

# A Deterministic Radio Propagation Model for Inter-Paraglider Communication

Juergen Eckert, David Eckhoff, and Reinhard German  
Dept. of Computer Science, University of Erlangen (FAU), Germany  
{juergen.eckert,david.eckhoff,reinhard.german}@fau.de

**Abstract**—It has been shown that paragliders could considerably benefit from ad-hoc communication, be it for safety or the prolonging of flight times through the exchange of thermal information. The simulation of these so called Flying Ad-Hoc Networks (FANETs) can help evaluate the feasibility and performance of these and other applications inexpensively and at large scale. Their specific communication characteristics, caused by inevitable suboptimal antenna placement and 3D node distribution, require accurate channel and propagation models in order to produce meaningful results in a simulation environment.

We identify two important parameters that heavily influence the Received Signal Strength (RSS), namely the vertical angle between paragliders and their horizontal relative bearing. Based on extensive real life experiments we present a deterministic and computationally inexpensive radio propagation model that is able to reliably predict our measurements. Our work allows the realistic simulation of wireless communication between paragliders.

## I. INTRODUCTION

Paragliding, as can be witnessed in almost every mountainous landscape, is experiencing a continuous rise in popularity. Although it is an individual sport, paragliders are almost never alone in an area but are flying within groups of other pilots, all with the same (oftentimes quite challenging) goal: to find columns of rising air to gain altitude and thus extend their flight times. In earlier work [1] we showed that using wireless communication between pilots is indeed feasible and can be used to not only exchange information about rising air but also for safety applications, such as search and rescue missions after emergency landings. Other possible applications include but are not limited to the transmission of wind information at take-off and landing sites to further increase the safety of this potentially dangerous sport.

These applications and the underlying protocols have to be carefully designed and tested. Unfortunately, field trials with paragliders are time consuming and cost intensive. Additionally, some of the more extreme situations would require putting pilots at risk; however, these may be the exact conditions for which safety protocols are designed. Therefore the simulation of these Flying Ad-Hoc Networks (FANETs) is a good tool to investigate the performance of envisioned applications allowing the exploration of a wide parameter space at low cost.

The challenges of such simulations are manifold: Currently, (GPS) traces seem to be the only possibility to create realistic node movement in a simulator, as there still exist no (openly available) mobility models for paragliders. Furthermore, the wireless channel properties, including bit error rates and radio

propagation can differ greatly from those of well-studied 2D ground sensor networks such as MANETs or VANETs. An antenna attached to the pilot can never be placed in an optimal way, causing a very characteristic radiation pattern (e.g., a flattened torus for half-wave dipole antennas). Also, their alignment is often suboptimal as paragliders are distributed in a large 3D space. When the antenna is placed in front or at the back of a pilot, the signal is sometimes attenuated by one or two bodies when the communication partners are not facing each other.

In this paper, we want to tackle the problem of modeling large and seemingly random variance in path loss. In brief, our contributions are:

- We identify the relative horizontal bearing and vertical angle as important factors in the signal path loss of wireless communication between paragliders.
- Based on extensive field trials we show the magnitude of their impact.
- We extend the state of the art by creating a deterministic radio propagation model that can be used for analytical studies or in simulation.
- To prove its correctness we cross validate it against a large set of measurements and find that it is able to accurately predict them well.

The remainder of this article is structured as follows: In Section II we give a short overview of related work. Section III describes the specific characteristics of radio propagation in FANETs and our approach to identify their impact, followed by an evaluation of our path loss model in Section IV. Section V discusses open points and concludes the paper.

## II. RELATED WORK

Compared to most sensor network research, the field of FANETs is relatively new, hence, there is only little related work on the topic. In their 2013 survey, Bekmezci et al. describe the infrastructure-less communication between unmanned air vehicles to form highly dynamic ad-hoc networks [2]. In manned aviation (e.g., classical gliding), wireless communication is usually considered to help avoid collisions by detecting intersecting flight paths and consecutively warning the pilot [3]. Several other applications, ranging from search and rescue to the exchange of thermal information were presented in [1].

Although several applications and concepts have been described, there is no radio propagation model for these networks to evaluate their performance outside of field tests.

