Exploiting Link Dynamics in LEO-to-Ground Communications

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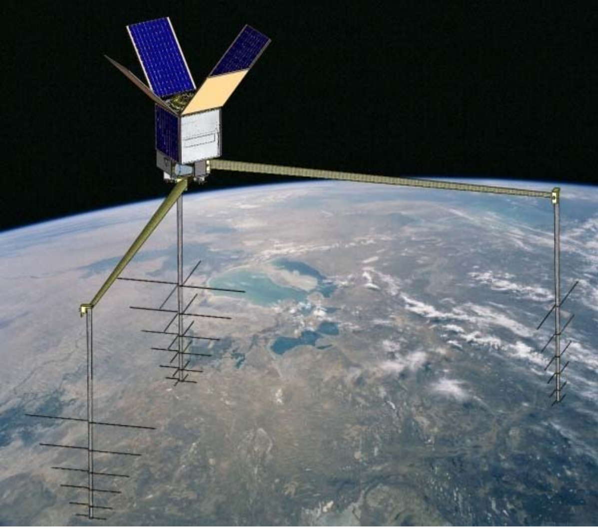
Paper Abstract: The LEO-to-ground radio link is highly dynamic. This is due to the large changes, relative to a stationary ground station, in signal propagation distance, antenna pointing, and sky noise during a typical twelve minute satellite pass. Traditional approaches to radio design assume worst-case 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 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 model results from the radio experiment being conducted at Los Alamos National Laboratory. The prototype radio will be 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.

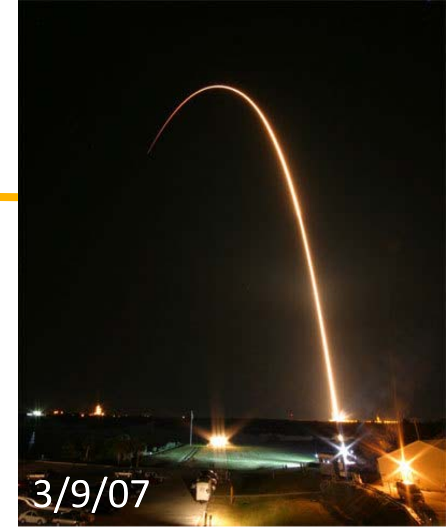
The successful development and operational deployment of adaptive satellite radios will be a crucial technology for enabling small satellites to fulfill wider range of missions.



Cibola Flight Experiment

Project Objectives:

- ♦ Technology Demonstration: responsive, flexible, multi-mission RF payload with continuous data processing
  - Reconfigurable Computing (RCC) technology for super-computer processing speeds at sensor
  - Adaptability: Re-configurable post-launch
- ♦Smart and adaptive computing at sensor for enhanced sensitivity and reduced data downlink



Payload Description:

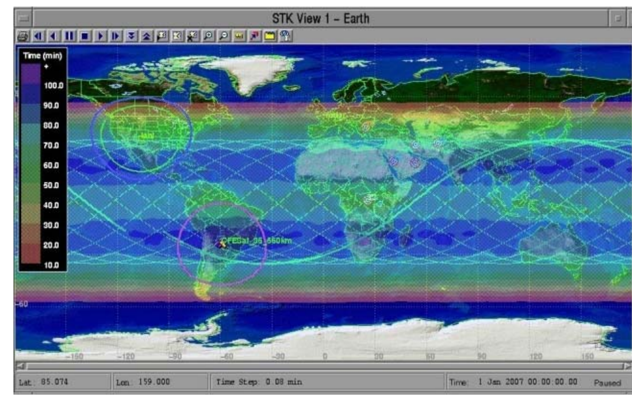
- ♦ 4-Channel Software Radio
  - Tunable 100-500 MHz with 20 MHz bandwidth
  - Sub-band tuning for enhanced signal detection
- ♦12bit ADC @ 100MHz

Technical Approach:

- ♦ On-board data processor using COTS parts
  - –Networks of Xilinx Field Programable Gate Arrays (FPGA) enable super-computer processing at sensor
  - –FPGA's allow post-launch reconfiguration to meet new and changing program requirements
  - –New digital signal processing applications developed on the ground are uploaded to the payload for execution
  - –Tailor processing application to each theater of interest
    - –Algorithms swapped time 1 min

Orbit:

- ♦560 km circ.
- ♦35° inclination
- ♦~10 min target

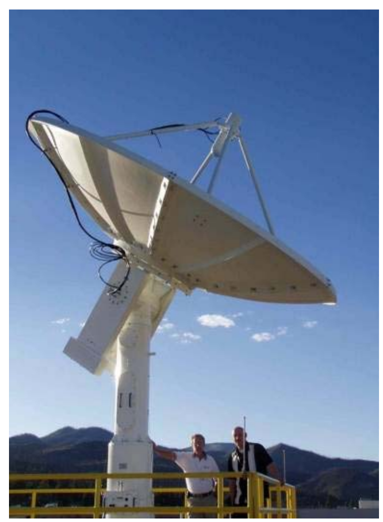


Tasking Algorithms:

- ♦Command Collect-periodic snapshot
  - Calibration and ionospheric studies
- ♦SnapShot Recorder-impulsive detector
  - Self adjusting record lengths
  - Lightning studies
- ♦Narrow Band Recorder
  - Calibration, ionospheric studies & Doppler geolocation
  - More than 3 min continuous collection

CONOPS:

