Wi-Fly: Widespread Opportunistic Connectivity via Commercial Air Transport

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ABSTRACT

More than half of the world's population face barriers in accessing the Internet. A recent ITU study estimates that 2.6 billion people cannot afford connectivity and that 3.8 billion do not have access. Recent proposals for providing low-cost connectivity include fielding of drones and long-lasting balloons in the stratosphere. We propose a more economical alternative, which we refer to as *Wi-Fly*, that leverages existing commercial planes to provide Internet connectivity to remote regions. In Wi-Fly we enable communication between a lightweight Wi-Fi device on commercial planes and ground stations, resulting in connectivity in regions that do not otherwise have low-cost Internet connectivity. Wi-Fly leverages existing ADS-B signals from planes as a control channel to ensure that there is a strong link from the plane to the ground, and that the stations intelligently wake up and associate to the appropriate AP. For our experimentation, we have customized two airplanes to conduct measurements. Through empirical experiments with test flights and simulations, we show that Wi-Fly and its extensions have the potential to provide connectivity to the most remote regions of the world at a significantly lower cost than existing alternatives.

1 INTRODUCTION

4.4 billion people around the world live without Internet connectivity [1]. Most of the world's offline population (64 percent) live in impoverished rural settings, where poor electric power and communications infrastructure, and lack of hardware for base stations and end-user devices impede Internet adoption[11]. More than 80 percent of people who are currently disconnected from the Internet are younger than 55 years old, and more than 42 percent are younger than 25 years old. Another recent study [24] has shown that reducing the cost of Internet access can help connect a significant population of the world (see Figure 1). In order to address the critical challenge of connectivity, several small scale[7, 8, 14] and large scale[19] efforts have been aimed at connecting the disconnected people around the globe. Unfortunately, not much has changed over the last decade. The small scale, community-based solutions help people but they require funding and ongoing technical support, which are both hard to provide, given the cost of existing solutions.

Figure 1: Impact of reducing Internet access costs on global connectivity. The vertical axis on the left shows the cost of access.

In this paper, we focus on the promise of leveraging commercial air transport system as a means of providing connectivity on a continental scale. At any given moment, there are over 10,000 aircraft flying globally and covering large swaths of geographical area. For our study we consider the possibility of utilizing all these aircrafts as access points that population hubs on the ground can connect to. By the virtue of the long distances these aircraft travel, we have shown that it is possible to connect large areas where connectivity has previously been unfeasible.

Our approach, called Wi-Fly, aims to leverage various technological components of existing infrastructure so that connectivity can be provided at low costs. Wi-Fly uses Wi-Fi frequencies and radios to communicate between the aircraft and ground stations. In our framework, ground stations (communication hubs) listen for ADS-B transmissions from aircrafts to learn when they are nearby, and where they will be in the near future, and power up and fine-tune their Wi-Fi hardware

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accordingly. Such a capability helps increase the throughput of the system by determining the best aircraft to communicate with when multiple planes and ground stations are operating.

Wi-Fly aims to provide connectivity to delay-tolerant applications by leveraging the existing Internet available in commercial planes using Ku and Ka bands. The goal of Wi-Fly is to support two primary scenarios. First, we seek to enable people to communicate with each other using emails, instant messages, and by downloading popular content. Second, we seek to provide communication to "things", such as sensors that would otherwise be disconnected in remote regions, e.g. in forests, deserts and agricultural tracts.

This work is a significant departure from Google's recently proposed Project Loon and Facebook's Aquila efforts. Instead of creating custom aerial vehicles, we aim to keep the costs down by utilizing existing infrastructure. Another key benefit of our approach is that Wi-Fly is much easier to deploy on a large scale. Finally, the design of our system is much more flexible and robust; consequently it has the potential to adapt to various aircraft scheduling constraints. In summary, the key contributions of this work are:

- Solution to the connectivity problem that leverages existing air transport infrastructure.
- Using ADS-B to detect the presence of aircraft and build a predictive model of connectivity.
- Real-world experiments with real aircraft data that shows the promise of the framework.
- Real-world deployment on general aviation aircraft that demonstrates empirical performance.

