, propagation, measurement based simulation**

I. Introduction

For the upcoming UAM we expect a dense urban air space with many autonomously flying unmanned aircraft (UA), often referred to as drones. To mitigate the risk of mid-air collisions in high-density drone scenarios, a fast, robust and reliable information exchange between all airspace users based on direct Drone-to-Drone (D2D) communication will be an essential part. In addition, a redundant higher-level safety net to coordinate and monitor traffic is common in civil aviation and other domains today, but still missing for UA. Therefore, we are aiming for a dedicated D2D communication and surveillance system that can perform reliably in safety-critical scenarios, while experiencing challenging communication channel conditions. In particular, the urban environment is challenging from a physical layer perspective with rich multipath propagation to be expected as well as strong and sudden shadowing and diffraction events when flying at relative low altitudes compared to surrounding buildings. In previous work, we have proposed our Drone Communications and Surveillance Technology (DroneCAST) [1] as a first step towards a novel D2D communications system for urban environments and discussed first design decisions and requirements with respect to the physical layer as well as the medium access control layer. Furthermore, we have conducted a wideband channel measurement campaign [2] in order to measure the D2D propagation conditions in an urban scenario with small sized hexacopters. In this work, we implement first design decisions of the DroneCAST's physical layer in software and evaluate its performance in different urban D2D communication scenarios by running Monte-Carlo simulations based on our measurements. Thereby, we investigate and present the impact of different transmission parameter of the design with different communication channel propagation characteristics and discuss modifications in the physical layer in order to enhance the robustness of DroneCAST for urban D2D scenarios. We present different flight scenarios and evaluate the link-level performance by analyzing the resulting packet error rates from our simulations.

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II. Characteristics of the Urban D2D Communication Channel

Measurements for the D2D propagation channel in urban environments revealed a rich multipath environment mainly caused by objects like fences, streetlamps or metallic constructions on the surrounding buildings [3], [4]. Due to the heterogeneity of the D2D channel, it is difficult to classify different scenarios with specific channel characteristics. Nevertheless, related work [5], [6] shows that there is at least a height dependency for the line of sight (LOS) probability and therefore the higher the relative height to surrounding obstacles like buildings, the higher the probability of receiving multipath signals and interference. Therefore, we consider following three different scenarios for D2D communication.

1) Scenario 1 - lower heights (drones flying relatively low in urban canyons: In this scenario, drones fly at low speeds (0 - 10 m/s) near and between buildings for approaches and departures at vertiports. The distance between individual drones is only a few meters, especially near vertiports. In this scenario, there is strong multipath propagation due to very nearby reflective objects but with limited number of components. The received signal power is relatively high and the signal delays are short. The drones experience rapidly changing visibility conditions to other drones and the probability of shadowing is relatively high. This is particularly critical, for example, when the trajectories of two drones cross at the edge of a building. The characteristics of the transmission channel are similar to urban crossing scenarios in the Vehicle-to-everything (V2X) domain. Compared to all three scenarios, we expect here the lowest delay and Doppler spreads.

2) Scenario 2 - medium heights (drones flying at heights of building's rooftops: In this scenario the drones fly faster than in scenario 1 at medium speeds (10 - 25 m/s), but also at greater distances from each other and at higher heights around the building's rooftops. Here again we are dealing with strong multipath propagation, but the probability of shadowing decreases and signal paths are also received from greater distances. In addition, the interference increases due to increased visibility to other transmitting drones. Compared to all three scenarios, we expect here the highest delay and Doppler spreads. In combination with the highest probability of fast changing LOS conditions, this scenario is assumed to be the most challenging one.

3) Scenario 3 - higher heights (drones flying relatively high above buildings: The drones' cruising altitude is above the roofs of buildings at a cruising speed of up to 50 m/s. All drones in the airspace have a continuous line of sight to each other, which leads us to expect a relatively high interference power. The multipath propagation is comparatively low in this scenario, as reflective objects are far away and thus the attenuation is high. The characteristics of the transmission channel are expected to be similar to the air-to-air (A2A) domain.

