High-Rate (130-Mb/s) Ka-Band Downlink Modulator Breadboard for the Advanced Deep Space Transponder

S. K. Smith,[1] N. R. Mysoor,[1] B. M. Cook,[2] J. P. Lux,[1] and B. N. Shah[1]

A 32-GHz (Ka-band) breadboard has been developed to demonstrate M-ary phase-shift keyed (PSK) and M-ary quadrature amplitude modulation (QAM) Ka-band modulations using a $\times 3$ 8-GHz (X-band) architecture. This breadboard consists of an X-band vector modulator that is driven by a field programmable gate array. The signal is mixed with an upconverted 24-GHz signal to give the Ka-band modulated output. Data rates from 650 kb/s to 130 Mb/s have been demonstrated with quadrature PSK (QPSK) and 16-QAM modulation formats.

I. Introduction

Future spacecraft telecommunications are expected to rely heavily on use of the 32-GHz (Ka-band) frequency spectrum. This has been clearly outlined in both the JPL and the NASA strategic technology plans, and efforts are ongoing to develop technology that will meet this projected need.[3] While 8 GHz (X-band) has long been the standard for deep-space telecommunications, a shift is necessary because of possible data rate limitations due to unavailable spectrum at X-band. The X-band Deep Space Network (DSN) allocation currently is being shared by many missions, limiting available bandwidth and therefore limiting telecommunications data rates. Use of the Ka-band spectrum allocation will significantly reduce this problem for two specific reasons. First, the Ka-band DSN allocation is ten times broader than that at X-band (500 MHz versus 50 MHz). Second, the Ka-band spectrum has fewer current users, so missions would be able to use a larger portion of the allotted spectrum.

The availability of the Ka-band DSN spectrum is made even more appealing by advances in technology that have produced more efficient modulation schemes. Although using amplitude modulation schemes is less likely for deep-space communications because of low-power signals, these schemes certainly will be used for near-Earth missions at the very least. Vector modulator technology allows for the option of using solely amplitude or phase modulation, or of using both together. This introduces significant flexibility in different modulation styles available with one device.

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[1] Flight Communications Systems Section.

[2] Autonomy and Control Section.

[3] *Strategic Technology Plan, 2005*, internal document, Jet Propulsion Laboratory, Pasadena, California, December 7, 2004.

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Future transponders will be utilizing these new technologies to increase communication efficiency. These factors, combined with the availability of the DSN Ka-band spectrum, would allow for rates well over 100 Mb/s to be attainable. Not only would this increase create the option of gathering more science data, but it would also decrease mission operations costs dramatically because the rate of transmission is inversely proportional to the cost of using a DSN station. In addition, faster data rates would take up fewer DSN resources, making these resources available to other missions.

This rationale has been one of the driving factors for the development of the Advance Deep Space Transponder (ADST) over the past several years [1].[4] Additional design drivers for transponder development include reduced size, mass, and cost. Improved transponder flexibility and efficiency are also desired, including in-flight frequency agility, in-flight reprogrammability, very high data rates, and advanced frequency-modulation capability.

As part of this development, a high-rate Ka-band downlink vector modulator breadboard has been developed. This breadboard uses vector modulator technology [2] to provide a variety of advanced modulation methods, including quadrature phase-shift keying (QPSK), offset-QPSK (OQPSK), and quadrature amplitude modulation (QAM). This breadboard is presented in this article.

II. Theory and Breadboard Design

An X-band ×3 architecture was used to generate the modulated Ka-band signal in this breadboard. This is different from older transponder technology, which utilized a ×4 multiplier architecture. Linear modulators were used specifically for certain types of phase-shift keying (PSK), and a Ka-band modulated signal would be obtained by feeding a modulated X-band signal through the ×4 multiplier. Although this design worked well for PSK modulation, other schemes that depend on the ability to discriminate the amplitude of the signal would not work through the multiplier. These types of modulations are called non-constant envelope modulation schemes, and the architecture presented in this article is capable of these types of modulation.

