Flying Ad-Hoc Network Communication for Detecting Thermals: Feasibility and Insights

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—**Foot-launched gliders rely on thermal columns in order to stay in the air. Unfortunately, it can be a very difficult task for a pilot to find these invisible thermals as accurate off-line computation and prediction of air flows is nearly impossible. We therefore propose to wirelessly interconnect hang and paragliders to form a Flying Ad-Hoc Network (FANET). This network enables pilots to collect and exchange live air flow information based on measured vertical climbing rates. Furthermore, we also show how Search and Rescue (SAR) missions can benefit from this technology.**

In this paper we prove the feasibility of our approach by conducting extensive real life experiments using custom built low-cost hardware. We discuss simulation techniques to efficiently evaluate other FANET applications by modeling the physical channel with its specific characteristics. We identify open challenges and show possible ways to address them in order to deploy an innovative network that could permanently change the sport of gliding.

I. INTRODUCTION

From impromptu wings in the 11th century [1], to Lilienthal's pioneering work in the late 1890s [2], up to the last commercially (military) used glider in WWII [3], gliding has always been an important part of human aviation. Revolutionized in 1948 by NASA engineer Francis Melvin Rogallo's ground breaking idea to utilize strings and fabric to form (semi-) flexible wings [4], it took over 20 years until production of first generation hang gliders started. Today, paragliders have superseded hang gliders in terms of popularity and both can be observed in vast numbers in popular thermal soaring areas (see Figure 1).

All gliding aircrafts need thermals, that is bubbles or columns of rising air, to gain altitude. However, it is an almost impossible task to predict when and where thermal columns develop and a lot of flying experience (or even luck) is needed to successfully find a so-called *lift* [5]. Variometers assist gliders in doing so by continuously measuring air pressure to display the current vertical velocity. This information, however, valuable for all surrounding pilots remains local and is at best shared by observing other gliders. Visually monitoring the relative variation of vertical speeds of a huge set of nearby pilots while controlling an aircraft requires a lot of flying skills. Even off-board thermal simulation utilizing a massive amount of background knowledge and weather information has been shown to only have limited success rates [6]. The fact that at a specific 3D position thermal characteristics can substantially change within minutes further contributes to the necessity of timely exchange of up-to-date information.

Fig. 1. Common sight in popular thermal soaring areas: Numerous paragliders flying in close proximity in relatively small space (Tolmin, Slovenia)

We therefore propose the exchange and aggregation of air flow information over a Flying Ad-Hoc Network (FANET) by equipping GPS-enabled variometers with radio technology. This enables pilots to obtain a better overall view of thermals in the area and allows to prolong flight times by disseminating information about rising and falling parcels of air.

From a scientific point of view this task is very challenging:

- All nodes are continuously moving in 3D at high relative speeds (up to $100\,\mathrm{km\,h^{-1}}$ for paragliders and up to $180\,\mathrm{km\,h^{-1}}$ for hang gliders).
- There is a great variance in the inter-aircraft distances ranging from a few meters up to a few kilometers.
- Resources such as energy, computational time and power, and memory are not limitlessly available. An application therefore has to take these constraints into account.

In this paper we examine the feasibility of exchanging thermal information over a highly mobile ad-hoc network. This technology could substantially change the sport of gliding. To the best of our knowledge, we are the first to investigate equipping foot-launched gliders with transceivers to enable inter-glider communication. Additionally, we show that FANETs can be also used for safety applications, e.g., in Search and Rescue (SAR) scenarios. We also discuss possibilities and challenges in order to efficiently evaluate other FANET applications in simulation. Lastly, we identify open challenges that need to be addressed to realize such a system.

II. RELATED WORK

The term FANET was coined by Bekmezci *et al.* in their 2013 survey on flying ad-hoc networks [7]. They consider these highly dynamic networks for infrastructure-less information exchange among autonomous operating multi Unmanned Air Vehicle (UAV) scenarios. In manned aviation, however, there is usually no direct air-to-air communication other than collision avoidance systems. For obvious safety and robustness reasons most communication is handled by reliable infrastructure on the ground. In this paper, we propose to combine both paradigms to enable a hybrid multi-hop network to enable innovative applications such as thermal detection or SAR assistance.

