Exploiting Link Dynamics in LEO-to-Ground Communications

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ABSTRACT

The high dynamics of the LEO-to-ground radio channel are described. An analysis shows how current satellite radio systems largely underutilize the available radio link, and that a radio that can adaptively vary the bit rate can more fully exploit it, resulting in increased data throughput and improved power efficiency. We propose one method for implementing the adaptivity, and present simulation results.

INTRODUCTION

The LEO-to-ground radio link is highly dynamic. This is due to the large changes, relative to a stationary ground station, in signal propagation distance, antenna pointing, and sky noise, during a typical twelve minute satellite pass. Traditional approaches to radio design assume worst-case operating conditions. This conservative design strategy can result in reliable and robust communications. But, due to the dynamic link this approach also leads to inefficient implementations because only a small fraction of the channel capacity is exploited. This is a severe limitation for small satellites due to restrictions on weight, volume, and power.

This paper reports on some of the results of a research effort being conducted at Los Alamos National Laboratory. The effort is developing advanced technologies which more fully exploit the dynamic channel, and thus provide an order of magnitude improvement in the efficiency of small satellite radios. In this paper we will 1) Fully describe and analyze the dynamic LEO-to-ground radio channel; 2) Discuss the potential impact these observations have on small satellite radio communications; 3) Provide simulation results. The prototype radio is able to detect and adapt, in real-time, to changing channel conditions, thus more fully exploiting the dynamic channel. We will show a 10x improvement in average data throughput, when compared to radios using the traditional engineering approach, all other factors being equal.

The successful development and operational deployment of adaptive satellite radios will be a crucial technology for enabling small satellites to fulfill a wider range of missions.

THE DYNAMIC LEO CHANNEL

Satellite Pass Geometry

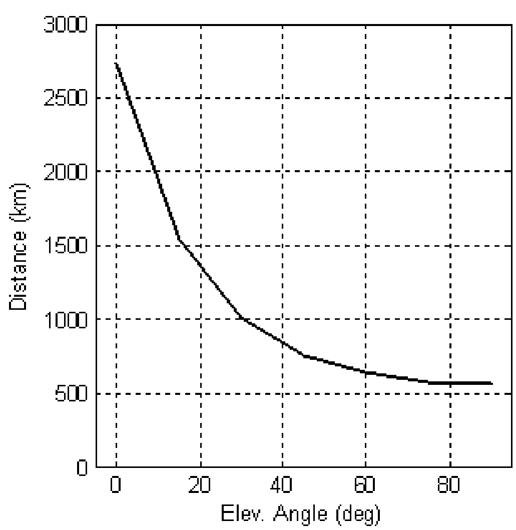
Suppose a fixed terrestrial ground station is configured to establish a radio link with a satellite in a 560 km circular orbit. We assume that the antenna of the satellite is nadir pointing, and the ground station has a tracking antenna. Figure 2 diagrams the geometry of the radio link between the satellite and the ground station.

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{R}{\sin C}$$

$$A = \sin^{-1}\left\{\frac{a}{b}\cos\theta\right\}$$

$$R = b\,\frac{\cos(\theta + A)}{\cos\theta}$$

Elev. Angle (θ)	Distance (R)
0	2,730 km
15	1,540 km
30	1,009 km
45	762 km
60	638 km
75	578 km
90	560 km