An additional significant benefit to this type of design is that, when coupled with the rest of the ADST breadboard, the X-band input to the Ka-band modulator board can come directly from the normal X-band downlink feed. The separate X-band oscillator that has always been necessary in older transponder designs for Ka-band capability is not needed in the ADST design.

This architecture utilizes an X-band vector modulator driven from a Nallatech Xilinx field programmable gate array (FPGA), which allows for a variety of modulation formats to be programmed into the FPGA and used in the system. Programming also allows for multiple modulations to be available for use and to be easily implemented. This architecture also uses the same 8-GHz synthesizer that is used to generate the normal X-band downlink in a spacecraft transponder. This synthesizer input is split between a ×3 branch, which upconverts the signal to 24 GHz, and the vector modulator branch. These branches are recombined using a mixer, resulting in a 32-GHz modulated signal. The architecture block diagram is shown in Fig. 1.

Band pass filters are necessary after the ×3 multiplier and mixer to block unwanted harmonics. Amplifiers are necessary at various points in the system in order to meet operating power levels for each system component. An isolator was inserted at the radio frequency (RF) output of the mixer in order to improve mixer performance. The Xilinx FPGA board is controlled with a computer via universal serial bus (USB) to provide the desired in-phase (I) and quadrature (Q) signals. I and Q (IQ) drivers were necessary to meet vector modulator IQ input requirements.

[4] S. K. Smith, N. Mysoor, J. Lux, B. Cook, B. Shah, and R. Lovick, *Frequency Agile Multi-Channel X-Band Coherent Receiver/Transmitter for the Advanced Deep Space Transponder*, R&TD Final Report (internal document), Jet Propulsion Laboratory, Pasadena, California, September 2005.

Five power supplies also were needed for the breadboard, and four of these were attached inside the metal case. The power supply for the vector modulator can be tuned to improve breadboard performance, and for this reason was provided externally from a low-noise, adjustable power supply. The IQ drivers were constructed using Analog Devices differential output buffer amplifiers. These amplifiers offer different advantages: one is capable of providing maximum power into the vector modulator chip, while the other is capable of higher speeds but does not maximize the input power to the vector modulator. W.L. Gore & Associates and Tensolite coaxial cables were used on the breadboard. K-connectors were used for frequencies above X-band. A picture of the breadboard is provided in Fig. 2.

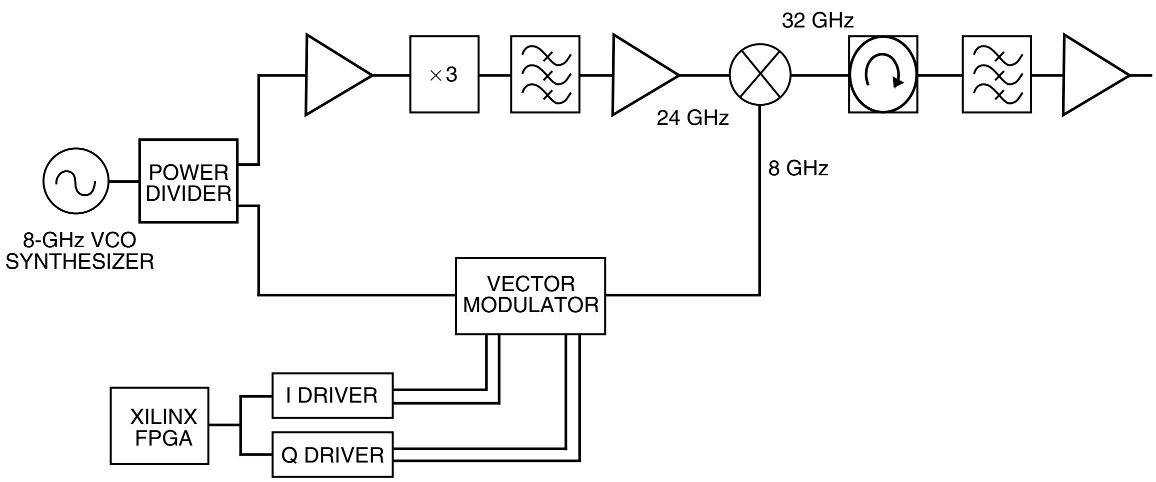

Fig. 1. The Ka-band ×3 vector modulator architecture.

