A Satellite Ground Station for Teaching Digital and Wireless Communications

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***Abstract*—With the advent of small satellites and affordable communications hardware, there has been an increase in academic interest in space education. Small satellites are often created with an educational purpose, and they transmit strong signals that are easy to detect. They pass over large areas of the planet a few times a day, providing increased opportunities for successful communication. On the hardware side, software-defined radio receivers can be connected to an amplifier and an antenna to create a ground station at surprisingly low cost.**

In this paper, our aim is to use satellite communications as a laboratory activity in already-existing courses on digital and wireless communications. These activities would supplement, rather than replace, established laboratory assignments. We believe that this has two main benefits. One is motivational: we believe students will be excited to receive and decode signals from space. The other is that, precisely since the signals come from actual devices, decoding the data will present a meaningful cognitive challenge.

I. Introduction

In the past few years there has been an increase in engineering communications courses that propose active, hands-on laboratory activities involving digital signal processing, software defined radio and the transmission and reception of physical signals [1]–[3]. Educators embracing this approach have benefited from increasing hardware capabilities at a decreasing cost. Today, it is feasible to design laboratory assignments for undergraduate and graduate courses where students transmit, receive, and process analog and digital signals with varying degrees of sophistication.

At the same time, there has been increasing interest in exposing students to space and satellite technology. The potential for exciting educational approaches is huge, and it has had an effect from elementary school to higher education.Today, many engineering and technology colleges have space exploration programs in which students play a leading role in multidisciplinary projects, to which they make substantial engineering contributions. Many of the efforts made by faculty to seize on the pedagogical opportunities offered by these developments have been reported in the engineering education literature. Some universities have designed (and even put in orbit by NASA and other organizations) their own cube satellites. New courses on satellites have been designed [4]–[8]; and others have been modified to include satellite-related content (not necessarily emphasizing communications [9], [10]). Others have focused on opportunities for senior or research projects based on satellites [11].

While taking part in the design, launch and operation of a satellite is, without doubt, an educational experience of considerable value, not every academic department is equipped for such a long and complex endeavor. Sustaining new courses can be challenging and, as a result, student participation in these activities is sometimes extracurricular, in academic clubs or as part of a research project. Similarly, not all technology programs can justify expanding their area of coverage to include courses on satellite communications.

In this work-in-progress paper, we are interested in using satellite communications to improve our existing wireless communications courses in electrical and telecommunications engineering technology. In this sense, this can be seen as a convergence of the trend towards using DSP and software defined radio in communications courses, on one hand, and the expanding opportunities in satellite communications, on the other. This works builds on experiences previously reported in [12] and [13].

In [12], a project is proposed in which students design a satellite earth station. The cost is reported as $4,000 USD. The purpose is to use the station for recruitment and retention, and for use in future projects. The station is designed for low-earth orbit amateur satellites, and consists of specialized hardware to decode continuous-wave, single sideband and frequency modulated voice. Other equipment consists of a computer, commercial software for tracking and decoding signals, and two high-gain antennas (one for VHF and the other for UHF). It is interesting to point out that, barely 15 years after this paper's publication, a more powerful ground station can be built for less than one quarter of the cost, as described in the following sections.

In [13], laboratory activities are proposed to receive non-commercial television stations in the Ku band, and to decode weather images from NOAA satellites in the VHF band. A course that mixes traditional topics in wireless communications with emphasis on satellite applications is proposed. Very positive student feedback was received during this course, in particular pointing out the value of the laboratory activities.

In the context of engineering technology wireless courses that already incorporate laboratory activities based on software defined radio, our aim is to update and improve on these early experiences and incorporate at least one laboratory experiment where students track a satellite, receive its signal, decode it and recover the information contained in it.

The paper is divided in two main sections. First, we describe a very simple, inexpensive ground station comprised of only three widely available elements: an omnidirectional antenna, a low-noise amplifier, and a software-defined radio tuned to the common satellite bands. We describe preliminary results on this station's performance, and comment on its ease of operation and cost.