A model purely based on geometry [4] cannot account for the special characteristics of inter-paraglider communication. Creating radio propagation models on empirical studies is a common approach in related research areas. To the best of our knowledge, we are the first to examine the specific characteristics of wireless communication for paragliders.

For example, shadowing can also be modeled using empirical stochastic models such as log-normal shadow fading [5]. The problem with these models is that they model shadowing of individual transmissions as a random process, which may be required when the wireless channel cannot be modeled accurately, for example, when it is too complex or geo-data is missing. For FANETs, however, this is not the case, making the use of a deterministic model such as the one presented in this paper the preferable approach.

An example for a deterministic model based on empirical data was presented by Sommer et al. [6]. They were able to predict the path loss induced by buildings blocking the Line of Sight (LOS) by introducing two parameters to compute the consequential signal attenuation. We use a similar approach to model the communication between paragliders in different situations: based on a large set of measurements we identify two attenuation components that can be worked into other deterministic propagation models such as the free-space path loss model [7].

It has been proposed to empirically determine the path loss exponent for the free-space path loss model to account for suboptimal radio propagation [7] in certain scenarios, for example caused by vegetation or small obstacles blocking the LOS. In a network of paragliders, however, channel conditions seem to be quite optimal, as the LOS is almost never obstructed, leading to the assumption that the default free-space path loss model should accurately predict the signal attenuation. Yet, in earlier work we already found that this is not the case, and that on average our measurements disagreed with the free-space path loss model by approx. 10 dB [1]. We therefore assume that specific properties of paragliders introduce additional signal attenuation. In this paper, we are able to identify these exact properties and create a deterministic propagation model allowing us to obtain accurate results not only on average but also for individual transmissions.

### III. RADIO PROPAGATION IN PARAGLIDER NETWORKS

To investigate the specific characteristics of radio propagation between paragliders we built a test bed and collected roughly 200 000 data points in a series of extensive field trials. The tests were conducted over a course of three weeks at four different locations using up to five pilots.

#### A. Test Setup

The setup for each pilot consisted of a custom built dongle (connected to a Skytraxx variometer) communicating over a Si4463 transceiver chip from Silicon Labs with a transmission power of up to 20 dBm. The half-wave dipole antenna (with a gain of  $G \approx 2$  dBi) [1] was mounted vertically on the harness in front of the pilot. To meet the RF regulations at our test

locations in Argentina the radio equipment was configured for transmission in the 915 MHz band. The physical layer is compatible with the IEEE 802.15.4g-2012 standard [8] (modulation: filtered 2 FSK, binary symbol rate:  $50 \text{ ksymbol s}^{-1}$  and bit rate:  $50 \text{ kbit s}^{-1}$ ). For the medium access layer we used Time Division Multiple Access (TDMA) with pre-assigned time slots for each device to avoid packet collisions on the wireless channel.

#### B. Preliminary Assumptions

For the communication between paragliders we assume that under optimal conditions, that is, when both sender and receiver have a direct LOS link and are flying at the same altitude, the free-space path loss model should predict our measurements quite well.

In this study, we neglect multipath propagation, as the main goal of this paper is to create a deterministic radio propagation model. As we have no exact geo-data of our test locations, we would have to employ a stochastic model. Therefore, the combination of deterministic path loss with fast fading models remains the focus of future work.

In earlier work [1], we found that the free-space path loss model does not fit our measurements well, but was overestimating the Received Signal Strength (RSS). On average, it was possible to capture this effect by adding a constant 10 dB penalty. However, this method is not able to reproduce single measurement points well enough.

In-flight Non Line of Sight (NLOS) situations can occur but are very unlikely due to the usually large altitude above ground of the paragliders. We reviewed the elevation profile of the test site and found that within the three weeks of recorded data only one single situation was identify where the Fresnel zone was clearly intersected by mountains. We therefore conclude that our propagation model does not have to account for NLOS communication to still be sufficiently accurate.

Using the considerably larger set of field experiments we identified the reason for the observed additional attenuation: the 3D alignment of the paragliders. We observed that besides the distance, also the horizontal and vertical angle between them are important factors.

