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EXTENSION OF DVB-S2 CAPABILITIES FOR HIGH RATE AISR DATA TRANSPORT

Chayil Timmerman, Michael Wright, and Todd Brick
 MIT Lincoln Laboratory
 Lexington, MA

ABSTRACT

In 2007, MIT Lincoln Laboratory began supporting the United States Air Force (USAF) MILSATCOM Family of Advanced Beyond Line of Sight Terminals Increment 2 (FAB-T Inc 2) program¹. The Laboratory led the development and implementation of the Ka-band high data rate (Ka HDR) waveform for the transportation of airborne intelligence, surveillance, and reconnaissance (AISR) data from air assets to any number of ground stations via the Ka-band capabilities of the Wideband Global SATCOM (WGS) system. This waveform is subject to all the technical challenges posed by the requirements of an airborne terminal, including: limited size weight and power (SWaP), a direct synthesis scheme on transmit, developing for a software defined radio (SDR) environment, and adhering to MILSATCOM requirements. After a research study of available waveform options, Lincoln recommended the Digital Video Broadcast Satellite Second Generation (DVB-S2) waveform to fulfill the Air Force's requirements. Because commercially available DVB-S2 modems currently only support rates of approximately 45 million symbols per second (Msym/s), Lincoln extended this capability to 280 Msym/s to satisfy the FAB-T Inc 2 requirements. This paper details the results of this extension and shows that the new system maintains much of the benefits of the commercial-off-the-shelf (COTS) components.

DVB-S2, ETSI (EN 302 307), is an advanced satellite communications standard developed to support commercial satellite broadcasting of television, interactive services, news gathering, and other broadband satellite applications. Its advanced forward error correction (FEC) scheme, multiple modulation types, and potential compatibility with the Joint Internet Protocol Modem (JIPM) made it a suitable candidate for FAB-T Inc 2.

INTRODUCTION

The numbers and types of airborne vehicles used to conduct airborne intelligence, surveillance, and reconnais-

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sance (AISR) has dramatically increased in recent years to support the Global War on Terrorism (GWOT) and other operations. The sensor packages aboard these platforms have become increasingly sophisticated and capable of collecting large amounts of data. Because of the requirement to disseminate this data in near real-time, a high-data rate (HDR) communications link from the aircraft to a ground station is required. However, line-of-sight (LOS) links limit the operating range of the missions because the ground station must be located in friendly territory. To address this limitation, the USAF sponsored a program called Family of Advanced Beyond Line-of-Sight Terminals Increment 2 (FAB-T Inc 2) to develop a beyond line-of-sight (BLOS) waveform for use over the Wideband Global SATCOM (WGS) constellation of satellites. In the WGS Block II payloads (WGS-4 and higher), a total bandwidth of approximately 400 MHz is available in the channelizer bypass mode. This mode could support BLOS AISR data rates approaching 300 Mbps.

A. FAB-T Increment 2 and HDR-RF

FAB-T Inc 2 is the second phase of an overall USAF military satellite communications (MILSATCOM) airborne terminal program. Whereas the focus of the first increment of FAB-T was focused on protected EHF communications to strategic assets, a major role of Increment 2 is to develop and deploy a high-bandwidth, high-throughput (HBHT) Ka-band waveform on a reconfigurable software-defined radio (SDR) platform for use on AISR platforms. Lincoln Laboratory's core responsibilities for FAB-T Inc 2 are the development and implementation of the HBHT waveform for use on Ka-band transponders. This high data rate (HDR) waveform is commonly known as the Ka HDR waveform. The FAB-T Inc 2 implementation of the Ka HDR waveform is used primarily in a transmit-only mode to a compatible ground terminal.

The counterpart to the FAB-T Inc 2 terminal is the High Data Rate Radio Frequency (HDR-RF) upgrade to the Ground Multi-band Terminal (GMT). The HDR-RF terminal will primarily employ the Ka HDR waveform in receive mode, but will also have the capability to function as a high rate transmitter.

B. Ka HDR Waveform Requirements

The FAB-T Inc 2 program office developed a set of requirements and major performance and functional characteristics specifically for the Ka HDR waveform. The waveform had to satisfy the following requirements:

- Support sustained user data rates of 274 Mbps, with the ability to scale to 548 Mbps
- Close the air-to-ground link within an available E_b/N_0 of 4.5 dB
- Support network-ready data types, including IPv6
- Meet size, weight, and power (SWaP) constraints when implemented in an SDR platform
- Comply with the Software Communication Architecture (SCA) 2.2 or higher

WAVEFORM SELECTION

The various environmental factors encountered in a mobile airborne platform complicate the waveform selection process. For example, Doppler frequency shifts, veloci-

ties, and accelerations can cause receiver acquisition difficulties. Other factors contribute to small link margins, such as a relatively small antenna aperture, waveguide losses, and limited RF amplifier power. Finally, FAB-T Inc 2 requires an SDR architecture for the airborne modem for re-programmability, along with waveform portability and reusability in other terminal such as HDR-RF.