- ♦Store & Forward, 800MB On-board
- ♦Psuedo-Bent-Pipe demonstrations @ LANL



Ground station:

- ♦-Automated GS @ LANL
- ♦-Tasking authority: LANL
- ♦19.2 kbps cmd uplink S-band
- ♦-4Mbps downlink S-Band
- ♦-6 passes: 800MB/day

Los Alamos NATIONAL LABORATORY EST. 1943

CFE QPSK Experiment
(Using ML- LDPC FEC Decoder)

CFE Reconfigurable Receiver

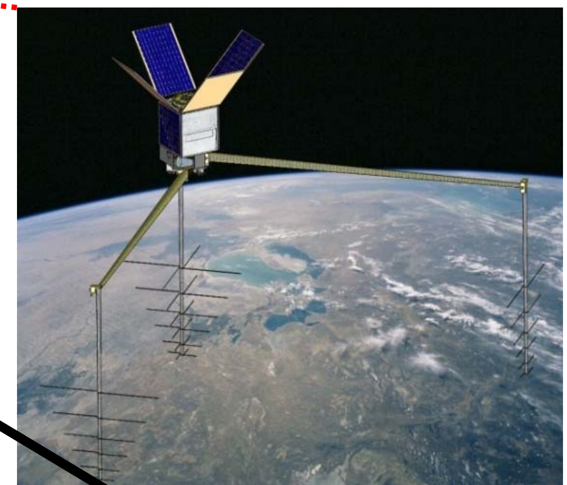
Tx

Decode

QPSK Demod

CFE Bus

4Mbps



500kbps

Workstation

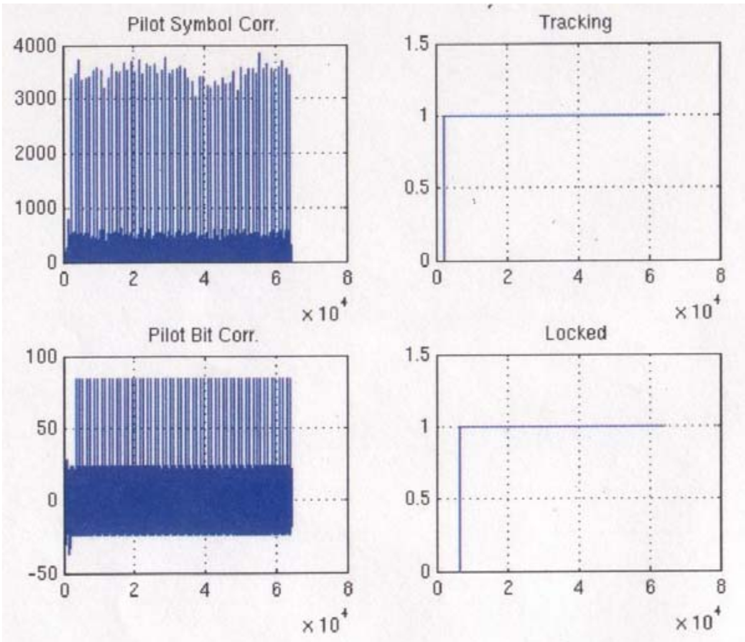
Data (Enet)

