Modeling the Drone-to-Drone Communications Channel for Urban Environments

Dennis Becker*, Uwe-Carsten Fiebig*, Lukas Marcel Schalk*,
*Institute of Communications and Navigation
German Aerospace Center (DLR)
Oberpfaffenhofen-Wessling, Germany
dennis.becker@dlr.de

***Abstract*—Preventing mid-air collisions between autonomously flying drones in urban airspace will be a crucial task for the future Urban Air Mobility (UAM). Especially in dense urban scenarios, the direct and fast information exchange between drones based on Drone-to-Drone (D2D) communications is a promising technology for enabling reliable collision avoidance systems. In order to design and validate respective communication systems, accurate knowledge about the specific underlying propagation characteristics is inevitable. Therefore, we performed a wideband channel sounding measurement campaign with two flying drones in different urban scenarios and investigated the underlying channel propagation conditions in previous works. In this work, we present a geometrical-statistical architecture to model the D2D communications channel for urban environments. It considers the identified propagation elements and effects from our measurements and shall serve as a basis to easily incorporate further statistics from our measurements or related other measurement campaigns. We show its feasibility by comparing the preliminary channel model results with a simple parameterization based on a measured scenario. The modeled channel characteristics show a good match with the measurements, but further investigation the underlying statistics in the measurements will refine model in the next.**

***Index Terms*—channel model, drone-to-drone communications, unmanned aerial vehicle, air-to-air, propagation**

I. Introduction

For the future Urban Air Mobility (UAM) we expect a highly frequented urban air space with many autonomously flying unmanned aircraft (UA), often called drones. In order to mitigate the risk of mid-air collisions in high dense drone scenarios, a robust and reliable information exchange between all airspace users based on direct Drone-to-Drone communication will be an essential part. Furthermore, a redundant higher-level safety net taking care of the coordination and monitoring of the traffic is common in today's civil aviation and other domains but still missing for UA. Therefore, we are aiming for a dedicated Drone-to-Drone communication and surveillance system that performs reliably in safety-critical scenarios, while experiencing challenging communication channel conditions [1]. But especially the urban environment is challenging from a physical layer point of view with rich multipath propagation as well as shadowing and diffraction events when flying close to buildings. In order to evaluate the reliability and performance of transmission systems for this scenario, an accurate channel model is mandatory that considers the specific underlying propagation characteristics. A wideband D2D channel model for urban environments allows the analysis without the need for complex and cost intensive flight trials. As a first step towards this, we have conducted a wideband channel measurement campaign in order to accurately measure the D2D propagation characteristics in an urban environment [2]. Our first findings have shown that the urban D2D communication channel exhibits rich multipath propagation and shadowing characteristics and we already identified dominant signal components by estimating the locations of their physical causes [3], [4].

The paper is structured as follows: In Section II, we present our channel model architecture by outlining the modeled elements and describing the flow graph of the simulation steps. We show how different propagation effects can be modeled and discuss possible limitations. In Section IV we model a scenario from our measurements and present the preliminary channel model results in section V by comparing them to the channel characteristics obtained from the measurement data. The paper concludes in section VI with a summary of our work and outlines next steps.

II. Channel Model Architecture

In order to model the Drone-to-Drone (D2D) communications channel, we are following a geometry-based stochastic channel model (GBSCM) approach, as it considers underlying geometry and eases the complexity of a full ray tracing approach. The approach allows to model non-stationary propagation effects for highly time-variant channels by modeling the identified deterministic components with specific statistical distributions derived from measurements. Thereby, the modeled propagation effects are closer related to their original cause than for fully stochastic approaches. Our model follows ideas and approaches presented for other geometry-based stochastic channel models for the air-to-ground channel[5] and the train-to-train channel[6]. For urban D2D scenarios, the drones are flying relatively close to buildings and we see in our measurements that propagation effects are highly related to the surrounding buildings. Scattering objects and reflecting surfaces are located in the vicinity of the rooftops and facades. Buildings are the main cause for shadowing

