JTRS FREQUENCY EXTENSION BEYOND 2GHZ AND SATCOM-ON-THE-MOVE (SOTM)

using Superconductor MicroElectronics

-- *a quantum leap in performance*

Jack Rosa (HYPRES Inc., jrosa@hypres.com)
Deep Gupta (HYPRES Inc., gupta@hypres.com)
Wes Littlefield (HYPRES Inc., wlittlefield@hypres.com)

HYPRES, Inc.
175 Clearbrook Road
Elmsford, NY 10523-1101 USA
914.592.1190 / 914.347.2239 (fax)
www.hypres.com

MILSATCOM Transformation Using HYPRES SME Technology

Next Generation MILSATCOM:

- **Enables JTRS SCA compliance > 2 GHz**
- **With << ½ the antenna sizes**
- **At < < ½ the terminal cost**
- **With “six-sigma” availability**
- **And, > twice the capacity**

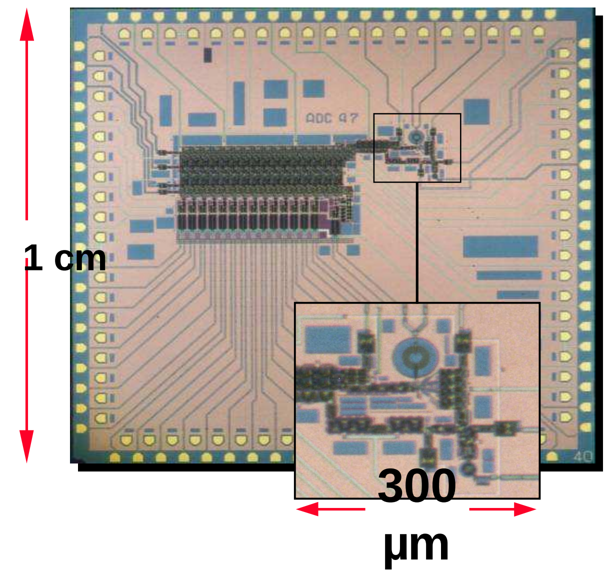
HYPRES technology offers the unprecedented potential to revolutionize MILSATCOM

HYPRES

• Superconducting MicroElectronics (SME) Technology

Demonstrated 15-bit ADC Chip

SME is an enabling technology that allows for digital signal processing directly in the RF domain (.1 to 55 GHz)



ADC chip: quantizer & digital filter

HYPRES

Fundamental Features of Superconductivity

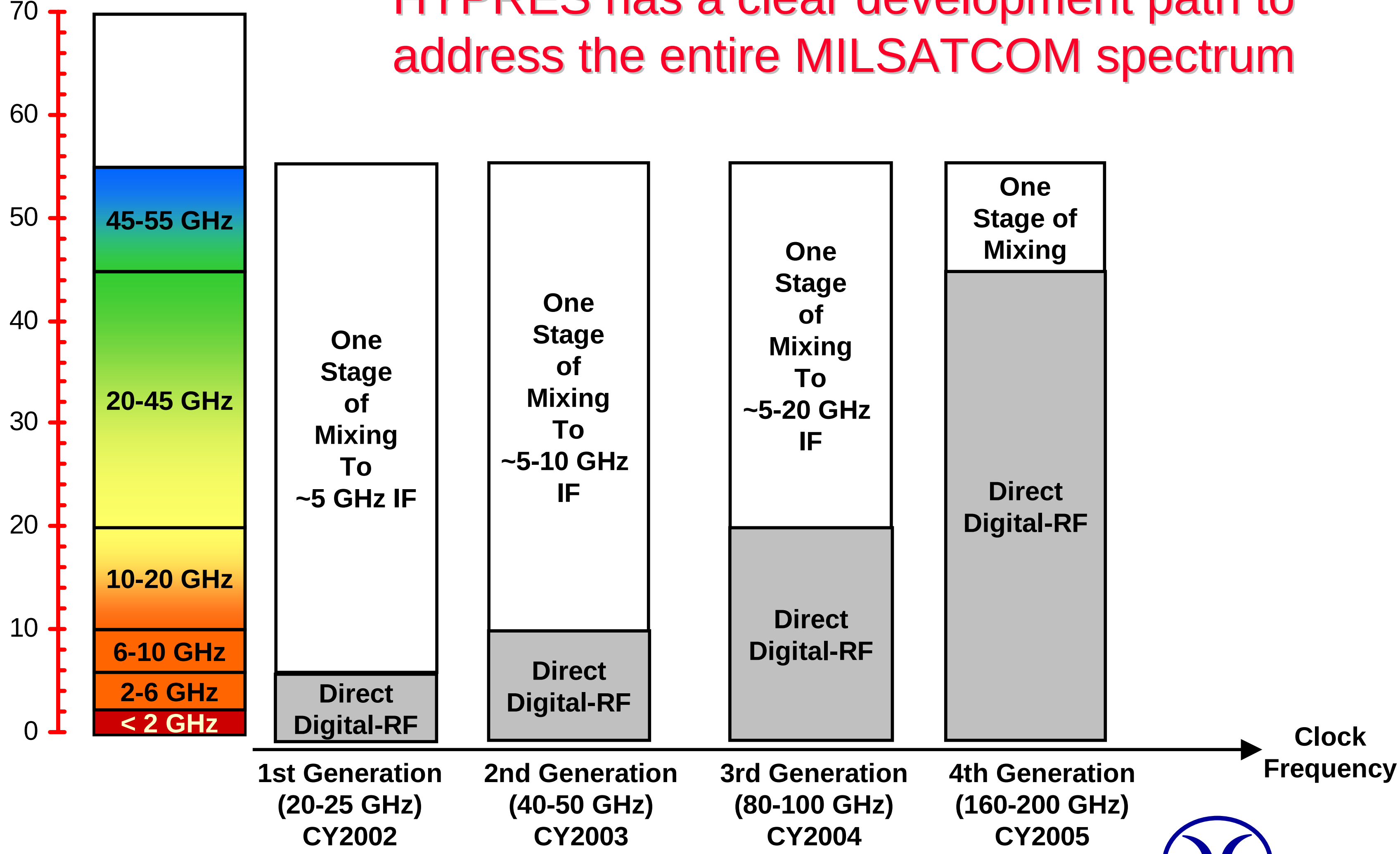
❖ **Ultra-high Sensitivity**	*capable of detecting energy of h/2 (magnetic equivalent of an electron)*
❖ **Quantum Accuracy**	*5ppb accuracy at 10V is achieved*
❖ **Ultra-High Speed**	*~1ps time constants for 3 um process extendible to 0.1ps for 0.4 um process*
❖ **Ultra-Low Power**	*pW dissipation in gates and mW in VLSI*
❖ **Extremely Low Noise**	*virtually no noise*
❖ **Ideal Interconnect**	*negligible loss, dispersion, and crosstalk*
❖ **High Speed RSFQ Logic**	*RSFQ logic gates have been demonstrated above 750 GHz. RSFQ is projected to extend up to 250 GHz in VLSI structures.*
❖ **Simple Fabrication**	*~10 steps, no expensive operations*

No Other Technology Has All These Features

HYPRES

HYPRES Direct Digital-RF Technology Growth

HYPRES has a clear development path to address the entire MILSATCOM spectrum



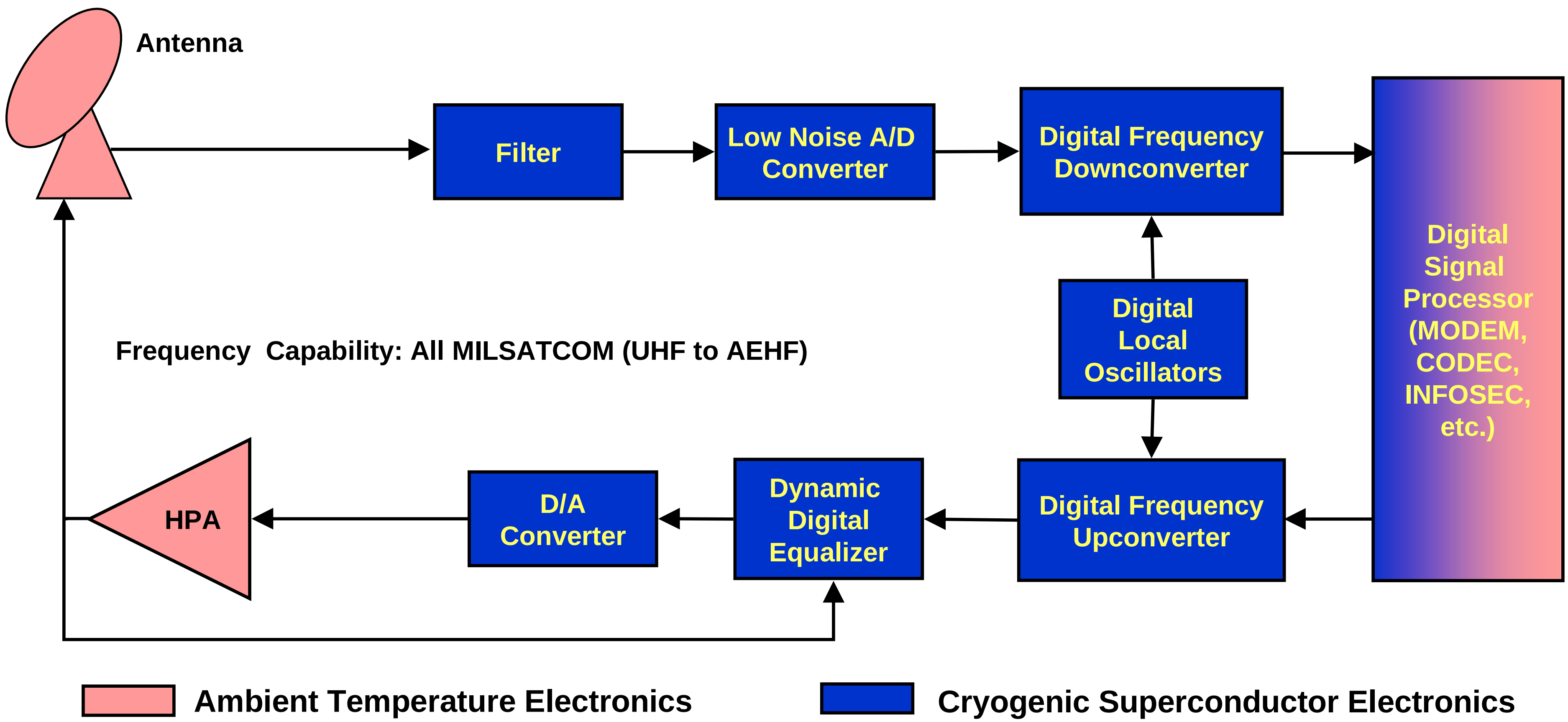
HYPRES

Advantages of Superconductive All Digital-RF Receivers

- **Digital-RF: Direct broadband digitization at RF**
  - **Replacing frequency-specific, noisy, nonlinear analog components with general-purpose, flexible, and noise-resistant digital components**
    - No analog mixers (less distortion)
  - **Single receiver digitizes a broad band with multiple channels**
    - Channelization done digitally (No I-Q imbalance)
- **High-sensitivity and high SFDR**
  - **More sensitive than any semiconductor front-end**
  - **Reduced receiver noise temperature**
  - **Much higher G/T-- typical improvements of 3 to 8 dB**