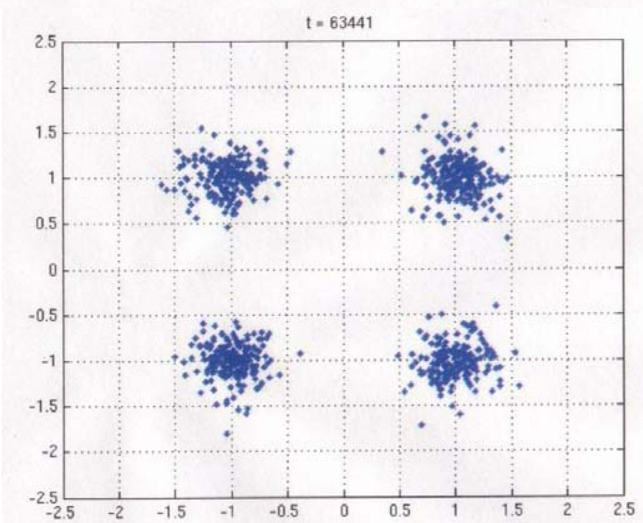
PC Reconfigurable Transmitter

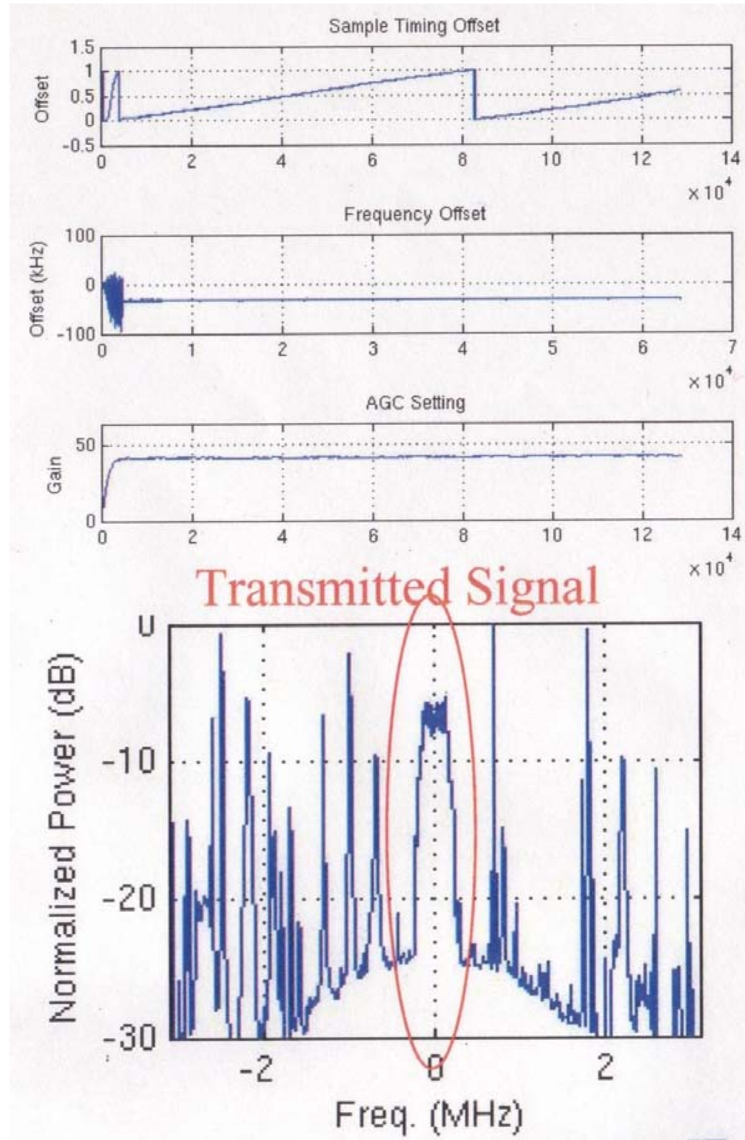
Coding

QPSK Mod

QPSK Experiment(2)







Key Observations

- **Recognition of extreme dynamics of LEO communications link**
  - Traditional approach targets worst case channel conditions but never exploits *best* case – leaving most of the channel capacity unused!
- **Elegant use of adaptability**
  - Use software defined radio concepts
  - Improve channel utilization
- **Complex acquisition algorithms implemented on ground segment**
  - Reduces space segment complexity
  - Exploits FPGA based DSP for extreme performance

Goals

- CubeSat compatible
  - *< 6W peak*
  - *<100x100x30mm*

- Provide 30dB of real-time communications adaptability
  - *Exploits best-case channel conditions*
  - *Robust against anomalies (attitude control)*

- >10x aggregate bandwidth over conventional radio
  - *Maintains optimal bit transmission rate for specified BER for channel*

- >10x improved overall energy efficiency
  - *10x the data for similar energy requirements*

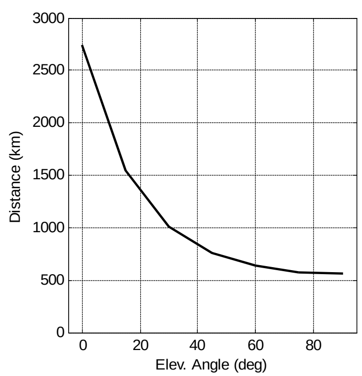
Received Power Dynamics: (86° Peak Elev.)

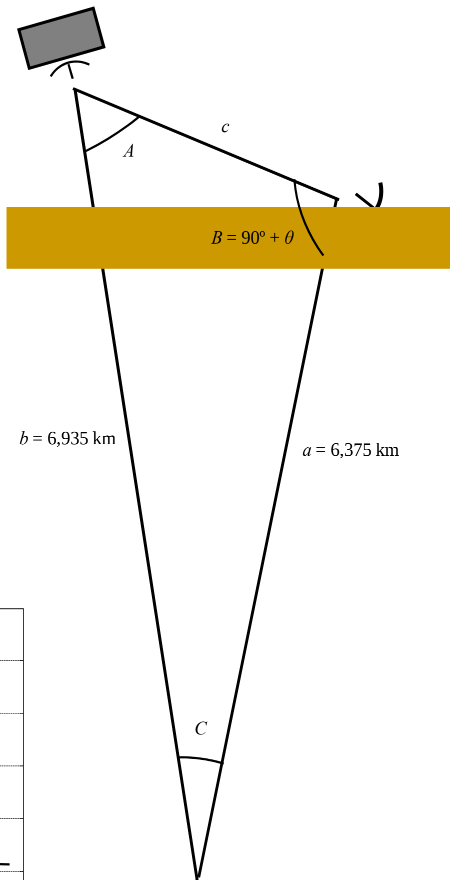
$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

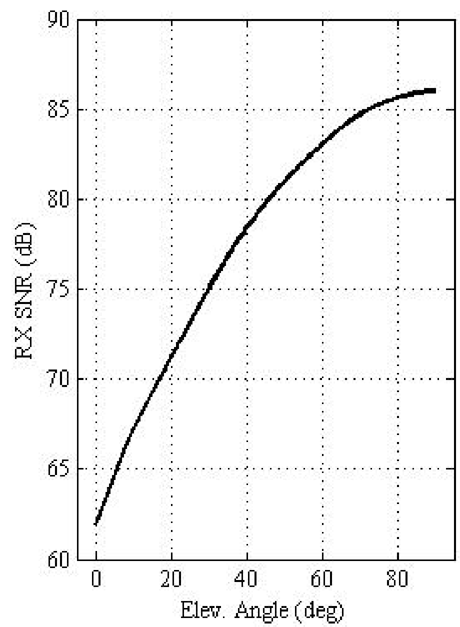
$$A = \sin^{-1}\left\{\frac{a}{b}\cos\theta\right\}$$