The most popular air-to-air flight communication system for hobby and sports pilots is provided by FLARM Technology GmbH, Switzerland. FLARM is designed as a low-cost collision warning system for classical gliders [8] by exchanging the required proximity data using single hop communication. Since 2004 the system has spread out into all sectors of general aviation and recreational flying, including hang and paragliding. For classical gliders and motorized aircrafts to avoid collision with light-weight foot-launched aircrafts, the latter are equipped with passive systems that emit the position of the glider but do not report any crossing flight paths to the hang or paragliding pilot. Active collision avoidance between foot-launched aircrafts is only of minor interest, as speeds are slower and visibility is usually very good.

Cumulus Humilis [9] is an opportunistic dissemination protocol for information exchange between classical gliders. Gliders, in contrast to hang and paragliders, are much more sparsely distributed, and have lighter constraints in terms of weight and energy consumption of the equipped radio. Baardman and Nirvana assumed in their simulative approach a bridgeable distance of up to 40 km, however, they have not conducted a conclusive real life experiment. We aim for a much smaller scale where thermals shall not only be detected but constantly measured using multiple 3D positions. We show the applicability of our approach by carrying out real test flights.

Advanced Sports Instruments Sarl (Switzerland) recently introduced *FlyNet 2*. The web-based services utilizes cellular networks to provide live tracking information of the pilots. Trajectories of nearby aircrafts, including their climb rate, can be acquired from this service using the same communication channel. However, paragliding is usually exerted in fairly unpopulated areas where cellular coverage might be low or not present at all. Additionally, european pilots are often not flying in their home country, requiring them to pay for cellular data roaming.

SPOT, a general web-based live tracking system built by Globalstar Europe Satellite Services Ltd., circumvents these regional cost by using a satellite up-link instead of a cellular network. It has been shown that the stability of this open-sky up-link is indeed robust enough [10]. However, the low update frequency of 10 min and high communication costs are clear downsides of this system.

Regional Atmospheric Modeling Systems (RAMSs) can be used to produce meteorological prediction maps for thermal soaring [11]. In addition to an exact local map, simulations require numerous atmospheric parameters and a large amount of computing power, requiring them to be conducted offline. Resulting high accuracy forecasts still have a geometric unsharpness of several kilometers, and are thus only valuable to performance Cross-Country (XC) pilots to help choose a flight path. However, hang and paragliders have a much lower Lift-to-Drag (L/D) ratio and therefore require a considerably more detailed forecast.

In contrast to existing approaches, we believe that locally measured thermal information is only of interest in a very limited area and does not need to be transfered to a server. In general, infrastructure (and the associated installing and preparation) is not necessarily required as computation, distribution and storing can be completely carried out in a decentralized way. A FANET can therefore be established on any thermal soaring side in the world.

III. FANET APPLICATIONS FOR GLIDERS

The main idea presented in this paper is the exchange of thermal information between foot-launched gliders such as hang or paragliders via inter-aircraft communication. The used network technology, however, enables various applications for gliders. In this section we will discuss three of them.

A. *Finding Thermals*

Most air flows are not constant in terms of vertical velocity; many have a certain time period were up- and down-winds are changing, others are completely random. Additionally, the power of the lift strongly depends on the position of the glider within the thermal column, while not only the vertical position is important but also the horizontal shift, as thermal columns are usually not fully upright.

Prior to take-off a pilot needs to memorize well-known lift areas. The main sources of information are other local pilots or air images containing manually drawn clues of usual thermal locations. Once airborne, the pilot can utilize three indicators to find a lift. Dependent on the density of gliders in the surrounding airspace, observing others can give valuable information on where air is rising or falling. Furthermore, geographic clues on the ground, such as rocks or grain fields, can give hints where thermal columns can be expected. However, the variometer is the only reliable device, as it measures the current vertical velocity at the current position of the aircraft. Air flows around and nearby the aircraft (be it up or down winds) can not be displayed and require the experience of the pilot to be estimated.

We propose that all aircrafts exchange their vertical velocity and their position among themselves. The variometer could then combine all this information to generate a complex knowledge-base of the current ambient air flow.

Communication between gliders can enable all variometers to form a distributed four-dimensional (4D) database (three-dimensional (3D) flow velocities over time) of the monitored air space. Based on the current 3D position of a glider, the variometer can then display approachable areas of currently rising air.