HYPRES

HYPRES SME All Digital-RF MILSATCOM Transceiver

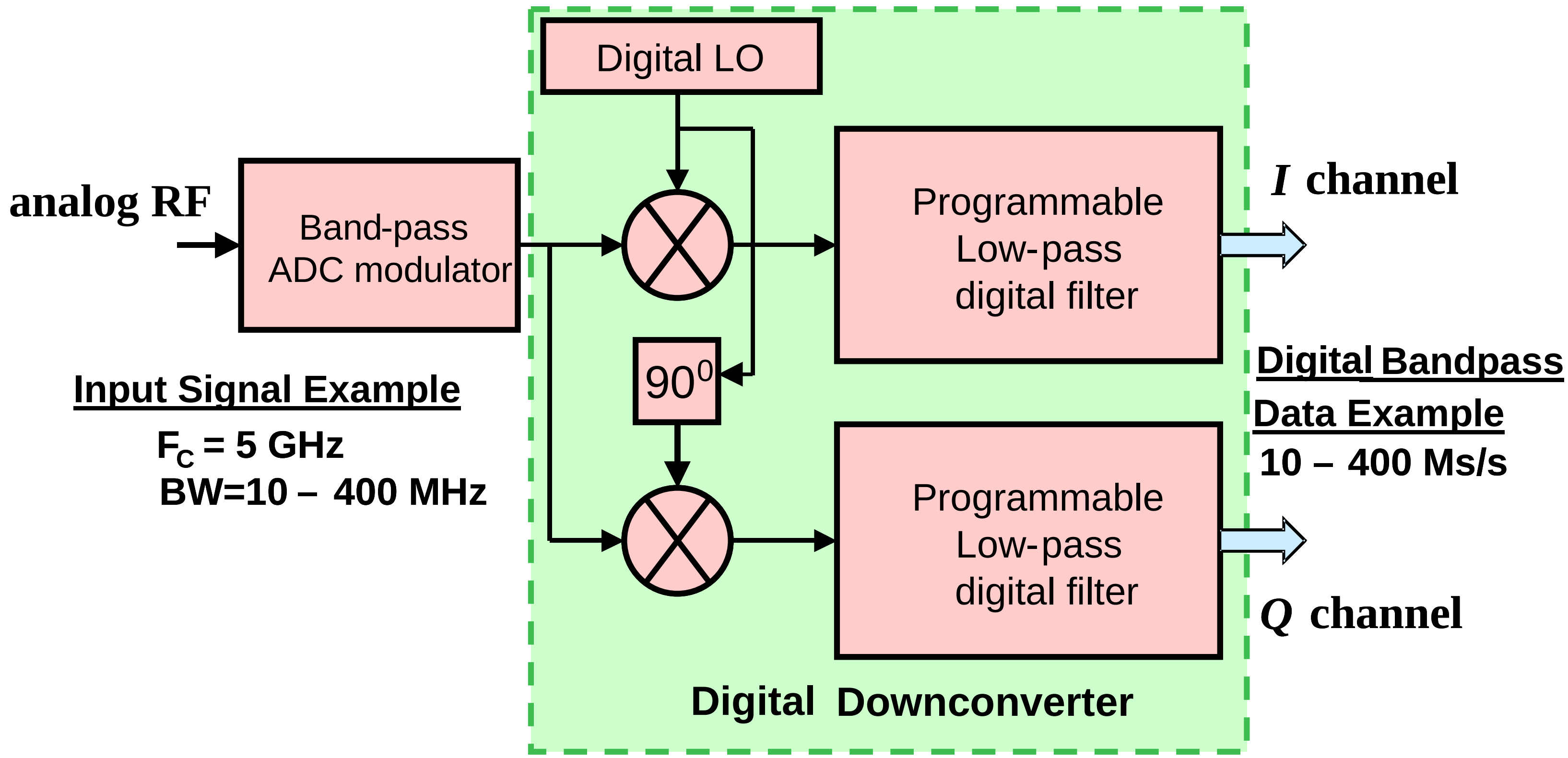


Direct Conversion & DSP at RF ⇒ No Analog Mixing/Amplification

SME = Superconductor MicroElectronics

HYPRES

Programmable Band-pass ADC and Digital Down Converter

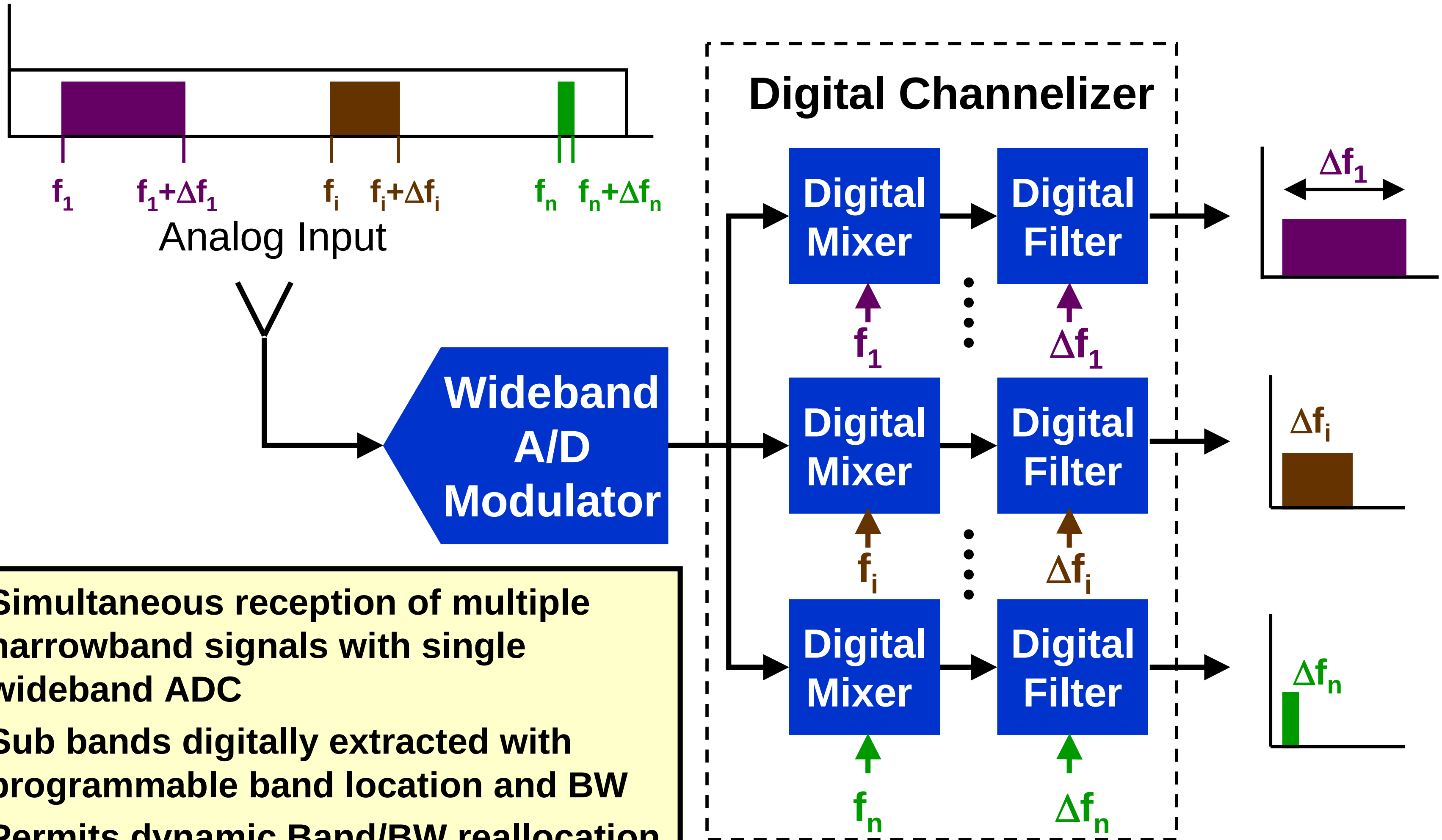


- **Dynamically Programmable Center Frequency**
- **Dynamically Programmable Bandwidth**

5 Ghz CF Digital Downconverter under development

HYPRES

Digital-RF Channelizing

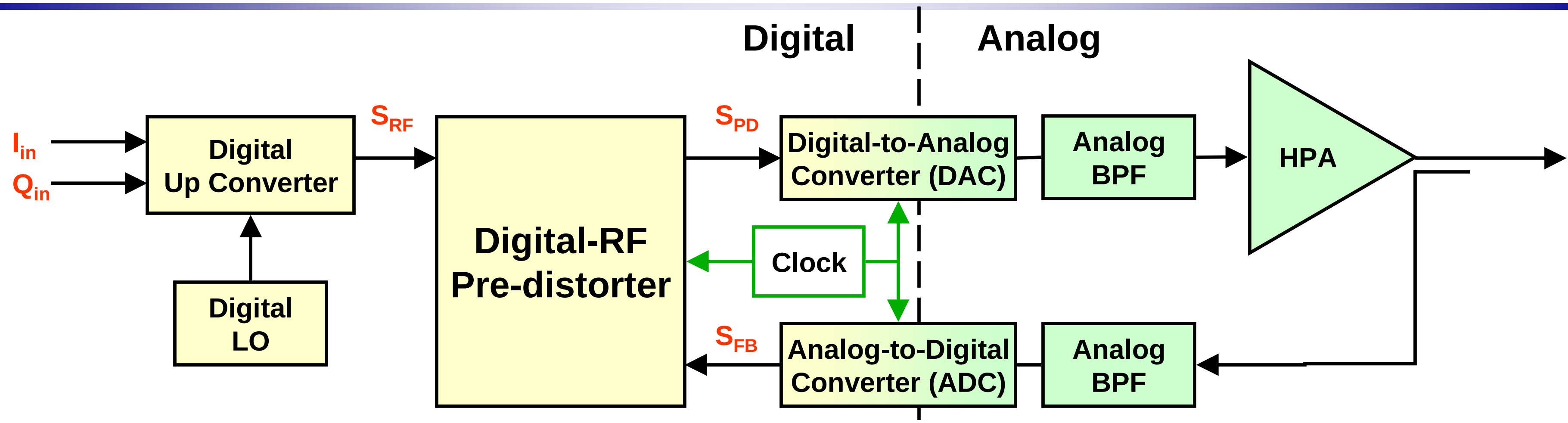


- Simultaneous reception of multiple narrowband signals with single wideband ADC
- Sub bands digitally extracted with programmable band location and BW
- Permits dynamic Band/BW reallocation

A wideband channel can be parsed as multiple narrowband channels for additional filtering