A. Waveform Candidates

To determine whether a completely new waveform was required, Lincoln evaluated existing candidate waveforms against strict screening criteria to assess their suitability for use as specified, or as modified waveforms that could be meet the Ka HDR waveform requirements. The candidate waveforms included: MIL-STD-188-165A, Enhanced Bandwidth Efficient Modem (EBEM), and Digital Video Broadcasting, Second Generation (DVB-S2). Also included were two proposed waveforms: the MITRE Ka-band HBHT waveform, and the Ka Transformational SATCOM (TSAT) waveform. Table 1 lists the significant waveform specifications for the candidate waveforms.

Table 1: Waveform specifications

	HBHT	165A	EBEM	DVB-S2	Ka-TSAT
Max Rate (Mbps)	274.176 ¹	51.84	155	120 ²	311
Rate Step	1.14Mbps	8kbps ³	8kbps ³	N/a ⁴	N/a ⁵
FEC type ⁷ and code block length	LDPC 11904	RS/CEVD (219,201) k=7	165A+TPC 4k/16k	BCH/LDPC 16k/64k	SCCC
FEC rates	½, ¾, ⅔	½, ¾, ⅔, ⅓	½ to 19/20	¼ to 9/10	⅓
Modulation ⁸	OQPSK, 8- PSK	BPSK, O/QPSK	165A+ 16APSK	QPSK, 8-PSK, 16/32APSK	OQPSK
Min E_b/N_0 (dB) @10 ⁻⁸ BER	1.50	5.80	2.60	1.05 ⁷	2.30
@Mode	½ + OQPSK	½ + OQPSK	½ Turbo + OQPSK	½ + QPSK and 64k block	⅓ + OQPSK

Notes:

1. Max rate is 548.352, but not required for Inc 2 implementation
2. Max rate quoted by COTS implementations; DVB-S2 does not state an upper limit
3. Rate step is for modes above 8 Mbps
4. No minimum rate step specified
5. Rates are fixed at 51.84, 155.52, and 311.04 Mbps
6. Performance expressed as packet error rate (PER) equal to 10⁻⁷ for 188-byte packets
7. LDPC=Low Density Parity Check, RS=Reed-Solomon; CEVD=Convolutional Encoding/Viterbi Decoding; BCH=Bose-Chaudhuri-Hocquenghem
8. PSK=Phase Shift Keying; BPSK=Binary PSK; QPSK=Quadrature PSK; OQPSK=Offset QPSK; 8-PSK=8-ary PSK; 16/32APSK=16/32-ary Amplitude-PSK

B. Waveform Analysis

Lincoln analyzed all the waveforms to determine their applicability to the Ka HDR waveform mission requirements. The primary performance requirement was link closure at 274 Mbps in the WGS bypass mode. The limiting factor was the available E_b/N_0 at that rate. This requirement was defined as the E_b/N_0 to close the link at 274 Mbps @ 10^{-8} BER. The analysis of representative link calculations gave a value of approximately 4.5 dB E_b/N_0 .

This value was derived using a data rate of 274 Mbps, EIRP and G/T specifications for the WGS satellite as published in Rev E specifications [1], and a ground terminal with a 6.25 m antenna. From this information, the HDR Link Budget Working Group (LBWG) established that the uplink and composite E_b/N_0 availability as 4.884 dB and 4.691 dB, respectively [2]. Additionally, a study by Lincoln Laboratory calculated that the E_b/N_0 available in uplink and composite as 5.3 dB and 4.3 dB, respectively. A mean of the two composite E_b/N_0 availabilities is approximately 4.5 dB, which is used as a reasonable value to select as the maximum E_b/N_0 requirement by the waveform that would result in a 0 dB link margin. Waveforms that cannot meet this E_b/N_0 requirement, regardless of mode and rate, would not be acceptable.