Moreover, having strong indicators for future thermals (based on the history of pulsing lifts), some kind of *turn-by-turn* navigation can be provided. This technology would significantly simplify the gliding sport.

B. Search and Rescue (SAR)

In emergencies, such as an unrecoverable stall or wing deformation, the pilot can pull a rescue parachute in order to avoid an unbraked fall. Nevertheless, this uncontrollable descent is much faster than a normal landing ($v_{vertical} \approx 5\,\mathrm{m\,s^{-1}}$) and can end up in rough terrain leading to injury or unconsciousness. The pilot may then not be able to call for help.

The likelihood for such accidents is much higher in sparsely populated mountain areas than in the lowlands, due to more extreme weather conditions and a smaller altitude reserve (time to regain control over the wing). Unfortunately, in these areas cellular networks for emergency calls are not always available. Another big issue is visibility, as hang and paragliders tend to get stuck just few meters below treetops, leaving nearly no visible clue of the accident from above. Oftentimes SAR missions continue until sunset because no exact position of the crashed pilot is known.

The technology presented in this paper is able to solve all these problems. Based on velocity variations over time (Global-Positioning-System (GPS) and barometer) the variometer is able to automatically detect such extreme situations. Inter-aircraft communication would then allow the variometer to automatically send periodic emergency messages to other pilots in the area. Other radio equipped aircrafts can receive and (store, carry and) forward [12] this information to a call center at the regular landing site, or, if non-existent, initiate other necessary actions to start a SAR mission.

Should a helicopter be required (which often is the case), this technology furthermore allows to autonomously generate an air corridor for the rescue operation by recommending all other pilots to leave this area in order to not endanger or prolong the salvage.

C. Starting and Landing

Starting sites for foot-launched gliders are oftentimes located on the top of a mountain requiring transport or a gondola to be reached. Information whether take-off is possible or not can only be obtained on-site. It is therefore desirable to inform pilots of the situation beforehand to avoid unnecessary trips to the starting site.

Landing sites, usually located in valleys in the mountains, tend to get very stormy and turbulent. If a pilot had exact information about the wind situation in the touch-down area, the risk of a bad landing could be considerably decreased.

When our FANET concept is extended by auxiliary Base stations (BSs) at starting and landing sites, both of these problems can be solved. BSs could periodically broadcast the current wind situation, giving pilots on the ground valuable information about a possible take-off without the need to be on-site. Pilots approaching for a landing could have winds displayed on their display in real time and thus be assisted in choosing the right landing spot and planning a proper approach minutes before the windsock is visible.

(a) Dongle with 100 mm antenna

(b) Mounting point of experimental radio equipment

Fig. 2. Measuring hardware

IV. FEASIBILITY STUDY

In order to gain valuable insights on the feasibility of our proposed application and inter-glider communication in general, we conducted real life experiments at the Monte Grappa Airpark near Bassano del Grappa, Italy. Our goal was not only to give a proof-of-concept but also to collect data to create models for simulation to allow for easier performance evaluation of FANET applications.

A. Experimental Setup

We equipped four pilots with a custom built dongle Figure 2(a) and a mobile phone for logging purposes. The dongle, consisting of a Bluetooth module and an antenna port, is attached to the rises (mounting point between wing and harness) of a paraglider (see Figure 2(b)). The long range radio link is realized using a *XBee-PRO 868 RF* transceiver module from Digi International and offers a transmission power of 1 mW to 316 mW (0 dBm to 25 dBm) on the *G3* frequency band (869.4 MHz to 869.65 MHz).

However, the European Conference of Postal and Telecommunications Administrations (CEPT) only allows high transmission powers of up to 500 mW effective radiated power (ERP) on a very narrow frequency band. We therefore chose to significantly reduce the transmission power to $P_{\text{tx}} \leq 25\,\mathrm{mW}$

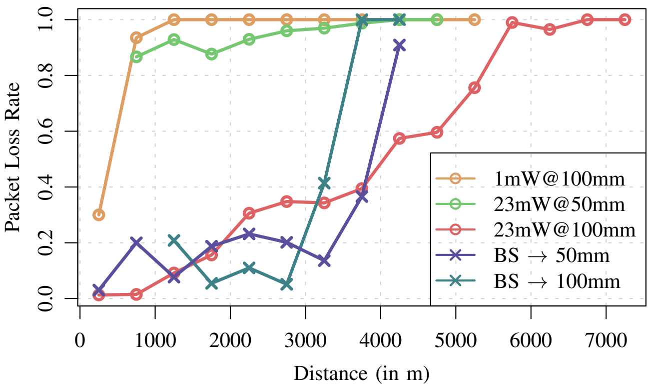


Fig. 3. Packet loss rate for various configurations.