#### C. Horizontal Angle

Assume two paragliders  $p_A$  and  $p_B$  are flying at the same altitude (see Figure 1(a)): Relative to the heading of  $p_A$ ,  $p_B$  has a bearing of  $\alpha_A$  degrees, and vice versa. Depending on these angles, the radio signal may be attenuated by the body of one or two pilots. In this example, (assuming the antenna is mounted in front of the pilots) a signal from  $p_A$  to  $p_B$  is attenuated by the body of  $p_B$  before it is received by the antenna.

As it is irrelevant for the attenuation whether the receiver is positioned left or right of the sender, we normalized this angle to be at most  $180^\circ$ .

We assume that the attenuation introduced by a body is equal for sender and receiver. Thus, both angles are equally weighted and can be summed up to the relative horizontal

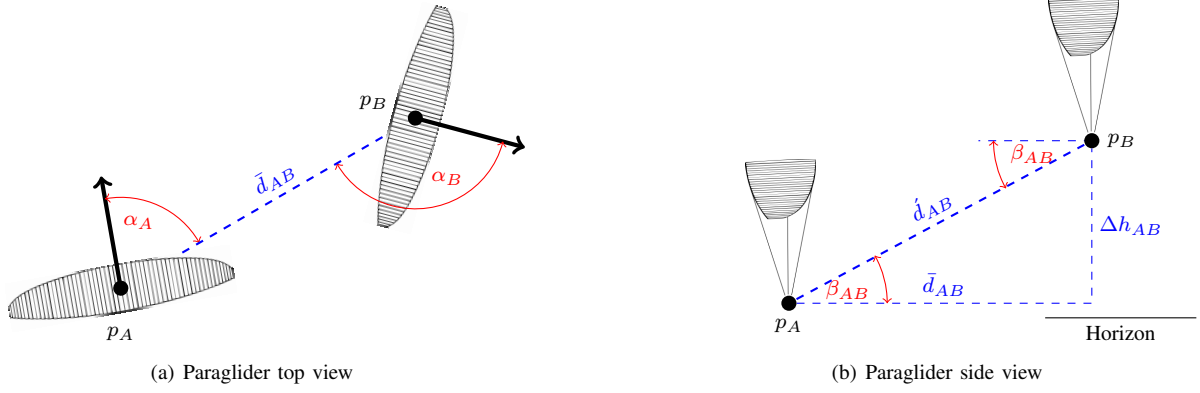


Fig. 1. Paraglider alignment

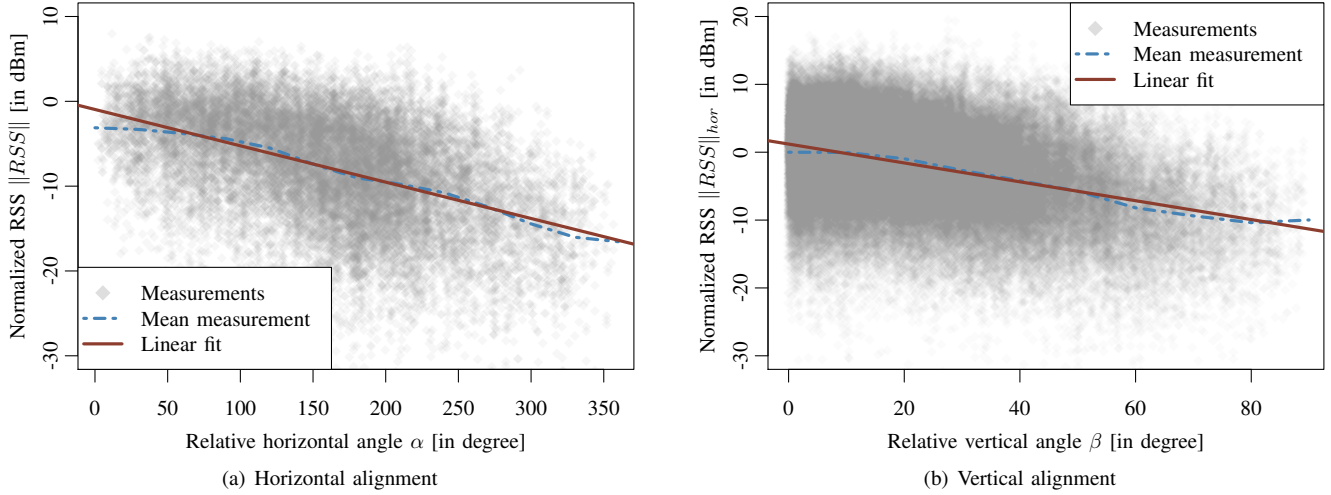


Fig. 2. Alignment effects

angle  $\alpha_{AB} = \alpha_A + \alpha_B$ . This angle defines whether the pilots are flying toward each other  $\alpha_{AB} = 0^\circ$  (i.e. LOS) or whether the pilots are flying away from each other  $\alpha_{AB} = 360^\circ$  (i.e., maximal attenuation).

To fully understand the impact of this effect, we isolated all data points where the flight levels of sender and receiver were similar ( $\beta_{AB} \leq 5^\circ$ , cf. Figure 1(b)), as follows: The RSS was normalized using the signal loss over the distances  $\bar{d}_{AB}$  (see Equation (5)) and the transmission power  $P_t$ :

$$\|RSS\|[\text{dBm}] = RSS + L_{fs}(\bar{d}_{AB}) - P_t \quad (1)$$