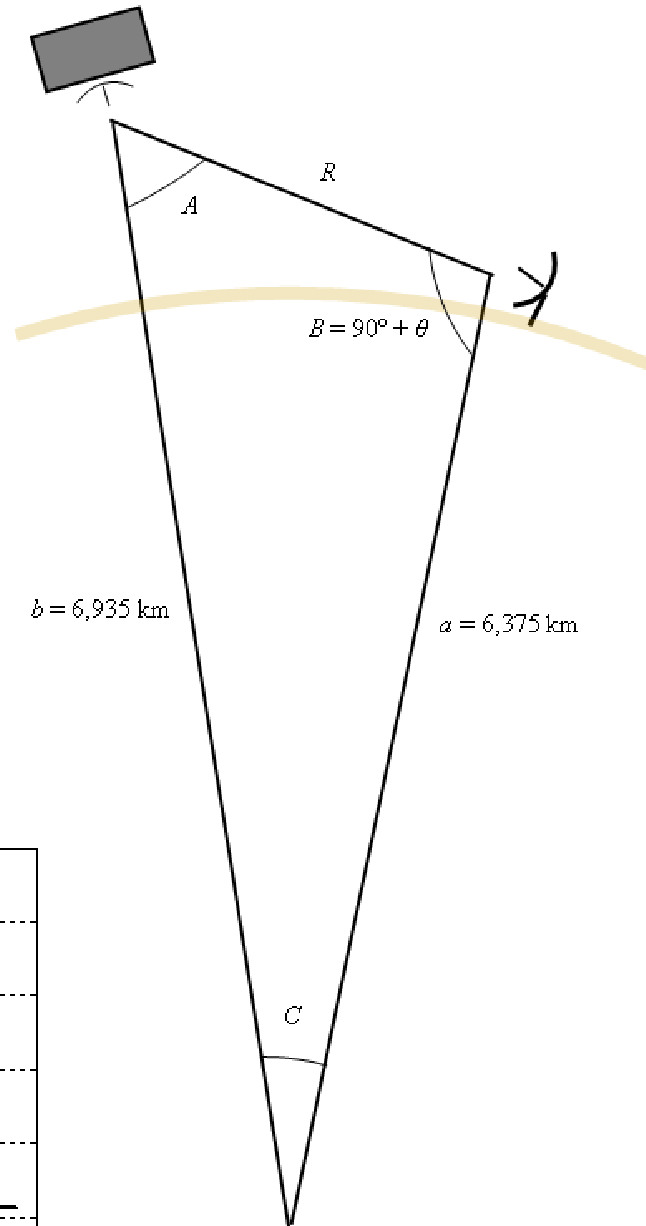


Figure 1. The radio link geometry during a LEO pass.

In Figure 2 there are four variables of interest:

1. *A* is the off-axis angle between the satellite and ground station antenna.

2. *θ* is the elevation angle of the satellite, i.e. the angle at which the satellite lies above the horizon, relative to the ground station.

3. *R* is the line-of-site distance between the satellite and the ground station.

4. *C* is the angle between the satellite and the groundstation, relative to the center of the Earth.

Note that *a* and *b* are fixed values representing the radius of the earth and the distance of the satellite from the center of the earth, respectively.

Using the Law of Sines---as shown in the top left of Figure 2---it is a simple task to compute the off-axis antenna angle *A* and line-of-site distance *R* given an elevation angle *θ*. In Figure 2 example values of *R* are plotted versus *θ*. This example shows that the radio signal propagation distance varies widely during a single satellite pass. This is particularly true for passes which are near zenith, i.e. the satellite passes directly overhead. In this case the radio propagation distance will vary between 2,730 km and 560 km during a period of only about 12 minutes.

Dynamic Link Effects

To better understand the consequences of the results shown in Figure 2, note that an RF (radio frequency) signal propagated over a distance of *R* will experience a power loss of

$$L_p = \left(\frac{\lambda}{4 \pi R} \right)^2 \qquad (1)$$

where L_p is the propagation loss, or reduction in received signal power, and λ is the wavelength of the RF carrier frequency in meters. For example, if we assume an RF carrier frequency of 2.4 GHz is used, λ is 12.5 cm, and L_p in decibels is -155 dB and -169 dB, respectively for distances of 560 km and 2,730 km. In other words, there is a variation of 14 dB in received signal power during the course of the pass solely due to changes in *R*.

The received signal power is also dependent on the off-axis antenna angle *A*. A real world satellite antenna emits RF power in a non-uniform beam called the antenna pattern. For real antennas, a certain angle will emit a peak power density and other angles result in reduced power. Figure 3 plots the antenna pattern for the S-Band Patch Antenna sold by SSTL, which is circularly polarized and is intended for small satellite applications. The antenna gain at 0 degrees is 7 dB. However, the gain decreases gradually with increasing angle. For the example geometry of Figure 2, when *θ* = 0 degrees, then *A* = 67 degrees. For a near-zenith pass the variations in *A* will result in the antenna gain varying between 7 dB and 1 dB. The combined effect of propagation loss and antenna pointing loss results in received power variation of 20 dB during the pass.