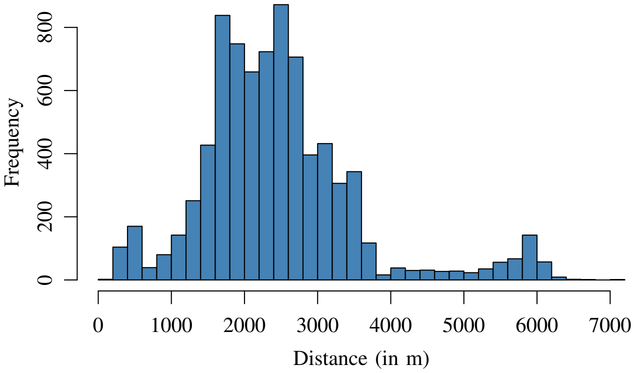


Fig. 4. Maximal link length of Weighted Minimal Spanning Tree (w/o BS)

ERP to utilize a much wider spectrum [13] and lower the chance of possible interference. In this low power range, the *XBee-PRO 868 RF* supports two power levels: 1 mW (0 dBm) and 23 mW (13.7 dBm). The receiving sensitivity of the radio is considered to be -112 dBm, the overall data rate on the medium is 24 kbit s^{-1}.

We tested three kinds of antennas with different lengths (50 mm, 100 mm and 350 mm). The 50 mm and 100 mm were used for glider-to-glider communication, the 350 mm antenna was mounted on a car at the landing site, serving as a BS at a constant transmit power level of 23 mW.

As channel access mechanism we used Time Division Multiple Access (TDMA) and statically assigned a time slot to each device to avoid packet collisions on the wireless channel. Dynamic slot assignment will be the focus of future work.

B. Experimental Results

During the days of the experiment the cloud base of the minor thermal activities was below 1250 m Mean Sea Level (MSL) and the ground-level of the overflight area was in the range of 200 m to 1000 m MSL. The pilots flew within a cylinder of 6 km radius and (due to the low cloud base) were forced to fly very close to the hillsides, resulting in a challenging scenario for radio communication as obstacles frequently intersected the fresnel zones.

In a first step we examined the packet loss rate of direct (single hop) communication over the sender-receiver distance for different configurations. Figure 3 shows our results for glider-to-glider (*transmission power@antennas length*; same antennas for receiving and transmitting pilots) as well for BS-to-glider (23 mW→*antenna length of pilots*) communication. Air-to-ground traffic is currently out-of-scope as we assume that a BS only reports the current wind situation to the pilots. For ease of interpretation, the configuration 1 mW@50 mm is omitted as it looks very similar to the results for the 100 mm antennas. As expected, a transmission power of 1 mW was not sufficient to bridge distances over 1 km. Surprisingly, using 23 mW with a 50 mm antenna does not significantly boost the transmission range. When compared with the performance of a 100 mm antenna the situation substantially improves, clearly motivating the use of the bigger antenna. We were able to bridge distances of more than 5 km with single-hop communication.

