Radiation Hardened, Modulator ASIC for High Data Rate Communications

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Abstract

Satellite-based telecommunication services are challenged by the need to generate down-link power levels adequate to support high quality (BER$\cong 10^{12}$) links required for modern broadband data services. Bandwidth-efficient Nyquist signaling, using low values of excess bandwidth (α), can exhibit large peak-to-average-power ratio (PAPR) values. High PAPR values necessitate high-power amplifier (HPA) backoff greater than the PAPR, resulting in unacceptably low HPA efficiency. Given the high cost of on-board prime power, this inefficiency represents both an economical burden, and a constraint on the rates and quality of data services supportable from satellite platforms. Constant-envelope signals offer improved power-efficiency, but only by imposing a severe bandwidth-efficiency penalty. This paper describes a radiation-hardened modulator which can improve satellite-based broadband data services by combining the bandwidth-efficiency of lo̊w-α Nyquist signals with high power-efficiency (negligible HPA backoff).

Functional Architecture

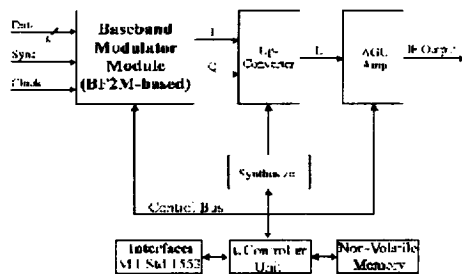The functional architecture of the modulator module is depicted in figure 1.

Figure 1. Space-Modulator Module

The Baseband Modulator Module (BMM) translates byte-wide parallel data into baseband quadrature analog signals which are then translated to a desired IF frequency. The key element of the BMM is a radiation-hardened CMOS ASIC which duplicates the functionality of SiCOM's existing BitFLOW2™ modulator (BF2M) ASIC; the BF2M functional architecture is depicted in figure 2. Many BF2M functions may be bypassed, and extensive built-in test (BIST) functionality has been incorporated to facilitate both ASIC and module validation testing.
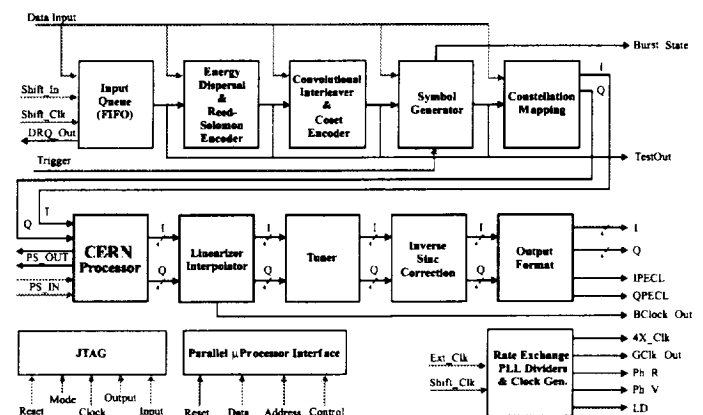

Figure 2. BitFLOW2 Modulator ASIC

Functional Description

Byte-wide data passes through a re-clocking queue (used to reduce input timing jitter), and is then scrambled. A programmable Reed-Solomon encoder generates a set of parity bytes corresponding to a user-defined block of information bytes. A programmable-length convolutional interleaver distributes received error bursts across multiple RS code blocks. The programmable coset encoder supports numerous convolutional and pragmatic trellis codes derived from the NASA standard Viterbi code by puncturing. The symbol generator groups sets of encoded bits into n-tuples, which are then mapped into the user-defined 2^n {I, Q} constellation points for the selected modulation.

BF2M supports any arbitrary pattern of constellation points, with any user-defined labeling scheme.

Complex {I, Q} values provide the weighting for the programmable pulse shaper; the basic pulse shape is used-defined via the programmable values of sixteen complex coefficients in a tapped-delay-line (TDL) filter. Concatenating successive weighted pulse shapes creates the modulated waveform, which constitutes the input to the constrained-envelope root-Nyquist (CERN) processor. CERN dynamically modifies the complex waveform to achieve very significant PAPR reduction, permitting use of bandwidth-efficient low-α root-Nyquist waveforms without requiring large HPA backoff. If activated, CERN accomplishes this key objective with minimal implementation complexity.