Figure 2. The radio link geometry during a LEO pass.

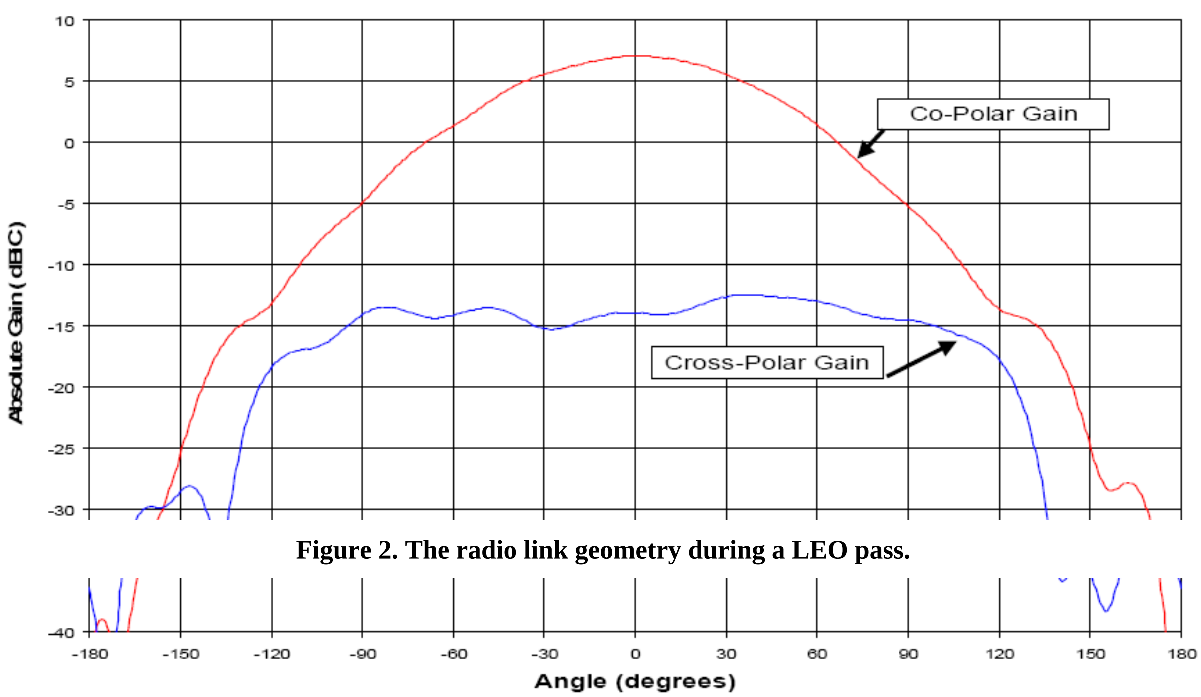


Figure 3. Antenna pattern for the S-Band Patch Antenna sold by SSTL.

A final dynamic effect is the noise introduced into the receiver by the antenna. If we assume that the ground station is the receiver, then the ground station antenna will receive a noisier signal when θ is small because the antenna picks up more thermal noise from the atmosphere. In terms of the signal to noise ratio, at 2.4 GHz with a 1.5 m parabolic antenna and a high quality low noise amplifier (LNA), the received SNR will vary by about 2 dB during the pass due solely to θ dependent variations in received noise. Therefore, the combined variability in received SNR (which is dependent on both received signal power and noise) is approximately 22 dB during the pass.

Other factors may affect received SNR, such as atmospheric induced fades, rain, interference, etc. But, in normal operation the effects of propagation loss, antenna pointing, and antenna noise are the most significant contributors. Figure 4 plots the received SNR versus θ on the left, and on the right versus the elapsed time from the start of the pass. The plots are for the same example described previously, and assume a near zenith pass. We again emphasize the over 22 dB change in SNR over the span of only about 6 minutes. Conventional satellite systems assume the worst case signal power, and design this assumption. But, we see in Figure 4 that there is a large amount of reserve power, called link margin, during most of the pass. This paper argues that through proper exploitation of the changing margin, a great deal more data may be transmitted during the pass, all other factors being equal.