Figure 2(a) shows our findings: the signal strength decreases nearly linearly with  $\alpha_{AB}$  and can therefore be fitted with only one coefficient  $\kappa$ . The absolute value of  $\kappa$ , which was  $-0.04283 \text{ dB}/^\circ$  for our setup, is depending on the actual antenna placement and used frequency.

#### D. Vertical Angle

The second factor, the vertical angle  $\beta_{AB}$  between the pilots, is depicted in Figure 1(b). Because the used antennas are omnidirectional but not isotropic, the power level is substantially depending on the vertical angle between sender

and receiver. Not only is the given antenna gain only correct if sender and receiver are at the same flight level, but also does the overall RSS rapidly decrease with an increasing  $\beta_{AB}$  between the paragliders.

Figure 2(b) shows the normalized RSS using the already found coefficient  $\kappa$  to account for the horizontal angle ( $\alpha_{AB}$ ):

$$\|RSS\|_{hor}[\text{dBm}] = \|RSS\| + (-\kappa \cdot \alpha_{AB}) \quad (2)$$

Again, for symmetry reasons of the vertical radiation pattern we only consider half of the value range:

$$\beta_{AB} = \left| \tan^{-1} \left( \frac{\Delta h_{AB}}{\bar{d}_{AB}} \right) \right|; \beta_{AB} \in [0^\circ, 90^\circ) \quad (3)$$

It shows that the attenuation also increases nearly linearly with the absolute vertical angle  $\beta_{AB}$ . We therefore introduce a second coefficient  $\zeta$  which when set to  $-0.1391 \text{ dB}/^\circ$ , fits our measurements very well. This parameter also models the directionality of antenna gains  $G_t$  and  $G_r$  of the used sender and receiver antennas, respectively.