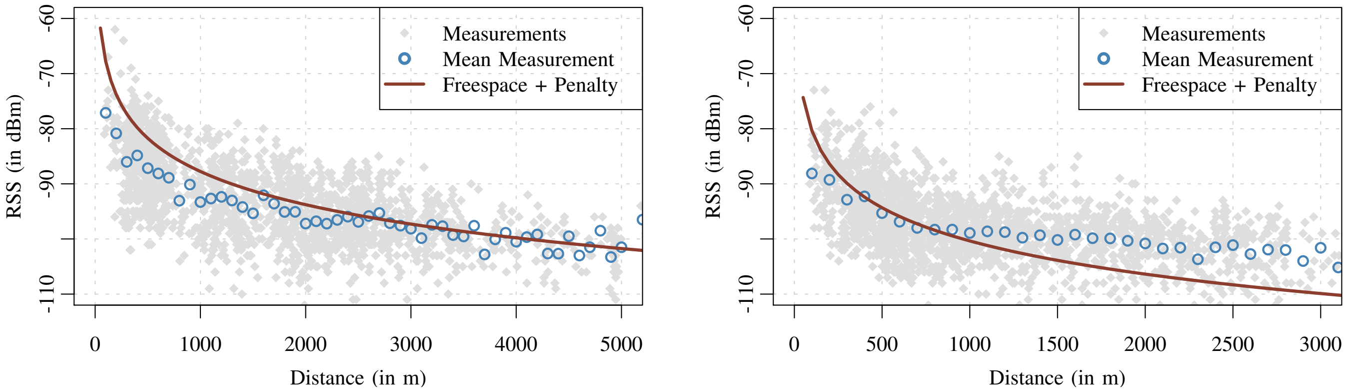
The curves for the ground-to-air communication (involving the BS with its 350 mm antenna) do not show this difference in antenna performance, showing that this issue is mainly caused by the transmitting antenna. The considerable increase of packet loss at distances of 3 km and higher is area specific as the pilots lost Line of Sight (LOS) to the BS.

The necessary communication range is heavily dependent on the use case, as different kinds of gliders cover differing distances. Dependent on the altitude reserves, a pilot is usually interested about thermals in a radius of 3 km. With the right antenna, our system was easily able to cover this area, proving the applicability of our idea.

In a second step we investigated the maximum link distance in a fully connected network/graph within the experiment in order to estimate the required maximum transmission power. This gives us valuable insights on the possible deployment of energy aware access schemes and also helps eventually scale a sophisticated device. Figure 4 shows a histogram for this maximum link distance which is considered to be the link requiring the highest transmission power. It can be seen that in most cases ($> 75\,\%$) a transmission range of 3 km would have been sufficient to maintain a fully connected network. However, this value is heavily dependent on weather conditions, flying area spread and the amount of pilots. During our experiment with only four paragliders we observed over 70 flying pilots in the area. Distance (and thus required transmission powers and battery drain) would have been considerably lower if as little as 10 % of them were equipped with radio modules. These results show that in our sparse density scenario a transmission power of 23 mW would have been enough to establish a fully connected graph to enable multi-hop communication.

V. FANETs IN SIMULATION

Performance evaluation of FANET applications is a non-trivial task as complex mobility patterns and channel characteristics make it difficult to use analytic models. Real life experiments can give valuable insights, however, the number



(a) Transmit Power: 23mW

(b) Transmit Power: 1mW

Fig. 5. Mean Measurements could be fitted well by the freespace model when adding a static 10 dBm penalty for antenna displacement

of scenarios that can be investigated is limited by cost and time constraints. Therefore, as for many other MANET applications, simulation is a suitable tool to measure the performance of network communication among hang gliders.

A. Mobility

Mobility of gliders is obviously heavily influenced by thermal lifts or moving air in general. We therefore suspect pure random movement models to lead to unrealistic results, however, to the best of our knowledge there is no freely available model to simulate the mobility of groups of hang or paragliders. For such a tool to be of use it would need to support an interface to bidirectionally communicate with a network simulator in order to influence network communication by mobility and vice versa. Until such a tool is available flight traces seem to be the only method to represent the mobility of paragliders in simulation, although the problem of not being able to influence glider movement during the simulation remains.

B. Network communication

Network communication in FANETs can be investigated by the use of open network simulators such as ns-3 or OMNeT++. Available models for these simulators already include measures for interference calculation and different signal propagation models to compute the path loss of the signal. However, as communication between paragliders is a very new field, we investigated which propagation model would fit our real life measurements best.