EXPLOITING THE DYNAMIC CHANNEL

In this section we perform a more detailed analysis of the potential capacity of the dynamic LEO channel. We do this by generating link budgets for several scenarios. We also propose a method for using these results to more fully exploit this potential.

Link Budgets

A fundamental principle of communication engineering is that the maximum data transmission rate is proportional to received signal power. In other words, power is the currency of radio design. When a new communication system is proposed a link budget is generated. The link budget quantifies the “assets” and “costs” of the system, in terms of power, and gives the potential information transmission rate of the system. We use this tool to demonstrate the benefit of adaptively changing the bit transmission rate during a LEO satellite pass, and compare this result with the conventional approach. For more background on link budgets, refer to [1] and [2].

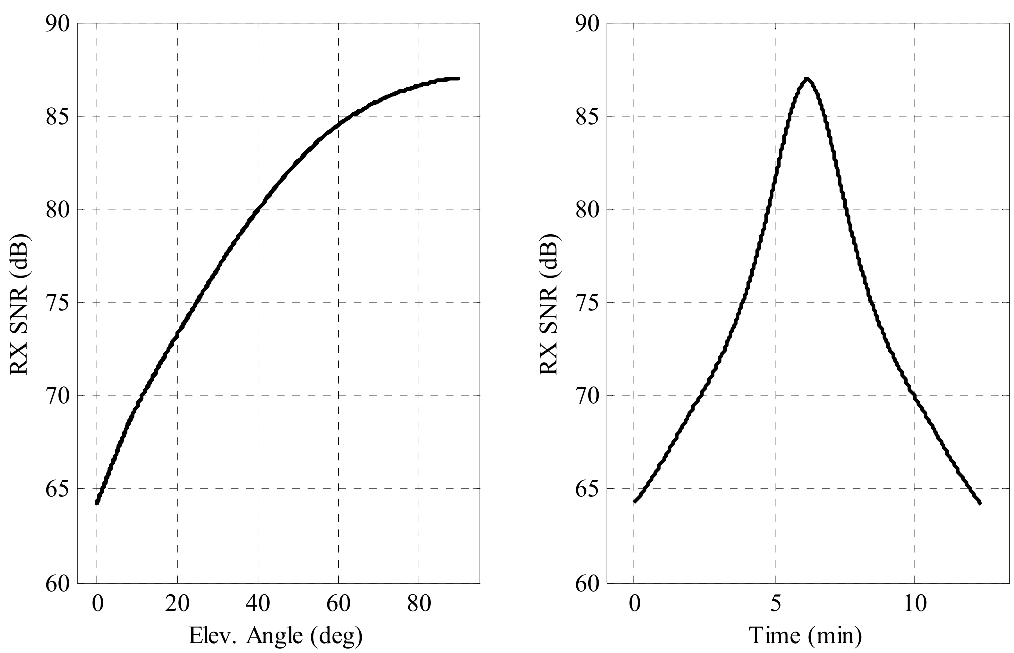


Figure 4. Received SNR versus elevation angle and time.

Table 1- Example Link Budgets

	Adaptive Radio Theoretical Best Case (90° Elevation)	Adaptive Radio Theoretical Middle Case (45° Elevation)	Adaptive Radio Theoretical Worst Case (0° Elevation)	Conventional Radio (5° Elevation)
TRANSMITTER				
10 cm patch @ ½ W				
EIRP	**4 dB**	**4 dB**	**4 dB**	**4 dB**
RECEIVER				
Antenna gain	30 dB	30 dB	30 dB	30 dB
Antenna noise temp.	20 K	25 K	90 K	55 K
Line temp.	35 K	35 K	35 K	35 K
LNBC noise figure	0.8 dB	0.8 dB	0.8 dB	0.8 dB
Boltzmann's Constant	228.6 dB	228.6 dB	228.6 dB	228.6 dB
G/kT	**238 dB**	**238 dB**	**236 dB**	**237 dB**
LOSSES				
Path distance	560 km	762 km	2,730 km	2,229 km
Carrier freq.	2.40 GHz	2.40 GHz	2.40 GHz	2.40 GHz
Propagation loss	-155 dB	-158 dB	-169 dB	-167 dB
Nadir angle	0 deg.	45.5 deg.	66.8 deg.	66.3 deg.
Misalignment loss	0 dB	-3.5 dB	-6 dB	-6 dB
Duplexer loss	-1 dB	-1 dB	-1 dB	-1 dB
Line loss	-1 dB	-1 dB	-1 dB	-1 dB
Polarization loss	-1 dB	-1 dB	-1 dB	-1 dB
Misc. losses	-3 dB	-3 dB	-3 dB	-3 dB
Total losses	**-161 dB**	**-168 dB**	**-181 dB**	**-179 dB**
C/N_0	**81 dB**	**74 dB**	**59 dB**	**62 dB**
Minimum E_b/N_0	7.3 dB	7.3 dB	7.3 dB	7.3 dB
Link Margin	1 dB	1 dB	1 dB	3 dB
MAX BIT RATE	**18,621 kbps**	**3,715 kbps**	**117 kbps**	**148 kbps**