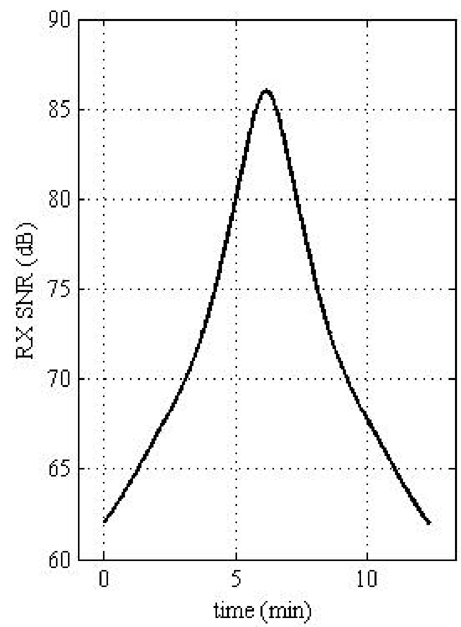
$$c = b\frac{\cos(\theta + A)}{\cos\theta}$$

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







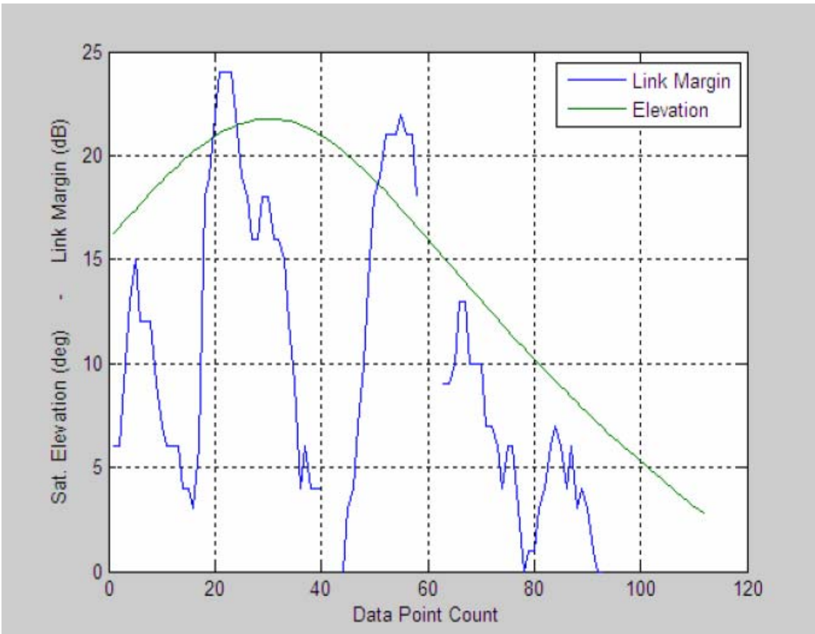


Link Varies* with:

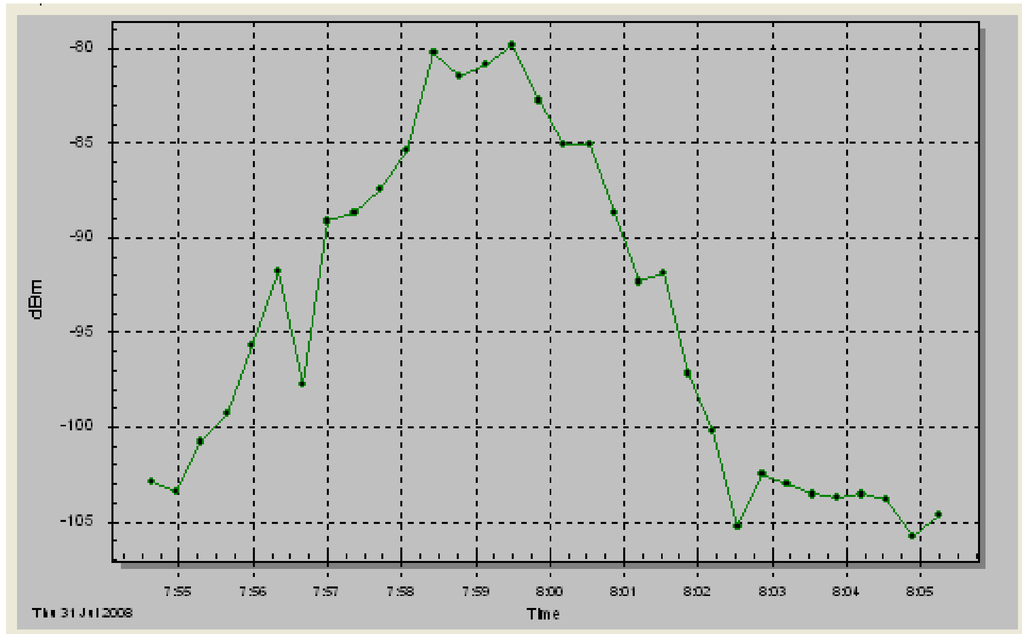
2. Range
3. Antenna pointing
4. Noise Temperature
5. Attitude anomalies
6. Designed for a ‘reference’ ground segment

*Cowley, W., “Performance comparisons for adaptive LEO satellite links”, Int. J. Satell. Commun. Network. 2006; 24:229–239

Measured Link Performance



*GeneSat-1 Link Dynamics**



CFE: Measured RSSI > 80° pass

1. ~25dB of observed variability
2. Consistent with analysis

*Mas, I., Kitts, C., "A Flight-Proven 2.4GHz ISM Band COTS Communications System for Small Satellites", Small Satellite Conference, 2007, Logan UT, paper XI-11.