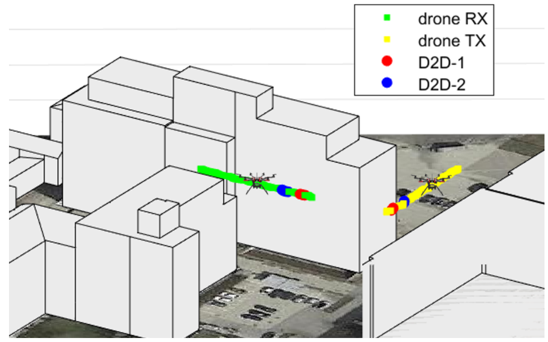
A. Measured D2D Scenarios in Urban Environment

We performed a Drone-to-Drone wideband channel sounding measurement campaign at C-Band with two flying small hexacopters in an urban environment at our campus site in Oberpfaffenhofen, Germany. The measurement setup and used equipment is presented in [2]. For the simulation based analysis of the physical layer design, we consider following three different D2D scenarios from our measurements that are related to scenario 2 mentioned in Section II.

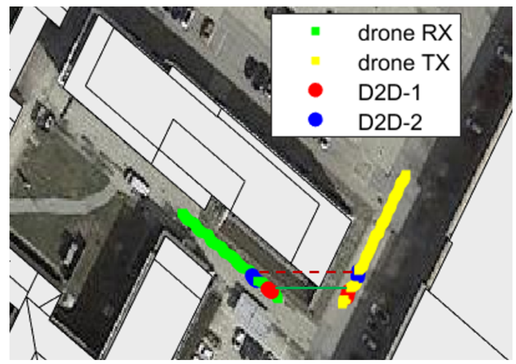
*1) Scenario **D2D-1** - Urban Crossing LOS:* In this measured flight scenario, the two drones are flying at around 10 m height in an urban canyon below the rooftops of the surrounding buildings while being on collision course and experiencing different signal propagation conditions. Fig. 1 illustrates the whole scenario and the analysed 2 seconds excerpt D2D-1, for which the drones were in LOS condition. Fig. 2 shows the measured channel impulse response for the whole flight and the indicated excerpts revealing strong specular and diffuse multipath components beside the LOS component. Fig. 3 shows the average of the normalized power delay profile for the analyzed excerpt and Fig. 4 shows the average of the normalized Doppler spectral density.

*2) Scenario **D2D-2** - Urban Crossing NLOS:* This scenario is part of the same measured flight as for scenario D2D-1 shown in Fig. 1, but a different excerpt for which the LOS path was obstructed by the building nearby. Fig. 2 shows the measured channel impulse response. Fig. 3 shows the average of the normalized power delay profile for the analyzed excerpt and Fig. 4 shows the average of the normalized Doppler spectral density.

*3) Scenario **D2D-3** - Urban Approaching LOS:* In this measured flight scenario, the two drones were approaching each other along a street at low heights around 5 m. Fig. 5



(a) **3D Layout**



(b) **2D Layout**

Fig. 1. Drone positions for scenario D2D-1 (Urban Crossing LOS) and scenario D2D-2 (Urban Crossing NLOS) - The drones are on collision course when flying around a buildings corner in an urban environment while experiencing different line-of-sight conditions.

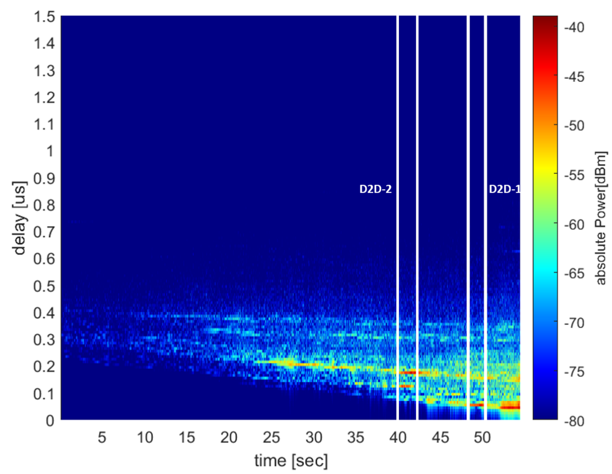


Fig. 2. Measured channel impulse response with indicated 2 seconds excerpts for analyzed scenarios D2D-1 and D2D-2.