A link budget depends on the assumptions made about system components and its proposed operational environment. Our link budgets are generated under the following assumptions:

- The satellite is in a 560 km circular orbit. Its space-to-ground transmitter transmits a 1/2 Watt modulated signal at 2.40 GHz using a 10 cm patch antenna which is nadir pointed.
- The ground station consists of a 1.5 m parabolic tracking antenna with 30 dB of gain. The receiver uses a low noise block converter with a noise figure of 0.8 dB.
- The modulated signal uses a rate-3/4 low density parity check (LDPC) forward error correcting code that provides approximately 3 dB of coding gain for a target bit error rate of 10^{-6}.

Table 1 lists four link budgets. Three budgets are for the adaptive radio at three different satellite elevation levels (as viewed by the ground station). A fourth link budget is for the same system, but using the conventional design approach of a fixed bit rate. Due to the fixed bit rate, the elevation angle is assumed to be 5 degrees, which is near to worst case. Also, the conventional radio uses a higher link margin, in order to better guarantee link availability. The adaptive case uses a lower link margin because the system can adapt the bit rate to account for anomalous operating conditions, whereas the conventional approach cannot.

The conventional approach results in a fixed bit rate of 148 kbps. Since worst case assumptions are made, this bit rate has a high probability of being obtained under a wide range of operating conditions. However, the link is underutilized most of the time. The adaptive radio is able to vary the bit rate between bit rates as low as 117 kbps and as high as 18.6 Mbps. By detecting the prevailing channel conditions, and adjusting the bit rate appropriately, the link can be more fully exploited.

Adaptive Bit-Rates

One method for exploiting the dynamic channel is to implement a communication setup as shown in Figure 5. In this setup the downlink from the satellite to the groundstation is adaptively adjusted. The ground station measures the signal strength and then uses a conventional bit rate uplink to command the satellite to an appropriate bit rate. The uplink can be the command and control interface to the satellite. In this case the bit rate commands are simply a new satellite command.

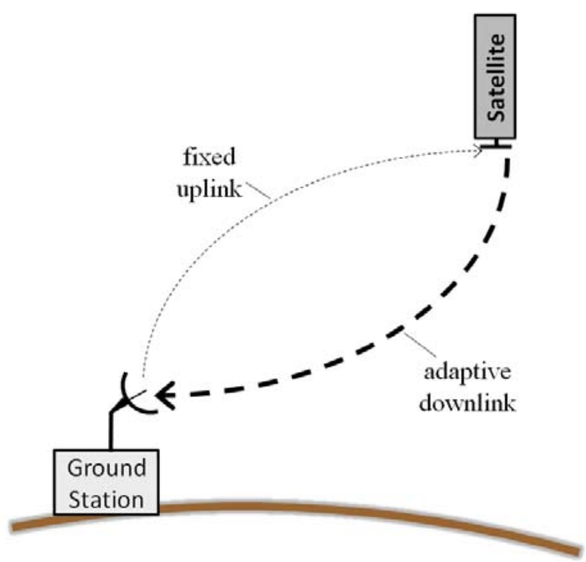


Figure 5. Signal flow between the satellite and the ground station.

It is not practical to adjust the bit rate in a continuous manner. Instead the bit rate can be adjusted in discrete steps. On way to do this is to monitor the received signal level, and when it drops below a certain threshold then command the satellite to a bit rate half the current bit rate. Likewise the bit rate can be increased by steps of two when the signal level rises sufficiently.