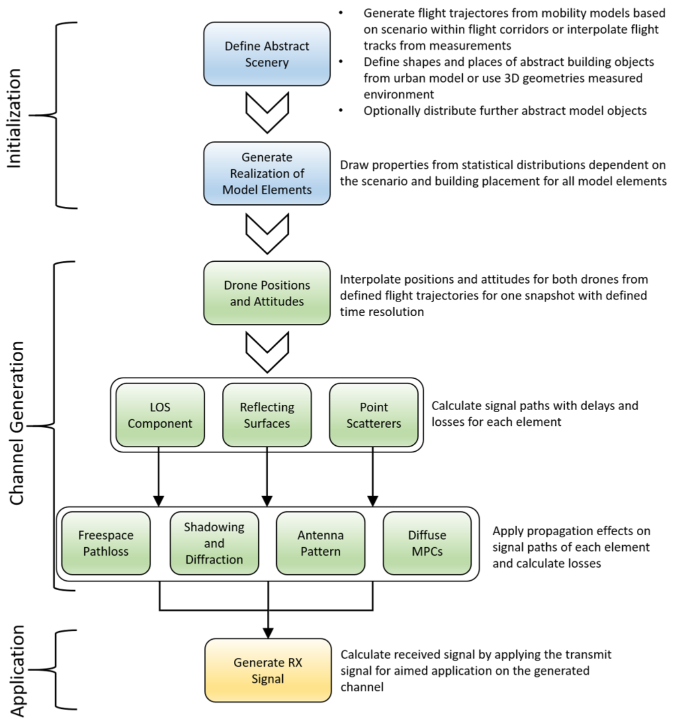


Fig. 1. Overview of the simulation chain for the D2D channel model.

events as they obstruct all the different signal propagation paths. Furthermore, diffraction effects are caused when signal paths travel close to the buildings edges. Overall, the locations and shapes of buildings in relation to the drones trajectories very much influence the propagation characteristics of the urban D2D communication channel. Depending on the scenario, several MPCs can be affected by the same shadowing and diffraction effect of the same building. Therefore, we propose to model the layout of buildings in a coarse-grained manner that represent the characteristics of the targeted scenario and use the modeled buildings for a more realistic distribution of further elements of the channel model. Due to the very heterogeneous nature of urban environments, a pure stochastic model approach would lead to relatively big variances in the statistical distributions and single realizations would then exhibit very different channel characteristics.

For the overall modeling we propose following simulation chain shown in fig. 1 consisting of three basic steps.

A. Initialization

For the initialization of the channel model, a parameterization of the modeled environment is required, which includes all model element properties that are drawn from statistical distributions. These statistical distributions are dependent on the chosen abstract scenery, which defines the shape and placement of buildings as abstracted objects with vertical and horizontal surfaces and the flight trajectories of the drones. This first definition eases the stochastic placement of several channel model elements and ensures that the drone trajectories

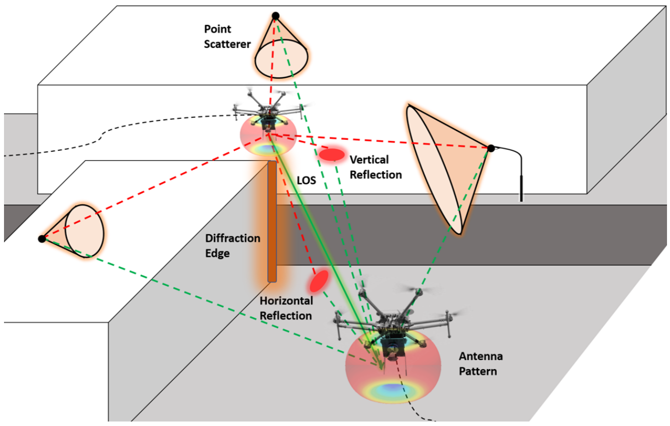


Fig. 2. Overview of elements for the D2D channel model.

and surrounding environment are in a realistic relation dependent on the targeted drone scenario. Beside abstract building objects, being a basis for other channel model elements, also further objects might be defined. For example objects that shall be distributed regularly like street lights might be used as predefined locations for point scatterers. Furthermore, beside static elements being present at the same location for every simulated snapshot of the channel model, also moving elements like cars might be considered by defining the respective locations of the cars for every snapshot. After initialization, the channel model is fully defined and deterministic for every snapshot representing a time-interval for the defined time resolution. It is one possible realization of the given statistical distributions and defined scenery.