HYPRES

Power Amplifier Linearization

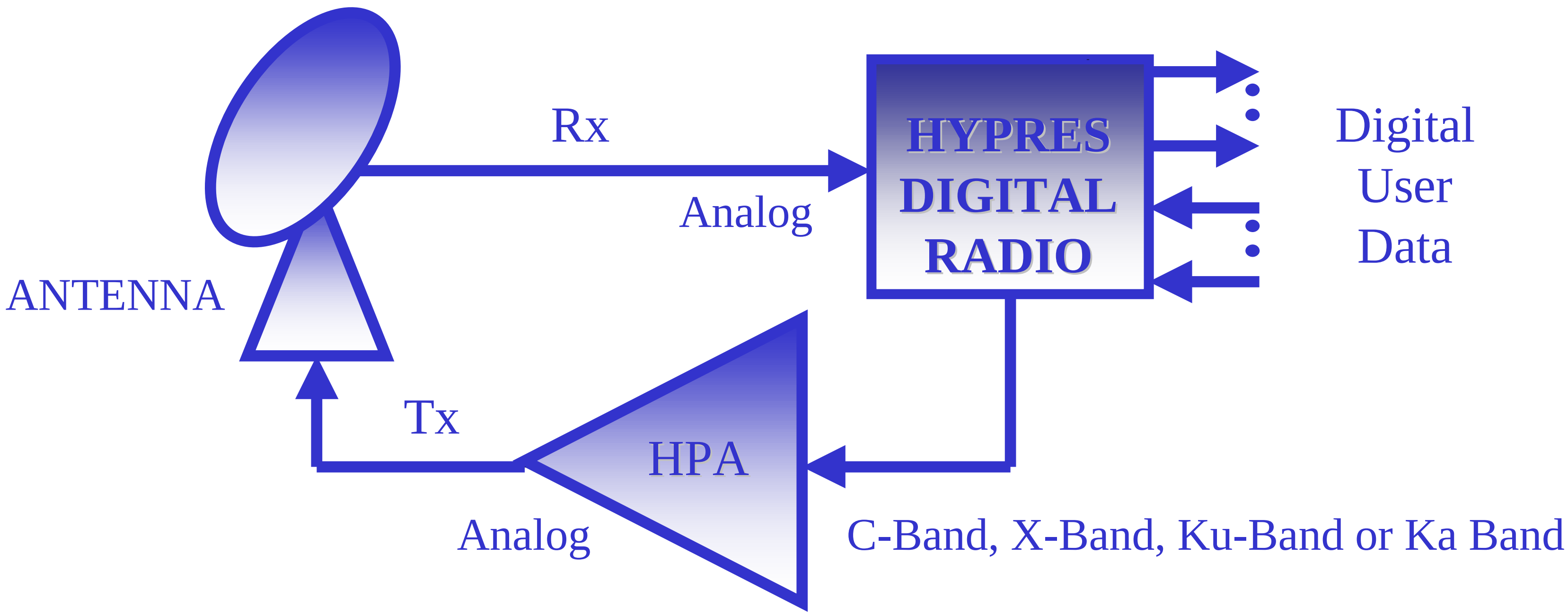


- ❑ Near real-time true digital Adaptive Linearization at RF
- ❑ Combines the advantages of
  - Digital baseband predistorters (Enhanced DC-to-RF efficiency)
  - Feed-forward amplifiers (Low distortion)
- ❑ Frequency (& Data Rate) independent to >0.2 Clock Rate
- ❑ Efficiency enhancement up to the inherent limit of the HPA

One HPA Covers Wide Bandwidths Consuming Less Power

HYPRES

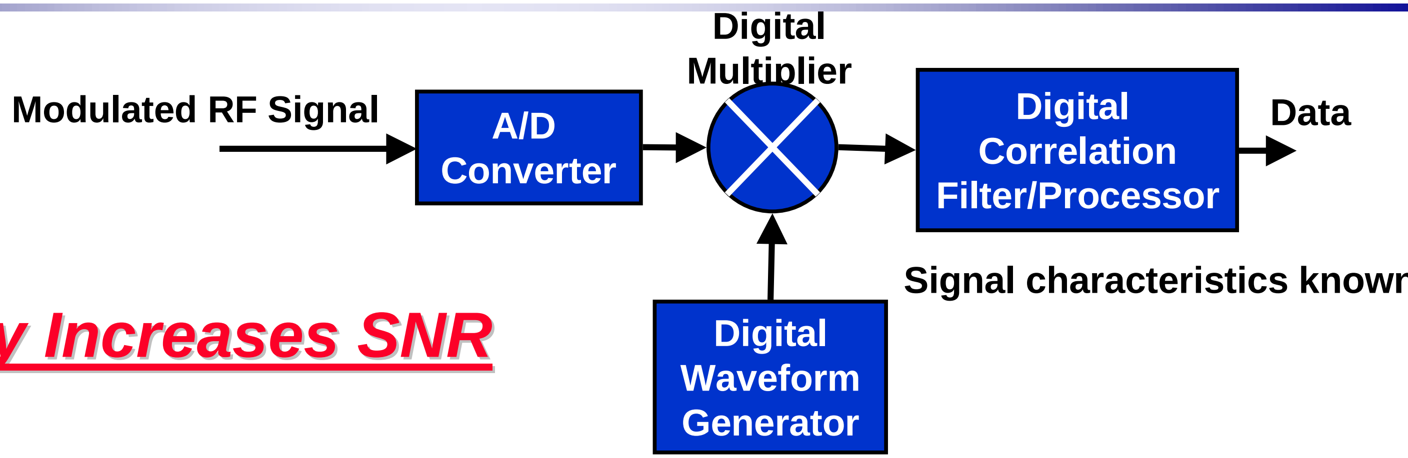
The Simplified SATCOM Digital Earth Terminal



Technology exists today to build a true direct digital radio at frequencies up to 6 GHz. Our 2nd generation product is extending this beyond 10 GHz. Technology limitation is > 55GHz.

HYPRES

HYPRES SME Correlation-Based Receivers Provide Optimum Performance in the Digital-RF Domain



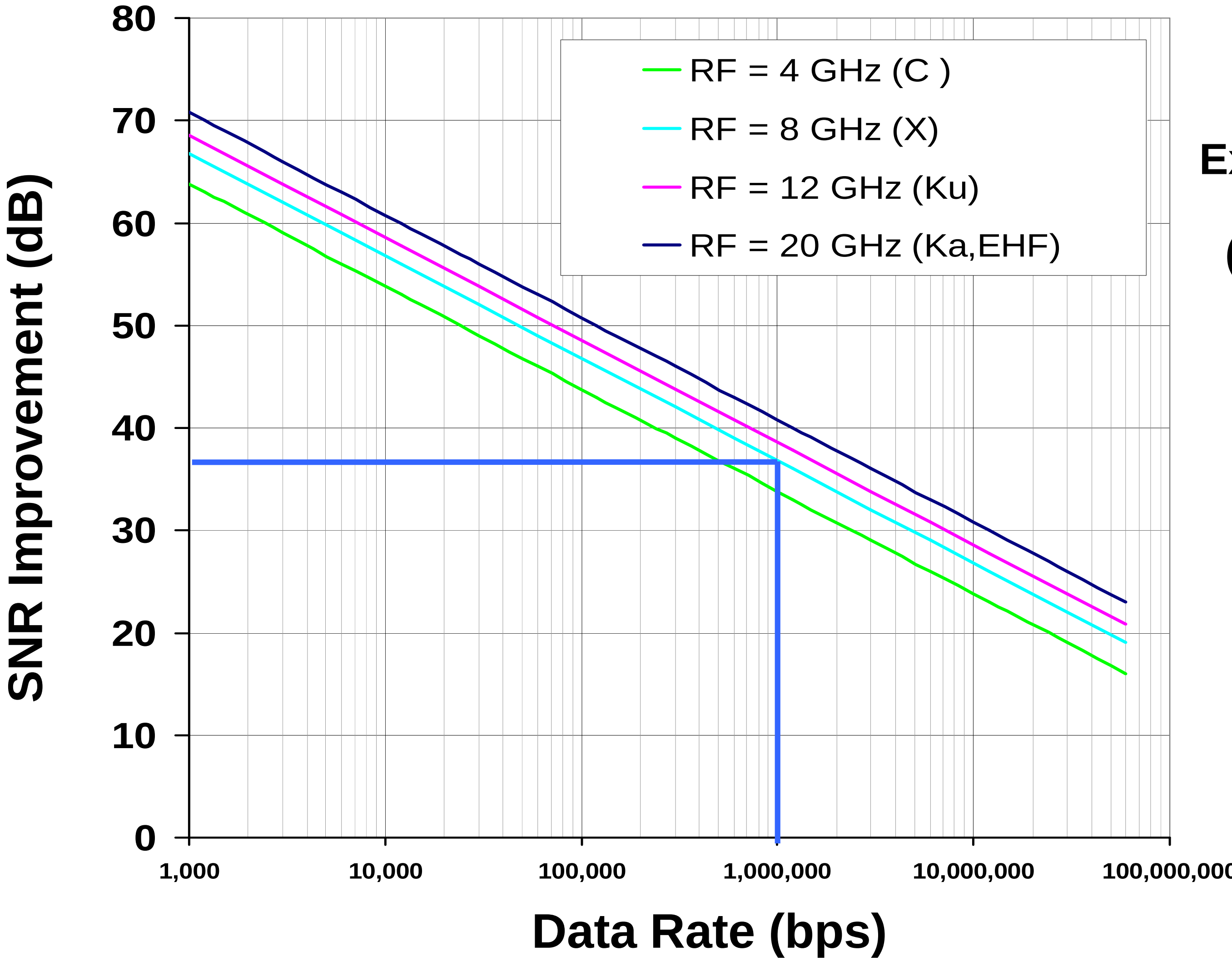
Significantly Increases SNR

- **Uses matched waveform to perform digital filtering (correlation) in both the time and frequency domain achieving maximum receive efficiency**
- **Hardware is not specific to any analog/digital modulation (FM, PM, MPSK, etc.) or multiple access scheme (FDMA, TDMA, CDMA, etc.)**
- **Real-time Correlator combines functions of downconversion, demodulation, and decoding ➡ Direct RF Digital Demodulation in one unit**
- **Rapid Φ locking to RF carrier permits tracking of signals with time varying phase and frequency: Tx drift, Doppler-shift, signal hopping, etc.**
- **Processes out (suppresses) un-correlated noise/interference over repetitive samples; i.e., significantly increases the system SNR**

HYPRES

SME Enables the (previously unattainable) Principles of Correlation Gain for High Speed Communications

Digital-RF Correlation Gain = (Correlation Time) X (RF Frequency)



Ex: Data Rate = 1Mbps, Corr. Time = .6µsec (60% of data period), RF Freq. = 8 GHz, Correlation Gain = 4800 or 36.8 dB

Near Real Time Correlation Gain

HYPRES

Application of SME Benefits to MILSATCOM

- **Much Higher G/T- typical improvements of 3 to 8 dB**
- **Enables use of optimum digital correlation techniques to increase S/N performance-improves satellite bandwidth utilization & user data rates while reducing antenna & HPA size**
- **Linearization of a near-saturated HPA allows for lower power sizing- Typical improvements of 3 to 6 dB**
- **More tolerance on systems parameters such as frequency drift**
- **Elimination of thermal and spurious noise generating analog frequency converters**

Correlation gains of 20 to 40 dB with G/T improvements of 3 to 8 dB, more than double system capacity, with plenty of system margin for interference/jamming/blockage

HYPRES

HYPRES SME TECHNOLOGY Provides Dramatic Impact on Terminal Sizing

Reflector Terminals

• Improved G/T: SME has negligible thermal noise: "LNA" < 10°K compared to 130°K (@ 20 Ghz)

•Improved EIRP: Ultra-Linearized HPA operates without back-off

•Reduced SNR: Correlation based receivers suppress noise 20 dB to 40 dB

Phased Array Terminals

• Improved G/T: SME has negligible thermal noise: "LNA" < 10°K compared to 285°K. Plus increased gain through improved beam focus

•Improved EIRP: Ultra-Linearized HPA operates without back-off. Plus increased gain through improved beam focus

•Reduced SNR: Correlation based receivers suppress noise 20 dB to 40 dB

SME Technology Reduces Terminal Size

HYPRES

HYPRES SME TECHNOLOGY Provides Dramatic Impact on Information Throughput

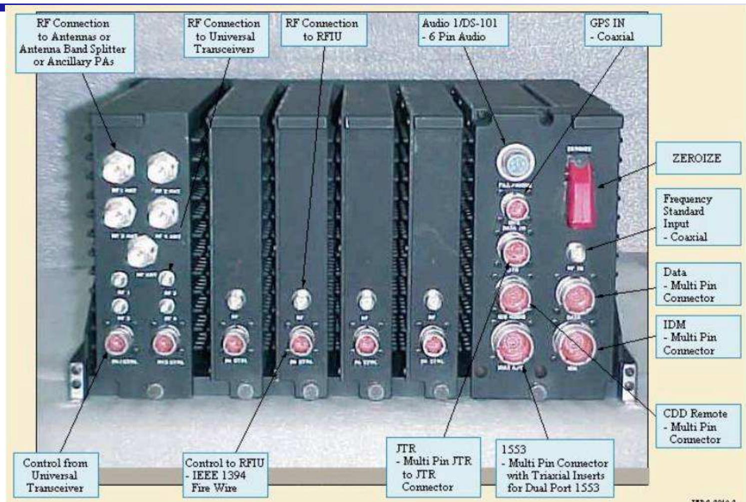
Theoretical Noise Improvement Needed to Double Information Capacity