Figure 6 plots on the top the bit rate during an example satellite pass, and on the bottom plots the total received bits during the course of the pass. The theoretical case adjusts the bit rate continuously. Our adaptive approach adjusts in discrete steps, and the conventional approach is fixed at very low data rate. During the pass, our adaptive approach does not accumulate as much data as the theoretical bound, but it is close and far exceeds that of the conventional approach by well over an order of magnitude.

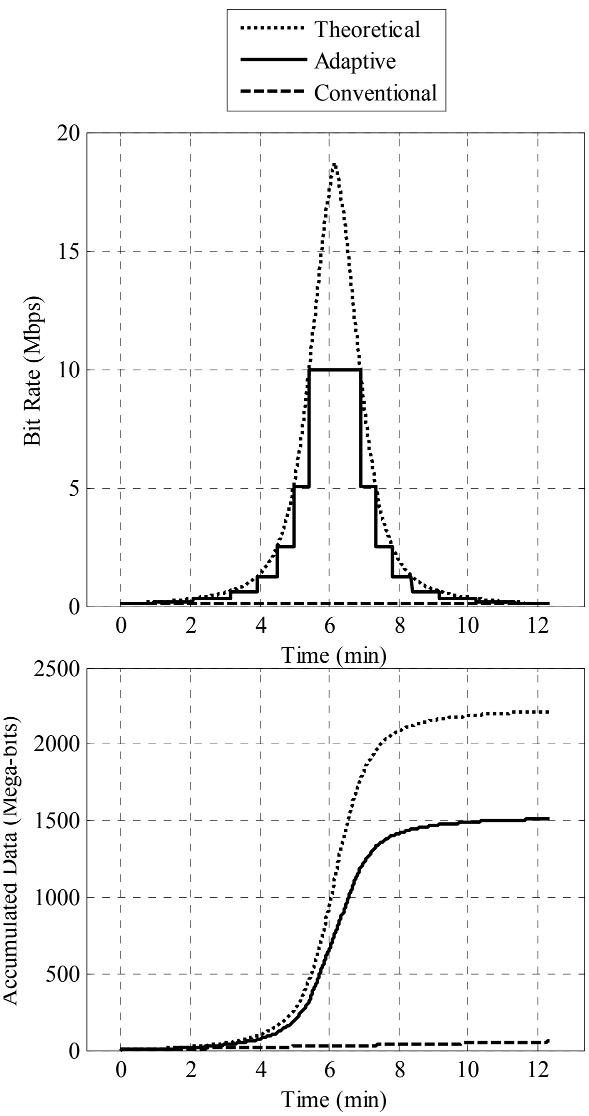


Figure 6. Comparison of bit rates and total received bits.

The important point is that, given identical power, weight, and volume, using the adaptive radio method results in an over 10x improvement in data download capacity, compared to using a conventional radio design.

EXAMPLE DYNAMIC LEO CHANNEL

The example of Figure 6 assumes a zenith satellite pass. Because a zenith pass exhibits the highest dynamics it is therefore useful to study what might be expected normally.

The Cibola Flight Experiment Satellite (CFESAT) is an experimental small satellite designed, launched, and operated by Los Alamos National Laboratory. It is in a 560 km circular orbit inclined by 35 degrees. On a typical day the satellite makes 5 – 6 passes over Los Alamos, NM. Table 2 lists the passes made by CFESAT over Los Alamos on July 23, 2008, with the peak elevation of the pass and the pass duration. CFESAT does not operate an adaptive radio. However, we use its pass schedule as an example.

Table 2 - Pass Summary for CFESAT on 7/23/2008

PASS NUMBER	PEAK ELEVATION	PASS DURATION
1	8.7°	9.0 min
2	34.1°	11.9 min
3	77.7°	12.3 min
4	78.5°	12.3 min
5	35.1°	11.9 min
6	9.2°	9.2 min

The peak elevation of each pass is different, and therefore the dynamics of the channel will also vary. This, as well as pass duration, impacts total data collected during a pass.