We also describe how we plan to use this ground station in our existing undergraduate and graduate wireless communications courses, to strengthen students' understanding of communications. Specifically, the use of a software-defined radio as the receiver in the ground station provides the flexibility necessary to allow students to explore every facet of the satellite-ground link, including antenna performance, synchronization, signal modulation, framing, noise, error correcting codes, etc. Even though there is readily available software that performs all of these functions, our goal is to have students implement and test their own signal processing algorithms.

The rest of the paper is organized as follows. In section II we discuss some technical aspects related to the ground station and its performance. In Section III, we provide more details about our educational proposal. In Section IV we present our conclusions and discuss future work.

II. Technical Aspects

Our purpose was to put together the smallest, cheapest and most portable ground station that still allowed for reliable satellite signal reception in the VHF (2 meters) and UHF (70 cm) bands. Our final hardware set up consists of only three elements:

1) A portable Yagi antenna tuned to the bands of interest. With the rise in popularity of amateur satellite radio communications, a variety of such antennas has emerged. We selected an Arrow II antenna [14]. Its approximate cost is $100 USD. With a length of 35 inches and weighing barely more than one pound, it satisfies our requirements. It is circularly polarized, which is convenient to minimize exertion when manually pointing it in the satellite's direction.
2) A software defined radio designed specifically for satellite communications, the FunCube Pro+ dongle [15]. This dongle, originally designed by AMSAT-UK, connects to a computer via USB, and presents itself to the operating system as a sound card. This means that it does not require device drivers or a complex installation procedure. Its volume is approximately one cubic inch and its weight is barely noticeable. It does not require any external power supply. Its cost is approximately $150 USD.
3) One computer to receive and process the satellite signals. Since the signals of interest are narrowband, and the SDR itself has a sampling rate of only 192 kilosamples per second, any relatively modern computer has more than enough processing power. With some effort, even a low-end computer such as a Raspberry Pi can be used, dropping the total cost of the station to less than $400 USD.

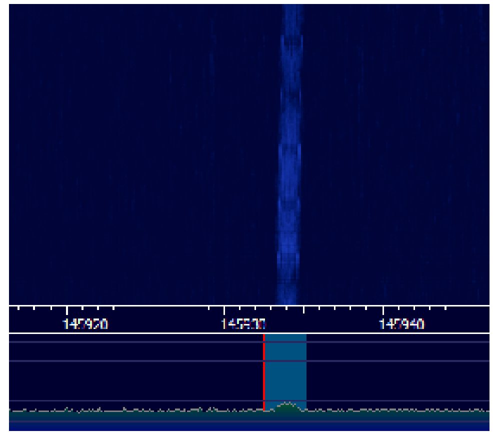

Fig. 1. Spectrogram of the beacon signal received from the FunCube amateur satellite.

It should be mentioned that this set up can be enhanced with a low-noise amplifier placed between the antenna and the radio. This may be helpful when receiving weak signals below the radio's sensitivity (nominally -105 dB in the VHF band). We have not had the occasion to require the LNA, though. It adds $50 to $100 dollars to the cost of the ground station.

Regarding software, there exists an abundance of choice. Many offerings are free of cost and open-source. Their performance seems to be at least adequate in most cases. We also remark that the fact that the software is open-source presents interesting educational benefits, since at least in theory, students are free to inspect the code and figure out the signal processing procedures and algorithms in use.

To test the performance of our proposed ground station, we have received signals from a few satellites and from the international space station. We detail two measurements. First, we detected the FunCube satellite's beacon using an omnidirectional, fixed rooftop mounted antenna that was known to be capable of receiving such a signal. We show the spectrogram of the received beacon signal in Figure 1. In particular, note the Doppler effect caused by the satellite's movement. We also verified that the beacon had the expected properties.

The second measurement we describe here was done with the handheld Yagi antenna, manually pointing it towards the space station. The minute-by-minute position of the station was calculated by software running on a laptop, which was simultaneously recording the signal. The antenna was pointed manually with the aid of a compass. The spectrogram of the recorded signal is shown in Figure 2.