2 MOTIVATION

In order to assess the efficacy of our connectivity model, we built a simulator using flight data from the website FlightAware [2], along with experimental data collected using our platform, detailed in Section 5. In May 2016, we downloaded the information of all planes flying across a single day over the continental US and Africa regions. The data was downloaded in the form of snapshots of currently flying airplanes at a given time. Each snapshot was downloaded approximately 5 to 10 minutes apart. For each flight that was in the snapshot, we noted the plane height, speed, and exact location in the region. In order to make sure that we were only using commercial planes that were in the air (as opposed to those parked at airports), we made sure that every plane under consideration was at an altitude above 20,000 feet, and had an airspeed of over 200 Knots[1].

As a preprocessing step, we studied the data carefully and worked to remove all potential discrepancies. We particularly looked at flights' unique IDs across snapshots and made sure that their locations were different, so as to ensure that we only considered flights that are constantly moving. Thus, we observed that several flights which were stationary at airports were being erroneously reported as flying by the FlightAware API. These flights were removed from the data. As mentioned earlier the data comprised a single day. We used a single day's data because flights follow a similar pattern for most days.

Along with gathering FlightAware data of planes in air, we also conducted experiments using a custom built measurement platform detailed in Section 5. In our experiments, we placed a commodity high-power Wi-Fi router which had a measured transmission power of 25dbm [2] in a modified single engine airplane, as shown in Figure 6. We placed the AP in the wingtip of the airplane, and allowed us to avoid making any structural changes to the plane. Note that the wingtip is made of fiberglass, a non-conductor. We attached dipole antennae with an estimated gain of less than 5 dbm in the plane and collected beacon packets sent by the router at a ground station. While the plane was in flight, we also collected a time-synchronized GPS log of the flight which gave us the exact distance between the receiver and the transmitter at all times.

2.1 Wireless propagation parameters

We chose to use the free space propagation model in the simulator as supported by previous studies[17, 18]. While multi-path models have also been used, they were based on special receivers (for example parabolic receivers following the airplane[21]), and in special terrain settings [17]. For the line of sight component independent of the terrain, the use of free space propagation is precedent. The free space propagation model is summed up by the Friis equation:

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{16\pi^2 R^2}$$

In the above equation, P_r and P_t denote the receive and transmit power respectively. G_r and G_t denote the receive and transmit gain. λ and R denote the wavelength and distance between transmitter and receiver respectively.

In order to fit a path loss model based on our experiments, we assumed that R is raised to a variable γ, and we estimated this parameter γ using experimental data we collect.

We use the received power (gathered from the measurement platform in Section 5), antenna gain of receiving and transmitting antennae, and applied curve fitting to calculate the value of the parameter γ. For wavelength calculation, we use the value of center frequency of channel 1 (2412 MHz), which the router was using to transmit the packets. In order to have diversity, we use two different receiving stations with two different receiving antennae. We use MATLAB for applying regression for estimation of γ.

We collect the data by flying the plane (in a circular pattern) at various altitudes, and using two different laptops to decode the packets. We record the packets received, and post-process them with the flight log from the plane. The estimated value of γ using this data was 2.12.

[1] Knot is unit of speed equaling 1.15078 miles per hour

[2] This is significantly lower than the legal limit.

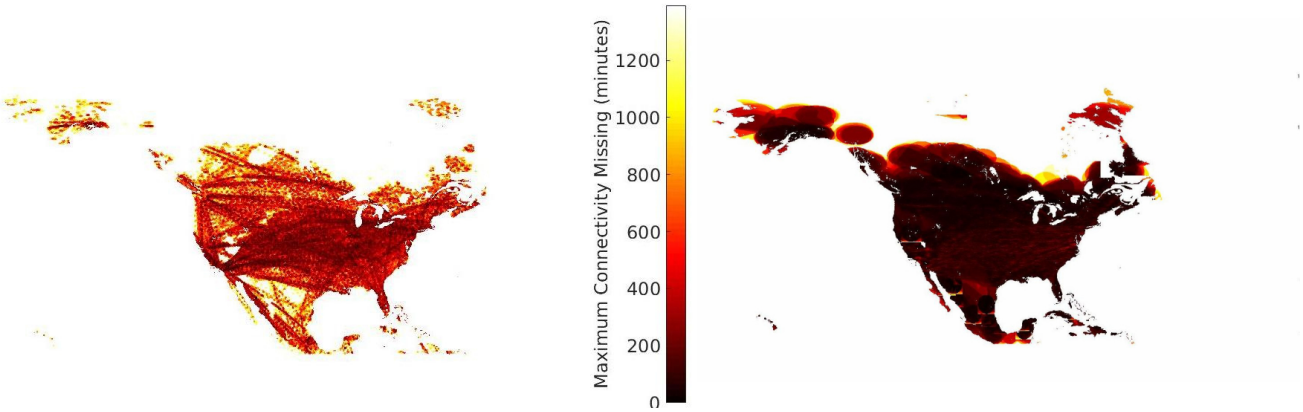

Figure 2: Coverage map for continental US with zero antenna gains (left) vs with 10 dbm gains at receiver and transmitter (right) using regressed parameters.