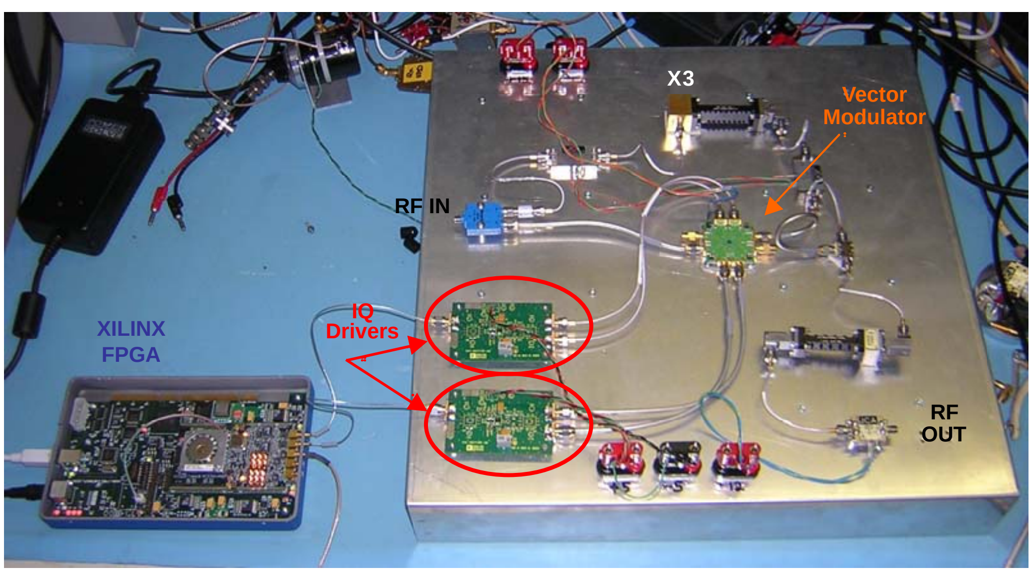

Fig. 2. Ka-band ×3 vector modulator breadboard.

III. Results

Modulated Ka-band data rates from 650 kb/s to 130 Mb/s have been demonstrated using the breadboard of Fig. 2. The highest data rate corresponds to QAM modulation at 32.5 Msymbols/s. The frequency spectrums for these rates are shown in Figs. 3 and 4. Results followed predicted behavior closely, both with power levels and with spectrum distribution. Both sets of IQ drivers were constructed and tested on the breadboard. The best performance was obtained from the full-power drivers. Power levels indicated in Figs. 3 and 4 represent the total power in the frequency spectrum.