III. Educational Proposal

A wireless communications course that includes activities based on a software defined radio and processing of real signals already addresses related issues, such as demodulation,

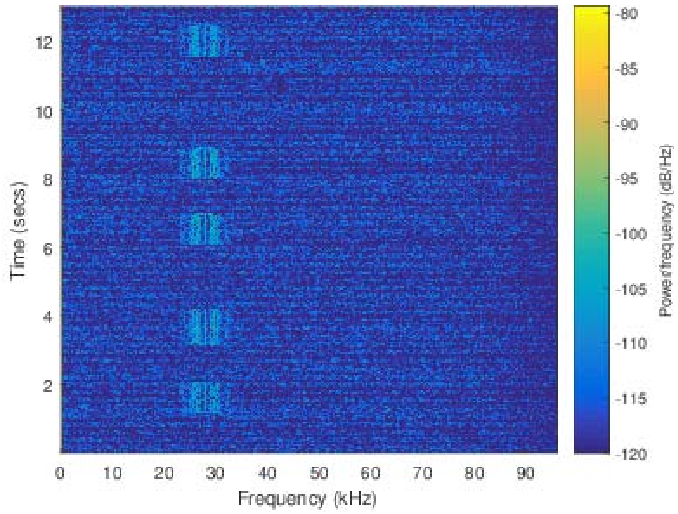

Fig. 2. Spectrogram of the downlink signal received from the international space station.

carrier synchronization, matched filtering, and so on. From this perspective, the signal from a satellite is not that different: it is still modulated to a certain carrier frequency, uses one of several common modulation schemes, encodes data in a certain way, etc. The main perceived benefit is motivational. Receiving signals from space and analyzing them is not something that is commonly done. Laboratory assignments should emphasize this to motivate students. A number of experiments suggest themselves:

1) Use voice transponders to communicate with other ham radio users in the area and with astronauts on the ISS. (Note that transmission requires the use of a duplexer and a small amplifier to the ground station).
2) Receive and decode the ISS television channel.
3) Receive and decode weather images from NOAA and other satellites.
4) Use FSK, BPSK, and GMSK decoders to implement full digital systems and recover telemetry and other data.
5) Perform BER calculations under different noise conditions.

Having said this, capturing and processing satellite signals involves a certain set of challenges. First, there is Doppler effect, as illustrated in the previous section. Additionally, the received signal is usually very weak, making the decodification of the underlying data more difficult. Students must also learn about satellite tracking, identification, how to determine the frequencies they use, and finally, how to operate the ground station. They must learn to predict when a signal may be detectable and be ready for it, since most satellite passes are over in a few minutes. Basic orientation skills are useful to manually point the antenna.

Given these challenges, we propose to divide the laboratory assignments into two parts. The first one is signal acquisition, where a good satellite pass is identified in advance, the ground station primed, and the signal (if detected) is recorded into a file.

In a second step, the signal can be processed offline. The processing steps involve:

1) Trim the signal to cover only the time periods where there was good reception.
2) Calculate the theoretical Doppler shift based on satellite altitude and speed.
3) Correct the Doppler shift and verify that it was done correctly.
4) Identify the signal modulation type. After final down-conversion to baseband, demodulate the signal.
5) Perform any additional steps (matched filtering, error correcting, carrier, symbols and frame synchronization) and display the recovered data.

The low cost and portability of the ground station also rises interesting possibilities. For instance, small teams of students could be fitted with equipment to perform signal captures at the most convenient times, outside regular laboratory hours. Given that there is a significant signal loss indoors, the portable ground station may make it easier to capture signals from places with good horizon visibility, to increase the time window when the signal can be detected.

IV. Conclusions

In this paper, we have presented a very low cost, portable and simple to operate satellite ground station capable of receiving signals in the most common VHF and UHF frequency bands. We have demonstrated that the proposed station can properly receive signals from a variety of satellites and from the international space station. This lays the groundwork for developing laboratory activities that will increase student motivation and learning in the field of wireless and digital communications, in both our undergraduate and graduate engineering technology programs. We hope that our colleagues at other universities are inspired by this work and improve upon it.

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