B. Channel Generation

The channel characteristics are generated snapshot-wise and the results only differ due to change of the positions and attitudes of the moving drones or other moving objects, if defined in the initialization. For every modeled element, the signal paths with delays and specific losses are calculated first. Then freespace pathloss and shadowing and diffraction losses are applied on all the resulting paths. The signals are also weighted by the modeled antenna radiation patterns. Finally, the resulting complex signal amplitudes are superimposed considering the different phase shifts.

C. Application

The generated channel can be used to calculate the signal to be received at the receiver's antenna by convolution of the transmit signal waveform with the channel for the relevant points in time.

III. Channel Model Elements

In the following we first describe basic channel model elements and propose modeling approaches for each of them. Fig.2 provides an overview of the channel model elements by illustrating an exemplary scenario with two small drones flying close to buildings.

A. Abstract Buildings

Incorporating knowledge about realistic shapes and location distributions of buildings for an urban environment helps achieving a more realistic distribution of all other channel model elements. We propose to model abstract building objects consisting of horizontal and vertical surfaces. The placement and shapes can be modeled by stochastic distributions representing the targeted scenario but also exact 3D geometries of buildings from real-world scenarios can be used. In our case, we are using a 3D geometry database from the national land surveying office that represents the buildings of our measured environment from the measurement campaign. The defined surfaces are considered in the placement of reflection surfaces and point scatterers as well as used to calculate shadowing and diffraction effects on the signal paths.

B. Line-of-Sight (LOS) Component

The LOS component models the direct LOS signal path between the two drones. Under normal conditions the LOS component is the component with lowest transmission delay and the strongest component in terms of received power, which follows freespace pathloss (FSPL) if not influenced by diffraction or shadowed by buildings. Additionally, the radiation patterns of the receiving and transmitting antennas affect the received amplitude. We calculate the direct distance between the drones antennas and check, if the signal path is obstructed by a building in between.

C. Reflecting Surfaces

As one part of multipath propagation, the transmitted signal can be reflected at surrounding surfaces that are in direct line-of-sight. Thereby, the reflection point moves along the surface depending on the positions of the transmitter and receiver and following the rule of achieving same incidence and reflection angle. We propose to model the reflection loss with the reflection coefficient Γ standing for all the losses that are dependent on different parameters like the material and angle of the incident signal wave. We calculate the reflection coefficient with

$$\Gamma(\Theta)=\frac{\sin\Theta - C}{\sin\Theta + C} \tag{1}$$

$$C=\frac{\sqrt{\eta - \cos^2\Theta}}{\eta} \tag{2}$$

$$\eta=\epsilon_{\mathrm{r}} - i60\sigma\lambda \tag{3}$$

given the incident wave angle Θ and the material properties ϵ_{r} for the relative permittivity and σ for the conductivity. Reflection surfaces have a certain size, shape and material and are located at the ground plane or at the surfaces of the predefined building objects. The properties are drawn from statistical distributions that are derived from measurements. A buildings surface might consist of several different reflecting areas depending on the targeted granularity of the model. In real world scenarios, the facades of buildings are not plain surfaces and exhibit a roughness due to several elements like windows. The sudden changes in the space domain lead to small quick changes in the signal propagation delay and is experienced as phase jumps by the receiver. Therefore, we propose to model phase jumps as statistical distribution for each modeled reflection surface.

D. Point Scatterer

In the real world, objects that are relatively small compared to the wavelength can scatter the signal in certain directions. We propose to model scattering events by point scatterers with defined by a location as well as an opening angle and opening direction from which the scatterer is visible. These properties as well as the scatterer specific scattering loss are drawn from statistical distributions. It might be possible to consider different real world scatterers by a representation with only one statistical distribution for each property, but also different scatterer specific distributions can be used and the distribution of them can be modeled as well. Fig. 2 illustrates this element by cones that are placed at defined positions and heights above the ground plane and the buildings rooftops with certain orientations in 3D.

