Dynamic Link Budget Simulation for High Altitude Balloon Data Link Experiment

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ABSTRACT

With the growing interest in high altitude balloon experiments for Science, Technology, Engineering, and Math (STEM) outreach, the desire for more capable data links, to include 802.11-based solutions, has also increased. This paper addresses the challenges of modeling and simulating an 802.11-based data link throughout its flight on a high altitude research balloon. Of special interest in this simulation are modeling of the 3-dimensional nature of the antenna gain for both the transmitter and receiver throughout the flight trajectory of the balloon and modeling of the balloon-borne antenna due to wind gusts. Key research questions to be answered are link stability over time and overall data throughput of the system throughout the duration of the mission. Once developed, this simulation will allow investigations into dynamic protocol modifications, such as modifications to the transmission rate, which may provide an increase in overall data throughput. Results from this simulation will be used to generate specifications for a high altitude balloon data link experiment that will feature a live streaming video link to a ground station during an experimental mission.

Author Keywords

High altitude weather balloon; near space; 802.11; Wi-Fi; data link; STEM education; radio frequency data transmission; model; simulation; Friis transmission equation; video streaming

ACM Classification Keywords

I.5.1 MODELS

I.6 SIMULATION AND MODELING
J.2 PHYSICAL SCIENCES AND ENGINEERING

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INTRODUCTION

With growing interest in providing students with experiential learning opportunities in Science, Technology, Engineering, and Math (STEM) programs, high altitude ballooning has become an affordable option to teach important engineering and scientific discovery principles [1]. The high altitude balloon platform provides students with an opportunity to propose, develop, and fly scientific instruments to study the physical properties of the stratosphere for significantly longer than rockets or other transient platforms. One challenge, however, is transmitting real-time, high data rate information, such as video feeds, reliably and consistently throughout a flight. Typical high altitude ballooning platforms use the amateur radio Automated Packet Reporting System (APRS) to relay data at a maximum of 1200 bps [2]. While this is sufficient to get small amounts of data, such as temperature and pressure readings from sensors, it is far too slow for the approximately 1 Mbps needed for real time video from the balloon.

The University of Nebraska's Advanced Computer Modeling and Environments (ACME) Lab team plans to investigate the feasibility of a high data transmission capability on a high altitude a weather balloon using a commercial off-the-shelf router to serve as a high bandwidth downlink. This experiment will take place on a high altitude balloon launch as part of a pilot program for Project HALON (High Altitude Learning over Nebraska), a STEM outreach effort to give high school students an opportunity to build and fly their own near-space experiments.

Project HALON Overview

Project HALON is an experiment being conducted by students and faculty from the University of Nebraska – Lincoln and the University of Nebraska Omaha. The primary objective of Project HALON is to introduce secondary students to systems engineering concepts as they develop a high altitude balloon experiment. The key to this approach is the coaching and mentoring that the teams receive by undergraduate students currently enrolled in STEM programs at the university. Through Project HALON, it is hoped that secondary students will have an exciting and rewarding experience that will encourage them to seek out educational and career opportunities in the STEM fields in the future.

The research platform for Project HALON consists of a high altitude weather balloon as the lifting device. Communications and tracking equipment and the research payloads are suspended under the balloon using a rigging system of nylon ropes and hooks. Per Federal Aviation Administration regulations, the limit for the total weight of the payload for unregulated launch of this platform is 12 lbs. For data acquisition and control, the teams were provided with a Raspberry Pi computer, which would allow them to take up to 8 channels of analog data at up to 30 Hz. Given these constraints, each of the two high school teams was given an overall weight limit of 2.4 lbs. from which they were expected to design an experimental payload that could collect data to support or refute an atmospheric research question about the stratosphere.