Next, the net E_b/N_0 requirement for each waveform was calculated using the waveform theoretical E_b/N_0 value, and adding an additional 2.2 dB of implementation and system losses:

Example: For the HBHT waveform,

$$\begin{aligned} & 1.5 \text{ dB } E_b/N_0 \text{ theoretical @ } 10^{-8} \text{ BER} \\ & + 1.7 \text{ dB Implementation loss} \\ & + 0.5 \text{ dB System loss (LBWG)} = \\ & \mathbf{3.7 \text{ dB } E_b/N_0 \text{ required}} \end{aligned}$$

Based on the value of E_b/N_0 for each of the waveforms in Table 1, the following waveforms could not meet this screening criterion (with E_b/N_0 requirement in parenthesis):

MIL-STD-188-165A (8.0 dB)
EBEM (4.8 dB)
Ka-TSAT (4.5 dB)*

*Note: The original Ka-TSAT link margin calculation resulted in a -0.6 dB (negative) for a 311 Mbps data rate and $\frac{2}{3}$ rate code. Adjusting for a lower data rate of 274 Mbps reduces the E_b/N_0 required by 0.6 dB, giving a 0 dB margin.

Assuming a positive link margin is required, the only surviving candidate waveforms were the HBHT and DVB-S2,

with estimated power requirements of 3.7 dB and 3.25 dB, respectively.

C. Waveform Constraints

In addition to the channel performance described above, the non-waveform requirements of SWaP and portability were also considered. Airborne communications equipment is constrained to physical volume, power draw, and thermal dissipation. The programmable SDR architecture requires that the usual performance benefits of using application specific integrated circuits (ASICs) must be traded for more flexible, but lower speed, field programmable gate array (FPGA) devices.

These constraints influence the hardware selection, and thus were included in the analysis of the waveform performance limits. For example, the target modem module contained three Virtex 5 LX330T FPGAs. The power draw and dissipation limits were calculated to be approximately 100 W for the modem module. Using these two constraints, we calculated the theoretical number of FPGA resources available for the waveform processing, along with an FPGA power draw ceiling that we checked against reference implementations of the system.

Determining actual resource and power requirements for waveforms that have not been implemented is not possible. However, previous experience with waveform development gave us reasonable assurance that both the HBHT and the DVB-S2 waveforms would fit in the available FPGA resources. Similarly, we used power estimates of other high-speed waveforms to conclude that the power draw and dissipation would not be a limiting factor with either waveform.

D. The Ka HDR Waveform Selection

Given that both the HBHT and the DVB-S2 waveforms meet the primary criteria and should meet the SWaP constraints, the choice of waveform selection rested with a choice between developing a new waveform, or leveraging an existing standard. During the analysis of the waveform candidates, the Department of Defense (DoD) published a memorandum defining the waveform standard for IP-based communications over transponded satellites. The DoD chief information officer (CIO) selected the DVB-S2 and associated DVB-RCS as the standard for teleports. At about the same time, a new modem program called the Joint IP Modem, or JIPM, was established to develop and deploy a common modem for use by the DoD community [3].

It was clear that the DoD enterprise was migrating to DVB-S2 as the preferred waveform. Our recommendation was to base the Ka HDR waveform on DVB-S2 to support FAB-T Inc 2 and HDR-RF. Because we were extending

the data rate of DVB-S2, we designated the Ka HDR waveform as the “HDR extension to DVB-S2.” However, because the phrase “Ka HDR waveform” was already widely in use, we refer to new waveform as such.

BENEFITS OF DVB-S2

Because the Ka HDR waveform is based on a commercial standard, there are several benefits to the developer as well as the implementing organization. First, the specifications on the functionality have already been established. This ensures consistency between various vendors. It also ensures that a waveform does not become a proprietary standard of a single company. In this regard, the development and porting costs can also be reduced by using commercially-available intellectual property for standard waveform processing blocks such as the forward error correction (FEC).

A second benefit of adopting DVB-S2 is that there are already commercial implementations available to test against, albeit at significantly lower symbol and data rates. However, many waveform functional checks can be verified at lower rates such as framing, FEC, scrambling, and modulation.

Finally, because the DVB-S2 standard offers five modulation types and eight code rates, the waveform can be adapted to many channel types. Additionally, DVB-S2 does not specify any particular symbol or data rates, allowing the modem to efficiently utilize satellite bandwidth.

DEVELOPMENT PLATFORM

The development platform chosen to implement the Ka HDR waveform consists of a single Virtex 5 FPGA and a high-speed digital to analog converter (DAC).

