Advanced Wireless Communications Technologies for Low-Power, Reconfigurable Small-Satellite Radios

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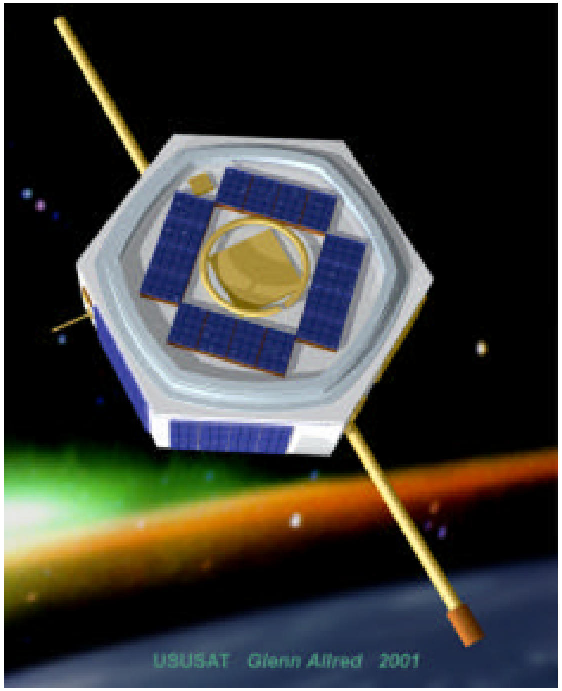
Overview

- Platform-based design approach
  - small satellites in general, their comm. systems in particular
- Candidate wireless technologies
  - High-efficiency and high-linearity power amplifiers
  - Digital and mixed-signal circuits: DSPs, FPGAs, ADCs, DACs
  - Smart antennas
  - Iterative error-correction techniques
  - Cognitive radio
- Modular approach, architectural considerations
- Hardware and software development efforts
- Educational aspects

Platform-Based Design Approach

- Common set of subsystems supports multiple missions
  - different combinations/configurations yield design variants
  - product families assembled as a set of design variants
- Widely embraced by other industries
  - common examples: automobiles, consumer electronics
- Goals
  - reduce development and manufacturing cost and time
  - obtain market advantage by using variants to target different market segments

From SUVs to Small Satellites?



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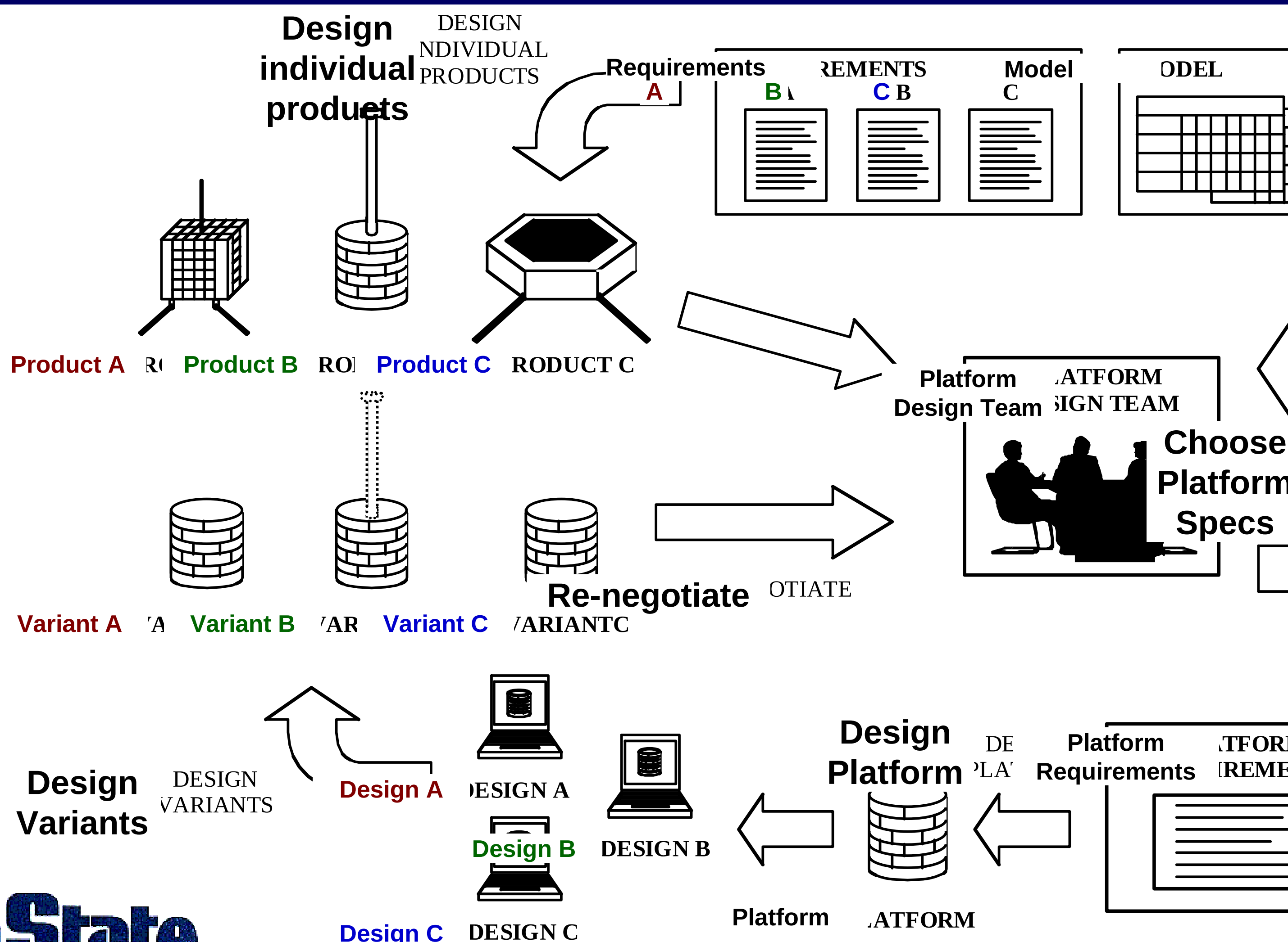
Platform-Based Spacecraft Design