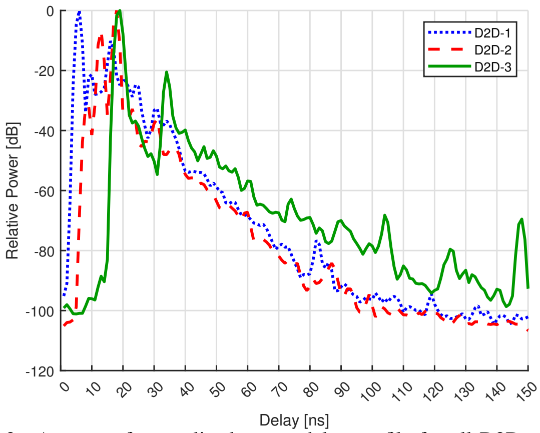


Fig. 3. Average of normalized power delay profile for all D2D scenarios.

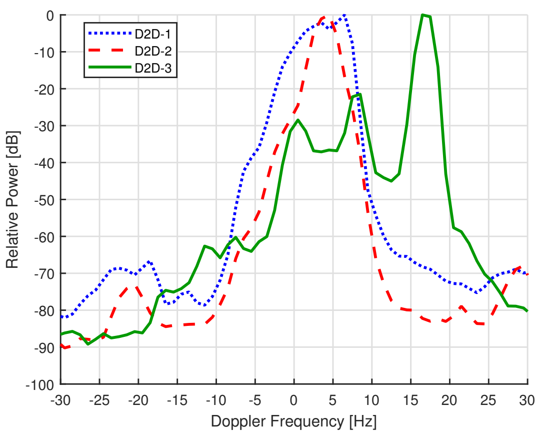


Fig. 4. Average of normalized Doppler spectral density for all D2D scenarios.

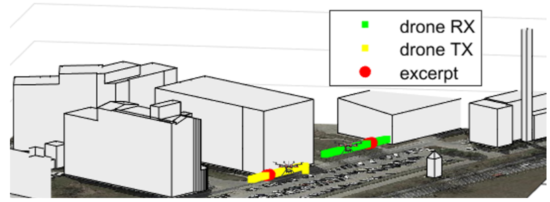
illustrates the geometries of this scenario and Fig. 6 shows the measured channel impulse response. Fig. 3 shows the average of the normalized power delay profile for the analyzed excerpt and Fig. 4 shows the average of the normalized Doppler spectral density.

B. V2V Scenarios in Urban Environment

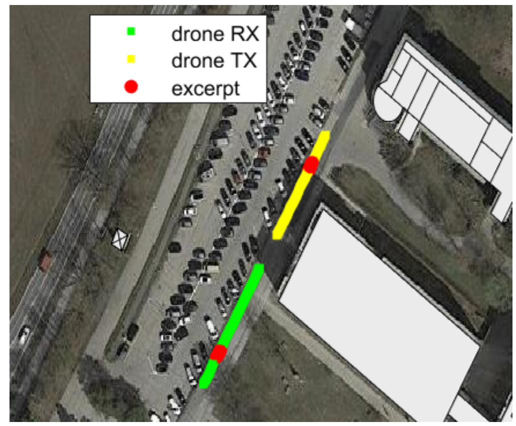
As mentioned in Section II, the D2D communication channel can be distinguished into three different scenarios and for scenario 1 at very low heights the channel characteristics are assumed to be very similar to the V2X domain in urban environments. Therefore, we make use of two urban V2V scenarios presented in [7] in order to compare our measured D2D scenarios with scenarios of higher Doppler frequencies. Table I gives an overview to the channel parameters for an urban crossing scenario with non LOS condition (V2V-1) and for an urban approaching scenario with LOS condition (V2V-2).

III. Requirements Relevant to Physical Layer for DroneCAST

In our previous work [1] we already analysed the requirements on DroneCAST in order to provide collision avoidance



(a) **3D**



(b) **2D**

Fig. 5. Drone positions for scenario D2D-3 (Urban Approaching LOS) - The drones are on collision course when approaching each other above a street being always in line-of-sight condition.