Modulation Technique	QPSK	16PSK
Capacity, R/W (Bit Rate/Bandwidth, BPS/Hz)	2	4
Required Eb/No @ 10^{-5}BER (Theoretical, Uncoded)	9.8dB	18.3dB
Additional Power Needed for double the information rate		3.0dB
Total Noise Improvement Needed to double the information rate		(18.3-9.8) + 3.0 = 11.5dB

Correlation Gains of 20 to 40 dB with G/T improvements of 3 to 8 dB <u>more than double system capacity</u> with plenty of system margin for interference/jamming/blockage

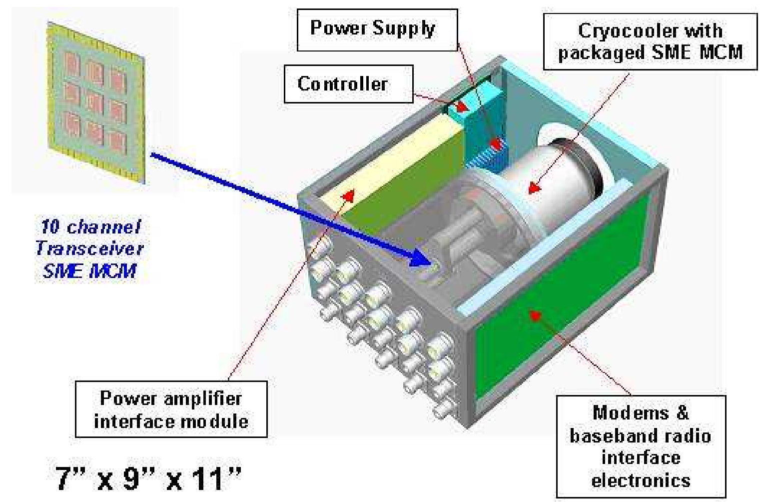
HYPRES

2. Joint Tactical Radio System (JTRS)



JTRS 4-channel half-duplex conventional receiver

SME Is A Key Enabling Technology for Practical JTRS

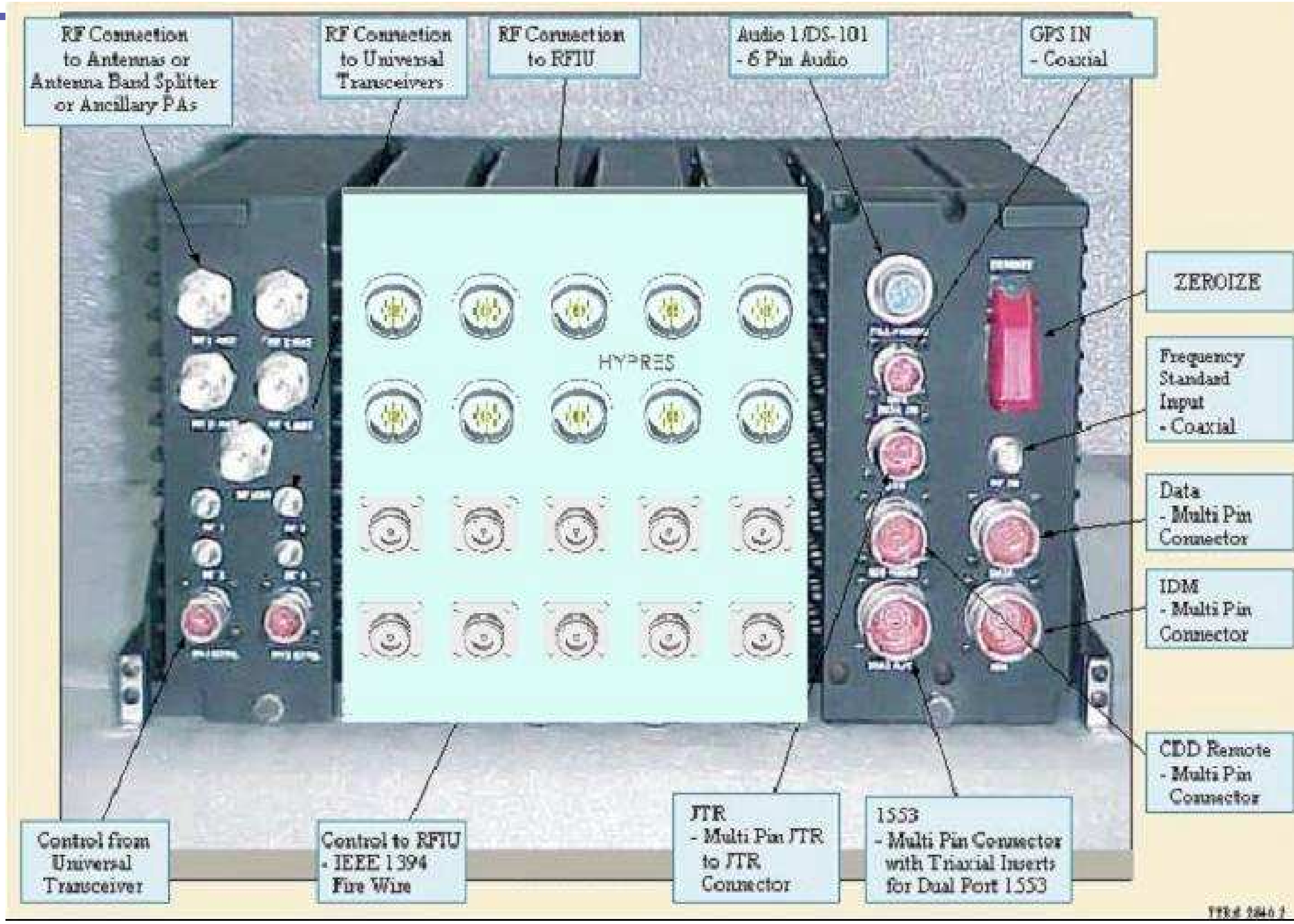


JTRS 10-channel full-duplex Wideband Digital RF

- **Brings digital domain to RF Front End**
- **Enables true SDR with full field programmability and flexibility**
- **Enables practical RF correlation receivers with true waveform portability**
- **Reduces SWaP**

HYPRES

10-channel full-duplex JTRS Transceiver Module with SME Transceiver inserted into the JTR



Replaces 4 individual half-duplex transceivers and upgrades the radio to a 10-channel full-duplex functionality

HYPRES

HYPRES Digital-RF Approach to JTRS Beyond 2 Ghz

- **Exploit the advantages of True Direct Conversion across the entire .1-55 GHz domain using Superconducting Microelectronics (SME)**
  - **Ultra-wideband, high-fidelity ADCs and DACs convert analog RF receive and transmit signals directly to digital <u>at all frequencies</u>**
- **Extend JTRS software programmability into the ADC and DAC**
  - **Patented, programmable, ultra-fast Rapid Single Flux Quantum (RSFQ) digital circuits process digital-RF signals**
  - **Digital channelization, up- and down-conversion, digital filtering, predistortion linearization, true-time delay**
- **Realize the goal of a generic RF platform for all JTRS frequencies**
  - **True interoperability is directly related to commonality**
  - **Realizable waveform portability is dependent on common hardware across the domains**

SME Simplifies Logistics

- **Significant reduction in size, weight and power (SWAP)**
- **A single universal configuration configured dynamically for many domains**
- **Demonstrated ultra-high reliability approaching MTBF’s > 100 yrs**
- **Commonality reduces sparing & maintenance**
- **Common user interface reduces user operations complexity**
- **Eliminates most analog RF & IF combiners, dividers, and coaxial cabling**
- **Very high radiation hardness, naturally resistant to EMI/EMC**
- **Rugged - shock and vibration resistant**

HYPRES

Summary – SME Enhances JTRS Interoperability

- Interoperability is a function of commonality in H/W and waveforms
- Programmable ultra-wideband Digital RF is critical to affordable portability
- Improved SWaP and simplified logistics pays for the investment many times over
- Multi-purpose applications through simultaneous spectrum monitoring and waveform processing
- SME can extend JTRS functionality across the MILSATCOM frequency bands

HYPRES Digital RF technology has the unprecedented potential to make JTRS Interoperability a Reality

HYPRES

3. Satcom On The Move (SOTM)

SATCOM On The Pause

SME Is A Key Enabling Technology for Practical SOTM:

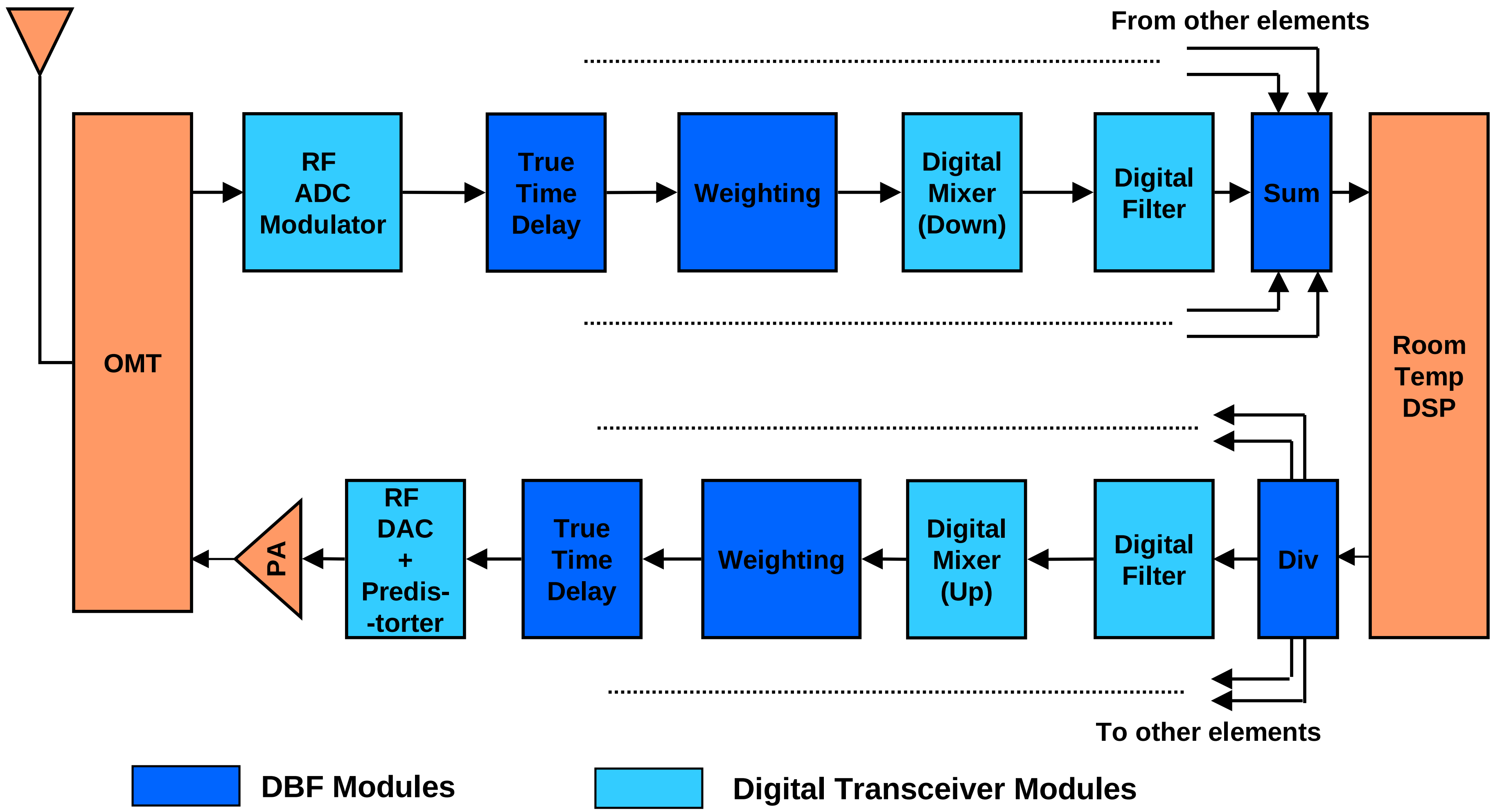
A fundamental Objective of Future Combat Systems