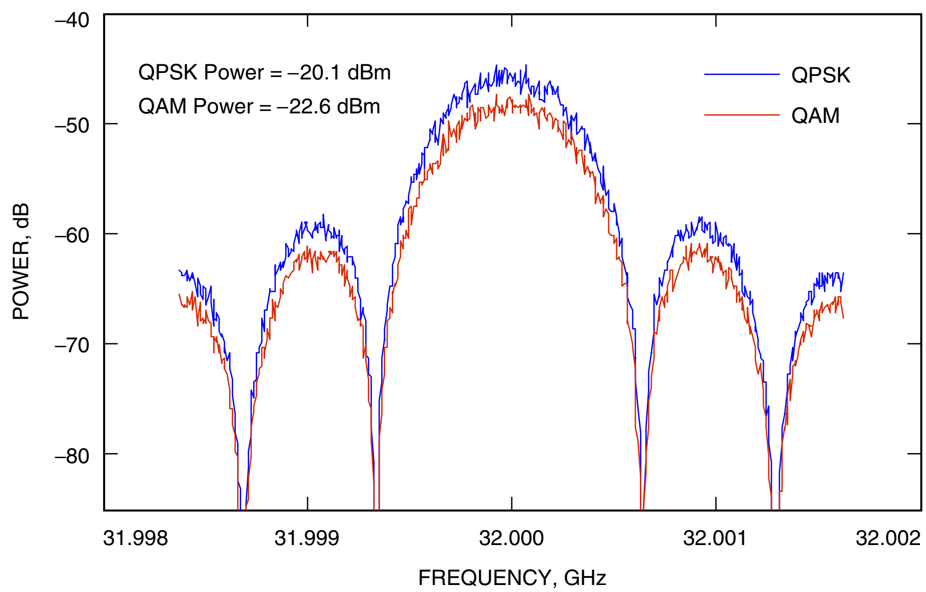

Fig. 3. QPSK and QAM modulations at 650 ksymbols/s.

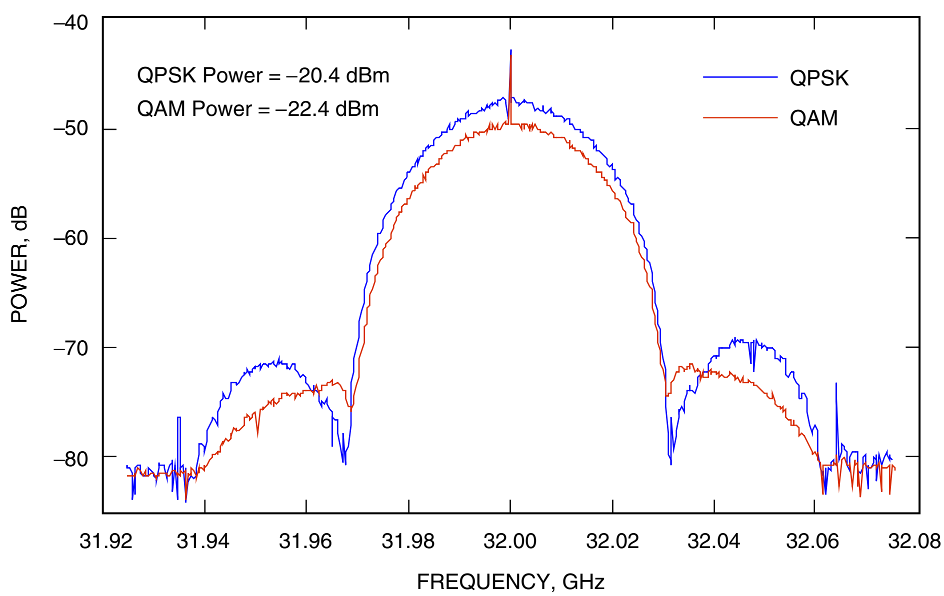

Fig. 4. QPSK and QAM modulations at 32.5 Msymbols/s.

As can be seen in Fig. 4, the 32-GHz carrier is not suppressed completely for higher data rates. This is due to IQ mismatch at high speeds and could be improved with a higher-speed FPGA and faster drivers. Low-pass filters were present on the output of the Xilinx FPGA, reducing the quality of the IQ signals at high data rates. In addition, the IQ drivers produced much sharper transitions at rates below 10 MHz due to an improved amplifier slew rate at lower frequencies. Close-in spectrum spurs were eliminated by slightly adjusting the relative DC offsets of the I and Q drivers. The 16-QAM modulations were ~2.5 dB lower than QPSK for all cases. This is because this breadboard was programmed so that the 4 QPSK states have the same phasor amplitude as the outermost of the 16-QAM states. The other 12 of the 16-QAM states obviously have a smaller amplitude phasor and, therefore, less power. This is why the power visible in the total 16-QAM spectrum is less than that for QPSK, and this is shown in Figs. 5 and 6. Transitional behavior between states is visible in the I versus Q plots. Ideally, only exact points corresponding to modulation states would be visible on the oscilloscope; however, it is impossible to have an instantaneous transition from one state to another. Scattered points reveal the oscilloscope sampling as the signal is transitioning from one state to another. Additional plots provided in Figs. 7 and 8 show that the signal is at the exact modulation states for a much longer period of time than in the transitional areas, and many of the pixels not at the exact modulation states in Figs. 5 and 6 represent only a single sample.