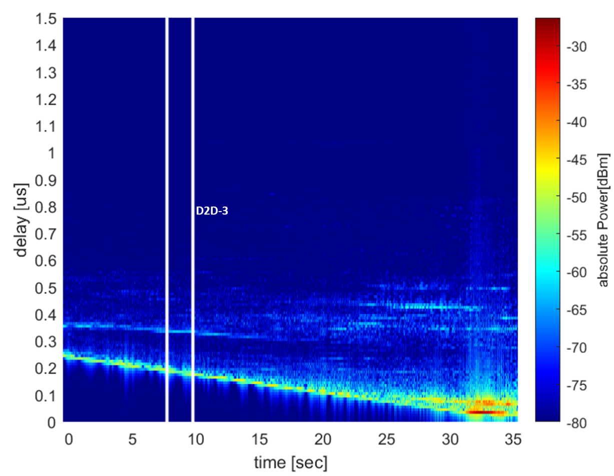


Fig. 6. Measured channel impulse response with indicated 2 seconds excerpt for scenario D2D-3.

for drones. In the following we present all requirements from regulations and other OSI-Layers that need to be considered in the physical layer design.

A. Drone Density

DroneCAST shall support drone densities up to 100 drones per square kilometer in order being prepared for high dense traffic scenarios like hotspots around vertiports. In addition, DroneCAST must transmit at least one message per second for reliable collision avoidance. Providing sufficient communication resources is a topic related to the medium access control (MAC) scheme, but the MAC layer design has an impact on

TABLE I
V2V CHANNEL PARAMETER

Scenario	Power [dB]	Delay [ns]	Doppler [Hz]
V2V-1 (Urban Crossing NLOS)	[0, −3, −5, −10]	[0, 267, 400, 533]	[0, 295, −98, 591]
V2V-2 (Urban Approaching LOS)	[0, −8, −10, −15]	[0, 117, 183, 333]	[0, 236, −157, 492]

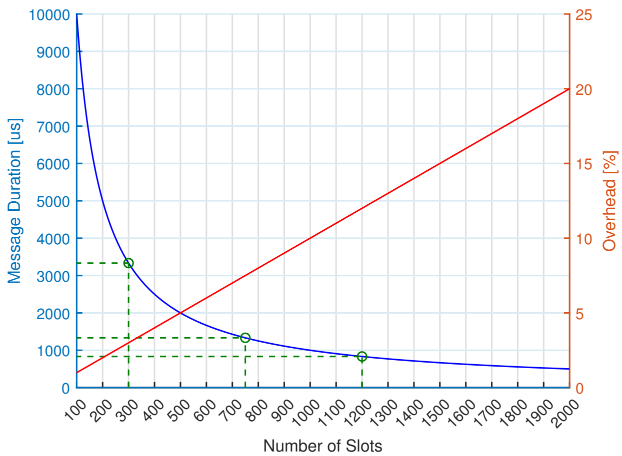


Fig. 7. Relation between number of TDMA slots and resulting message duration limits.

the maximum message duration at the physical layer (PHY). DroneCAST uses an time division multiple access (TDMA) based MAC scheme and therefore the maximum message duration is inversely proportional to the required number of time slots in order to serve all participants within a certain time. Depending on the radio range this results in up to $\approx$ 300 drones assuming 1 km range and up to $\approx$ 1200 drones for 2 km range, considering that all drones have to share the communication resources. Fig. 7 shows this relation and it can bee seen that the resulting message durations must not exceed $\approx$ 1 ms or $\approx$ 3 ms in order to allow to serve 300 or 1200 drones respectively. For the minimum radio range of DroneCAST we assume 1 km to be sufficient for the urban airspace and the targeted range is between 1 km and 2 km. Therefore, the targeted maximum message duration shall be close to 1 ms.

B. Frequency Band and Bandwidth

DroneCAST is expected to work in unused spectrum in the C-band from 5030 MHz to 5091 MHz that is foreseen for future drone communication [8] and we restricted the bandwidth to not exceed 5 MHz.

C. Message Size

The main foreseen application of DroneCAST is collision avoidance and we defined a position report message that will be broadcast-ed regularly by all drones and needs 402 Bits [1]. In addition to this we foresee appending 256 Bit signatures to every message in order to implement authentication methods for DroneCAST, which are not yet defined. Furthermore, a CRC-32 checksum is added to all messages in order to being able to detect bit failures and thereby increasing the trust in successfully transmitted messages. In summary, a DroneCAST position report message needs 402 + 256 + 32 = 690 Bits.