From measurements the scattering loss SL_{i} for scatterer i can be derived by subtracting the estimated FSPL $A_{\mathrm{FSPL},i}$ from the measured received signal power $L_{\mathrm{RX,i}}$ with

$$SL_{\mathrm{i}}(t) = L_{\mathrm{RX,i}}(t) - A_{\mathrm{FSPL}}(dist_{\mathrm{i}}(t)) \tag{4}$$

E. Diffuse MPCs

Compared to specular multipath components, diffuse MPCs have relatively low power and broad delay distribution. We propose model them by colored noise term that is derived by removing all specular components. But measurements revealed that the specular MPCs are the dominant components of the channel in most cases and therefore the impact on the transmission system might be low. In further studies we will evaluate the necessity of this element.

F. Freespace Pathloss

The freespace pathloss is a function of the signal wavelength λ and the traveled distance. We apply it on every signal path defined by the aforementioned modeled elements by calculating

$$A_{\mathrm{FSPL},i}(dist_{\mathrm{i}}(t)) = 20 \cdot \log 10 \left[\frac{4\pi}{\lambda} dist_{\mathrm{i}}(t)\right] \tag{5}$$

with estimated distances $dist_{\mathrm{i}}$ for the signal paths.

G. Shadowing and Diffraction

We consider shadowing and diffraction effects by the single knife-edge diffraction loss model presented in [8] and calculate the attenuation with

$$A_{\text{KE}}(t) = 20 \cdot \log 10 \Big[0.5\sqrt{[1-R(v)-I(v)]^2+[R(v)-I(v)]^2} \Big] \quad (6)$$

$$v = \sqrt{\frac{2dist_{\text{direct}}(t)}{\lambda}\alpha_1\alpha_2} \quad (7)$$

$$Fres(v) = \frac{1+j}{2}\int_v^{\inf}\exp[\frac{-j\pi t^2}{2}]dt \quad (8)$$

$$R(v) = \Re(Fres(v)) \quad (9)$$

$$I(v) = \Im(Fres(v)) \quad (10)$$

given the direct distance $dist_{\text{direct}}(t)$ between the transmitting and receiving position and the angles α_1 and α_2 between the direct signal path and the pathes between the transmitting and receiving positions and the related edge of the building that is closest to the signal path.

H. Antenna Pattern

All the measurements are influenced by the radiation patterns of the transmitting and receiving antenna. For our measurements, the antennas were mounted closely to the drones and therefore the air-frames affect the known ideal antenna patterns. Thus, we will measure the resulting specific patterns of our equipped drones in an anechoic chamber in the next and consider the influence on the measurement data.

IV. Scenario Description

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 [2]. Table I summarizes the parameters of our measurements. In order to evaluate the proposed channel model, we model one measured scenario and compare the resulting channel parameter with the modeled channel results. For a simple parameterization of the preliminary channel model, we deterministically define the element properties based on the evaluation of the measurement data. This represents one possible realization of the channel model without the need of drawing values from statistical distributions that we will derive in future work.

In the given scenario, shown in fig. 3, the two drones are flying at low altitudes in an urban canyon and are on a collision course around a buildings corner. At the beginning of the scenario, the drones are in nonLOS condition and start to see each other at the end when coming close to the buildings corner. For the parameterization, we first identified the MPCs in the measurements following an approach we presented in previous work [7], [4]. Table II gives an overview of the identified MPCs and the defined model element types. For the given scenario, the ground reflection cannot be directly resolved but a closer investigation reveals that it is superimposed in the LOS component for a certain time interval. In addition we present the model elements for the identified MPCs by their estimated locations in fig. 3 and show the abstract building objects defined by known 3D geometries of the measured environment.