An interpolator then processes the complex {I, Q} sample stream to maintain a quasi-constant BF2M output sample rate over the entire symbol rate range. The BF2M ASIC also incorporates a programmable complex linearizer, compatible with a wide variety of linearization algorithms, able to rapidly to adapt to any specific HPA AM- AM and AM- PM transfer characteristic. The interpolation/linearization processing supports a non-integer number of samples per symbol to enhance the output signal's spectral purity. The resultant complex sample stream is then processed to provide fine-resolution frequency tuning. Subsuming the fine resolution tuning in digital form greatly simplifies the design of an IF tuner, which may then use large frequency steps and a wide loop bandwidth to greatly reduce its contributed phase noise. The inverse-sinc filter processes the sample stream to pre-compensate for the sine-weighting imposed by digital-to-analog converter (DAC) processing. Finally, the four-fold parallel sample streams are multiplexed together to provide the very high rate complex sample stream for which constitutes the DAC input.

Capabilities
The BF2M scrambler conforms to the DVB-S standard, defined by the polynomial $p(x) = x^{15}+x^{14}+1$. The Reed-Solomon encoder subsumes the DVB-S standard, with a field generator polynomial $p(x)=x^8+x^4+x^3+x^2+1$, and primitive field element $\lambda = 02_{hex}$, but supporting any shortened code-block size with 16 parity bytes, not only the DVB-S standard block length of 204. A user-definable synchronization byte must be included between all RS code blocks. The convolutional interleaver conforms to the DVB-S standard, a Ramsey type III approach with interleaving depth 12 and depth (M) of 17.

Error correction coding
The coset encoder supports all modes and code rates of the DVB-S standard inner convolutional encoder, as well as all DVB-SNG standard trellis codes (8PSK, rates 2/3, 5/6 and 8/9, and 16QAM, rates 3/4 and •);

all unique interleaving associated with DVB-SNG 8PSK and 16QAM is also incorporated. In addition to fully complying with the DVB-S and DVB-SNG standards, the coset encoder also supports higher-order modulations, including 32QAM, 64QAM, 128QAM and 256QAM; each of these modulations is supported with a pair of programmable inner code rates. For example, 64QAM can use an inner code rate of either 5/6 or 11/12; 128QAM can use an inner code rate of either 6/7 or 13/14.

Power-efficient modulation
In addition to supporting high-order standard QAM modulations, the BF2M ASIC supports a novel new class of constellations referred to as SiQAM (Silicon-QAM). High-power amplifiers (HPAs) are peak-power-limited, rather than average-power-limited; SiQAM exploits this fact by quasi-uniformly distributing the modulation's constellation points within the constraints of a unit circle, rather than the inscribed square (QAM). As figure 3 shows, uniformly spreading constellation points within the larger peak-power constraint (unit circle) should theoretically offer to improve BER performance by nearly 2dB in this manner. A far more sophisticated analysis validates this conclusion.[1]
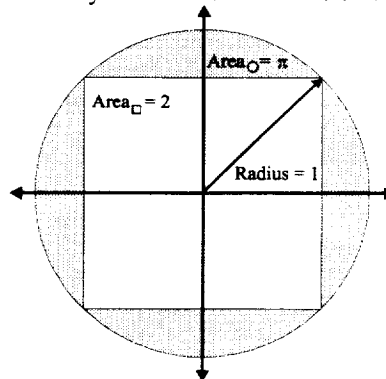
Figure 3. SiQAM's CompetitiveEdge

Simulations confirm that SiQAM can improve bit-error-rate (BER) by nearly 1.5 dB over conventional QAM modulation.