IV. Physical Layer Design Decisions for DroneCAST

The main goal of the physical layer design for DroneCAST was to find a suitable transmission system and to optimize its parameters in order to meet the all mentioned requirements and keeping robustness as high as possible by considering the specific channel characteristics. For the basic architecture of the physical layer of DroneCAST an Orthogonal Frequency Division Multiplex (OFDM) transmission system was chosen. Especially in the case of strong multipath signal propagation, as is particularly the case in urban areas, a multi-carrier system in general and the OFDM method in particular offer many advantages like high spectral efficiency and the ability to cope with frequency-selective channels in rich multipath environments by adding guard intervals in time domain to combat inter-symbol interference (ISI). Therefore, OFDM was widely adopted in various telecommunication and WiFi standards. In [1] we already discussed the suitability of existing technologies and showed that especially the latest V2X standard IEEE 802.11bd [9] seems suitable also for D2D communications. Therefore, in this work we focus on the OFDM system parameter evaluation and briefly summarize its main PHY layer features that are inspired by IEEE 802.11bd [9] standard. DroneCAST utilizes Dual Carrier Modulation (DCM) for increased robustness by transmitting redundant symbols over different subcarriers for enabling frequency diversity. For synchronization and carrier frequency correction DroneCAST uses the Schmidl-Cox algorithm [10]. Furthermore, LDPC codes with rate 1/2 are used for channel coding in combination with interleaving and scrambling. For the design procedure of the OFDM system, most of the parameters are interrelated and trade-offs must be solved. Therefore, we present and discuss feasible value ranges in the following. The final design decisions are based on the simulation results in Section V. Table II provides an overview to all the considered OFDM parameters and Fig. 8 illustrates the OFDM frame exemplarily for certain parameters. Thereby, the preamble consists of training symbols and a signal field that indicates the message type and includes optional information regarding modulation scheme, pilot symbol settings and payload length. For a DroneCAST position report message, there is no need to decode the optional information as all settings are fixed like shown in Table II. For future applications beside collision avoidance different message types might be introduced and the optional fields can be used for arbitrary messages with variable length.

The available bandwidth B is divided into N_c sub-carriers resulting in the sub-carrier spacing

$$\Delta f = \frac{1}{B/N_c} \quad (1)$$

that has to be chosen smaller than the expected coherence bandwidth B_c, in which the the communication channel can be

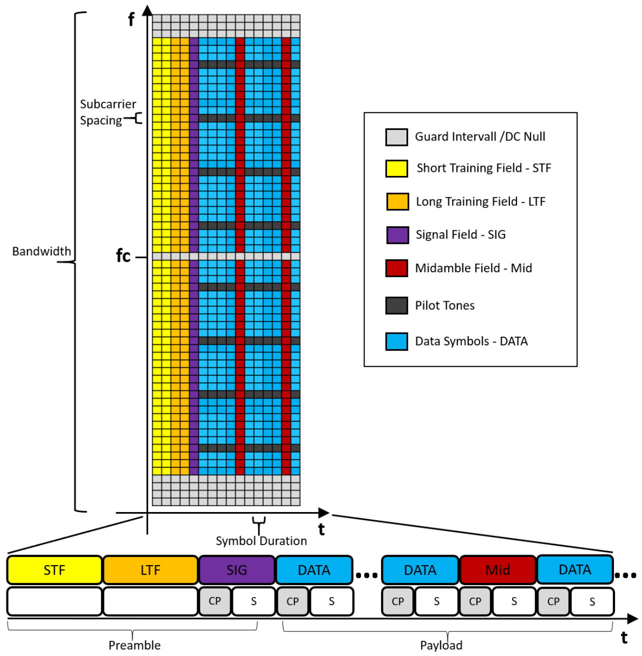


Fig. 8. DroneCAST OFDM frame shown with targeted 64 subcarriers, 8 pilot carrier and midamble rate of 4.