Link Budget Comparison

	ADAPTIVE RADIO THEORETICAL Best Case (90° ELEVATION)	ADAPTIVE RADIO THEORETICAL Worst Case (0° ELEVATION)	CONVENTIONAL RADIO (5° ELEVATION)
TRANSMITTER			
10 cm patch @ ½ W			
EIRP	**3 dB**	**3 dB**	**3 dB**
RECEIVER			
Antenna gain	30 dB	30 dB	30 dB
Antenna noise temp.	20 K	90 K	55 K
Line temp.	35 K	35 K	35 K
LNBC noise figure	0.8 dB	0.8 dB	0.8 dB
Boltzmann's Constant	228.6 dB	228.6 dB	228.6 dB
G/kT	**238 dB**	**236 dB**	**237 dB**
LOSSES			
Path distance	560 km	2,730 km	2,229 km
Carrier freq.	2.45 GHz	2.45 GHz	2.45 GHz
Propagation loss	-155 dB	-169 dB	-167 dB
Nadir angle	0 deg.	66.8 deg.	66.3 deg.
Misalignment loss	0 dB	-8 dB	-8 dB
Duplexer loss	-1 dB	-1 dB	-1 dB
Line loss	-1 dB	-1 dB	-1 dB
Polarization loss	-1 dB	-1 dB	-1 dB
Misc. losses	-3 dB	-3 dB	-3 dB
Total losses	**-161 dB**	**-183 dB**	**-181 dB**
C/N_0	**80 dB**	**56 dB**	**59 dB**
Minimum E_b/N_0	7.3 dB	7.3 dB	7.3 dB
Link Margin	1 dB	1 dB	3 dB
MAX BIT RATE	**14,791 kbps**	**59 kbps**	**74 kbps**

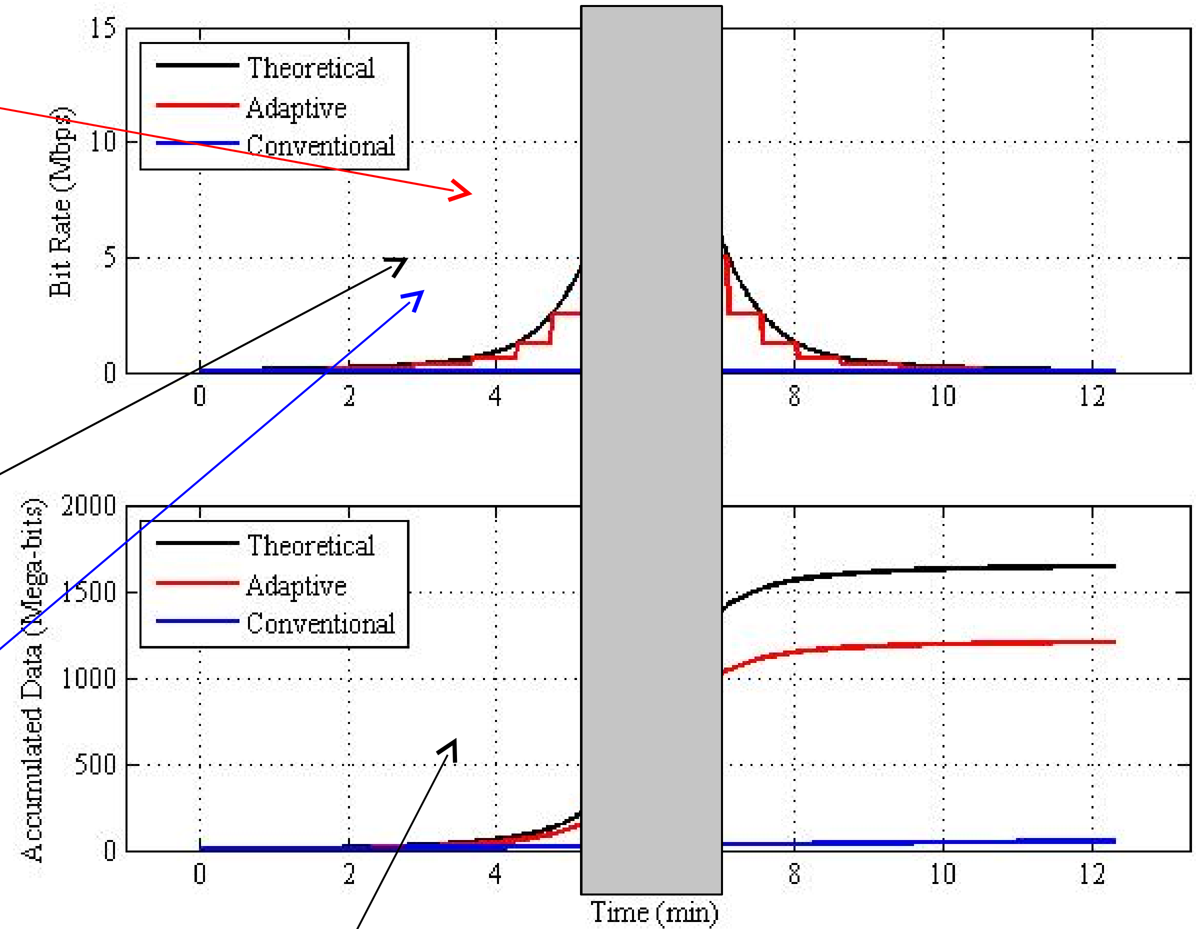
1. 1.5m ground segment dish antenna assumed
2. CFE orbit assumed
3. Link dynamics less severe with increasing altitude