Peak-to-average-power-ratio (PAPR) reduction
The BF2M ASIC provides a fully-programmable pulse shape, supporting a wide range of root-Nyquist excess bandwidth values ($0.125 < \alpha < 0.5$), including pre-distortion for linear channel distortion. For known distortion, it is better to pre-distort rather than attempt to equalize the combined signal plus noise at the receiver. While pre-distortion addresses linear channel distortion, a different approach is required to address the impacts of the nonlinear distortion associated with the satellite's HPA. The classic HPA challenge involves the tradeoff between improving power-efficiency by minimizing backoff, while assuring that the spectral regrowth induced by low backoff still satisfies the transmitter's spectral mask constraints.

A well-known problem with the very bandwidth-efficient low-α pulses is the fact that they exhibit large and undesirable PAPR values,[2] requiring many dB of additional backoff to avoid spectral splatter at the HPA output. Figure 4 depicts the sensitivity of PAPR to excess bandwidth (α) for several of the most common modulation types. 8PSK exhibits strong PAPR sensitivity for $\alpha < 0.4$, increasing by 3.5 dB for an α value of 0.12. While bandwidth-efficiency improves by fully 25% as α is reduced from 0.4 to 0.12, the PAPR increases by nearly 3.5 dB, exacting a severe cost in power-efficiency. For satellite-based links, this tradeoff is seldom attractive.
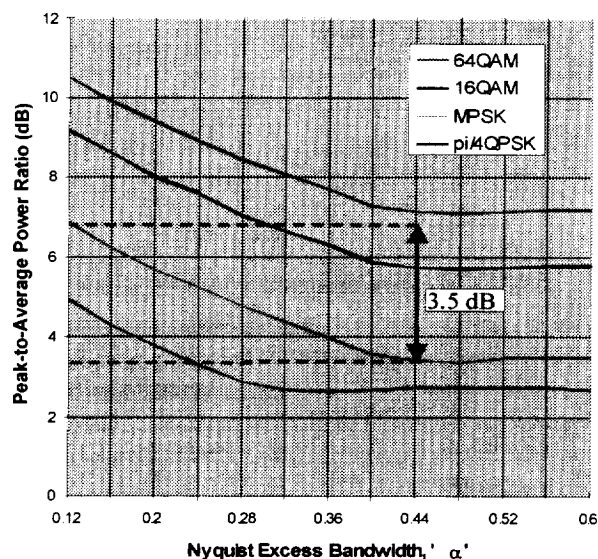

Figure 4. Sensitivity of PAPR to Excess Bandwidth

The BF2M ASIC incorporates a recent breakthrough called **CERN** (constrained-envelope root-Nyquist) signaling which directly addresses this PAPR sensitivity problem. CERN's conceptual basis is readily appreciated in terms of the statistics of the signal magnitude, expressed as a probability-density-function (pdf). The magnitude pdf of low-α root-Nyquist waveforms exhibits a very long tail, as depicted in figure 5. The mechanisms for spectral regrowth may readily be appreciated if the nonlinear HPA characteristic is replaced by its ideal linearized equivalent, also depicted in figure 5. Sensitivity of spectral regrowth to nonlinear amplification is such that if *any* portion of the magnitude pdf extends beyond the linearized HPA breakpoint, unacceptable spectral regrowth occurs.

Consequently one must operate an HPA with many dB of backoff, where the degree of backoff is determined by signal peak magnitude. It is instructive to consider the impact of using bandwidth-efficient root-Nyquist
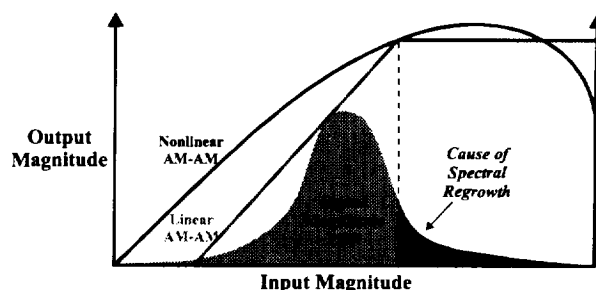