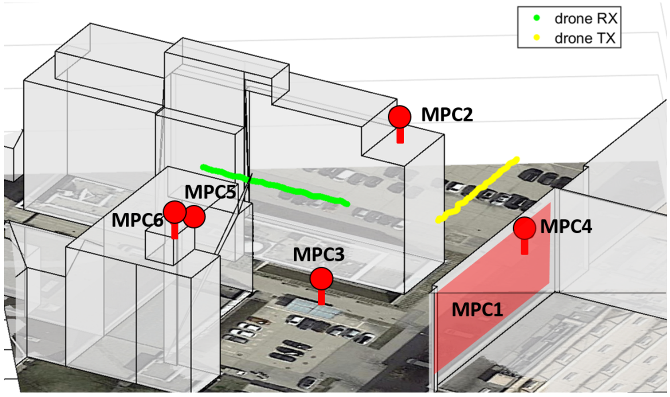


Fig. 3. Overview of the modeled urban D2D scenario with indicated locations of the modeled point scatterers, reflection surfaces and drone trajectories.

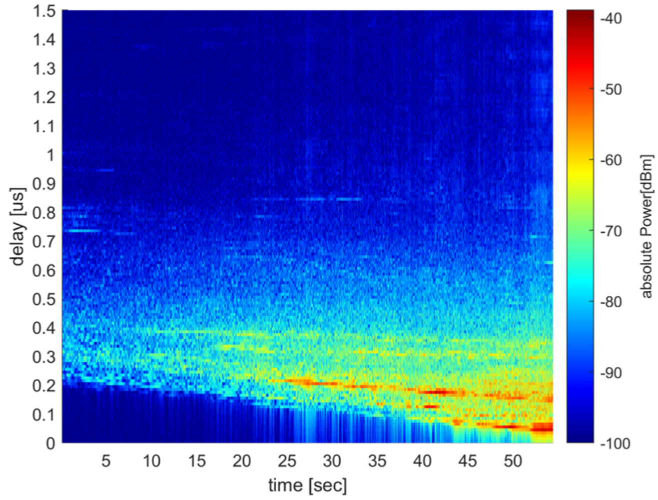
TABLE I
Measurement Parameter

Parameter	Symbol	Value
Center frequency	f_c	5.2 GHz
Bandwidth	B	100 MHz
Tx Power	P_{tx}	30 dBm
Signal duration	T_p	12.8 μs
Signal period	T_g	1.024 ms
Antenna Tx		omni-dir. V-polarized 0 dBi
Antenna Rx		omni-dir. V-polarized 0 dBi
Velocity of drones	V	0.5 $\frac{m}{s}$

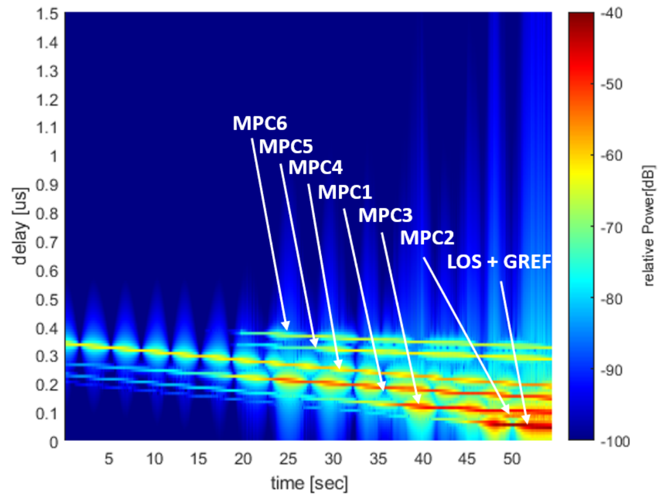
For the modeled elements, we define following properties. The reflection coefficient for the ground reflection **GREF** is calculated with setting the relative permittivity $\epsilon_r = 15$ and the conductivity $\sigma = 0.0005\frac{S}{m}$. We model the whole ground plane as one reflecting horizontal surface with same properties. For the reflection coefficient of the reflecting vertical surface for **MPC1** at the buildings facade we assume the metallic material to be an ideal reflector and set it to $\Gamma = 1$. We model the whole facade as the same reflecting surface. All other building surfaces do not contain any reflecting areas. The remaining point scatterers **MPC2-6** are placed as indicated in fig. 3. We model them to radiate omnidirectionaly with scattering losses set to the mean values obtained from evaluation of the measurement data. We do not model diffuse MPCs and leave this for future work.

