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Demonstration of Multi-Gbps Data Rates at Ka-Band Using Software-Defined Modem and Broadband High Power Amplifier for Space Communications

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Abstract

The paper presents the first ever research and experimental results regarding the combination of a software-defined multi-Gbps modem and a broadband high power space amplifier when tested with an extended form of the industry standard DVB-S2 and LDPC rate 9/10 FEC codec. The modem supports waveforms including QPSK, 8-PSK, 16-APSK, 32-APSK, 64-APSK, and 128-QAM. The broadband high power amplifier is a space qualified traveling-wave tube (TWT), which has a passband greater than 3 GHz at 33 GHz, output power of 200 W and efficiency greater than 60 percent. The modem and the TWTA together enabled an unprecedented data rate at 20 Gbps with low BER of 10^{-9}. The presented results include a plot of the received waveform constellation, BER vs. E_b/N_0 and implementation loss for each of the modulation types tested. The above results when included in an RF link budget analysis show that NASA's payload data rate can be increased by at least an order of magnitude (>10X) over current state-of-practice, limited only by the spacecraft EIRP, ground receiver G/T, range, and available spectrum or bandwidth.

I. Introduction

NASA is in need of a versatile, higher data rate integrated space communications network to provide services to space flight missions located throughout the solar system (Ref. 1). The driving requirements for the network are quite broad, covering space based navigation and communications for manned and robotic missions from near-Earth to deep space, all with emphasis on higher data rates in the Gbps range. The justification for Gbps data rates is closely linked to the capabilities of remote spacecraft sensors, which are quickly outstripping the ability of current data links to rapidly move the sensor information back to Earth (Ref. 2). Four data links that are potential elements of NASA's integrated space communications network are: satellites in low Earth orbit (LEO), lunar relay satellites (LRS), spacecrafts stationed at the second Lagrangian point (L2), and spacecrafts in deep space (DS). In addition, Gbps data rate technology is useful for fixed, mobile, broadcast, broadband and commercial Earth imaging satellite services (Ref. 3).

In this paper, we present experimental results, which can enhance the RF communications capability of NASA's spacecraft-to-Earth data links identified above. We demonstrated in a laboratory setting very high data rates on the order of multi-Gbps (20 Gbps) at Ka-band frequencies using software-defined modems (SDMs), bandwidth efficient modulation (BEM) techniques (PSK, APSK, and QAM) and a broadband high efficiency high power space amplifier. To the best of our knowledge this is the first ever demonstration of such high data rates through a high power space amplifier at Ka-band frequency. The presented results include a plot of the received waveform constellation, BER vs. E_b/N_0, and implementation loss for each of the modulation types investigated. These results, when included in an RF link budget analysis, show that the data rate of the above links can be enhanced by an order of magnitude (>10X) over current state-of-practice. By simultaneously using RHCP and LHCP for transmission, the data rate can be doubled (~20X). If a dual-polarization/dual-beam system is used, the data rate can be quadrupled (~40X).

II. Enabling Technologies

The two technologies, high-speed software-defined modems and Ka-band broadband high efficiency high power space amplifiers, are critical components in meeting the above goals of increasing user data rates.

(a) (b) (c)

Figure 1.—L-3 CSW Gbps software-defined modem (SDM). (a) The enclosed modem is 6 by 4 by 1.5 in. and contains (b) two digital cards and (c) mixed signal card with A/D and D/A converters. One module is used for transmission and one for reception.

A. Software-Defined Modem (SDM)

State-of-the-art mixed signal, fully software-defined modem (SDM) based on the latest field programmable gate array (FPGA) technology (Fig. 1) have been implemented, which currently support lower-order modulations (QPSK and 8-PSK) and are programmable for higher-order modulations (Ref. 4). In addition, an advanced modem breadboard consisting of laboratory test equipment and in-house developed software has also been implemented, which can support 16-APSK, 32-APSK, 64-APSK, and 128-QAM waveforms operating in real time while transmitting standard pseudo random bit stream (PRBS) test patterns (Ref. 4).