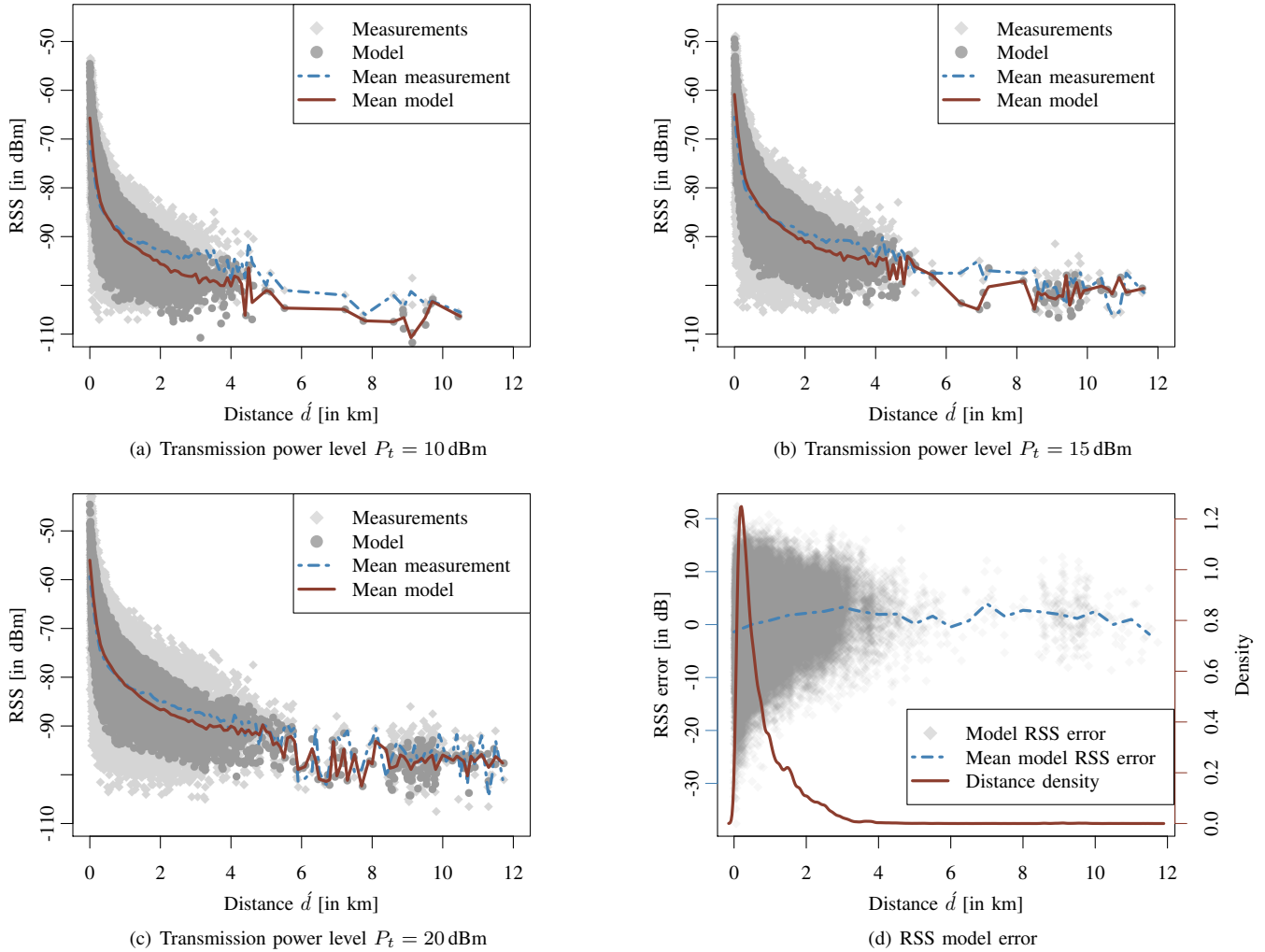


Fig. 3. Comparison between real life measurements and our radio propagation model

### E. The Final Model

The overall model for computing the receiving power  $P_{B,r}$  of a paraglider  $p_B$  for a packet emitted by another paraglider  $p_A$  using the transmission power  $P_{A,t}$  can be summarized as follows:

$$P_{B,r}[\text{dBm}] = P_{A,t} - L_{fs}(\hat{d}_{AB}) - L_{hor}(\alpha_{AB}) - L_{vert}(\beta_{AB}) \quad (4)$$

Where  $\hat{d}_{AB}$  is the 3D distance (not the horizontal distance  $\bar{d}_{AB}$ ) between the paragliders.

The presented path loss model uses three different attenuation components, namely the commonly known free-space path loss attenuation  $L_{fs}$ , as well as the introduced horizontal  $L_{hor}$  and vertical  $L_{vert}$  attenuation components, defined as:

$$L_{fs}(d)[\text{dB}] = 10 \log_{10} \left( \frac{16\pi^2 d^2}{\lambda^2} \right) \quad (5)$$

$$L_{hor}(\alpha)[\text{dB}] = -\kappa \cdot \alpha \quad (6)$$

$$L_{vert}(\beta)[\text{dB}] = -\zeta \cdot \beta \quad (7)$$

*Nota bene:*

The used linear regression technique generates two coefficients for each fit: a slope (here:  $\kappa$  or  $\zeta$ ) and an offset. As the offsets of the horizontal and vertical approximation were very small and canceled each other we omitted them in the model for simplicity reasons.