Theoretical Channel Capacity: Exploitation

Instantaneous Capacity

<u>Link Optimization</u>

- Finite number of bit rates
- Peak output limited by
  - computation
  - bandwidth



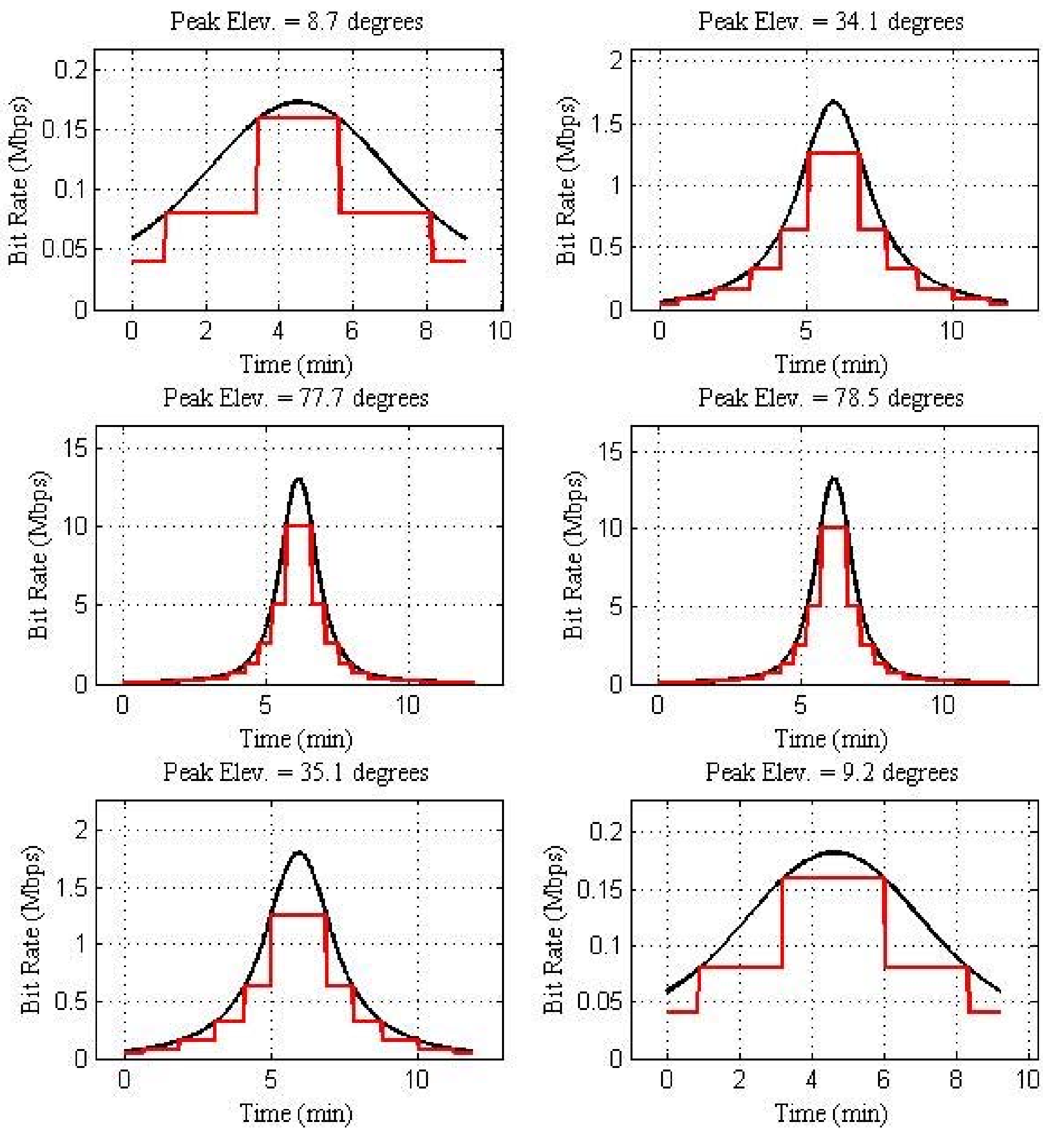
Channel Bandwidth Limit

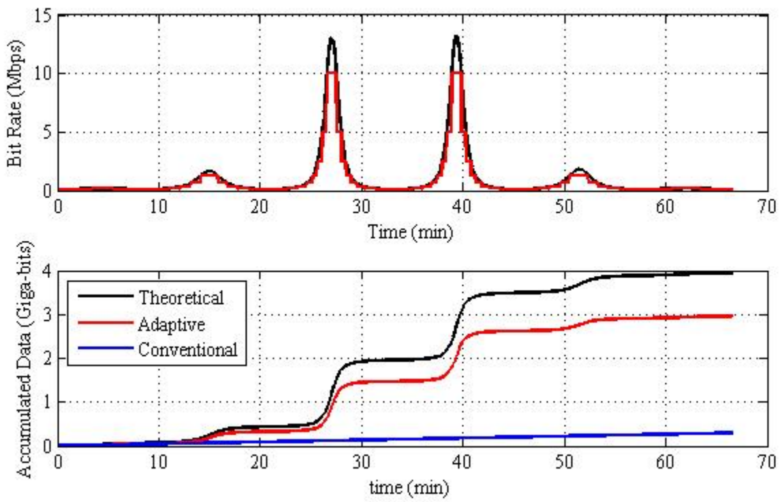
Conventional Radio (Blue)