- **Difficulties: How small satellites differ from SUVs**
  - lack of product volume
  - production lag times and rapid technological advancement may make variants obsolescent before subsequent builds
  - reliability requirements-- once on orbit, you can't just swing by the dealer!
- **Solutions**
  - advanced manufacturing processes may make it cost effective to custom manufacture in small quantities
  - low variant lifetimes imply incorporation of latest technological advancements
  - subsystem reuse provides flight heritage
  - low-cost launch allows for replacement instead of repair

Small Satellite Platform Approach



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Platform-Based Small-Satellite Communications Subsystems

- **Modular communications subsystem design approach demonstrated successfully by AeroAstro and SSTL, among others**
- **Goals of this effort:**
  - **take modularity to a very low level**
  - **employ a software-defined radio for flexibility**
  - **exploit modularity to incorporate advanced wireless technologies developed for terrestrial applications**
  - **provide unique educational experiences to Utah State students both in the research lab and in the classroom**
- **Supported by the Space Dynamics Laboratory and the Richard and Moonyeen Anderson Wireless Research and Education Center**

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Candidate Wireless Technologies

- **High-efficiency power amplifiers**
- **High-linearity power amplifiers**
- **Digital signal processors and field-programmable gate arrays**
- **Advanced signal conversion circuits**
- **Smart antennas**
- **Iterative error-correction techniques**
- **Cognitive radio**

Power Amplifiers

- Can greatly impact peak- and orbit-averaged power consumption on small satellites
- Inefficient amplifiers complicate thermal design
- More efficient high-linearity power amplifiers
  - required for applications with high envelope dynamic range
  - leverage linearization techniques developed for CDMA handsets
  - can make bandwidth-efficient modulation possible on small sats
- High-efficiency nonlinear power amplifiers
  - nonlinear amplifiers acceptable for some applications where a constant-envelop modulation scheme is used
  - take advantage of tremendous improvements in semiconductor devices and low-loss lumped elements
  - exploit huge investment in low-voltage high-efficiency amplifiers

Digital and Mixed-Signal Circuits

- **Digital signal processors and field-programmable gate arrays**
  - **smaller devices, reduced bias voltages, lower power consumption**
  - **continuously becoming more capable and power efficient on a per-operation basis**
- **Signal-conversion circuits pervasive in consumer electronics products**
  - **many specifically designed for low-power applications**
  - **higher sampling rates, greater precision, lower power consumption, and/or smaller packages**
- **Rapid evolution due to massive consumer electronics markets, including wireless industry**
- **Essential to develop an architecture that allows for these new components to be integrated rapidly as they emerge**