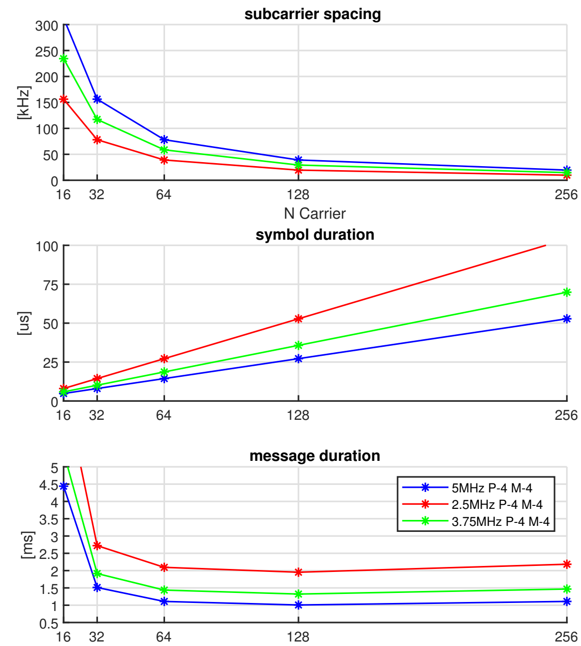


Fig. 9. Impact of bandwidth and number of sub-carrier on the OFDM parameter sub-carrier spacing and symbol duration and resulting overall message duration for DroneCAST position report.

assumed frequency-flat for improved channel equalization. For the D2D communications in the C-Band we assume several hundreds of kilohertz as the order of magnitude for the coherence bandwidth. The lower limit of the sub-carrier spacing is defined by intercarrier interference (ICI) and peak-to-average-power-ratio (PAPR). ICI arises from frequency offsets due to Doppler spreads and oscillator mismatches. Therefore, the lower the sub-carrier spacing the more susceptible the datalink is to these effects. The maximum expected Doppler shift for DroneCAST can be up to $\approx \pm 1.7kHz$ when assuming relative speeds up to 100 m/s, but the expected maximum Doppler spreads are much lower in the magnitude of tens to hundreds of Hertz. The PAPR of the waveform increases with the number of sub-carriers and must be kept low in order to limit non-linear amplifying effects at the transmitter amplifier.

The symbol duration t_{symb} is directly related to the sub-carrier spacing Δf and the chosen guard interval t_{guard} with

$$t_{\text{symb}} = \frac{1}{\Delta f} + t_{guard} \tag{2}$$

. The maximum symbol duration must be chosen smaller then the expected coherence time T_c, in which the channel can be assumed time-flat. The symbol duration is limited by targeted maximum message transmission time. For DroneCAST, a collision avoidance message must be transmitted within one time slot of the TDMA scheme. In Fig. 7 we see that the resulting message duration is limited to 3 ms to 1 ms depending on the radio range, but should be closer to 1 ms as the number of provided slots drastically decreases for higher durations. The resulting message duration is dependent on the symbol duration, the message size and the achieved bitrate dependent on used bandwidth and overhead introduced by channel estimation and synchronization resources. Fig. 9 and Fig. 10 show the impact of different bandwidths, number of sub-carriers, number of pilot carriers and midamble rates on the resulting sub-carrier spacing and symbol duration as well as the achieved message duration for the DroneCAST position report message when using BPSK modulation, LDPC channel coding and DCM. It can be seen that with number of carriers of 64 and 128 the achieved message duration is lowest and very similar for these two numbers. Considering PAPR, 64 carriers is the most suitable value. In order to come close to the targeted message duration of ≈ 1 ms, the full bandwidth of 5 MHz must be used and the midamble rate must be chosen higher than 4. The guard interval t_{guard} must be chosen at least as long as the expected delay spread of the channel. For the C-Band the freespace pathloss (FSPL) is relatively high and from our D2D measurements and various Vehicle-to-Vehicle (V2V) measurements we see that delay spreads are unlikely to exceed 1.6 us range. As the guard interval adds an overhead and lowers the resulting bandwidth efficiency, this value should be kept small.

Considering all previously mentioned design decisions, Table II gives an overview to all relevant design parameter with feasible value ranges for DroneCAST that are further investigated in software simulations.

A. *Discussion and Comparison to Related Systems*

The final design decisions for DroneCAST's physical layer are very similar to the IEEE 802.11bd standard, which is well optimized for V2X communications in urban environments.

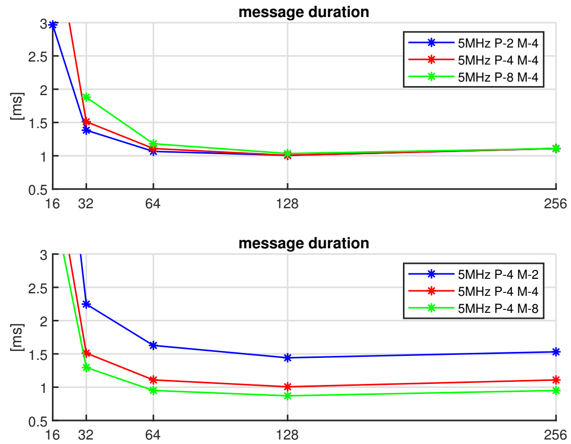


Fig. 10. Impact of pilot carrier spacing, midamble rate and number of sub-carrier on resulting overall message duration for DroneCAST position report.