Accumulated Data

Optimum Period for Energy Efficiency

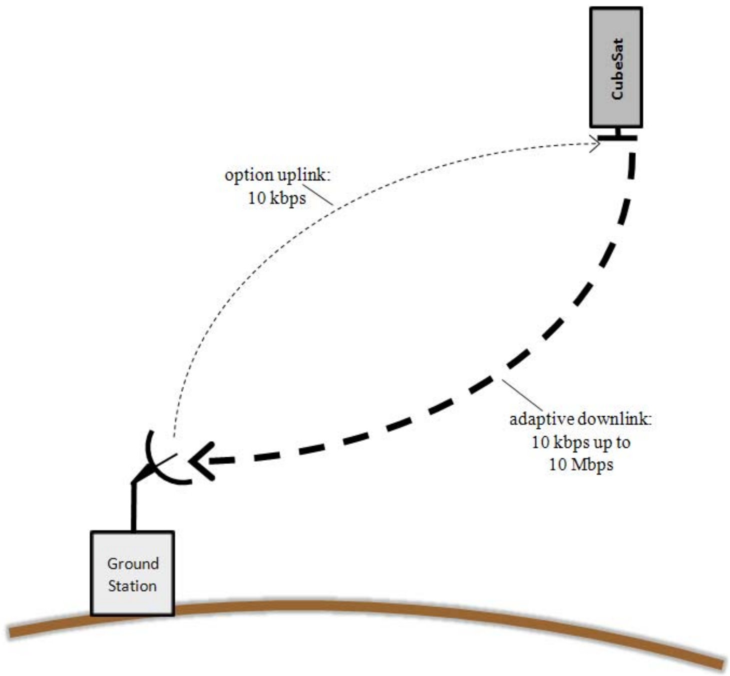
Analysis of Aggregate Link Capacity: 1 Day of CFE





Cumulative Results
6 passes from a day
in the life of CFE
> 10x

Adaptation Concept



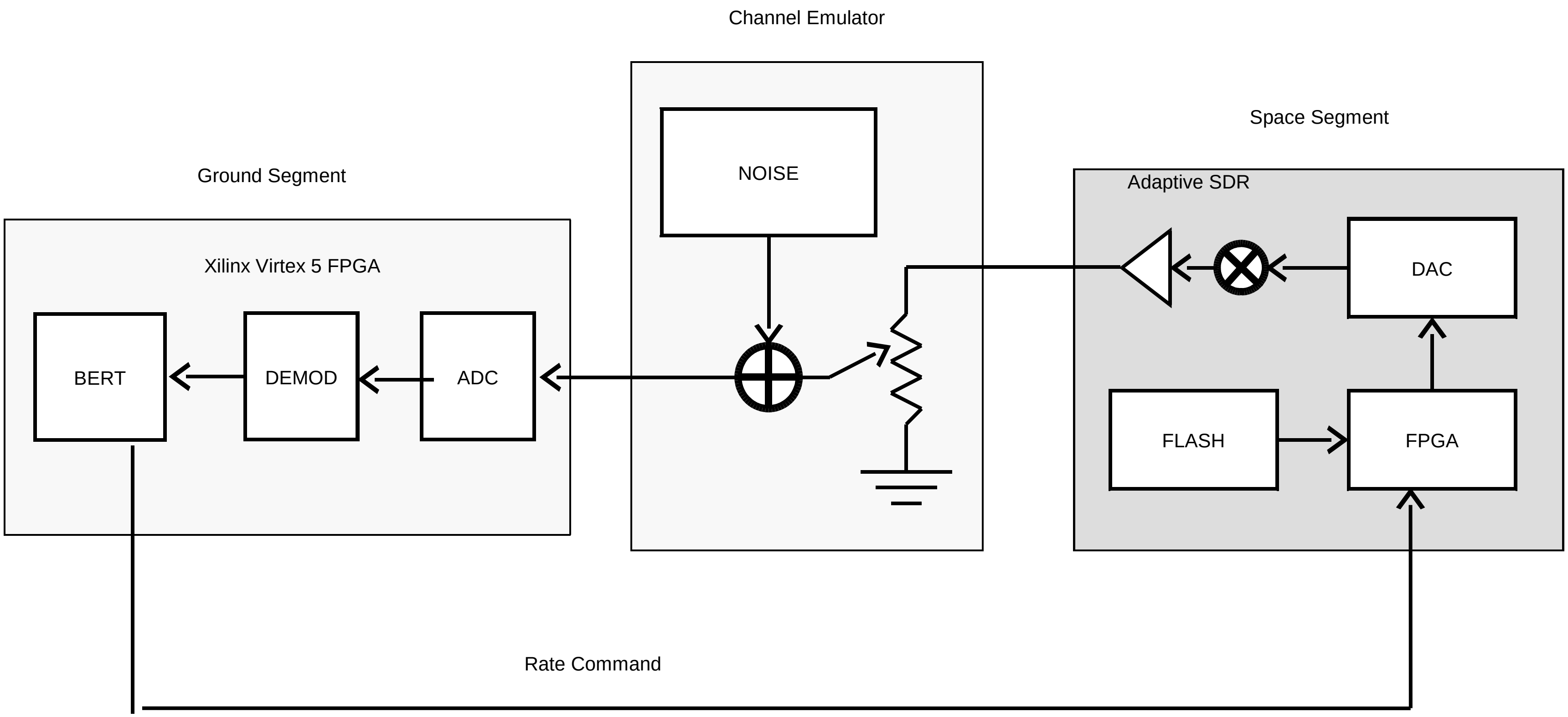
Real Time Handshaking

- Ground Segment Evaluates RX SNR
- Commands space segment to optimum SNR to maximize rate, maintaining nearly constant BER
- Ground segment demodulator does not require rate command knowledge