Figure 5. HPA-induced Spectral Regrowth Mechanism

signaling on the peak signal magnitude. Although 8PSK is often thought of as a constant-envelope signal, use of a bandwidth-efficient low-α root-Nyquist waveform introduces large peak signal excursions. The lighter curve in figure 6 depicts the simulated signal trajectory of an 8PSK signal with an α=0.13 root-Nyquist waveform. The peak magnitude of this signal is nearly twice the magnitude of the unit circle upon which the 8PSK constellation points are located.
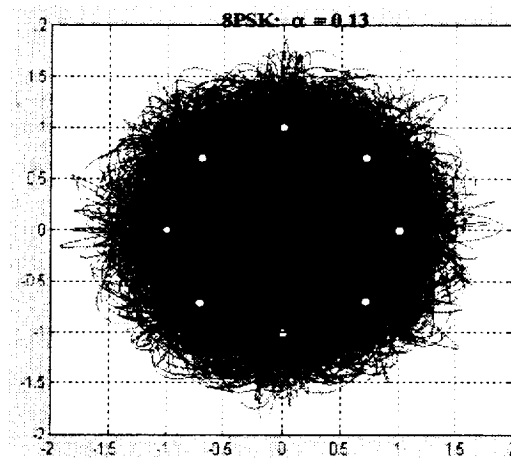

Figure 6. Vector Plot of 8PSK Signal

The darker signal trajectory corresponds to the same signal when CERN processing is employed. Even though the signal spectrum remains identical, the peak has been reduced by over 3 dB. Consequently, the HPA may be operated with 3 dB less backoff for the same degree of spectral regrowth. The net effect is that the signal at the HPA output has nearly 3 dB greater average power using CERN than using conventional root-Nyquist signaling. Recall that, while the link bit-error-rate (BER) is driven by the average signal power, spectral regrowth at the transmitter is driven by peak signal power. PAPR reduction processing addresses the need to maximize the received average signal power subject to the peak power constraint on the HPA.

CERN's revolutionary alteration of the tradeoff between bandwidth-efficiency and power-efficiency merits further clarification. Figure 7 depicts the simulated output spectrum of an 8PSK low-α root-Nyquist signal subjected to ideal clipping at various levels. Severe spectral regrowth occurs even at a clipping level over 1.6 times the radius of the 8PSK constellation. In contrast, figure 8 depicts the corresponding spectral plot in which CERN's PAPR-reduction processing has been employed; even severe clipping introduces only modest spectral regrowth.
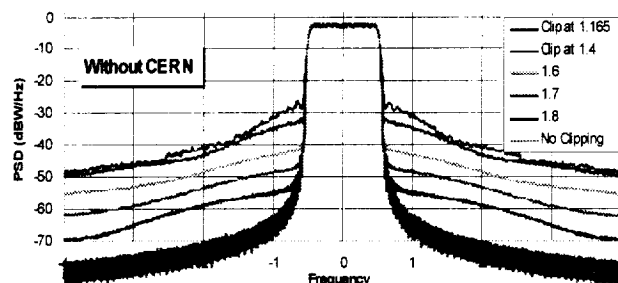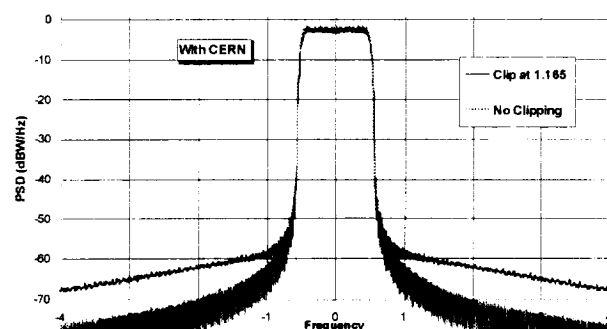

Figure 7. Spectral Regrowth: Clipped Signal

Figure 8. Spectral Regrowth: Clipped CERN Signal

Conventional root-Nyquist signals exhibit a magnitude probability-density-function (pdf) with a very slowly decaying tail. Figure 9 depicts both this phenomenon and the abrupt truncation of the tail of the signal's magnitude pdf which constitutes the physical basis for CERN's PAPR reduction.
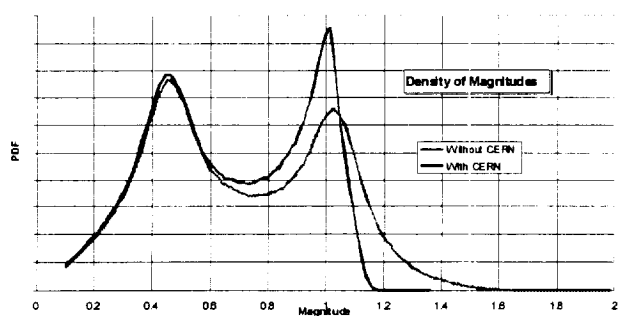