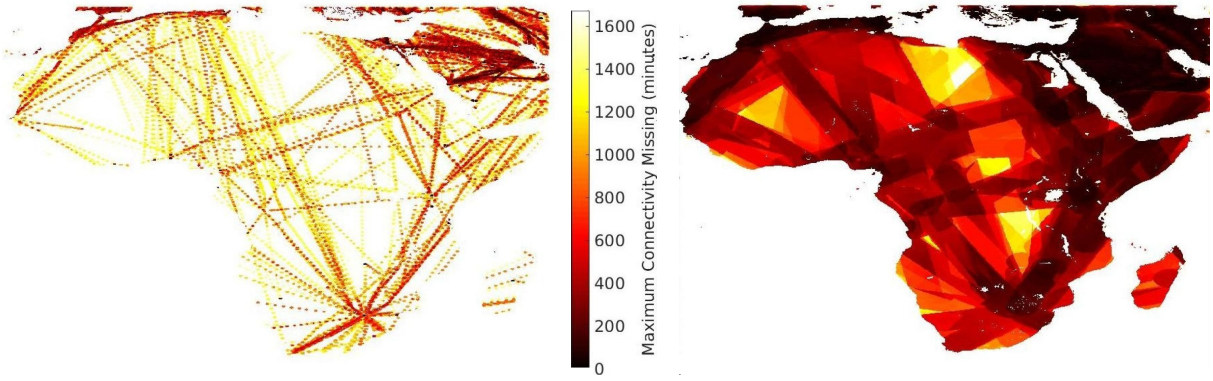

Figure 3: Coverage map for Africa with zero antenna gains (left) vs with 10 dbm gains at receiver and transmitter (right) using regressed parameters.

2.2 Coverage Results

After estimating propagation parameter γ, we use the FlightAware data of the planes to estimate which areas will get coverage in different regions around the world. For these coverage simulations, we assume a transmit power of 2W. We use different values of transmitter and receiver antenna gain. We also use a gain of 0 dBi or 10 dBi in order to show beam-forming gains. We calculate SNR using thermal noise for the bandwidth of the system. We assume connectivity if the SNR was more than 0 dB. Figure 2 and Figure 3 show the regions of America and Africa respectively, that can be covered by Wi-Fly, and the maximum amount of time that each region would *not* have Internet access during a day. We evaluate the potential coverage with and without antenna gain.

As we see in these figures, most regions can be provided Internet access with overhead commercial aircrafts, with most of the covered regions losing connectivity for at most 10 hours. This map was made operating under the assumption that all the flights are using our system to provide coverage. As we expect the number of flights to increase with time, the coverage for this map will only increase, further motivating the design and study of such a system.

For the Africa maps shown in Figure 3, we also did a population coverage analysis based on publicly available population maps [6]. We calculate that 80% of the population requires less than 10 hours of maximum connectivity loss based on the coverage shown by high gain transmitter and receiver on the right in Figure 3. We also calculate that even with the conservative parameters used in the map on left in Figure 3, 50% of the population in the region is connected during the course of the day.

3 WI-FLY ARCHITECTURE

Wi-Fly leverages commercial air transport to provide Internet access to remote areas. The goal of the Wi-Fly system is to support two primary scenarios. First, we seek to enable people to communicate with each other using emails, instant messages, blogs, etc., and also download popular content such as news and weather updates. Second, we seek to provide connections to "things", such as sensors that would otherwise

be disconnected in remote regions, e.g. in forests, deserts, and agricultural tracts, to enable access to sensed data.

Planes in Wi-Fly have local Internet access either using a satellite connection over the Ku [10, 12] or Ka bands [3], or from another ground station [4]. Nearly 70 airlines around the world offer Wi-Fi in flight. Worldwide 39% of airline passengers already have an internet connection, 68% of which is high quality Internet [9]. This percentage is on the rise with US taking the lead with 80% of flights having Wi-Fi [9]. Furthermore, governments of many countries are exploring opening up additional spectrum [5, 12] that will enable airplanes to provide even higher bandwidth Internet connectivity in the near future. In an alternate approach, the methods we propose can also be fielded in the absence of plane connectivity via special satellite or ground stations; planes employing the local communication with the ground stations can cache and sync content when they land at airports.