The SWaP requirements on the Ka HDR waveform implementation dictate a single FPGA solution for the transmitter. The Virtex 5 SX95T contains 640 DSP 48E slices, 244 36-kbit block RAMs, and is capable of supporting a clock rate in the range of 300 MHz [4]. The SX95T’s capabilities made it a suitable choice for the signal processing portion of the development platform.

The Maxim 19692 DAC supports a 2.3-GSample/s clock. This high sample clock allows for direct synthesis of the intermediate frequency (IF) at L-band. The DAC is used in its “RF” mode which provides for a smoother, higher power, frequency response in the second Nyquist zone [5].

The DAC provides the FPGA with its signal processing clock, which is $1/8^{\text{th}}$ of the sample clock. There are four 12-bit data lines between the FPGA and the DAC. Each data line transports a new sample on the rising and falling edges of the clock. The effective data rate of each line is $1/4^{\text{th}}$ the sample clock. An Agilent 4428C Signal Genera-

tor (ESG) provides the DAC sample clock at 2.24 GHz and +12.0 dBm.

The Ka HDR development platform does not contain an analog filter. For operational use, analog filters are required to attenuate undesired harmonics produced by the system.

DIGITAL IMPLEMENTATION

Figure 1 shows the FPGA architecture for the Ka HDR transmitter. The portion of Figure 1 enclosed by the box comprises the core transmitter functions and are hardware agnostic. The portions of the design outside the box are platform specific functions that are FPGA dependent, and are not discussed in this paper.

For clarity, Figure 1 does not show the inter-module first-in-first-out memories (FIFOs) between the different modules. All modules transport data via FIFOs, with the exception of the outputs of the root raised cosine (RRC) filters. Their outputs are streamed directly to the DAC interface. The use of FIFOs between modules allows for easier portability between different development platforms and systems. The FIFO interfaces allow adjacent modules to reside in different FPGAs, which increase reusability and portability of the design.

The baseband framing module captures data from the input for transport. The data is then packaged into DVB-S2 Baseband Frames and scrambled. The DVB-S2 standard provides padding in the case of data underflows. The standard also provides for two frame lengths, normal and short. The normal frames offer between 0.2 to 0.3 dB better performance than the short frames [3]. For this reason the implementation, described in this paper, only supports normal sized frames. In the future, short frames may be added to the design to provide a fully compliant DVB-S2 solution.

Fully constructed baseband frames are then passed onto one of two DVB-S2 FEC encoders. A 280-Msym/s rate, which is needed to support a data rate of 274 Mbps at QPSK 1/2, requires two FEC encoders. Each encoder processes every other baseband frame based upon the selected modulation and code rate. In the case of 8PSK, it also interleaves the results. (There is no interleaving for QPSK.) Finally it constructs the DVB-S2 FEC frames.

The encoder is an intellectual property core, purchased from Xilinx. However, the use of Xilinx intellectual property does not lock the design into using a Xilinx based platform. Several vendors offer intellectual property targeted to DVB-S2.