A common approach is the use of the *Free-space path loss* model (Equation 1) that estimates attenuation only based on sender-receiver distance d and the wavelength λ.

$$L_{\text{freespace}}[\text{dB}] = 20 \log_{10}\left(4\pi \frac{d}{\lambda}\right) \tag{1}$$

However, Received Signal Strength (RSS) computed with the Free-space path loss model was considerably higher than what we measured in our real life experiment. We conclude that this is caused by antenna placement and directivity. Due to fast and unpredictable movements of the pilot the antenna was often covered by parts of the body or oriented suboptimally. We therefore propose an empirically derived static penalty $L_{\text{penalty}}[\text{dB}] = 10\text{dB}$ to account for this. This results in a computation of the RSS based on the transmit power P_{tx}:

$$RSS = P_{\text{tx}} - L_{\text{freespace}} - L_{\text{penalty}} \tag{2}$$

Figure 5 shows our results for test runs with values for P_{tx} of 23 mW and 1 mW (13.7 dBm and 0 dBm, respectively). As can be seen our model fits the 23 mW measurements quite well, while slightly overestimating RSS for close range communication. For the 1 mW experiment, our model still fits satisfactory, though underestimating the receiving power for distances larger than 1 km. This could be an indicator for multi-path signal propagation, however, such models are complex to calculate as they not only require a lot of computing power but also exact elevation data of nearby territory. Simplifications of these models, such as the two-Ray ground model are only applicable if such elevation data is available. The figures also show that measurements were quite noisy and unstable, likely also caused by antenna orientation and directivity. We believe that adding a noise model that follows a certain distribution, such as a log-normal distribution [14], could be able to capture this effect. More real life experiments are needed in order to present reliable results.

In simulation, determining whether a packet can be successfully decoded is usually done by the use of a bit error model. For Binary Phase-Shift Keying (BPSK), the Bit Error Rate (BER) can be computed as $\text{BER} = 1/2 \cdot \text{erfc}(\sqrt{SNR})$, resulting in a packet error probability $p = 1 - (1 - \text{BER})^n$ with n being the length of the packet in bits. This model agreed with our measurements to a certain extent, though more measurements are needed to present a fully accurate bit error and noise model for the used channel.

VI. OPEN CHALLENGES

The devices used in this paper were custom built prototypes. A real world use would require optimization in terms of size, weight, cost and integration with existing variometers. This is challenging as variometers are light-weight devices which typically lie in the range of 100 g to 300 g. Only low-cost and easy-to-incorporate hardware can be used in order to remain attractive for the fairly small market demand.

Extending these devices with radio equipment is not only challenging in terms of size and weight but especially in energy consumption. Despite their very limited capacity (less than 10 W h), variometers need to be fully operational for several hours (typically 20 h to 50 h). It needs to be carefully investigated how much and over what time period data between gliders can be exchanged without critically draining the battery of the variometer. We propose operation in the 868 MHz frequency band for Europe (915 MHz for America) as it offers a good balance between the two primary constraints, energy consumption and communication range.

Prolonging the battery life of the node by carefully selection transmission times and channel access mechanisms is a crucial task [15]. It needs to be investigated how current energy aware MAC layer schemes for Mobile Ad-hoc Networks (MANETs) perform in the context of FANETs with respect to currently available low-cost hardware [16]. GPS synchronization among nodes offers great potential for MAC tuning to save power [17].

Once information is collected by the communication device it has to be analyzed and eventually transferred to the pilot. However, variometers have only limited amount of computation and memory resources. Data aggregation and analysis has to be tested on these devices, and lastly, a simple, yet effective visualization has to be created in order to assist the pilot in finding thermal columns.

When simulating the lower layers of a FANETs consisting of hang and paragliders wide spread path loss and fading models are possibly not accurate enough. Antennas cannot be placed optimally and the effects of constant variation in altitude between sender and receiver combined with specific antenna characteristics is complex to capture in a simulation model. Furthermore, the bodies of pilots will always attenuate the radio signal in some directions. A careful study is required to conclude which fading and path loss models are suitable (or extendable) to capture all these effects.

Lastly, mobility models are required to simulate networks of gliders to also observe effects introduced by applications like the one presented in this paper. Network communication influences the mobility as pilots are given information where thermal columns can be found. This, however, influences the network topology, resulting in a closed-loop system.

VII. CONCLUSION AND FUTURE WORK

In this paper we proposed the deployment of a Flying Ad-Hoc Network (FANET) using foot-launched gliders. This does not only enable applications such as the measuring and exchange of air flow information (with currently unreached accuracy) among pilots but can also help support SAR missions in sparsely populated areas. Low proximities and a high number of pilots in good thermal soaring areas offer a promising basis to establish an ad-hoc network.