Wi-Fly extends the connectivity in the planes to various kinds of ground stations including connectivity hubs for people and sensors. Each plane is equipped with antennas, and a transceiver that communicate with special Wi-Fly ground stations. This equipment is in addition to the other transceivers that are used on the plane. Although excess weight could be a potential concern, our experimental setup adds only a small additional weight of three lbs, which is acceptable, per our private communications with commercial flight companies.

The ground stations also have a transceiver and an antenna pointed at the sky. In our current design, aimed at high bandwidth applications, Wi-Fly requires a phased array antenna to maximize the coverage of the horizon, while also providing high gain. Since the antenna configuration of each station is cumbersome, the Wi-Fly system for broadband connectivity uses an alternative technology such as Open Cellular platforms[7, 8, 14], TV white spaces[22], Wi-Fi access points, point to point links [20], or GPRS, for the eventual last mile connectivity. For IoT applications, that have a much lower throughput requirement, Wi-Fly modulates the signal over a narrow bandwidth that has a much lower noise floor. Hence, the antennae do not need as much gain, and therefore each sensor has an attached omni-directional antenna, and each sensor also directly communicates with the plane.

To achieve good connectivity between the ground stations and the planes, Wi-Fly needs to solve three main challenges:

- First, to ensure good throughput between the plane and the ground station, Wi-Fly needs to dynamically adapt its wireless parameters. Using Wi-Fi, or any existing ground communication system as is, leads to poor throughput. Existing Air-to-Ground systems, such as the ATG4 used by Gogo Wireless use a much slower EVDO technology.
- Second, Wi-Fly needs to scale to multiple airplanes and ground stations. This requires the design of a unique media access control (MAC) protocol. In contrast to Wi-Fi or cellular systems where the clients are mobile, in Wi-Fly, the airplanes (base stations) are mobile. Furthermore, we seek to do an optimization that considers multiple parameters: the clients need to associate with the plane that is close enough to provide a sufficient signal, that is also least lightly loaded, and that promises association for the longest period of time.
- Third, Wi-Fly ground stations need to support a low-power mode to allow IoT devices to communicate with the planes. Having them always on would consume a great deal of power, and heavily duty cycling the sensors might miss communication opportunities with an overhead plane.

4 ADS-B ASSISTED CONTROL CHANNEL

The challenges highlighted at the end of the previous section require techniques for ground stations to learn about the presence of nearby aircraft. If a ground station is aware of all the planes, they can connect with a correct plane to maximize throughput, and if there is no plane, they can deactivate the base station to save power and reactivate at a later time when there is a plane available.

One approach could be to download a schedule of plane flights. However, planes may be delayed and may deviate from scheduled flight paths (e.g., due to wind and/or weather). Another approach is to perform active polling, where ground stations periodically probe for incoming planes. However, such an approach adds latency in establishing the link, and introduces extra overhead messages on the channel.

To circumvent these challenges, Wi-Fly uses a control-channel–based approach. However, instead of using a separate radio on the plane to implement the control channel, the Wi-Fly control channel uses existing ADS-B (Automatic Dependent Surveillance - Broadcast) [23] signals sent by planes. ADS-B signals are sent on 1090 MHz or 978 MHz, with a 50 KHz or 1.3 MHz bandwidth respectively, and encoded using PPM. Planes use these signals as an alternative to secondary RADAR. The aircraft transmits its latitude, longitude, speed, bearing, pressure, altitude, callsign, etc. in separate messages of 10 bytes each, with a total packet size of 112 bits.

Each packet in ADS-B is identified using some data fields known as Downlink Format (bits 1 to 5) and Type Codes (bits 33 to 37). Wi-Fly proposes sending of some extra packets from the plane using unused type codes carrying useful information like current load and available capacity. We call our technique ADS-B Assisted Control Channel, using which the aircraft can send small amounts of data to the ground stations. We use the Downlink Format 17 which is meant for broadcast and caps the maximum packets sent to a very few packets per second. This enables Wi-Fly to have a lightweight, push-based approach, where planes signal their presence without clogging the data channel. We would like to note that we collected ADS-B data over several weeks in different cities and realized that there are several unused Type Codes, in particular Type Codes 5-8, 25-27 and 30 are not being used.