B. Traveling-Wave Tube Amplifier (TWTA)

Space TWTAs for near-Earth and deep space missions at K-band and Ka-band frequencies are currently flying in space. Efficiencies of these amplifiers are in the range of 50 to 60 percent and the corresponding RF output power level is in the range of 35 to 200 W. In References 5 and 6, examples of NASA space TWTAs and their RF performance characteristics including size and mass are presented. The typical design bandwidth has been 500 MHz, but these amplifiers perform well with bandwidths in excess of 3 GHz. The TWTA provides very high efficiency, high power, wide bandwidth, and good linearity. These characteristics, combined with pre-compensation in the SDM and in the advanced modem breadboard, allow dense higher-order waveform constellations to be supported with small implementation losses.

III. Waveform Design and Implementation

The waveforms investigated include the digital video broadcasting-satellite, second-generation (DVB-S2), family. Details of the modulation, constellation mapping, interleaving, and encoding for QPSK, 8-PSK, 16-APSK, and 32-APSK modes are available in Reference 7. We extend the DVB-S2 modulation suite to higher-order modulation types and use the 64-APSK constellation given in Reference 8 and the 128-QAM cross II constellation from Reference 9. The forward error correction (FEC) employed in our work is the low-density parity-check (LDPC) rate 9/10 code described by the European Telecommunications Standard Institute (ETSI) (Ref. 7).

A. Using Software-Defined Modem

The waveforms are implemented in the FPGA-based SDM shown in Figure 1. The modem has a transmit and a receive module. The transmit module has an I/Q-sampler and a two-stage X-band/Ka-band up-converter and the receive module has a two-stage X-band/Ka-band down-converter as analog interfaces. The SDM supports QPSK and 8-PSK waveforms. Each also supports continuously configurable data rates (and bandwidth) via digitally interpolated symbol timing and a fixed sample clock.

B. Using Advanced Modem Breadboard

The advanced modem breadboard consists of laboratory test equipment and in-house developed software that provides the capability to test waveforms over actual channels. The advanced modem breadboard uses the same digital algorithms as used in the SDM at the same symbol rate and bandwidth at any data rate and modulation up to 20 Gbps. The advanced modem is used to test 16-APSK, 32-APSK, 64-APSK, and 128-QAM waveforms.

C. Distortion Mitigation

To achieve high data rates, the advanced modem breadboard includes non-linear pre-compensation for the TWTA AM/AM and AM/PM, as well as compensation for the I/Q modulator distortions. Figure 2 shows the output spectrum of the TWTA, given a frequency-flat 3 GHz input signal, without and with pre-compensation. Notice that with pre-compensation the signal is flatter.