IV. Conclusions and Future Work

The breadboard performed well and demonstrated capability for QPSK and 16-QAM data rates above 100 Mb/s. Additional carrier suppression is possible with digital equalization, additional filtering, and IQ balancing. We will consider these factors in the next design iteration. In addition, we will conduct a bit-error rate (BER) test to compare performance at various power levels, modulations, and data rates. The breadboard results indicate that this vector modulator technology would allow for a flexible, highly integrated, high-speed, and efficient Ka-band downlink for the next-generation Advanced Deep Space Transponder.

The majority of breadboard components could be designed as monolithic microwave integrated circuit (MMIC) chips. It is anticipated that 3 to 5 chips would be necessary in a multi-chip module measuring less than 25 cm^2. Regulators could be used to provide the necessary DC voltages from a constant supply bus. This sort of a module would consume less than 6 W.

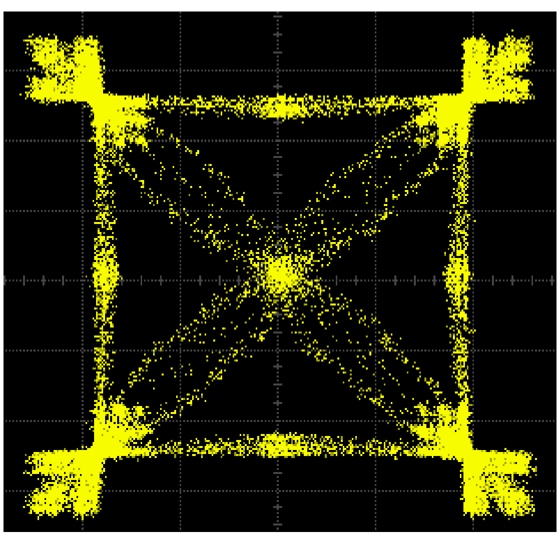

Fig. 5. QPSK I versus Q plot.

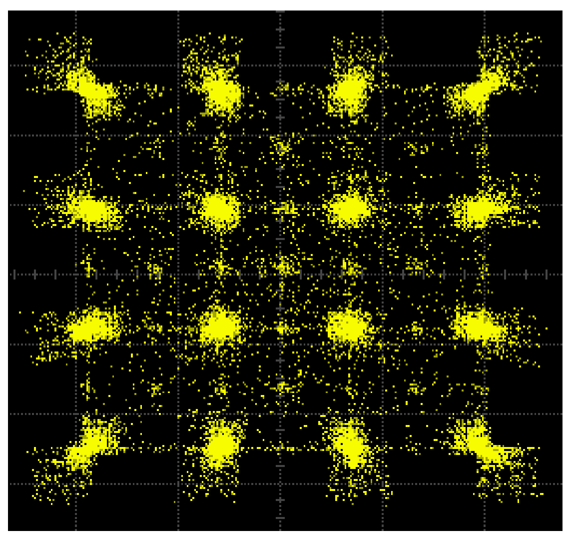

Fig. 6. 16-QAM I versus Q plot.