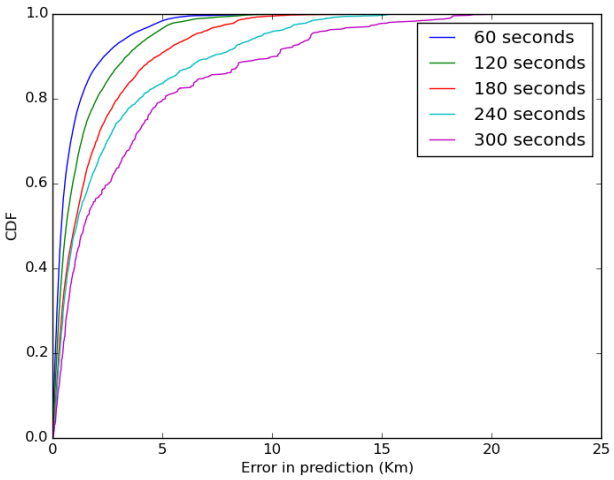

Figure 4: Errors in prediction of planes locations at various times in the future based on ADS-B data. Different lines indicate different times into future for which predictions were made and error calculated based on actual plane location.

We note that ADS-B signals operate in a lower frequency, and are sent at a higher power. Hence they propagate farther than the data (transmitter in 2.4 GHz). Such a range mismatch between the control and data channel has been shown to cause inefficiencies in protocol design. For example, when the control channel is used as a contention medium [16], then many more devices will hear the transmission on the control channel, and backoff, while they might never have heard the packets on the data channel. However we don't have this problem in Wi-Fly because ground stations never transmit on ADS-B channel and just use one way packets to learn the exact location and heading of the plane.

We use the ADS-B assisted control channel to help address the challenges discussed in the previous section. ADS-B packets provide telemetry data like location, speed and heading of planes which we use to calculate how long a plane will be able to connect to a base station. In figure 4 we show the accuracy of this approach using real ADS-B data. Using location prediction and current load on the plane (which is sent by leveraging unused Type Codes) the base station on ground chooses to connect with the plane that has the least load and will stay connected for the longest time hence increasing the throughput of the system. The ADS-B signal is also used as a wake-up signal to re-activate base station on ground when a plane comes around.

5 MEASUREMENT PLATFORM

We instrument a general aviation aircraft to carry the equipment. Specifically, the wing tips of the aircraft are hollow and built out of fiberglass and provides ample space for the antennae and the Wi-Fi router to be installed. Figure 6 shows

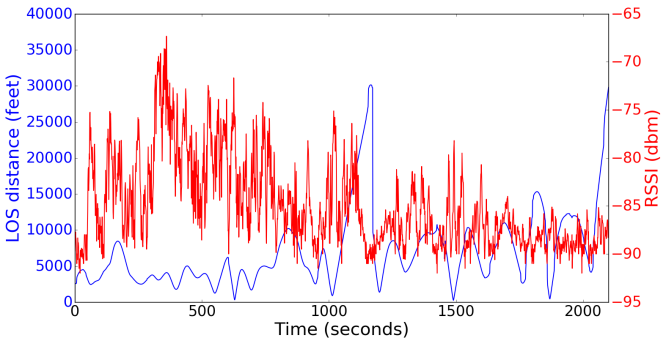

Figure 5: Correlation between distance and RSSI of packets at a per second granularity during flight experiments.

the details of the installation. The red color on the aircraft depicts the wing tips where the equipment was installed. In our installation, we used an off-the-shelf RadioLab router and 2.4 GHz Wi-Fi antenna that were cased in a custom aviation form factor. The antennae were mounted on steel plates, which provided the required ground plane, and were attached to the aircraft's wing ribs. We made sure that we have maximum separation between the antennae while not doing any enhancements to the shape of the wing. The aircraft was also equipped with a Mode-C transponder, and during the test flight, the Air Traffic Control (ATC) was contacted, who then assigned a squawk code for the Mode-C broadcast.

On the ground, we collect data at two different channels. The ADS-B and Mode C telemetry channel at 1090 MHz and Wi-Fi channel at 2.4 GHz. The telemetry data was collected using a USRP N210 with an SBX daughter card, and a 1090 MHz helix antenna. The mode-C squawk code assigned by the ATC allowed us to distinguish the packets sent by the test aircraft from other broadcasts. The Wi-Fi channel data was collected using 2 Wi-Fi receivers on the ground. One receiver was a Lenovo T430 Laptop with the built in Wi-Fi chip, and the second receiver uses the external Intel 5300 Wi-Fi card connected to a HP Pavillion laptop over the express card slot.