In the following we will evaluate the overall performance of our radio propagation model by cross validating it against a large set of measurements.

## IV. EVALUATION

Figures 3(a) to 3(c) shows the performance of our radio propagation model for different transmission power levels  $P_t$ . Each light gray point represents one real transmission in our experiments and may include any horizontal and vertical angle between the paragliders. For our evaluation we tried to reproduce these measurements with our propagation model by using the 3D positions and heading (and therefore the angles)

of the gliders. It can easily be seen that the co-domain of our model lies within the co-domain of the real measurements and that the variance in RSS is indeed caused by different alignment of the communication paragliders. The mean of our model is in agreement with the mean of the real measurements.

At lower distances (see also Figure 3(d)) we observe that the variance in the measurements is slightly bigger than the one generated with our model. The reason for that is that these measurements are more likely to have been recorded near the take-off and landing sites, and that therefore multipath propagation has a stronger impact on the signal as the paragliders are closer to the ground. To capture these effects, the deployment of fast-fading models such as Ricean [9] or Nakagami-m [10] needs to be investigated. However, this is out of scope of this paper.

For distance  $\hat{d}_{AB} > 4$  km not enough measurements were available to produce a stable mean. It can be seen that even under these conditions the theoretical mean follows the measured mean without significant outliers, giving strong evidence that our model is able to accurately reproduce the RSS for single transmissions.

At values close to the receiving threshold of the used radio chip  $P_{r,min} = -106$  dBm the plotted mean for the measurements overestimates the *real* mean, because we were only able to record the RSS for successfully received packets. Due to a high portion of lost packets at larger distances, it is likely that our propagation model is actually more accurate than the figures suggest. Another reason for the underestimation is that the actual transmission power of the antenna likely slightly differed from the configured one.

Figure 3(d) shows the difference, that is, the error (gray points) between the measured RSS and the computed RSS using our radio propagation model. The mean estimation error for distances greater than 1 km indicates that our model slightly underestimates the true readings, possibly caused by multipath propagation. The red density curve shows the distribution of sender and receiver distances in our collected data, explaining a less stable mean for greater distances. It can be seen that the mean modeling error is very small for all distances, showing the correctness of our model.

#### A. Portability

In previous work [1] we used an entirely different hardware setup, a slightly different frequency and different test locations. We proposed to add a constant penalty of  $L_{penalty} = 10$  dB to the free-space path loss model.

In this paper, the mean of all recorded horizontal and vertical angles is  $\bar{\alpha} = 168.3^\circ$  and  $\bar{\beta} = 22.0^\circ$ , respectively. Multiplying these values with the corresponding compensation factors ( $\kappa$  and  $\zeta$ ) results in an average loss of  $\bar{L}_{hor+vert} = 10.3$  dB.

The fact that our model is able to almost exactly explain the results of our previous experiments further suggests its correctness and its ability to accurately predict the impact of different paraglider alignment on the RSS.

## V. CONCLUSION AND FUTURE WORK

In this paper, we presented a deterministic radio propagation model for the communication between paragliders to form a so-called FANET. Based on a large set of field experiments, we identified two important components that influence the signal: the horizontal and vertical angles between the pilots. Both effects can be fitted linearly, allowing the deployment of a computationally efficient and intuitive radio propagation model. We showed that this model is able to accurately reproduce real-life measurements making it ideal for the use in analytical studies and in simulation environments.

Some challenges, however, remain: Fast fading cannot be ignored as the signal is not only reflected by the ground but also by the usually present mountains at paragliding sites. To avoid the use of complex ray tracing models, a non-deterministic fast-fading component should extend our deterministic model to capture these effects. Lastly, specific bit error models for the utilized radio hardware and modulation need to be employed to realistically model the wireless channel and precisely evaluate FANET applications and protocols.

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