Figure 9. Magnitude pdfs: with and w/o CERN

Figure 10 converts magnitude pdfs into corresponding cumulative density functions (cdfs) to facilitate quantification of CERN's benefit. From figures 7, 8, and 10, we can see that acceptable levels of spectral regrowth require less than 0.01% clipping, which occurs at clipping levels of 1.165 and 1.7 for CERN'd and conventional signals, respectively. Thus, CERN processing reduces HPA backoff by about 3.3 dB [$=20\log_{10}(1.7/1.165)$].
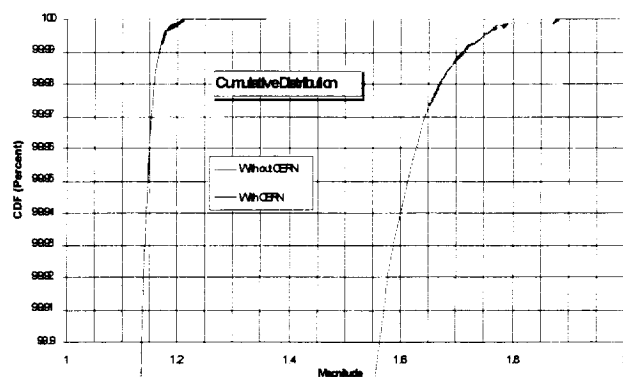

Figure 10. Magnitude Cumulative Density Functions

CERN's net benefit is less than the amount of HPA backoff reduction, since CERN processing introduces a signal-dependent noise, resulting in an attendant BER degradation. Figure 11 depicts the impact of this noise on link BER; in this case, CERN-noise causes a 1.2 dB BER degradation.
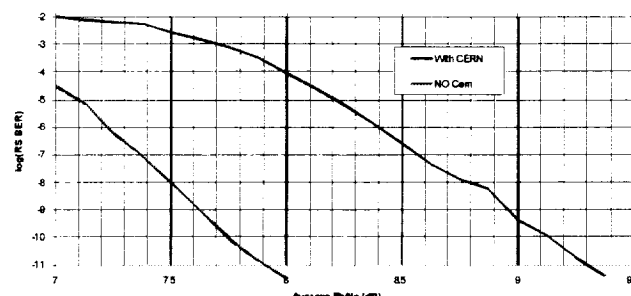

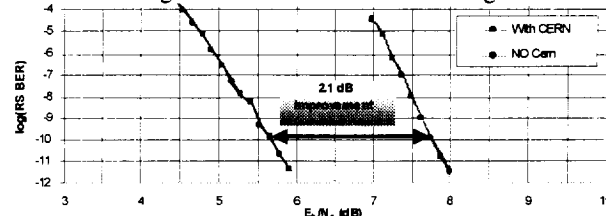Figure 11. CERN-noise BER Degradation

Figure 12. Net BER Improvement with CERN

Link Performance

The innovative modem architecture, including the modulator described herein incorporates, in addition to SiQAM and CERN, an unprecedented degree of

flexibility for supporting the demand of any wireless link for modulation and coding which is optimal for that link's unique pathologies and signal-to-noise ratio. Figure 13 depicts modem BER-vs-E_bN_o performance for a variety of modulation and coding configurations.
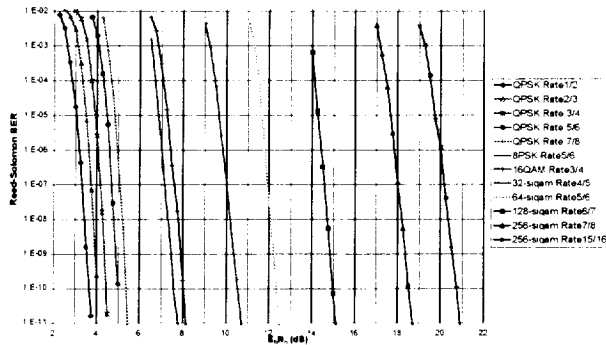

Figure 13. Modem Performance

With sufficient signal-to-noise ratio. the modem architecture & ASICs will support data rates up to 1 Gbps (256 QAM. uncoded).