Forecast

- Based on analysis, buffer rate command changes on space segment
- Execute space segment commands at appropriate time
- No uplink requirement

Proof-of-Concept Experiment



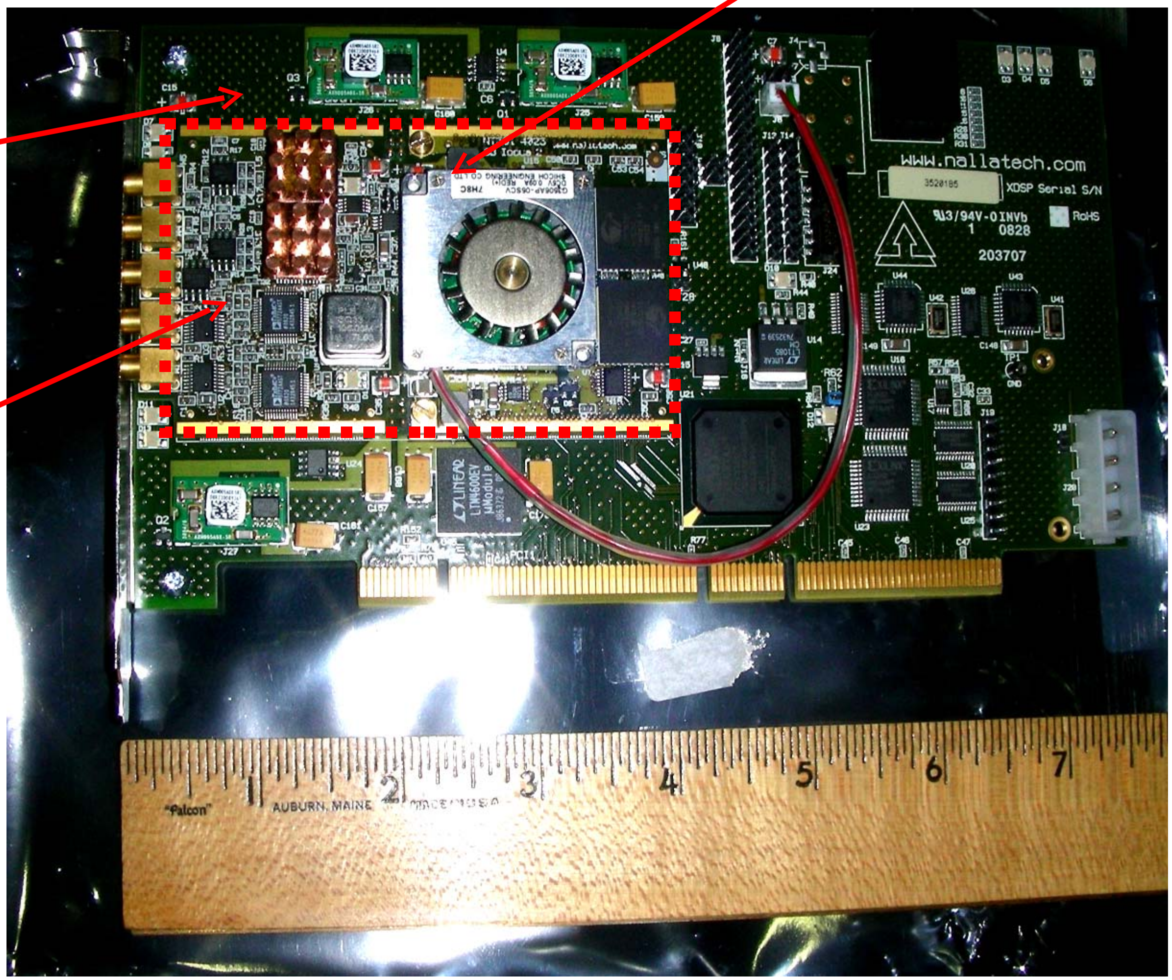
- Experiment implemented in commercial laboratory equipment
- Pseudo random sequence generated in space segment FPGA
- Sequence verified in the ground segment (FPGA)
- Test software varies the channel

Implementation Hardware

FPGA

ADC

DAC



Xilinx Virtex 4/5

Laboratory implementation platform for digital baseband and IF processing.

Current Status & Conclusion

- **Software Defined Radio Potential:**

  Enabling *for high bandwidth* CubeSat missions
  - High performance downlink capacity
  - Extremely energy efficient
  - Robust against anomalies
  - Real-time support for diverse ground stations
  - Responsive to evolving conditions (its almost software defined)
  - Enhancements are both quick and affordable (its almost software)
- **Modeling is complete**
- **Modulator firmware complete**
- **Demodulator firmware in transition (VHDL -> FPGA)**