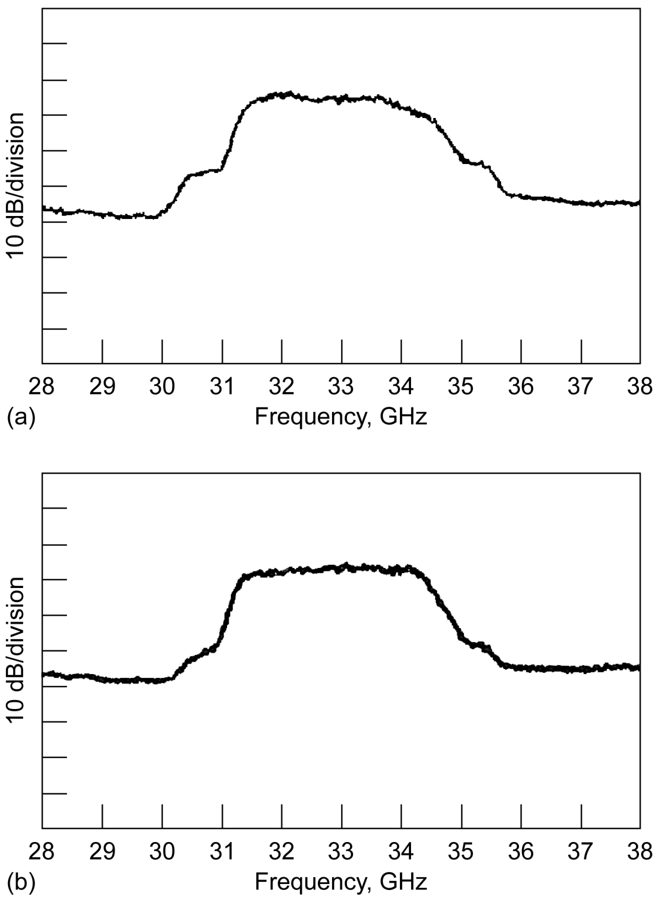

Figure 2.—Spectrum analyzer capture of the RF spectrum including that of the up- and down-conversion and the TWTA: (a) Without. (b) With linear pre-compensation.

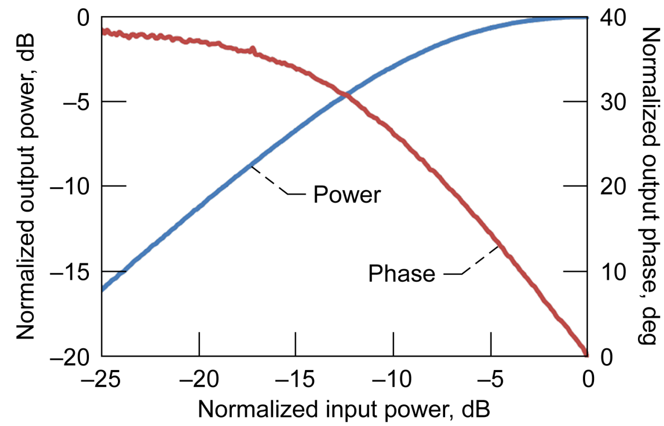

Figure 3.—Normalized output power and phase of the TWTA as a function of the input drive power at f_0 = 33 GHz. These parameters are needed for pre-compensation. P_{sat} = 125 W.

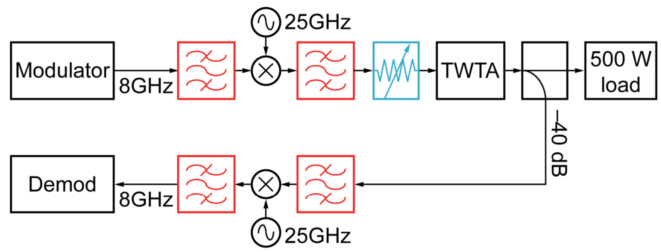

Figure 4.—System level block diagram of the experimental setup. The “Modulator” and “Demod” blocks shown represent either the software-defined modem or the advanced modem breadboard.

IV. Experimental Setup

The TWTA output power and phase as a function of the input drive power was measured across the 31 to 35 GHz band. For these measurements, the TWTA voltages and currents were set so that the saturated output power (P_{SAT}) was 125 W. Figure 3 shows the measured normalized output power and phase of the TWTA as a function of the input drive power at f_0 = 33 GHz. Supporting hardware was set up around the TWTA to match the IF of the modem to the Ka-band test channel. A system level block diagram of the experimental setup is shown in Figure 4. The advanced modem breadboard modulator is comprised of a personal computer (PC) hosting software that emulates a software-defined modulator, a Tektronix Arbitrary Waveform Generator and a Hittite Microwave I/Q Mixer. The advanced modem breadboard demodulator consists of a PC hosting software that emulates a software-defined demodulator and a Tektronix digital oscilloscope.

V. Advanced Modem Performance Results

Transmitting a modulated waveform through the TWTA and then demodulating the received waveform enabled an assessment of the waveform performance through the test channel at 33 GHz. In order to induce bit errors for the purpose of a BER measurement, the advanced modem breadboard demodulator digitally added generated pseudo noise at precisely controlled levels to the received A/D output samples. The implementation of the digital noise generator is based on the work of Marsaglia and Tsang (Ref. 10) on the Ziggurat method for generating random variables. Modulation schemes of QPSK, 8-PSK, 16-PSK, 32-APSK, 64-APSK, and 128-QAM were tested in conjunction with the DVB-S2 LDPC 9/10 FEC codec.