ASIC Physical/Radiation Characteristics

The ASIC will be packaged in a 352-pin quad flat-pack. 3" on a side. with 6-8 watts at maximum clock rate. The ASIC will be produced in a process capable of 100K rads (Si) total radiation dose. with $LET_{TH} \geq 30$ MEV, and no latchup.

Potential Applications

High data rate communications technologies are required for NASA's science missions and similar commercial space ventures to meet the demands of future space and Earth-observing science instruments and communications/data processing systems. The radiation hardened modulator module has potential application in meeting the demands for more efficient use of spectrum as NASA and commercial systems transition from S-and X-band to Ka-band frequencies. For example. with higher-order, bandwidth- and power-efficient modulation and coding, this unit can be coupled with a high efficiency. 26 GHz active phased array antenna[3] to enable use of the wider frequency allocations available for RF downlinks. NASA Glenn Research Center (GRC). along with NASA Goddard Space Flight Center (GSFC). are proposing to demonstrate this technology on future Earth science flight opportunities. such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS) follow-on technology demonstration.

A high-speed modulator based on this design. can be applied to GRC's Direct Data Distribution (D^3)[4]

Project. which seeks to demonstrate key technologies for high rate downlinks (622 Mb/s) from low earth orbit direct to Earth. The project will fly an experimental communication package onboard the Shuttle with integrated Ka band (19 GHz) phased array antenna and high-speed modulator demonstrating high data rate communications to small. low cost ground terminals.

In addition. programs such as the International Space Station continue to seek out newer technologies for high data rate links direct to Earth or via the next generation of TDRSS spacecraft. Future space science missions will seek extremely bandwidth-efficient. high data rate links (for instance. ARISE[5] requires 8 Gbit/sec in a 1 GHz bandwidth) in small. lightweight packages. Space environmental effects programs may also benefit from these technologies. where the use and characterization of rad-hard ICs are critical to the success of the missions.

Summary

The development of the ASIC modulator chip is scheduled for completion in January 2001. with plans of integrating the ASIC chip with additional electronics to develop a space ready modulator module. The modulator module will utilize the rad-hard ASIC with associated D/A converters. interface and control circuitry and RF electronics aimed at meeting the future high data rate communications needs of NASA missions. Plans are to develop the companion demodulator ASIC as funding becomes available.

This technology will demonstrate the viability of bandwidth efficient modulation. when combined with non-linear amplification mitigation techniques. that will meet the needs of future NASA missions which have typically relied on bandwidth inefficient schemes in the past. The programmability and adaptability of the current design will meet the future changing needs of next generation NASA missions and commercial applications allowing for the seamless integration of data between Government and commercial systems.

[1]R. Müller. et al., "Multilevel Coding for Peak Power Limited Complex Gaussian Channels," *Proceedings of the 1997 Int'l Symposium of Information Theory*. Ulm, Germany.
[2]Miller and R. O'Dea. "Peak Power and Bandwidth Efficient Linear Modulation." *IEEE Trans. Commun.*, vol. 46. pp. 1639–1648. Dec. 1998.

[3]Pellerano, F., "High Rate User Ka-Band Phased Array Antenna," Ka-Band Commercialization Workshop, GSFC, March 1998.

[4]Wald, L. et al., "An Advanced Ka Band Phased Array Communication System at Commercial Frequencies," Space Technology and Applications International Forum, Albuquerque, New Mexico, January 30–February 3, 2000.

[5]J.S. Ulvestad, R.P. Linfield, and J.G. Smit, "ARISE: The Next Generation Space VLBI Mission," AIAA 1995 Space Programs and Technologies Conference, September 26–28, 1995, Huntsville, AL.

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