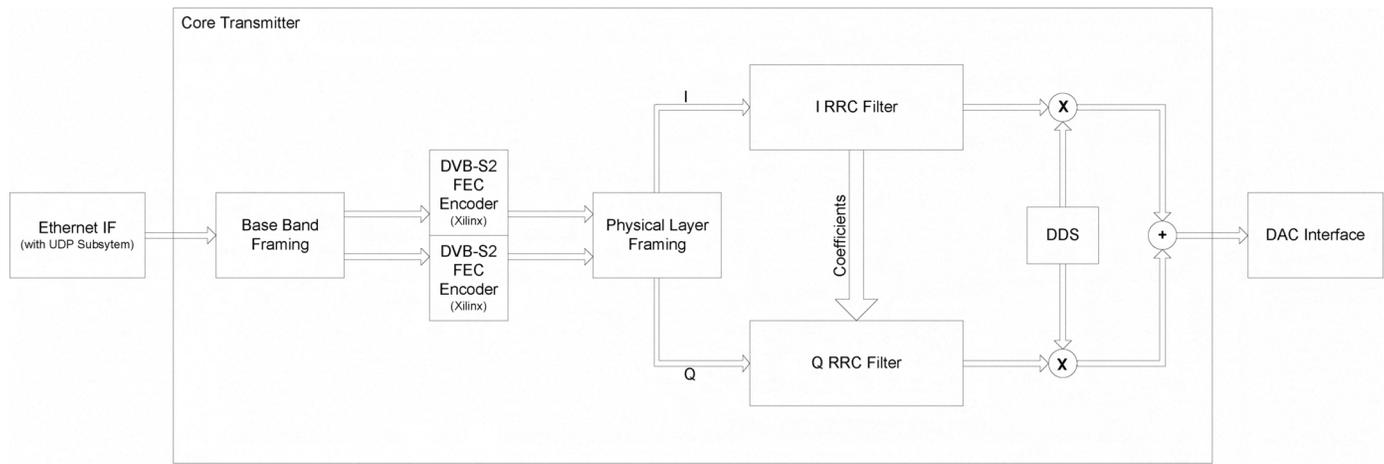


Figure 1 Ka HDR transmitter digital architecture

The physical layer framing module scrambles the FEC frames and appends a 90-symbol $\pi/2$ -BPSK header. The DVB-S2 standard supports the insertion of extra pilot symbols to aid in receiving. This module implements that functionality before the physical layer frame is mapped to symbols and passed to the root-raised cosine (RRC) Filters.

There are two RRC filters shown in Figure 2. The RRC design for this implementation is a purely real filter and operates independently for the I and Q channels. The filter pulse shapes and interpolates the input symbols to the sample rate of the DAC. This implementation only supports an alpha of 0.35. The filter is capable of supporting any arbitrary symbol rate from 1Msym/s to 280 Msym/s, in $1/2^{32}-1$ steps. The upper limit on the symbol rate is a function of the DAC sample clock, and is $1/8^{\text{th}}$ the sample clock.

The RRC filter comprises eight parallel 18-tap filter banks to provide a minimum of eight samples per symbol. Each tap has a lookup table of 512 coefficients, stored in RAM. The I and Q channels share the coefficients, thus reducing the required memory. The coefficients cycle as needed by the filter to achieve the ability of arbitrary symbol to sample rate conversion. The coefficients were scaled a-priori to prevent saturations in the hardware, thereby removing the need for loss of precision circuitry. The filter does not require any multipliers since the supported modulation types are only phase dependent.

Upon leaving the filter, the eight I and eight Q samples are multiplied with a cosine and sine wave, respectively. The sinusoid waves are generated via the direct digital synthesizer (DDS) shown in Figure 1. The DDS is based on a look-up table (LUT) and provides eight samples for each channel every clock. The DDS also sup-

ports the generation of a single test tone at any frequency in the 2nd Nyquist region of the DAC's frequency response. The resulting products are summed to provide eight composite samples for the DAC.

DIGITAL IMPLEMENTATION PERFORMANCE

The following tests were performed on the digital implementation to characterize its performance:

A. Frequency Response

This test measured the frequency response of the DAC across the 1st and 2nd Nyquist zone. The data is generated by configuring the DDS in a carrier only mode and sweeping the frequency from 1130 to 2240 MHz, in 25 MHz steps. An Agilent E4448A spectrum analyzer (PSA) measured the relative power of each tone, in both the 1st and 2nd Nyquist zone. The results track the published frequency response of the Maxim 19692 DAC, in the "RF" mode.

B. Spurious Free Dynamic Range Test

This test measured the spurious free dynamic range (SFDR) of the DDS. The Agilent E4448A PSA measured the spectral output of 219 tones across L-band. Figure 2 shows the spectral output of the DDS, (y-axis) given the requested DDS output frequency (x-axis). The relative power of each spectral component, above the -80 dBc threshold, is denoted in color.

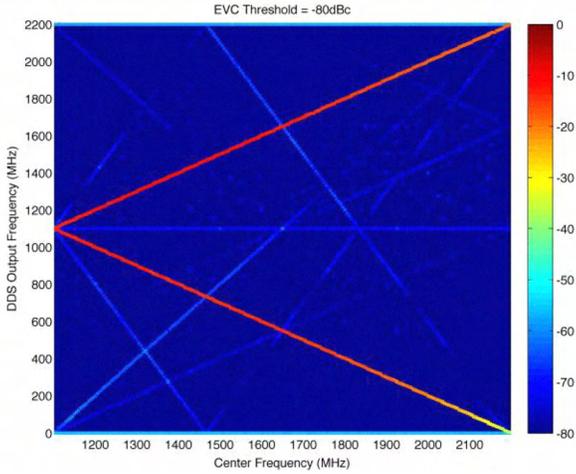


Figure 2 1.5 GHz spur, generated by 1.7 GHz tone

C. Carrier Phase Noise Test

This test measured the carrier phase noise of the DDS. Table 2 lists the phase noise values, using an Agilent E4448A PSA along with the Ka HDR waveform phase noise requirements. As detailed by the values in the table, the DDS phase noise satisfies the phase noise requirements.