In addition to the experiments from the high school teams, the undergraduates from the ACME Lab Team also proposed experiments for the balloon launch. Along with the previously-discussed high data rate transmission capability, the ACME Lab Team also intends to collect data on the six degree of freedom movement that the payload experiences while the balloon is in flight. This movement includes both translation and rotation in the *x*, *y*, and *z* axes measured via accelerometers placed on the payload. Using accelerometers, the team plans to collect data throughout the duration of the flight to determine the amount of control authority required to develop a camera pointing system on a balloon payload platform. Understanding this operational environment is important as the team plans to begin construction of a tracking system to track objects, such as the Sun, during high altitude balloon flights. On August 21st, 2017, NASA predicts that a solar eclipse will occur with the path of totality transiting across Nebraska [3]. The ACME Lab Team plans to launch a high altitude balloon with an optical tracking payload during this solar eclipse in order to capture footage of the eclipse from a near-space vantage point.

Systems Engineering

To ensure that payloads are properly designed to achieve the goals of the experiment, participants were guided through a condensed version of NASA's space systems engineering process [4]. To be accepted for flight, each team must complete a Preliminary Design Review (PDR), Critical Design Review (CDR), Test Readiness Review (TRR), and Flight Readiness Review (FRR) prior to the actual launch of the weather balloon. This process ensures that each team understands the operational environment of the payload, develops a solid operational concept for their experiment, and designs an experimental sensor kit to answer their research question. For the PDR, a panel of external reviewers will examine each team's research question, payload specifications, estimated costs, potential risk issues, need for outside assistance, and a brief system design. Following the PDR, the CDR focuses on refining the design, developing electrical and mechanical drawings, and researching component costs. Only after the teams have completed CDR do the teams move into the fabrication phase and begin construction of the payload. Upon completion of payload fabrication, the TRR and FRR ensure that the design functions as intended and will have the greatest chance for success during the actual high altitude balloon launch.

Problem Description

As previously mentioned, current APRS telemetry links do not have adequate bandwidth to effectively stream live webcam footage of the mission to a ground station. The most common method of getting high resolution imagery and video from balloon launches is to use a camera attached to the balloon that saves images and video to a memory card. While this telemetry alternative is not real-time, it does provide some means to capture exciting images and video from near space, provided that the payload and camera are recovered. Recent experience with the NASA-Nebraska High Altitude Balloon Program, proves that equipment recovery is not always guaranteed during these flights.

On November, 8th, 2014, a payload built by a student from Metropolitan Community College in Omaha, Nebraska was launched from Ashland, Nebraska on a high altitude balloon as part of Near Space Science – Nebraska High-Altitude Ballooning Adventures [5]. During this launch, at an altitude of approximately 72,000 feet, an experimental pod containing the GoPro camera used to record images of the flight separated from the rest of the balloon assembly and fell to earth. While the pod was eventually recovered, the GoPro camera was lost, along with all images captured during the flight.

To add the capability to provide real time imagery during high altitude balloon flights and overcome the possible loss of data from equipment failures, the ACME Labs team is exploring the possibility of adding a high data rate communication capability to high altitude balloon experiments. The first step in this determining the feasibility of this concept is to build a communications link budget model and simulate the operational conditions under which the data link would operate.

LINK BUDGET MODEL & SIMULATION

To reduce cost and complexity for this experiment, it was decided to use off-the-shelf communications components. As a result, an 802.11 (Wi-Fi) solution was selected as the equipment is readily available, has existing protocols and interfaces, and does not require additional radio frequency licensing. The link budget model for this scenario is fairly straightforward: the balloon payload has a router with a linear antenna that transmits webcam images to and receives signals from a ground station computer with a high gain directional antenna.

Link Budget Model

For the baseline concept, the ACME Labs Team chose the Linksys WRT54G 802.11g router to provide the data link with the ground station computer that has an Ubuiquiti Wi-Fi Station EXT as its communications link. According to the data sheets, the WRT54G router has a transmitter power of 15 dBm and antenna gain of 5 dBi [6] and the EXT has a maximum transmit power of 30 dBm, an antenna gain of 6 dBi, and receiver sensitivity of -97 dBm [7]. In the current configuration, these values satisfy the Federal Communications Commission maximum power transmit limits of 1 W or 30 dBm for the 2.4 GHz industrial, scientific and medical band, however, the transmit power of any high gain antenna would need to be lowered to meet FCC guidelines for Equivalent Isotropic Radiated Power maximums [8].