TABLE II
DRONECAST PARAMETER OVERVIEW

Parameter	Symbol	Value Range	Chosen Value
Center frequency	f_c	5,030 – 5,091 GHz	tbd
Bandwidth	B	2.5 - 5 MHz	5 MHz (4.45 MHz)
Subcarrier	N_c	32,64,128	64
Subcarrier Spacing	Δf	39 - 156.25 kHz	78.125 kHz
Guard Interval	t_{guard}	1.6 - 3.2 μs	1.6 μs
Symbol Duration	Δt	8 - 20 μs	14.4 μs
Modulation	MCS	BPSK	BPSK
Pilot-Carrier	N_p	2,4,8	8 (625 kHz)
Data-Carrier	N_d	22 - 114	48
Guardband-Carrier	N_g	[4,3],[6,5]	[4,3] (312.5 kHz)
Midamble Rate	R_m	2,4,8,12	4 (72 μs)
Dual Carrier Modulation		yes,no	yes
Channel Coding		LDPC	LDPC-$\frac{1}{2}$

Major differences are the lower required bandwidth, the decreased subcarrier pilot tone spacings as well as shorter preambles used for DroneCAST despite increased symbol durations. Furthermore, DroneCAST aims using a lower frequency band that might be reserved exclusively for UAM communications. Compared to ADS-B (Automatic Dependent Surveillance - Broadcast) used for collision avoidance and surveillance in civil aviation today, DroneCAST is based on a multicarrier transmission system and targets much lower radio ranges. Furthermore, DroneCAST will implement a TDMA based medium access control (MAC) layer tailored to the specific requirements of urban air mobility in to cope with the high expected traffic densities [1].

V. Analysis of the Physical Layer Design

A. Simulation Framework

Our simulation framework is implemented in Matlab and based on an existing simulation frameworks that implement the IEEE 802.11bd standard [11] and the IEEE 802.11p standard [12]. We extended the framework in order to allow for a very flexible and easy modification of all parameters and sub-modules. For the simulation we use different tapped delay line channel models and our measured channel impulse responses. Thereby, the power normalized channel impulse within a quasi-stationary region is convolved with the generated and waveforms for a DroneCAST position report message, which are up-sampled to the measurement bandwidth of the channel. Beside taking channel characteristics into account, the simulation framework also considers different hardware dependent real world effects like phase noise, non-linear amplification and carrier frequency offsets.

B. Simulation Results

Within our simulation framework we investigated the impact of different parameter on the overall performance with regards to packet error rate when transmitting the DroneCAST position report message over different channels defined in Section II. For this we transmitted 2000 random messages for all different simulated signal-to-noise-ratio (SNR) values with the chosen physical layer parameters shown in Table II. Fig. 11 shows the impact of DCM and it can bee seen that it decreases the packet error probability in all cases. The cost for this improvement is halving the available data carrier for every OFDM symbol and thus almost doubling the message duration. Fig. 12 reveals that the impact of different number of used pilot carriers is relatively low for the used D2D scenarios and the difference between using 8 or 4 pilot carrier is marginal, but the results show that higher number of pilot carriers improve the robustness. As our main goal is increase robustness of DroneCAST, we chose 8 pilot carriers that still meet the requirements for maximum message duration. Fig. 13 shows that there is almost no difference for the D2D channels with different midamble rates. This results from the relatively low velocities of the drones resulting in quite low Doppler shifts. For the V2V channels with much higher Doppler shifts the results show higher impact of the midamble rate on performance and indicate that the midamble rate can be chosen too low and decrease performance with a midamble rate of 2 in this case. As a midamble rate of 2 also drastically increases the message duration like shown in Fig. 10, we chose a rate of 4 for DroneCAST. The simulation results of different sub-carrier spacings revealed a relatively high impact of the simulated carrier frequency offset on the performance. Like mentioned in Section IV this real-world effect creates ICI and increases with lower sub-carrier spacings. As this is very dependent on the hardware performance and simulation results without this effect were very similar, we could not determine an optimal setting but considering PAPR and the achieved message duration, we chose 78.125 kHz with 64 sub-carriers at 5 MHz as a suitable value.