5.1 Collecting Channel State Information (CSI)

We use the modified Intel 5300 firmware and driver [13] to collect CSI information from air to ground. This tool collects CSI for various kinds of packets, but the biggest challenge we faced was how to keep the base station associated with the AP in the plane. In order to keep the plane associated, we used a replicated setup of client and AP on the ground and in the aircraft. We used a CSI collecting laptop on ground which was connected to an AP on ground. The AP on ground pretended to be the AP in air, this meant that the AP on ground had the same IP, MAC, BSSID and Wireless channel as the AP in the plane's wingtip. The only difference was that the AP on ground did not send any 802.11n High Throughput (HT) packets for which the modified Intel 5300 card collects CSI. In the plane we put a replicated client which looked like the

Figure 6: Instrumentation of the plane.

CSI client on ground but it did not have the Intel 5300 card to collect CSI. The client in the plane was constantly associated with the AP in the plane and was pinging the plane while the client on ground was constantly associated with the server on ground.

This replicated setup was done in the hope of getting the 802.11n HT packets that were intended for the client in the plane, and to collect them at the client on the ground, and consequently gather CSI from them. We were able to collect CSI packets in this manner consistently during the flight, giving us a deeper understanding of the channel from the plane to the ground. We use the data collected for throughput simulations shown in earlier sections. For a single flight, the correlation between distance from the receiver and RSSI value of all received packets is shown in Figure 5.

6 DISCUSSION

Spectrum considerations: In the US and many other countries, the frequency range 2400-2483.5 MHz (2.4 GHz band) is authorized for use by devices that do not require individual licenses. Depending on the country, these devices are referred to as unlicensed devices, license-exempt devices, class licensed, etc. With some changes to the wording based on the country, the general rule is that unlicensed devices cannot cause harmful interference to–and cannot claim protection from interference from–any device operating in the 2.4 GHz and adjacent bands. There is typically a minimum set of technical rules for these unlicensed operations, which serves to create a low barrier for innovation as well as a low compliance cost. Furthermore, in the International Table of Frequency Allocation, mobile and fixed services are co-primary in this spectrum range, and there is no prohibition on aeronautical mobile use. The 2.4 GHz band is home to technologies such as Bluetooth, Zigbee, and Wi-FiTM Certified devices (Wi-Fi) that are compliant with different WLAN standards developed by IEEE 802.11. Additionally, the authors do not see any technical reasons why unlicensed LTE-based technology cannot be made to operate in the band if operators so choose.

Changing aircraft routes for maximizing coverage: An interesting possibility with the proposed framework is that we can consider modest re-routing of aircraft based on the demand for connectivity. For example, bandwidth requirements can vary depending upon various factors such as time-of-day, special events, population density, etc. Due to the mobile nature of the access points (aircraft), it should be possible to dedicate more resources to areas that need better connectivity at minimal costs. In fact, similar ideas have been explored in the context of weather prediction using aircraft [15]. Similar to that work, we can envisage an analysis where we can determine best actions (aircraft re-routes) to take so that it maximizes *value-of-connectivity*.

Incentivizing Wi-Fly adoption: For Wi-Fly to work as a potential means for providing affordable Internet connectivity for people and things in some of the most remote and geographically challenging areas in the developing world, we require a globally reproducible model for subsidization of airliners willing to adopt Wi-Fly. We see the feasibility of business models where Internet service providers and governments can partner with the airlines to provide connectivity based on regional routes of planes. We need such partnerships to catalyze Wi-Fly adoption.

Open questions: More work is needed to identify the best approach to be used for PHY layer. This includes exploration of MIMO based approach, antenna design at receiver and sender while taking into account economics of fuel efficiency and plane design.

7 CONCLUSIONS

We present Wi-Fly, a communications methodology and architecture aimed at providing opportunistic connectivity in remote and under-served regions around the world. We demonstrated the efficacy of our system using simulations based on real-world measurements using instrumented aircrafts. Wi-Fly leverages ADS-B assisted control channel to provide low powered base stations for connectivity. Contrary to other solutions, Wi-Fly promises to be low-powered and inexpensive via its leveraging of the existing widescale infrastructure of commercial air transport.

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