TABLE II
Modeled Elements

Name	Source Object	Element Type
LOS	direct path	line-of-sight component
GREF	ground reflection	reflecting surface
MPC1	metallic surface of building	reflecting surface
MPC2	object on rooftop	point scatterer
MPC3	bike station	point scatterer
MPC4	object on rooftop	point scatterer
MPC5	object on rooftop	point scatterer
MPC6	object on rooftop	point scatterer



(a) Measured



(b) Results from channel model

Fig. 4. Channel impulse response for scenario under investigation in logarithmic scale.

V. Results

For a fair comparison between model results and measurements, we consider the effect of the limited bandwidth f_{BW} in our measurements resulting in a sampled circular sinc representation instead of receiving ideal dirac impulses for every data bin. We transform the calculated received power $P_{\mathrm{RX,i}}$ for every modeled element i and snapshot t_0 with

$$P'_{\mathrm{RX,i}}(t_0) = \sum_{\tau}^{\tau_{\max}} \sum_{i}^{N} P_{\mathrm{RX,i}}(t_0) \frac{\operatorname{sinc}(\tau - \tau_i(t_0) f_{\mathrm{BW}})}{\operatorname{sinc}(\frac{\tau - \tau_i(t_0) f_{\mathrm{BW}}}{I})} \tag{11}$$

given the element specific delays τ_i. Figure 4 shows the measured and modeled signal power distributions over delay for the measured time interval of the given scenario. By visual inspection, we can clearly see that the strong specular components of the modeled channel match the measurements quite good. Most of the signal components are shadowed at the beginning and become more and more visible as the drones come closer to each other until being in direct line-of-sight at the end. **MPC4** is stronger and visible for a longer time period for the modeled channel. This results from the fact that we modeled an omnidirectional scatterer but in the measurements we see that this scatterer exhibits a certain opening angle. Overall, the measurements reveal more power variations that we do not consider yet in our model.

VI. Conclusion and Outlook

In this paper we presented a geometrical-statistical architecture to model the D2D communications channel for urban environments and described the modeling of basic elements as well as the necessary steps of the simulation chain. For a preliminary channel model, we applied a relative simple parameterization by incorporating knowledge from one measured urban D2D scenario and defined the model element properties deterministically in order to simulate one possible realization of the channel model. Results show that the model is feasible and can reproduce the dominant signal components and propagation effects from measurements. This D2D channel model be more refined in future by incorporating more detailed knowledge about the element properties and their stochastic distributions.

References

[1] Schalk, Lukas Marcel und Becker, Dennis (2022) DroneCAST – Analysis of Requirements and Discussion of First Design Decisions. 41th AIAA/IEEE Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA.

[2] D. Becker and L. Schalk, "Enabling Air-to-Air Wideband Channel Measurements between Small Unmanned Aerial Vehicles with Optical Fibers," 2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC), San Diego, CA, USA, 2019, pp. 1-7

[3] D. Becker, U. Fiebig and L. Schalk, "Wideband Channel Measurements and First Findings for Low Altitude Drone-to-Drone Links in an Urban Scenario," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5

[4] D. Becker and U.-C. Fiebig, "Measurement Based Identification of MPCs in an Urban Drone-To-Drone Propagation Scenario," presented at the 2022 16th European Conference on Antennas and Propagation (EuCAP), Madrid, 2022.

[5] N. Schneckenburger et al., "Modeling the air-ground multipath channel," in 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, Mar. 2017, pp. 1434–1438. doi: 10.23919/EuCAP.2017.7928222.

[6] P. Unterhuber, "Geometry-Based Stochastic Channel Model for Train-to-Train Communication in Open Field Environment," presented at the 2022 16th European Conference on Antennas and Propagation (EuCAP), 2022.

[7] D. Becker, U.-C. Fiebig, and L. M. Schalk, "Approach for Localizing Scatterers in Urban Drone-to-Drone Propagation Environments," in 2021 15th European Conference on Antennas and Propagation (EuCAP), Dusseldorf, Germany, Mar. 2021, pp. 1–5.

[8] ITU, "RECOMMENDATION ITU-R P.526-15 - Propagation by diffraction," p. 45, 2019.