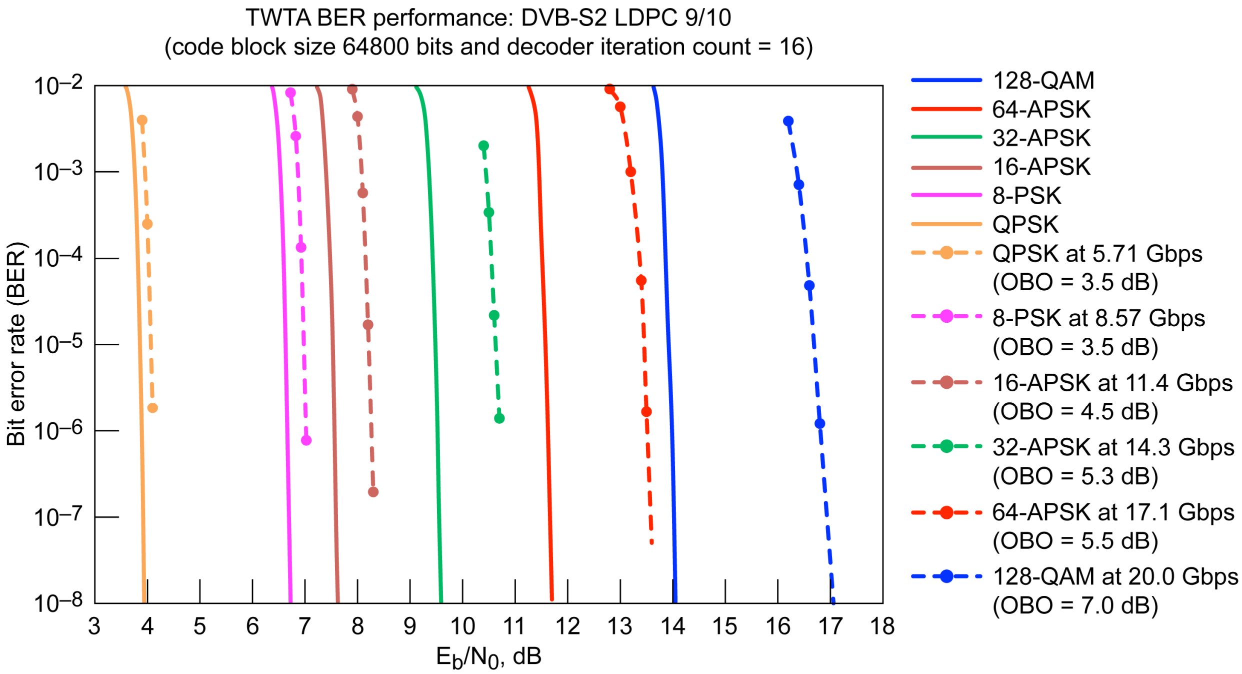

Figure 5.—BER versus E_b/N_0 for each of the modulation types tested with the DVB-S2 LDPC 9/10 codec. Solid line is a floating-point model and dotted line is measured data. The difference is the implementation loss, which is attributed to an underlying system noise floor due to quantization noise, thermal noise, and other types of distortion-induced noise and intermodulation products of the channel.

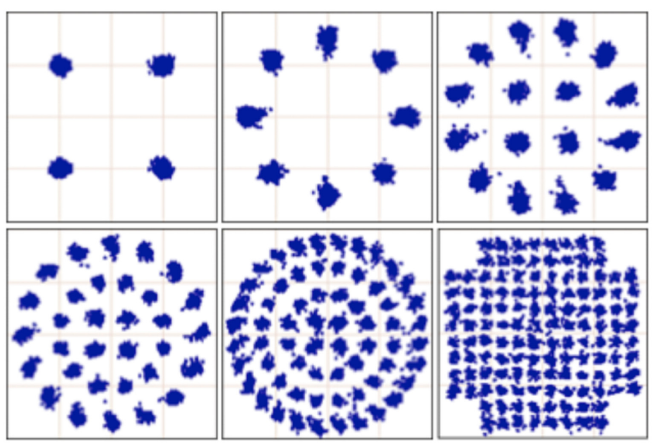

Figure 6.—Received constellation for QPSK, 8-PSK, 16-APSK, 32-APSK, 64-APSK, and 128-QAM at 3.2 Giga-symbols/second through the Ka-band TWTA. Transmitter pre-compensation was enabled.