Based on real life experiments we proved the feasibility of our proposal in the 868 MHz band, using 100 mm antennas at transmission powers of only 23 mW. This setup enabled us to cover distances of over 5 km

For simulations, the free-space path loss model subtracting a penalty of 10 dB can be used, but should be extended using a fast-fading model or random distributions to account for suboptimal antenna placement.

Future work includes addressing discussed open challenges and finding a suitable network stack for exchanging and processing data.

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REFERENCES

[1] L. White, “Eilmer of Malmesbury, an Eleventh Century Aviator: A Case Study of Technological Innovation, Its Context and Tradition,” *Technology and Culture*, vol. 2, no. 2, pp. 97–111, April 1961.

[2] O. Lilienthal, *Birdflight as the Basis of Aviation*. Longmans Green, 1911.

[3] A. Wood, *History of the World’s Glider Forces*. Patrick Stephens, November 1990.

[4] F. M. Rogallo, “Flexible Kite,” 1951, US Patent 2,546,078.

[5] S. Kawa, *Sky Full of Heat: Passion, Knowledge, Experience*. CreateSpace Independent Publishing Platform, December 2012.

[6] L. Haas, “Lowland Thermal Moods [Thermiklaunen im Flachland],” *DHV-Info*, vol. 180, no. 1, pp. 28–30, March 2013.

[7] I. Bekmezcia, O. K. Sahingoza, and S. Temel, “Flying Ad-Hoc Networks (FANETs): A survey,” *Ad Hoc Networks*, vol. 11, no. 3, pp. 1254–1270, May 2013.

[8] T. Baumgartner and U. Maeder, “Trajectory Prediction for Low-cost Collision Avoidance Systems,” in *IEEE/AIAA 28th Digital Avionics Systems Conference (DASC)*, Orlando, FL, October 2009, pp. 1.C.5–1–1.C.5–8.

[9] R. Baardman and N. Meratnia, “Cumulus Humilis: Wireless Mesh Networking for Gliders,” *Technical Soaring: An International Journal*, vol. 35, no. 1, pp. 16–22, January 2011.

[10] A. Sarwar, B. Li, and A. Dempster, “SPOT in Location Based Emergency Services, LBES Detailed Analysis,” in *International Global Navigation Satellite Systems Society Symposium (IGNSS)*, Qld, Australia, December 2009, pp. 1–15.

[11] E. Hindman, S. M. Saleeby, O. Liechti, and W. R. Cotton, “A Meteorological System for Planning and Analyzing Soaring Flights in Colorado USA,” *Technical Soaring: An International Journal*, vol. 31, no. 3, pp. 68–82, July 2007.

[12] M. Riordan and D. Grigoras, “Data Mule Service for Mobile Ad-Hoc Networks,” in *11th International Symposium on Parallel and Distributed Computing (ISPDC)*, Munich, Germany, June 2012, pp. 227–234.

[13] “European Research Council 70-03: Relating to the use of Short Range Devices (SRD),” European Conference of Postal and Telecommunications Administrations (CEPT), ERC Recommendation, October 2012.

[14] F. Hansen and F. Meno, “Mobile fading – Rayleigh and Lognormal Superimposed,” *Vehicular Technology, IEEE Transactions on*, vol. 26, no. 4, pp. 332–335, November 1977.

[15] I. Dietrich and F. Dressler, “On the Lifetime of Wireless Sensor Networks,” *ACM Transactions on Sensor Networks (TOSN)*, vol. 5, no. 1, pp. 1–39, February 2009.

[16] A. H. Mohsin, K. A. Bakar, A. Adekiigbe *et al.*, “A Survey of Energy-aware Routing protocols in Mobile Ad-hoc Networks: Trends and Challenges,” *Network Protocols and Algorithms (NPA)*, vol. 4, no. 2, pp. 82–107, 2012.

[17] M. Coupechoux, B. Baynat, C. Bonnet, and V. Kumar, “CROMA–An Enhanced Slotted MAC Protocol for MANETs,” *Mobile Networks and Applications*, vol. 10, no. 1-2, pp. 183–197, February 2005.