Figure 7 shows the variable bit rate and collected data for the entire day recorded in Table 2. The plots for each pass are concatenated together for a total of 67 minutes of pass time for the entire day. During the day, the ground station is able to collect 3.9 Gigabits using the adaptive radio. In contrast, the conventional approach is able to collect only 0.3 Gigabits. Therefore, there is an over 10x improvement in total data collected during the entire day.

CONCLUSION

In this paper we have shown that the radio channel involved in LEO-to-ground communications is highly dynamic. Because of the high dynamics, and because conventional satellite radio designs use fixed bit rates, these radio channels are greatly underutilized.

We have analyzed the link dynamics, and shown that a radio which is able to adapt the bit rate to changing channel conditions will be able to send over 10x the amount of data during a satellite pass, given a fixed power budget. Conventional fixed rate radios decrease the potential data throughput and are not power efficient. Small satellites have inherently small power generation capacity. We have shown that and adaptive radio can more efficiently use the available power.

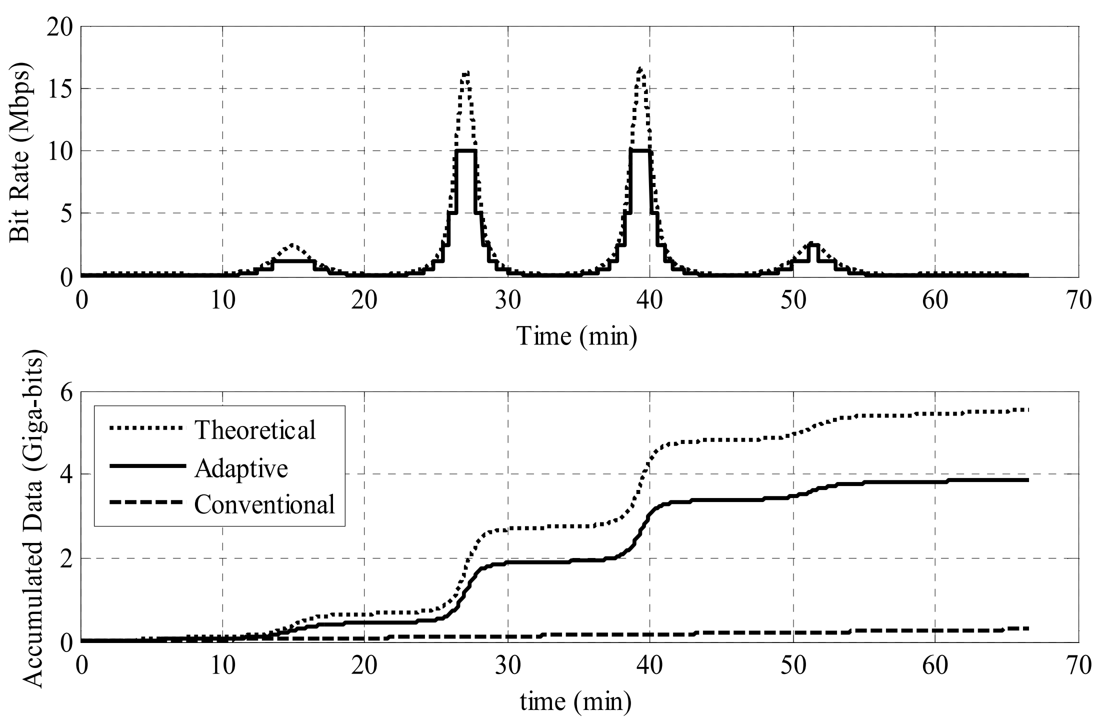


Figure 7. Data collection for an entire day.

Los Alamos National Laboratory has designed a novel satellite radio system that leverages the ideas presented in this paper. The radio design has been implemented in real-time analog and digital hardware, in a prototype format, and is currently being tested. The radio is able to transmit at bit rates ranging from 100 kbps up to 13.7 Mbps, in increments of 2x. A future version of the radio will extend the potential adaptivity further on both the high and low end. We also hope to build a flight test version and test it on a space flight within the next 18 months.

REFERENCES

1. Rice, M., Digital Communications: A Discrete-Time Approach, Pearson Education, Inc., New Jersey, 2009.
2. Roddy, D., Satellite Communications, Fourth Edition, McGraw-Hill, New York, 2006.