- Decreases Size
- Improves Performance
- Reduces Costs
- Enhances Reliability & Logistics

SATCOM On The Move

HYPRES

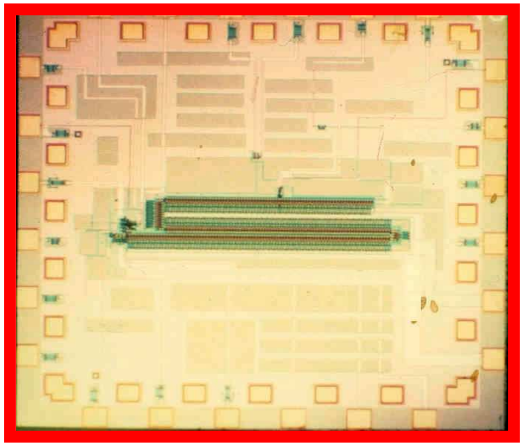
Digital-RF Beamforming Element Architecture (Single Beam)



HYPRES

SME Digital Beamforming Technology Provides High Accuracy & Resolution

- **Fast and accurate digital true-time delay (TTD) allows precise and simultaneous, frequency independent forming of multiple independent beams.**
- **One (1) picosecond true-time delay adjustment between elements provides dramatically improved resolution*.**



True- time Delay line

***1ps = ~ 3 degrees at X band compared to 45 to 90 degrees for current technologies**

HYPRES

Digital (SME) Phased Array Performance Features

- **Low-noise, high SNR/SFDR bandpass ADC modulator digitizes RF**
- **Lower system noise temperature on receive (~ T_a). Results in significantly improved G/T.**
- **Fast and accurate digital true-time delay (TTD) allows precise and simultaneous, frequency independent forming of beams**
- **Precise, high resolution weight controls add finer beamshaping and augments ultra–fast adaptive nulling. Improves gain (Tx & Rx G/T) and provides deeper nulls.**
- **Accurate digital-RF correlator-based TTD control allows fine and reliable beamsteering. Always on beam peak.**
- **Universal, all-digital modular design allows different system configuration with different number of beams and functions**

HYPRES

Example: AWS & WGS SOTM ARRAY DESIGN IMPACT USING SME

	Analog	SME	IMPACT
Array Diameter (ft.)	3	1.3	55% reduction
Array Area (ft²)	7	1.4	80% reduction
Number of Elements	6000	1200	80% reduction
Rx Gain (dBi) @ 20 GHz	42.5	36.5	-6.0 dB
LNA NT (deg. K)	285	10	
System NT (deg. K)	355	80	+6.5 dB
G/T (dB/K)	17	17.5	+0.5 dB
Tx Gain (dBi) @ 30 GHz	46	40	-6 dB
PA Output Backoff (dB)	6	0	+6 dB
Total PA Power (W)	25	25	Same
EIRP (dBW)	55	55	Same

HYPRES

HYPRES SME Brings Dramatic Performance Gains to SOTM

- Much Higher G/T — Typical improvements of 3 to 6 dB for reflector antenna systems and 6 to 8 dB for phased arrays — reduces antenna sizes 50% to 85% without loss of performance
- Enables use of optimum digital correlation techniques to increase S/N performance (20 to 40 dB) —
  - improves satellite bandwidth utilization & user data rates while further reducing antenna & HPA size
  - or can be used to compensate for partial blockages and/or jammers
- Linearization of a near-saturated HPA allows for lower power sizing — Typical improvements of 3 to 6 dB — Balancing the link

HYPRES

4. Summary: HYPRES SME is a Transformational Technology that will meet the needs for JTRS and the Objective Force

- Earth Station and Satellite capacity ("bits per hertz") can be more than doubled requiring fewer satellites to meet the same communications mission.
- Smaller earth stations & fewer satellites can provide up to $6 billion in savings to the US military.
- Reduces antenna sizes by at least half, dramatically improving transportability while lowering the equipment profile.
- Reduces terminal cost and life cycle costs by more than half.
- Robust all digital design provides six-sigma availability.
- Enables JTRS SCA objective compliance at all MILSATCOM frequencies.
  - Scaleable & Expandable to add or reduce functionality based on specific mission needs.
  - Creates a single universal platform that can be configured dynamically and/or periodically to suit many different waveforms, services & missions.

HYPRES

Backup Slides

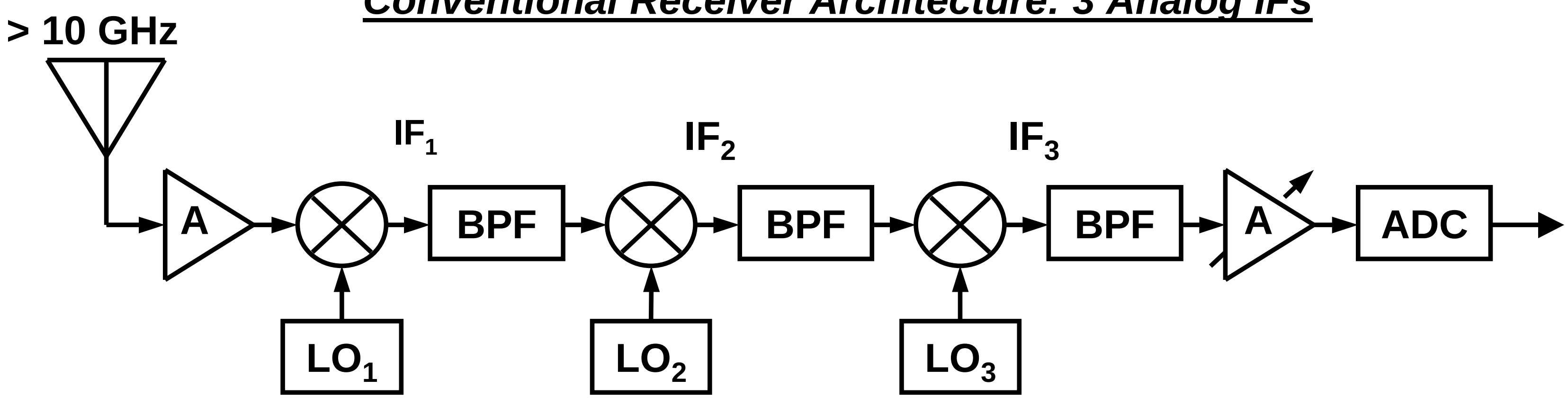
Direct SME Application to SATCOM RF Front Ends

SATELLITE	BAND	UPLINK	DOWNLINK	DIRECT RF	GEN.
MUOS UFO	UHF	290-320MHz	240-270MHz	TODAY	1ST
Commercial	C	5.85-6.4GHz	3.625-4.2GHz	TODAY	1ST
DSCS DSCS SLEP WGS AWS TSAT	SHF/X BAND	7.9-8.4GHz	7.25-7.75GHz	2003	2ND
Commercial	Ku	14-14.5GHz	11.7-12.2GHz	2004	2ND/3RD
AWS WGS TSAT	Ka	30.0-31.0GHz	20.2-21.2GHz	2005	3RD/4TH
AEHF MILSTAR TSAT	EHF EHF	43.5-45.5GHz	20.2-21.2GHz	2005	4TH

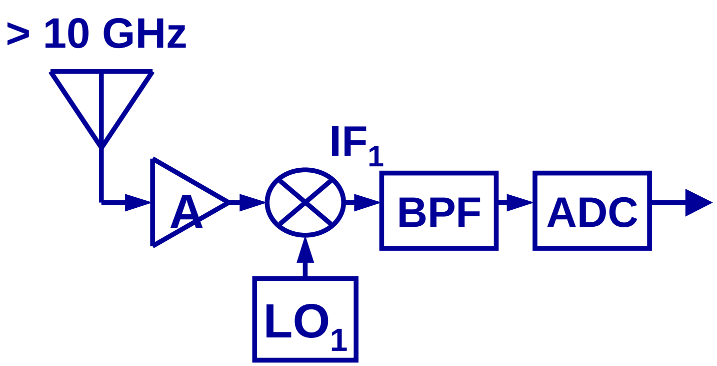
HYPRES

HYPRES Frequency Converter Architecture Progression

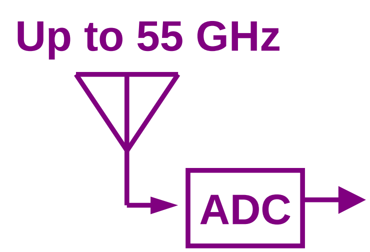
Conventional Receiver Architecture: 3 Analog IFs



HYPRES Intermediate Receiver Architecture: Only one IF



HYPRES Ultimate Receive Architecture: No IF



HYPRES

STATEMENT OF JOHN P. STENBIT
DEPARTMENT OF DEFENSE CHIEF INFORMATION OFFICER

APRIL 3, 2003

BEFORE THE SUBCOMMITTEE ON TERRORISM, UNCONVENTIONAL THREATS AND CAPABILITIES HOUSE ARMED SERVICES COMMITTEE, UNITED STATES HOUSE OF REPRESENTATIVES

Joint Tactical Radio System (JTRS): The radio-based or wireless segment will migrate to the software radio-based JTRS technology. Software radios are essentially computers that can be programmed to imitate any other type of radio, thus, they can be readily configured to operate in different networks based on different standards. The JTRS radio will also be capable of acting as a gateway between users with different hardware radios – a capability that speeds the transition to universal interoperability.

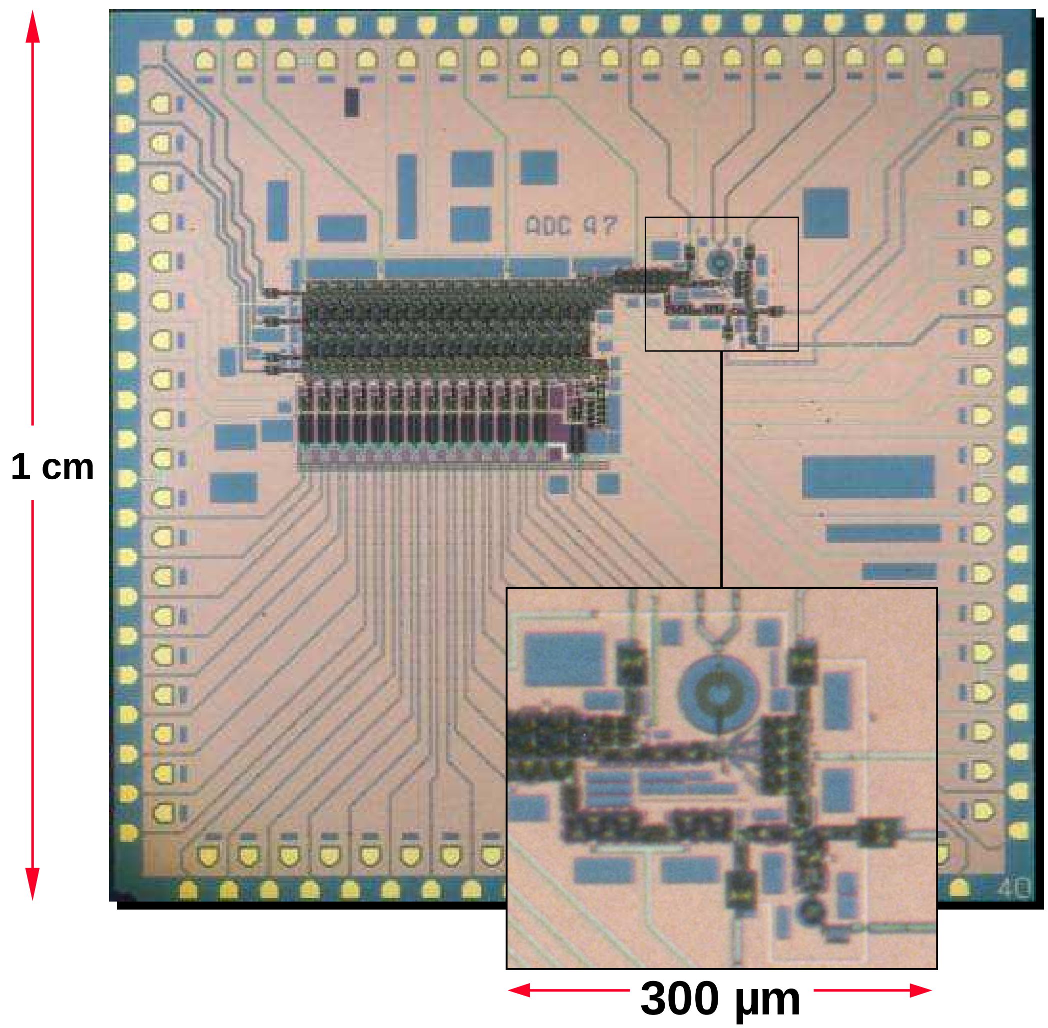
Advanced Wideband System (AWS) / Transformational Communications Satellite (TSAT): The space-based segment of the transformational communications architecture is critical because many users are deployed in areas where optical fiber is unavailable, and many of our information sources, particularly intelligence, surveillance and reconnaissance capabilities, are airborne – making them especially difficult to link into a wideband network. AWS will, in essence, extend the network's full capabilities to mobile and tactical users. TSAT will expand AWS capabilities and incorporate internet protocol and laser communications capabilities into the Department's satellite communications constellation.