Using the Friis Transmission Equation [9] and expressing the effective area in terms of antenna gain [10], the power, in watts, at receiver can be calculated as shown in Equation 1 below:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \text{ (W)} \qquad (1)$$

In (1), P_t is the output power, in Watts (W), from the transmitter, G_t is the gain of the transmitter antenna in the direction of the receiver, G_r is the gain of the receiving antenna in the direction of the transmitter, λ is the wavelength, in meters (m), of the signal, and R is the distance, in meters (m), between the two antennas. For this experiment, the ground station will be assumed to be the receiver and will be co-located at the launch site.

Over the course of a high altitude balloon flight, both the range and angles between transmitter and receiver antennas will vary as the balloon rises to burst height and then descends on the parachute for recovery. When the received signal strength drops below the receiver's minimum detectable signal level, -97 dBm, link is broken and the balloon can no longer transmit video images to the ground station.

Link Budget Simulation

In our simulation model, we will be testing the balloon in different scenarios to see how the link budget responds. Figure 1 shows the relative position of the balloon and the ground station as well as a representation of the antenna patterns of the transmitter and receiver. The antenna gain angles, θ_t and θ_r for the transmitter and receiver, respectively, represent the angle between the angle between the main beam of the antenna and the direction to the balloon or ground station. To account for the variation in elevation gain as described by Kraus [10], the gain of a quarter wave antenna is varied as a function of $\cos^2\theta$. Figure 2 shows how the gain pattern of the quarter wave dipole used in this simulation varies as a function of elevation angle, θ.

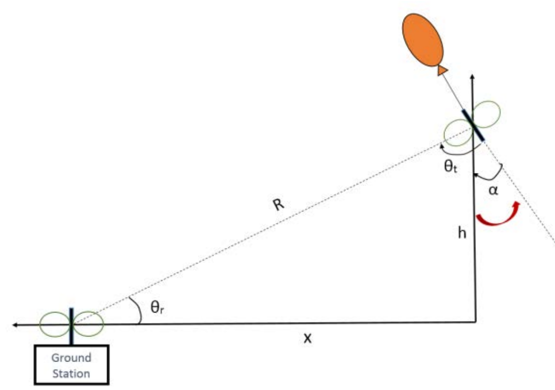

Figure 1. Diagram of relative positions of balloon and ground station and antenna patterns.

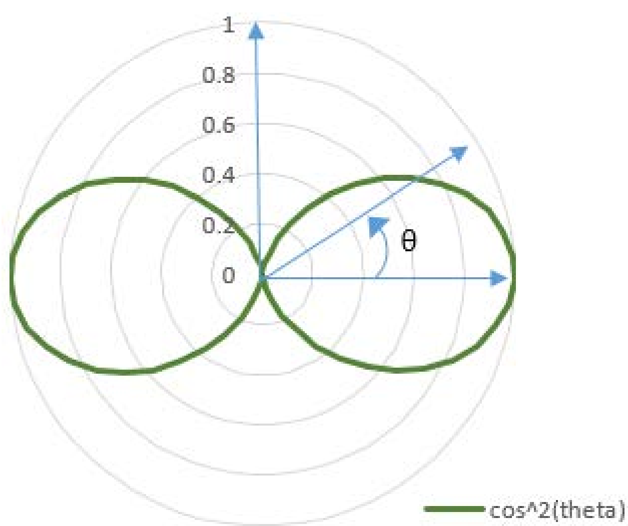

Figure 2. Quarter wave dipole antenna gain pattern as a function of elevation (θ).

SIMULATION RESULTS

Scenario 1: Vertical Ascent – Baseline

The first scenario uses the baseline equipment and antennas aligned with main beams pointed directly one another. In this best case scenario, the balloon was allowed to rise from ground level to 30,000 m. The result of this simulation was encouraging in that using the equipment "as is," our team could establish a video data link to an altitude of 14,500 m.