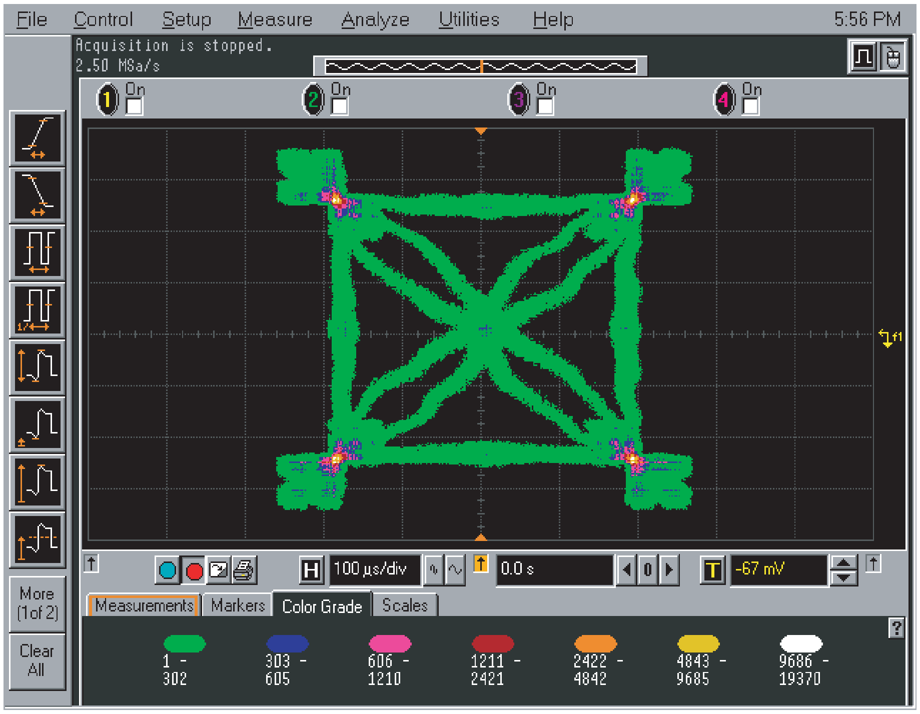

Fig. 7. QPSK IQ plot showing a sample distribution.

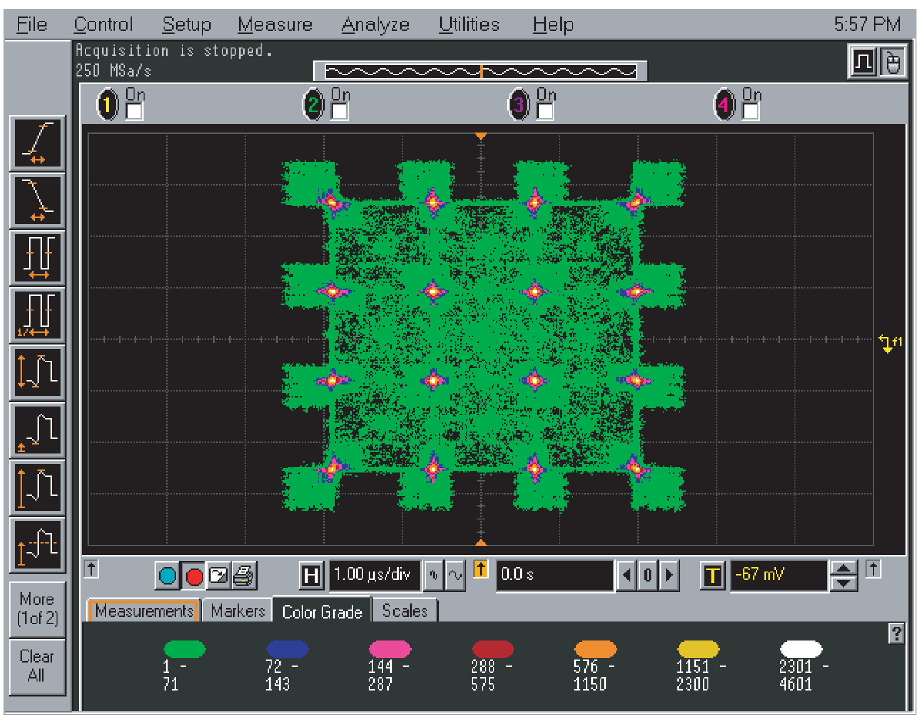

Fig. 8. 16-QAM IQ plot showing a sample distribution.

Acknowledgment

We would like to acknowledge Kathleen Sowles for her outstanding fabrication work.

References

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[2] J. Penn, "A Balanced Ka-band Vector Modulator MMIC," *Microwave Journal*, vol. 48, no. 6, pp. 84–90, June 2005.