GIG Bandwidth Expansion (GIG BE): Current telecommunication lines are not robust enough to handle the volume of information needed to facilitate optimum, strategic decision-making. The GIG-BE is designed to be robust enough to address current bandwidth constraints. It will use advanced fiber optic backbone and switching technology to upgrade telecommunications lines at DoD's critical installations, and provide networked services with unprecedented bandwidth to operating forces and operational support activities. The GIG- BE will provide approximately 100 times the current telecommunications capacity to critical Defense sites around the world. An increase in capacity of this magnitude will permit dual use of the bandwidth – with warfighting command, control, and intelligence functions as a primary mission. New security technologies are being developed to keep pace with expanding capacities and enhance performance.

HYPRES

Demonstrated 15-bit Low-Pass Delta ADC Chip

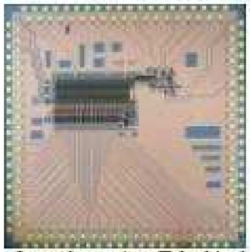
ADC chip: modulator + digital filter



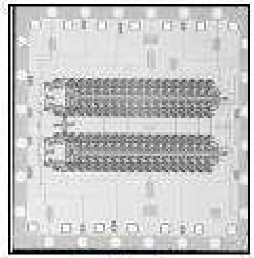
- **Dynamically programmable bandwidth**
- Delta ADC modulator with unique phase mod-demod architecture
- Large oversampling ratio (OSR) - 20 GHz sampling clock
- 6,000 Josephson Junctions
- Selectable decimation ratios – 1:128, 1:64, 1:32, 1:16
- Fabricated in HYPRES 3-µm foundry process

HYPRES

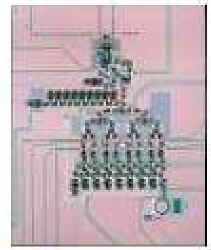
HYPRES Superconductor Digital-RF Infrastructure



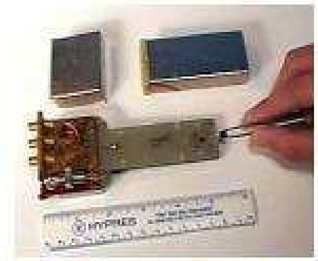
Analog-to-Digital Converter (ADC)



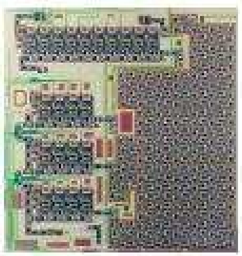
Multiplier



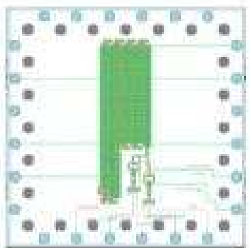
Low-jitter On-chip Clock



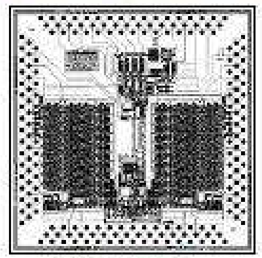
Optical I/O and Packaging



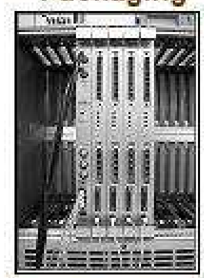
Digital-to-Analog Converter (DAC)



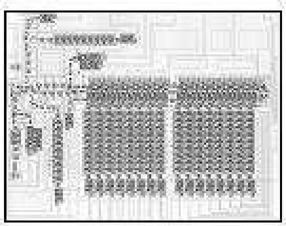
Shift Register



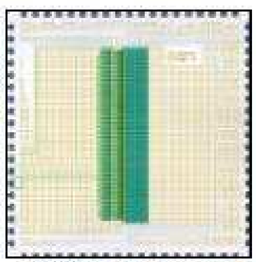
Digital I&Q Converters



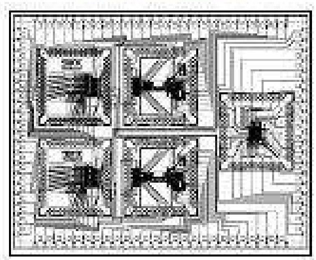
User Interfaces



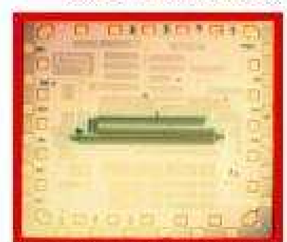
Correlator



Random Access Memory (RAM)



Multi-chip Module Packages (MCM)



True- time Delay line

HYPRES

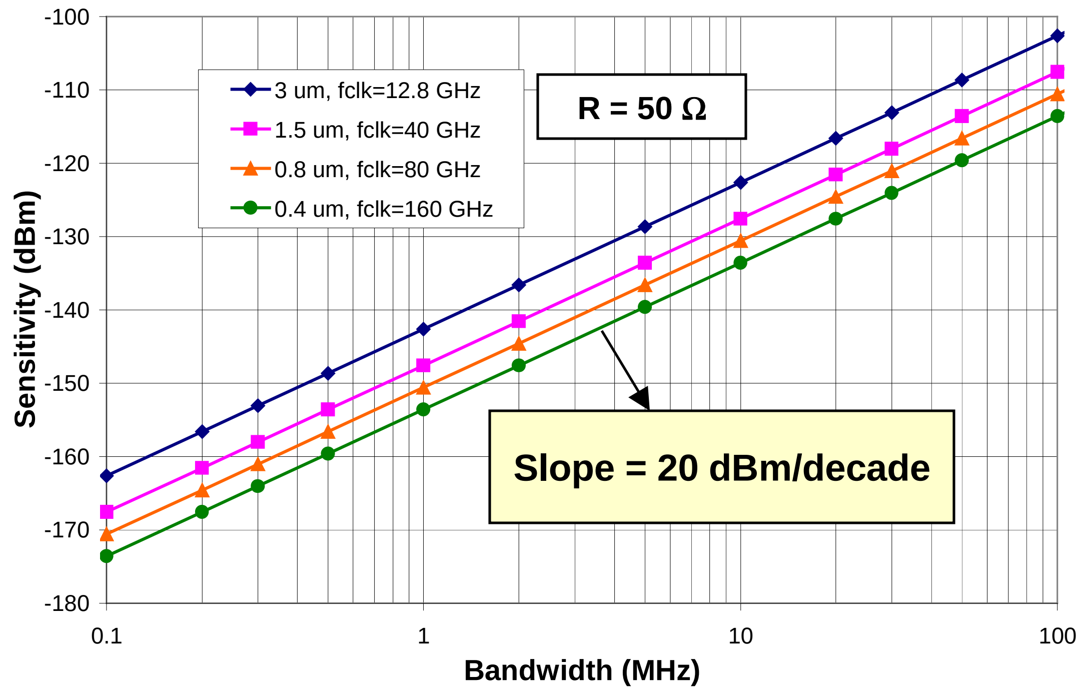
Ultra-high ADC Sensitivity

- Sensitivity (ΔI) is the least significant bit (LSB)

$$\Delta I = \frac{\Phi_0}{2Mm\sqrt{N}} \propto \frac{\Delta f}{\sqrt{f_{clk}}}$$

$$(\Delta I)^2 R \propto \frac{(\Delta f)^2}{f_{clk}}$$

  - M = Mutual inductance
  - m = Number of synchronizer channels
  - f_{clk} = Clock frequency
  - Δf = signal bandwidth
  - N = Oversampling ratio = $f_{clk}/(2f_s)$



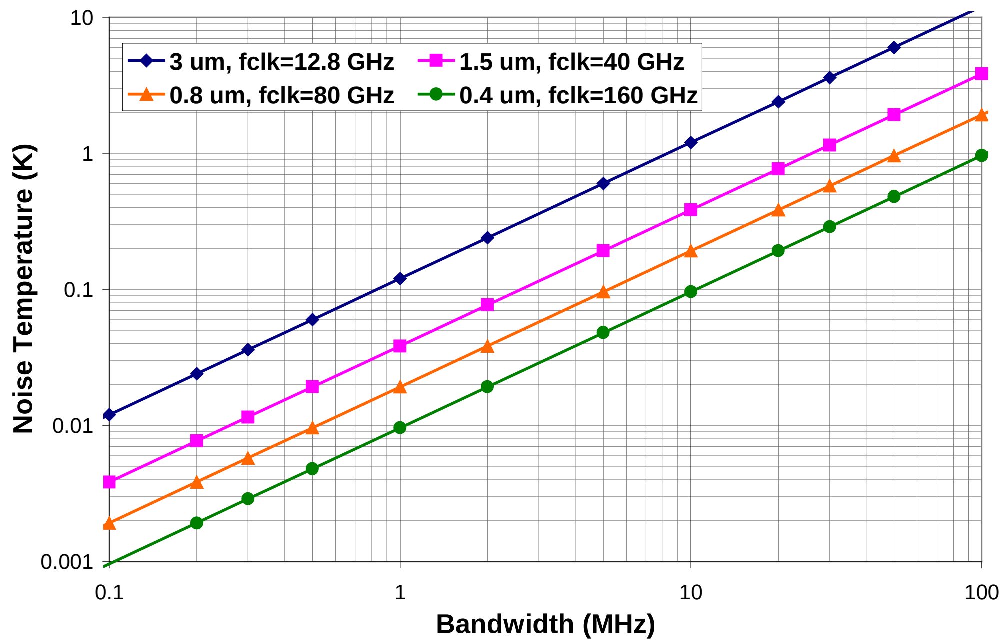
HYPRES

Ultra-low ADC Noise

- At 5 K, thermal noise is 60x less than at room temperature
- ADC only produces a "quantization error" (I_N)
- With dither, I_N has a noise-like spectrum
- Noise Temperature (T_N)

$$T_N = \frac{(I_N)^2 R}{k_B f_s} = \frac{\pi}{12 k_B L_2}\left(\frac{\Phi_0}{km}\right)^2 \frac{\Delta f}{f_{clk}} \propto \frac{\Delta f}{f_{clk}}$$