Smart Antennas

- Problems addressed by smart antennas
  - small satellites can rarely afford gimballed reflectors
  - undesirable to rely on spacecraft attitude control system for antenna pointing
  - wide-beamwidth antennas constrain link budgets, pose interference hazard to other users
- Smart antennas employ arrays of elements, signal processing in both space and time
  - provide electronic beam-steering for transmit and receive
  - useful for receive-side interference mitigation on uplink, although adaptive techniques are computationally intense
- Phased arrays are inherently modular systems
- Technology developed for next-generation terrestrial wireless systems due to billion-dollar spectrum costs

Iterative Error-Correction Techniques

- Two examples: turbo and low-density parity-check codes
- Near Shannon-bound performance possible
  - requires long block lengths, near-perfect synchronization
- Very well suited for small-satellite downlinks
  - low transmit-side (coder) implementation complexity
  - highly complex, computationally intense decoder can be implemented terrestrially
- Can typically achieve 5 to 9 dB of coding gain
  - depends on specific implementation
  - synchronization requirement limits received SNR lower bound, but receiver complexity can be exchanged for *some* reduction in downlink transmit power
  - iterative synchronization techniques emerging to solve this

Cognitive Radio

- Defined as the ability to adapt to changing link conditions and spectrum availability
- Major market forces pushing for optimum use of terrestrial spectrum
- Spectral congestion increasingly problematic for space-born communications, as well
- Excellent application for small-satellite downlinks:
  - use modular radio with both high-linearity and high-efficiency power amplifiers, switchable
  - use constant-envelope waveform, high-efficiency PA, and lower bit rate when limited link margin is available (e.g. near horizon)
  - use linearized PA, bandwidth-efficient modulation scheme, and higher bit rate (in same bandwidth) when link conditions allow
  - optimal use of both spectrum allocation *and* available power

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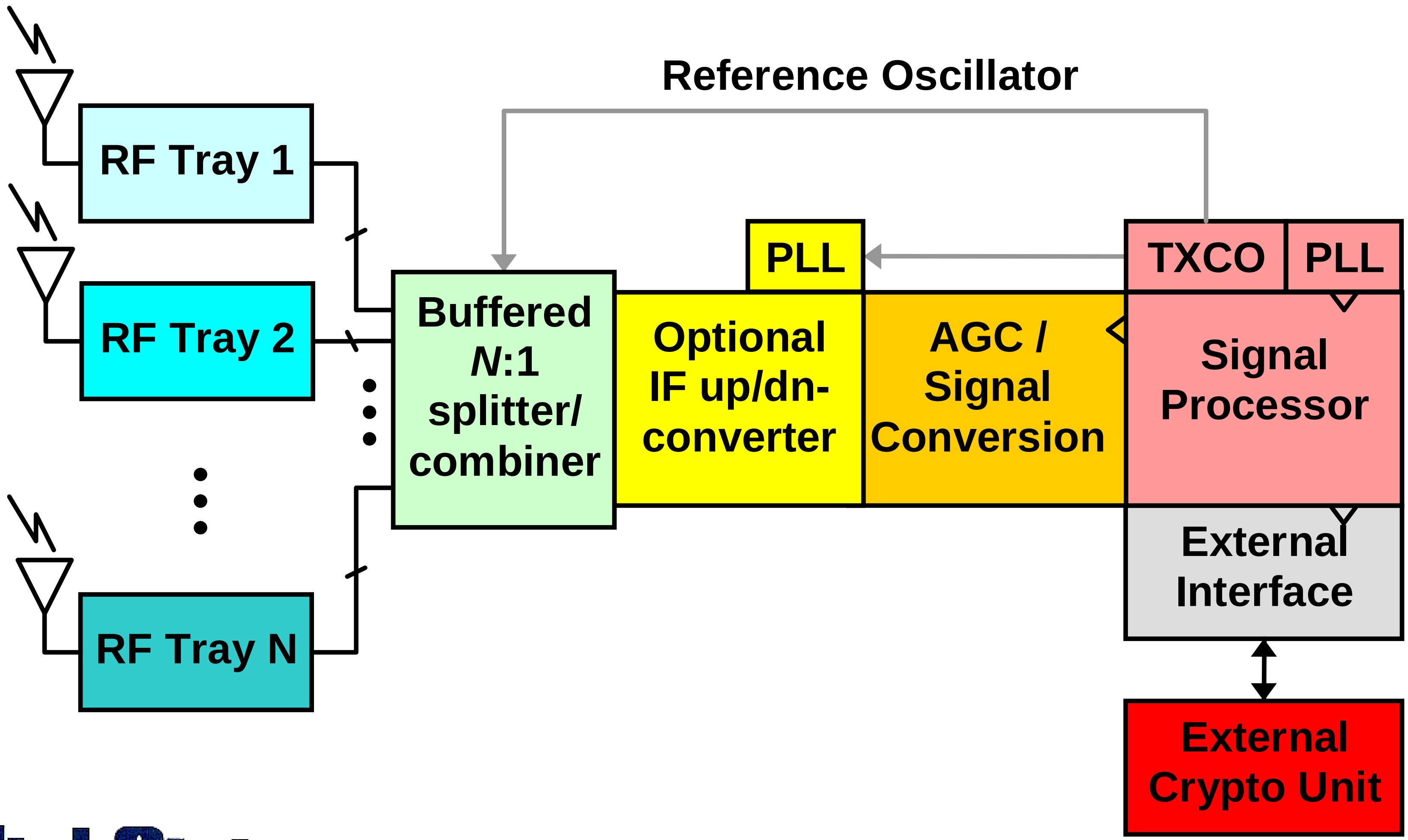
Radio Architecture