Scenario 2: Vertical Ascent – High Gain Receiver

For the second scenario, the ground station was equipped with a high gain, directional antenna with a 16 dBi main beam gain pointed toward the balloon at all times. During this simulation, the ground station was allowed to track the balloon throughout the experiment. Using this approach, the data link was maintained throughout the flight to 30,000 m.

Scenario 3: Realistic Flight – High Gain Receiver

With Scenario 3, the balloon is allowed to follow a more realistic flight path to the burst point. Using data from a previous launch, a balloon can travel a 40 km ground track before reaching the burst altitude of 30,000 m. With this trajectory, the gain pattern depicted in Figure 2 becomes a factor in the amount of radiated power that reaches the receiver. Results from this simulation showed that even with the high gain antenna, the link is only maintained to an altitude of 16,500 m and down range ground track of 26 km. If the transmitter power is increased to 100 mW, the balloon and ground station are able to communicate throughout the duration of the flight.

Scenario 4: Realistic Flight with Gust Loads

With Scenario 3, many of the challenges of high altitude ballooning are addressed, including the variability of the attitude of the balloon as it ascends. When subjected to gust loading at altitude, the balloon can rock and spin, which affects the relative angle between the transmitting antenna and the receiver. For this simulation, a random gust load was applied that altered θ_t by as much as 45° for each measurement. This approach resulted in sporadic outages for the configuration with the high gain antenna at altitudes as low as 13,500 m. To compensate for this, the high gain antenna was paired with the higher gain transmitter, 100 mW. In this configuration, the drop-outs did not occur until the balloon reached an altitude of 26,000 m. By increasing the transmitter power to 200 mW, still below the FCC limit for a 16 dBi radiator, the connection was maintained throughout the duration of the flight.

Proposed Configuration

Based on this model and simulation, the ACME Labs team will pursue a high data rate, high altitude balloon experiment with the following as shown in Table 1 below. Using equipment that satisfies these parameters should provide a good likelihood of maintaining high data rate throughout the duration of the flight and have margin for gust loading.

Transmitter Antenna Gain	3.16 dBi
Transmitter Power	200 dBm
Receiver Antenna Gain	16 dBi
Receiver Sensitivity	-97 dBm

Table 1. Recommended transmitter and receiver configuration.

RECOMMENDATIONS FOR FUTURE WORK

Before this equipment is flown, a rigorous testing program must be undertaken to ensure that the model is valid. Once the equipment has been purchased and configured to relay data to the ground station, the first priority is to execute ground tests to determine what modifications must be made to the equipment to ensure that a consistent connection can be maintained in spite of distance. These modifications may include adjusting transmitter and receiver antenna gain, adjusting transmitter power, and testing different antennas to increase the overall transmission.

Using several tall buildings near the University of Nebraska-Omaha's campus, the team plans to perform open air testing with up to 2 km between the transmitter and receiver. By varying the transmitter power, the team can simulate the high altitude range effects. Similarly, by changing the relative angles between the transmitting and receiving antennas, the team can simulate gust loading and changes due to down range translation of the balloon during flight. If the results of these pre-flight experiments are not satisfactory, the team may resort to using a high gain, log periodic antenna on the ground to increase G_r.

In addition to the antenna challenges, this system may also suffer from power and weight limitations that affect performance. Still to be determined is the amount of energy required to operate the data link for the duration of the flight (~90 minutes) and the weight of the source that would be required to power it. This weight, along with the antenna and camera weights must be factored into the limit for the overall weight of the payload.

CONCLUSION

As demonstrated by this link budget model and simulation, it is possible to provide a reliable high data rate link with some modifications to an off-the-shelf router and Wi-Fi dongle. Using this approach will provide a reliable video source during high altitude balloon experiments. While several implementation hurdles have yet to be completed, this simulation has provided a useful tool to help design the first iteration of a functional high data rate link that will provide a unique outreach capability for participants in the Nebraska near space experimental community. This capability will be especially useful for getting "above the weather” and providing stunning, live video of a rare solar eclipse passing over Nebraska in 2017.

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