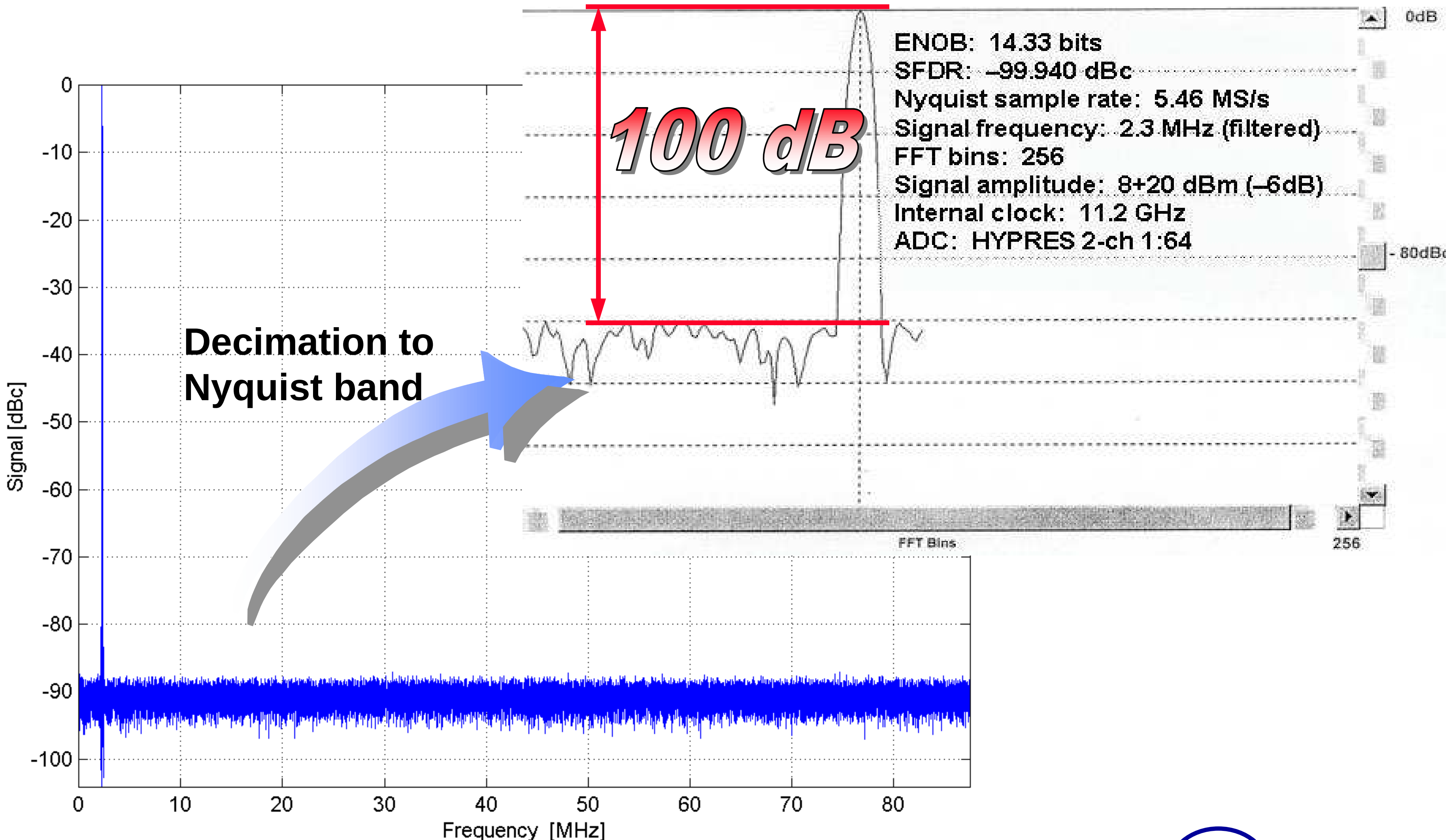
  - L_2 = Front-end inductance
  - m = # of synchronizer channels
  - f_{clk} = Clock frequency
  - Δf = signal bandwidth