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Modularity

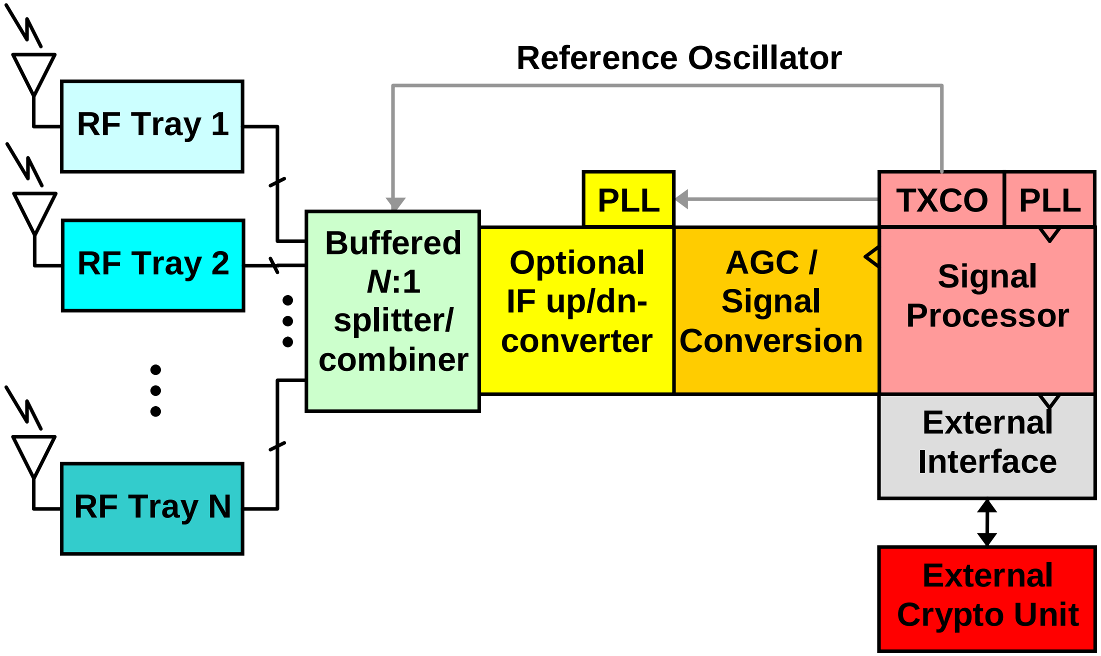
1) Makes more variants possible for less developmental overhead and

and

2) Minimizes the amount of redesign required to inject new technologies into existing radios

Architectural Considerations

- Allow for rapid integration of new circuit technologies
- Support a variety of signal conversion methodologies
- Provide a range of options for redundancy and fault tolerance
- Standardize interfaces and footprints as much as possible
- Allow for an additional level of modularity in the RF trays
  - customization is particularly critical here (many variants)
  - develop a wide range of reusable modules, establish heritage