VI. Conclusion

In this work, we presented the physical layer design of DroneCAST (Drone Communications and Surveillance Technology) and discussed the specific requirements and constraints from regulations, different OSI layers and the expected channel characteristics for D2D communications in urban environments. The focus of the design was evaluating and deciding on suitable OFDM parameter values. In order to analyse different design parameters and their impact on the

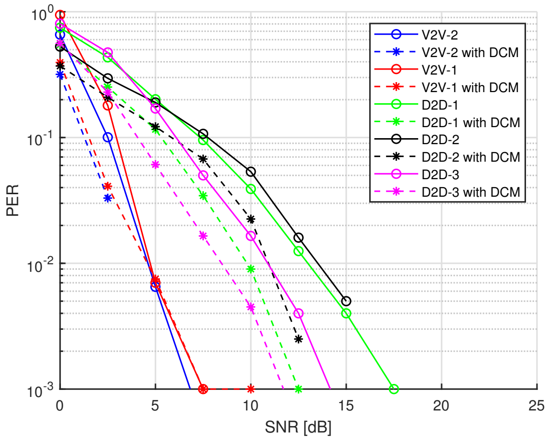


Fig. 11. Influence of Dual Carrier Modulation on packet error rate over signal-to-noise ratios for the transmission of a DroneCAST position report message over different channels.

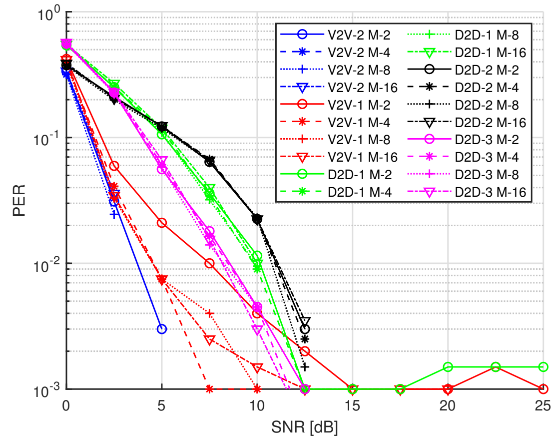


Fig. 13. Influence of midamble rate on packet error rate over signal-to-noise ratios for the transmission of a DroneCAST position report message over different channels.

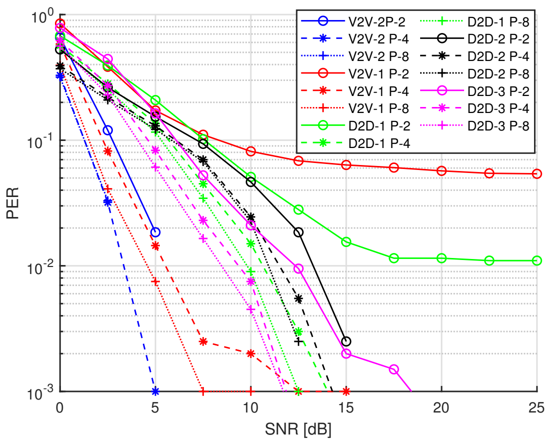


Fig. 12. Influence of number of pilot carrier on packet error rate over signal-to-noise ratios for the transmission of a DroneCAST position report message over different channels.

overall performance in terms of achieved packet error rate, we built a simulation framework that implements the physical layer of DroneCAST and simulates the transmission of the waveform over different channels, taking into account non-ideal real-world effects of a transmission system. This allows a comprehensive analysis based on measurements in order to support the decisions in the design process by fine-tuning the parameters of the OFDM transmission system for DroneCAST. Our D2D measurements provide relatively low Doppler values as the drone velocities during measurements were relatively low. Therefore, we also considered V2V scenarios providing higher Doppler spreads and compared the results as we assume similar channel characteristics for D2D scenarios at lower heights. For future work, we will further analyse the performance of DroneCAST's physical layer by considering more measurements from literature and using a D2D channel model that is currently under development that will allow the simulation of different D2D scenarios. Nevertheless, we assume the chosen OFDM parameter to be in a suitable range.

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