ADC does not degrade the system noise temperature

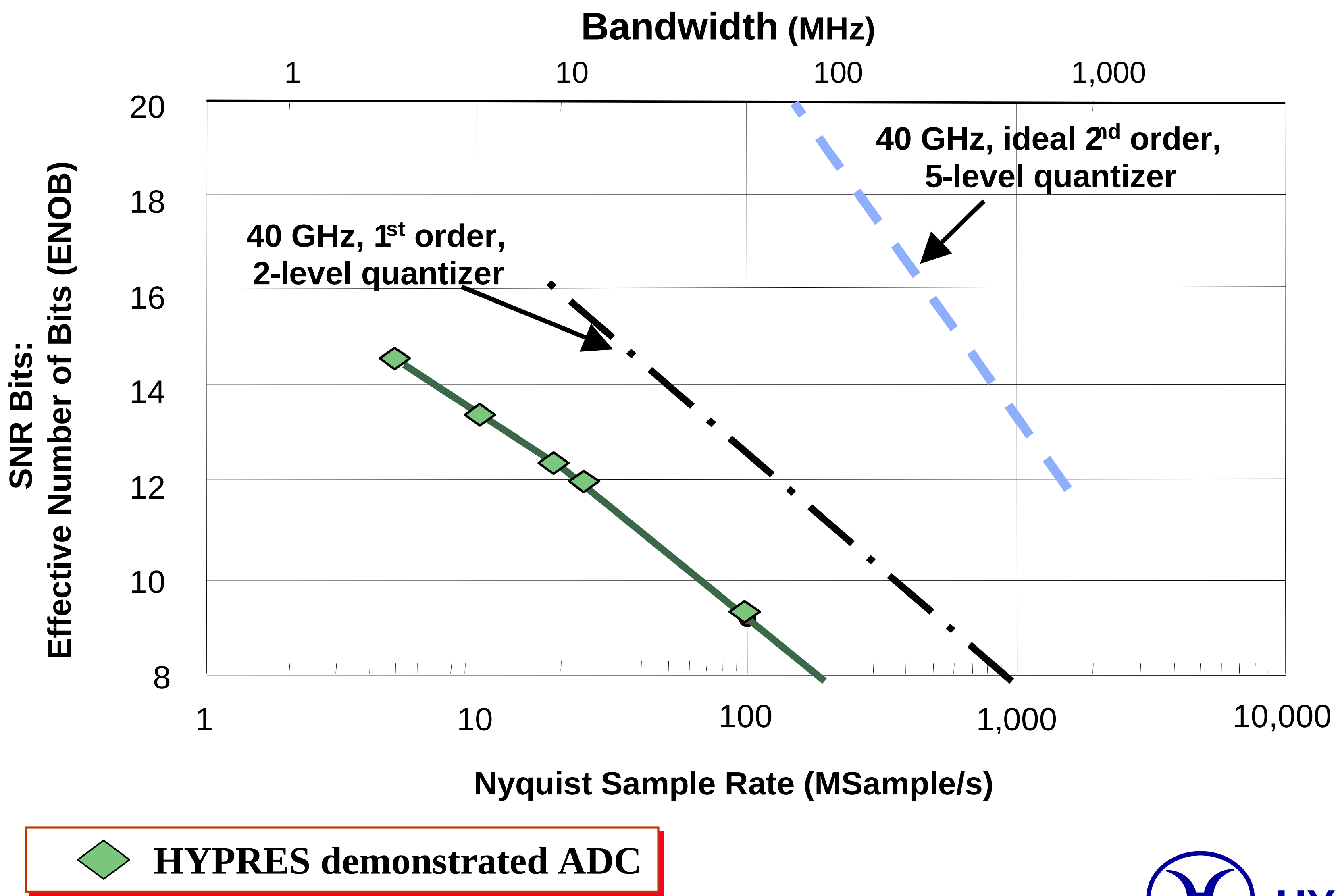
HYPRES

Deep FFT Shows 100 dB SFDR



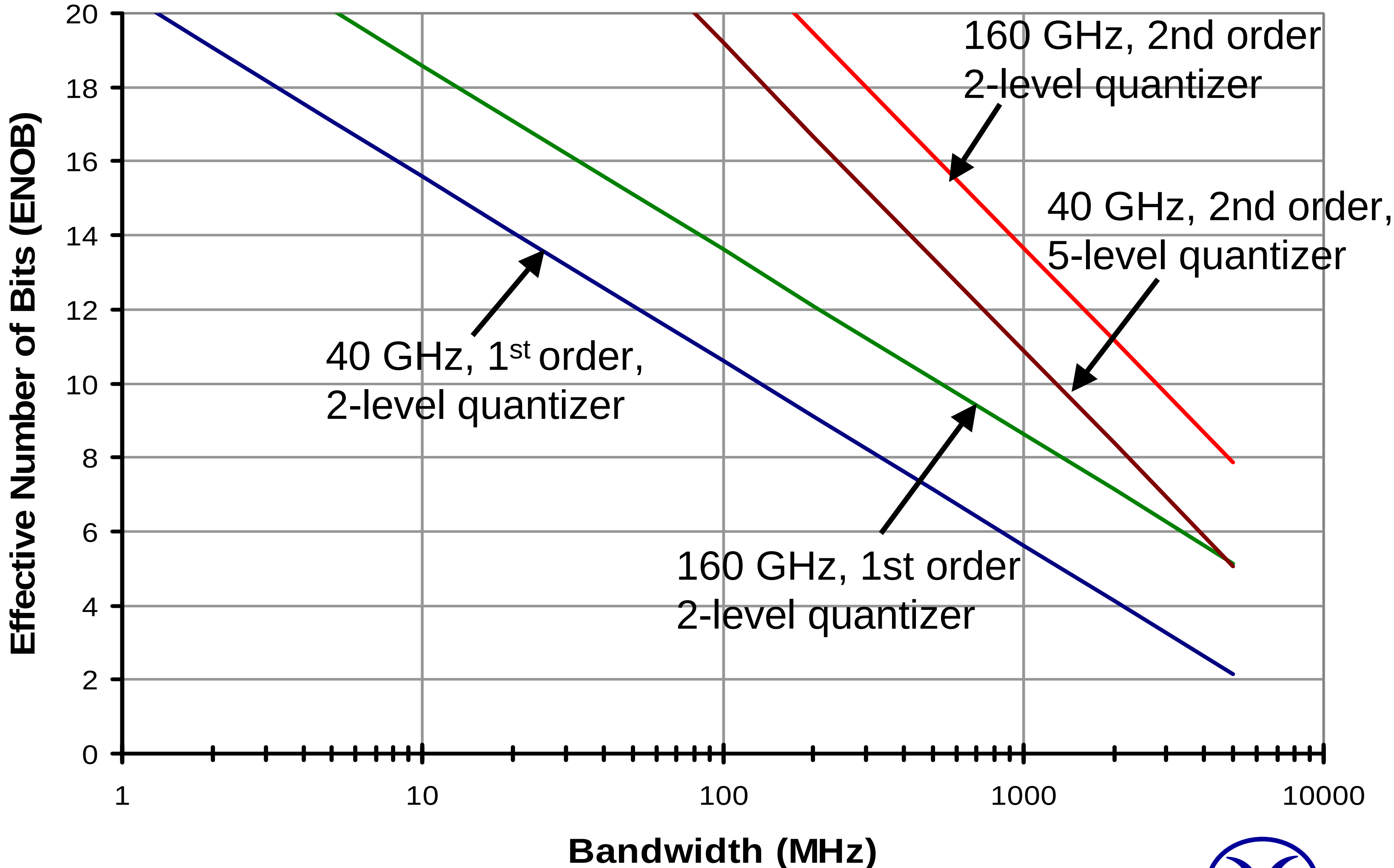
HYPRES

SNR (SINAD) Bandwidth Performance



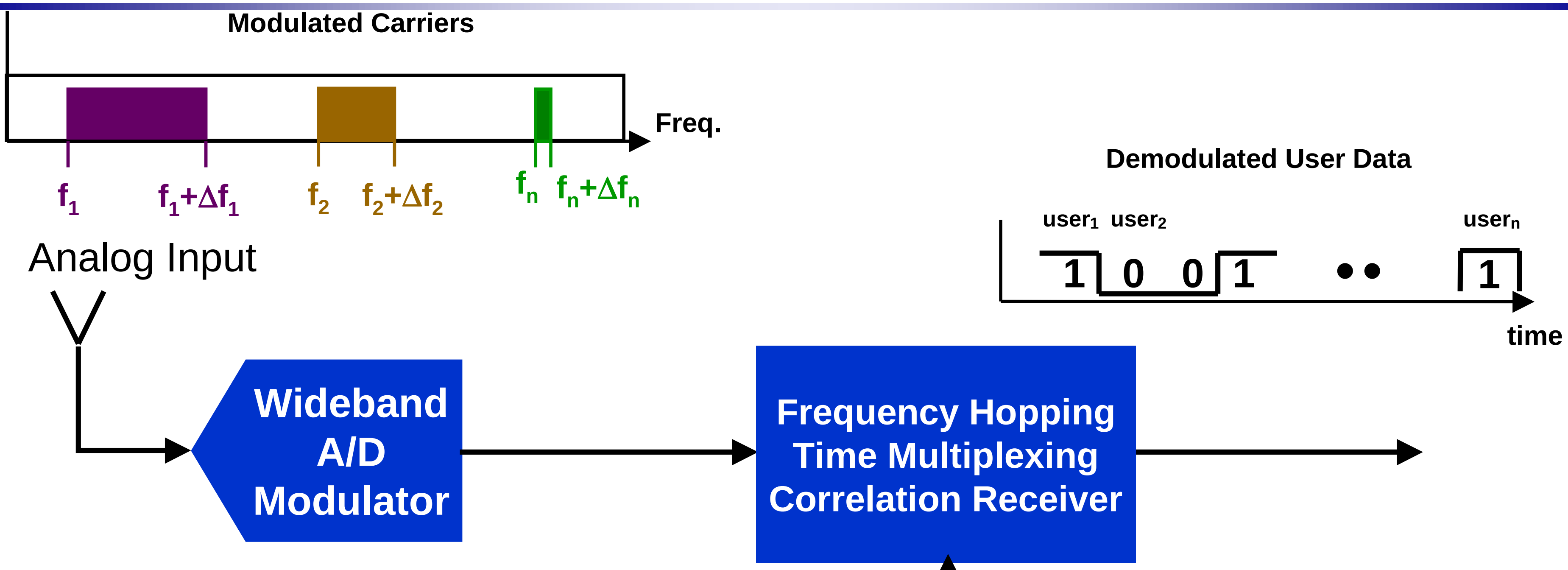
HYPRES

ADC Performance Enhancement

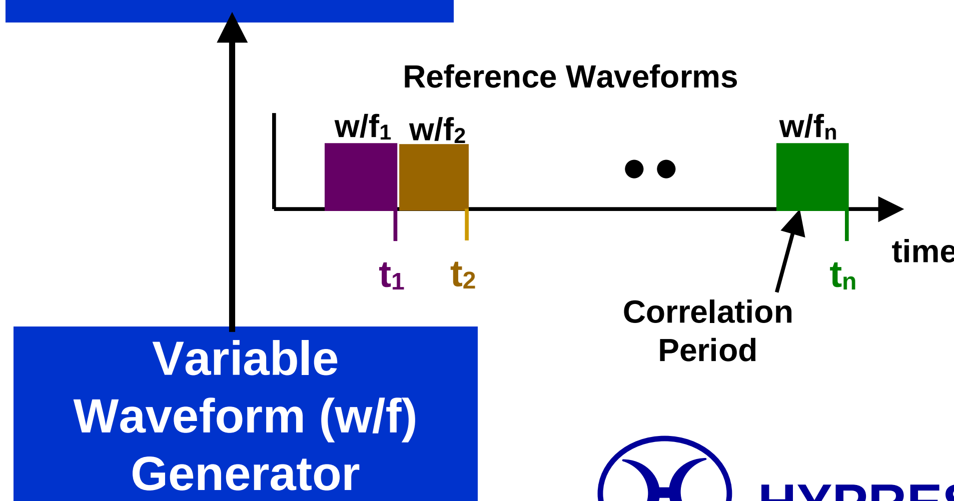


HYPRES

Multi-Channel Correlation Receiver

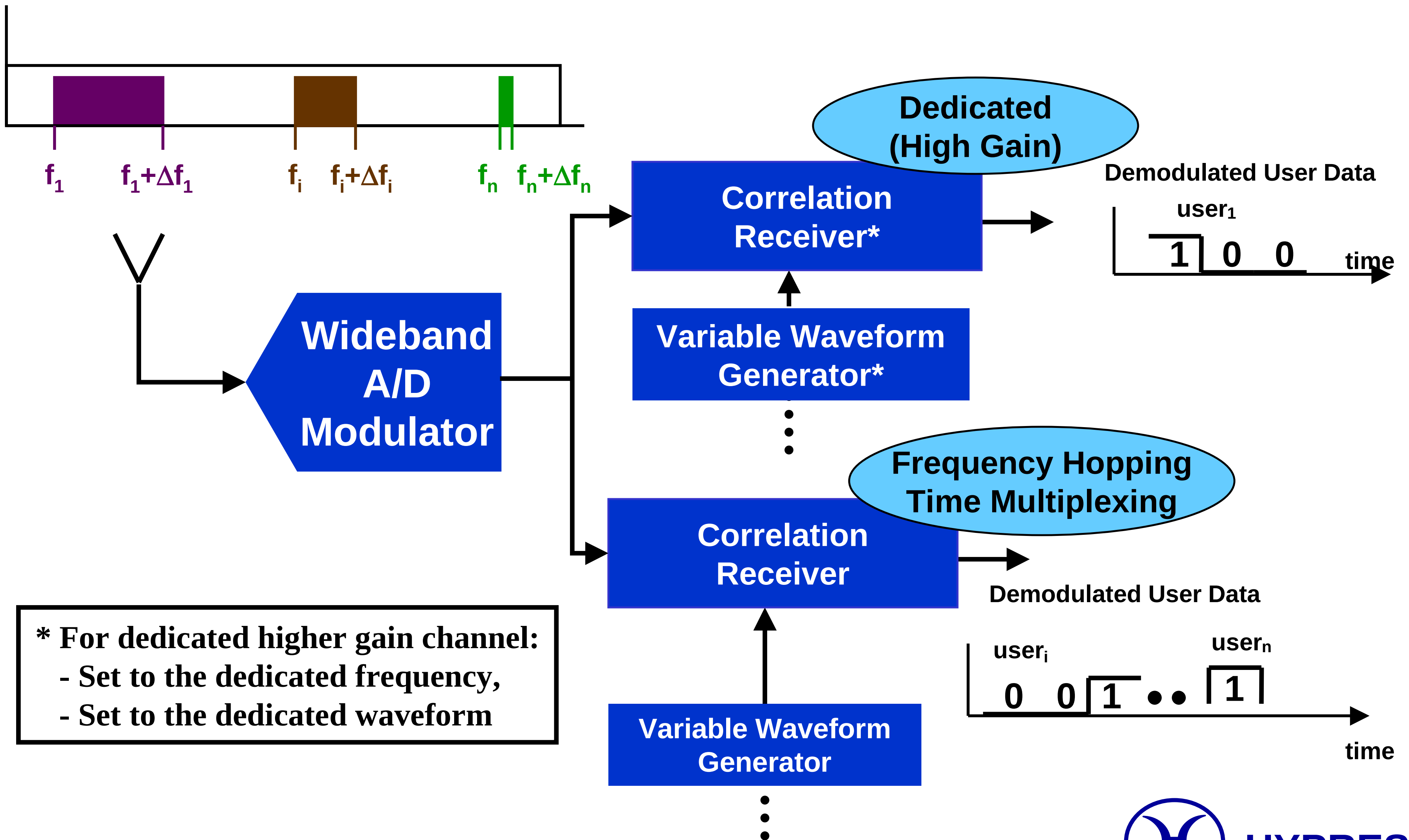


- Reuses the same electronics to process each channel with sequential,time multiplexing
- Total available correlation gain (for all carriers) = the available gain for the aggregate of all the data rates



HYPRES

Dedicated/Multi-Channel Correlation Receiver



*** For dedicated higher gain channel:**
- Set to the dedicated frequency,
- Set to the dedicated waveform

HYPRES

Cryocoolers: Use and Facts

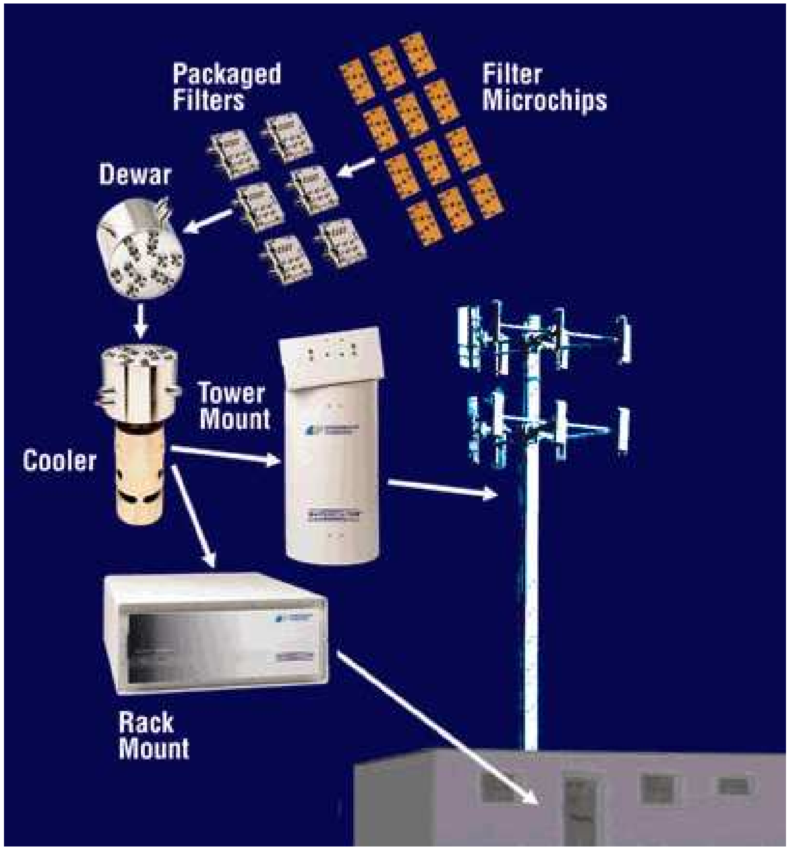
- Used today in cellular base stations
- Used today in high performance, high end systems
- Available commercially today
- Analogous to the infrared sensor cryopackage
- Roadmap for compact cryocoolers established

HYPRES

Cryocoolers are in Field Use Today: Communications

~ 3000 HTS filter subsystems installed (September 2002)
Volume sales to major customers underway

Superconductor Technologies Filter Subsystem



Conductus Filter Subsystem

Illinois Superconductor Filter Subsystem

HYPRES

Demonstrated Reliability

11,200,000

~~6,300,000~~

~~3,500,000~~

~~1,600,000~~ hours of operation

Demonstrated MTBFs of 90+ years!!

Estimated uptime of 99.998%

HYPRES

MILSATCOM Transformation Using HYPRES Technology

Tomorrow is NOW

Enables JTRS SCA compliance > 2 GHz
With << ½ the antenna sizes
At << ½ the terminal cost
With Six-sigma availability
And, > twice the capacity → much fewer satellites
Six satellites @ $1B each → $ 6B savings

HYPRES technology offers the unprecedented potential to revolutionize MILSATCOM

HYPRES