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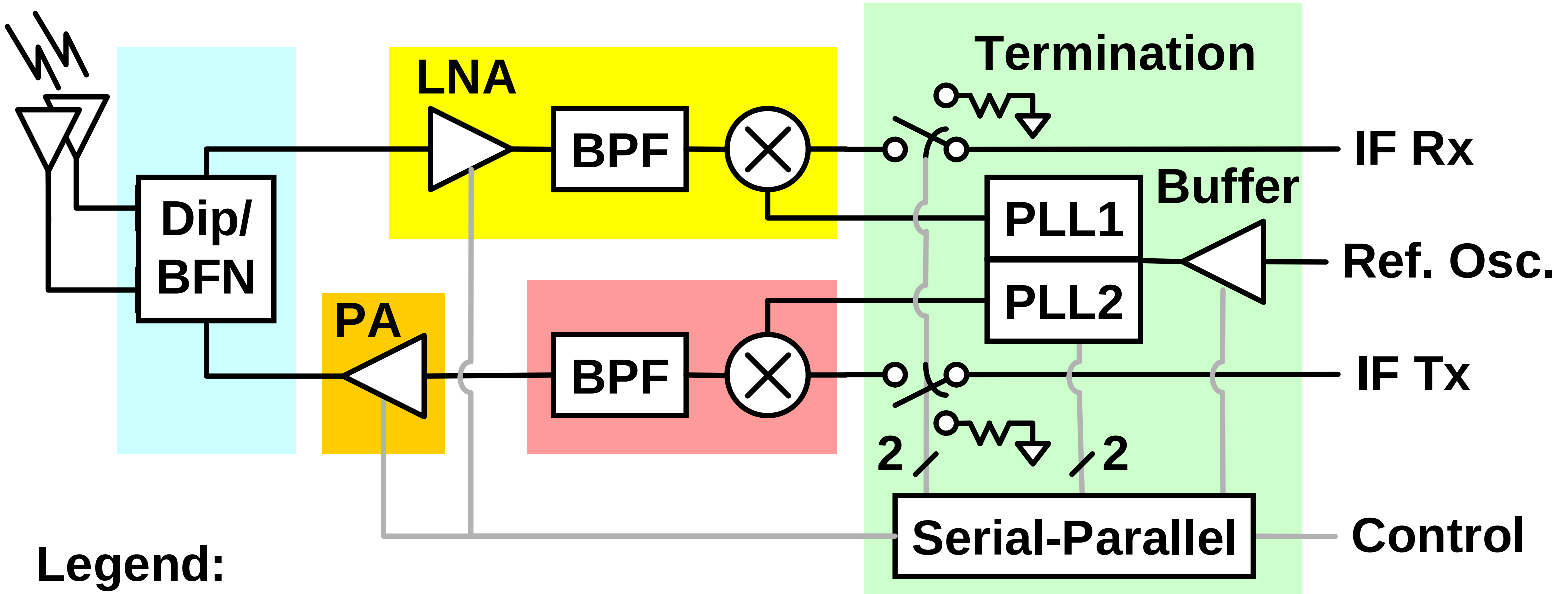
Example Full-Duplex RF Tray



Legend:

- Antenna interface module (diplexer and beamforming net.)
- Power amplifier module
- LNA/RF downconverter module
- RF upconverter module
- RF tray interface module (control signal distribution, local oscillator generation, and solid state switches)

Hardware Development Effort

- **Initial efforts focusing on high-efficiency PAs, modules for software-defined radio**
- **Starting with off-the-shelf components as placeholders, for example:**
  - **PC with ADC/DAC card, real-time processing**
  - **off-the-shelf LNAs, diplexers, oscillators (synthesizers)**
- **Will address interfacing, mechanical design, and EMI/EMC issues**
- **Do not intend to develop flight hardware in near term**
  - **will assemble a range of modules, build and characterize the performance of several variant radios**

Software Development Effort

- **Will support a wide range of modulation formats, bit rates, error-correction coding schemes**
- **Not undertaking effort to provide network-level functionality at this point**
- **Need software for both space and ground segments for hardware validation**
- **Intend to employ commercially-available and open-source tools where possible, such as**
  - **RT Linux for ground station processor**
  - **MathWorks / Xilinx System Generator for FPGA design simulation and implementation**
  - **DSP code generators**

Educational Aspects

- Excellent hands-on experience for graduate and undergraduate research assistants
- Many components will translate directly into classroom examples, laboratory activities
  - electromagnetic theory, microwave engineering, and satellite communications courses, among others
  - make use of Anderson Wireless Center educational laboratory
- Software-defined radio a particularly useful tool
  - demonstrate envelope distortion in nonlinear PAs, for example
  - makes it possible reinforce communications theory with practical hardware experience, e.g. observing & measuring bit error rates
- Generate excitement, produce engineers with a better understanding of the concepts industry needs

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Conclusions

- Advantages of a platform-based design
  - cost and schedule benefits
  - market advantage
  - wide range of possible variants, including those using latest wireless technologies
- Small satellites should leverage circuit and signal processing advances made by the wireless industry
- We are developing hardware and software testbeds to this end using highly modular, platform-based designs
- Significant educational impacts

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