For each modulation type, the bit rate was selected such that a constant channel symbol rate of 3.2 Gsps was achieved. This led to an information bit rate of 5.7 Gbps for the lowest-order modulation tested, QPSK, and up to 20 Gbps for the highest-order modulation tested, 128-QAM. For each waveform under test, the input power to the TWTA was set such that its average output power back-off (OBO) from saturation was approximately equal to the peak-to-average power of the waveform in an ideal undistorted state. Figure 5 plots BER vs. E_b/N_0 for each of the modulation types tested with the DVB-S2 LDPC 9/10 codec. The recovered signal constellation diagrams for the six waveforms, when pre-compensation as well as adaptive equalization are applied, are shown in Figure 6. Notice that the symbols are distinct, which indicates excellent compensation for system non-linearity.

VI. Space-To-Earth RF Link Budget Analysis

The above results are included in a RF link budget analysis, which besides other parameters takes into account the TWTA output power, spacecraft antenna diameter, available spectrum or bandwidth, atmospheric attenuation, range, ground antenna diameter and G/T ratio. The analysis generates the achievable data rates for NASA's four data links discussed in Section I. Table I compares the achievable data rates with the current state-of-practice. The data rate improvement factor in all cases is an order of magnitude or greater (>10X). Commercial Earth imaging satellites transmit 800 Mbps from LEO, using two orthogonally polarized 400 Mbps channels, at X-band. If the next generation Earth imaging satellites migrated to Ka-band, the achievable data rate and improvement factor per polarization would be as high as 2.8 Gbps and 7X, respectively, using our advanced modem technology.

TABLE I.—CURRENT STATE-OF-PRACTICE, ACHIEVABLE DATA RATE AND IMPROVEMENT FACTOR FOR NASA'S FOUR DATA LINKS IN SECTION I

Current state-of-practice			
Type of link and distance	Center frequency, GHz	TWTA P_{SAT}, W	Data rate, Mbps
LEO, 700 km	X-band, 8.45	20	150
LRS, 384000 km	K-band, 25.65	40	100
L2, 1.5 million km	K-band, 25.9	58	28
DS, 1 AU	X- and Ka-band, 8.45 and 32.05	100 (X-band) and 35 (Ka-band)	6

Achievable data rate at Ka-band and improvement factor TWTA P_{SAT} = 40 W, Spacecraft ant dia. = 1 m, Bandwidth = 500 MHz			
Type of link and distance	Ground antenna dia. (m) and elevation angle	Achievable data rate, Gbps	Improvement factor
LEO, 700 km	2, 5°	2.8	19X
LRS, 384000 km	18.3, 10° (G/T>46.5 dB/K)	0.95	10X
TWTA P_{SAT} = 100 W, Spacecraft ant dia. = 4 - 5 m, Bandwidth = 300 MHz			
L2, 1.5 million km	18.3, 10° (G/T>46.5 dB/K)	0.95	34X
DS, 1 AU	34, 10° (G/T>60 dB/K)	0.08	13X

VII. Conclusions and Discussions

The paper presents the first ever research and experimental results regarding the combination of a software-defined multi-Gbps modem and a broadband high power space amplifier when tested with the extended industry standard DVB-S2 and LDPC rate 9/10 FEC codec. The modem and the TWTA together enabled an unprecedented data throughput of 20 Gbps with low BER of 10^{-9}. The presented results include a plot of the received waveform constellation, BER vs. E_b/N_0 and implementation loss for each of the modulation types tested. The above results when included in a RF link budget analysis show that NASA's payload data rate can be increased by at least an order of magnitude (>10X) over current state-of-practice. Finally, the above demonstration shows that a Ka-band transmitter with data rate at 20 Gbps is achievable and the link capacity is limited only by the spacecraft antenna EIRP, ground receiver G/T, range, and available spectrum or bandwidth.

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14. ABSTRACT
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