D. Spectral Confinement

This test measured the Ka HDR waveform DVB-S2 spectral mask using an $\alpha = 0.35$. An Agilent E4448A PSA was used to capture the spectrum, centered at 1.55 GHz, from the output of the transmitter. Figure 3 shows the spectral footprint of a 275 Msym/s QPSK, rate $\frac{1}{2}$ signal. The red lines in the figures represent the upper and lower bounds of the spectral mask.

Table 2 Phase noise requirement and measured values

Offset (Hz) ▼	Requirement (dBc/Hz)	Measured Phase Noise Density (dBc/Hz)			
		1.25 GHz	1.50 GHz	1.75 GHz	2.00 GHz
10	-30	-77.8	-74.4	-75.7	-75.2
100	-58	-89.2	-86.6	-86.7	-85.6
1k	-68	-99.9	-97.8	-98.0	-97.7
10k	-78	-111.0	-109.6	-109.4	-108.6
100k	-87	-119.4	-118.2	-118.4	-117.2
1M	-93	-135.9	-135.2	-134.1	-132.1
10M	-105	-139.2	-139.6	-138.4	-134.9

The DAC produces two constant spurs at its sample clock and $\frac{1}{2}$ its sample clock. These spurs are independent of the transmitter and are present even when the transmitter is disabled. Figure 3 highlights the $\frac{1}{2}$ DAC

sample clock spur to the left of the desired signal. Both spurs must be removed by additional analog filtering. Aside from this spur, the RRC filter in the transmitter is sufficient to meet the spectral confinement requirements.

Figure 3 shows an in-band gain variation of approximately 2 dB. This variation is consistent with the frequency response of the Maxim 19692 DAC. This frequency response can be flattened with channel equalization filters on the output of the transmitter, which could also correct for the affects due to the follow-on analog circuitry. Even with the gain variation the measured error vector magnitude (EVM); for the 275 Msym/s QPSK, rate $\frac{1}{2}$ signal; is still under 2.5%.

E. DVB-S2 Interoperability

The Ka HDR waveform implementation must be interoperable with a certified DVB-S2 modem for commonly supported modes and rates. The transmitter in this paper was verified against two independent commercial off-the-shelf (COTS) modems: a Newtec NTC/2263 receiver, and an Efficient Channel Coding, Inc. (ECC) 3100 SkyPhy ASIC Evaluation receiver. Table 3 details the test matrix used to verify interoperability between the implementation described in this paper and commercially available DVB-S2 modes.

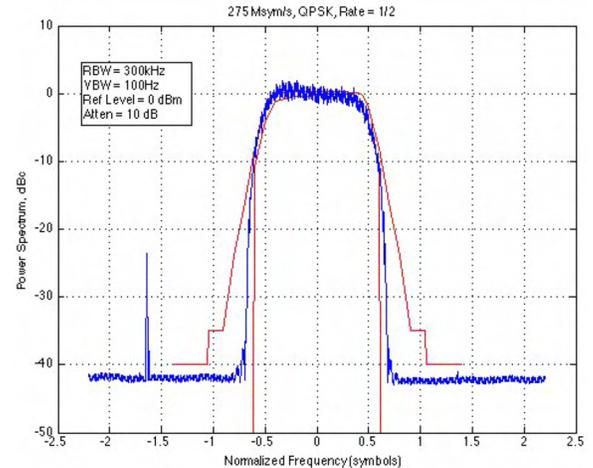


Figure 3 275 Msym/s QPSK spectrum

Table 3 DVB-S2 interoperability test matrix

Modems	Symbol Rate (Msym/s)	Modulation	FEC Rate	Additional Pilots
Newtec	5	QPSK	1/2	No
Newtec	5	QPSK	1/2	Yes
Newtec	5	QPSK	3/4	No
Newtec	5	QPSK	3/4	Yes
Newtec	38.52	QPSK	1/2	No
Newtec	38.52	QPSK	1/2	Yes
Newtec	38.52	QPSK	3/4	No
Newtec	38.52	QPSK	3/4	Yes
Newtec	5	8PSK	2/3	No
Newtec	5	8PSK	2/3	Yes
Newtec	38.52	8PSK	2/3	No
Newtec	38.52	8PSK	2/3	Yes
ECC	5	QPSK	1/2	No
ECC	5	QPSK	1/2	Yes
ECC	5	QPSK	3/4	No
ECC	5	QPSK	3/4	Yes
ECC	38.52	QPSK	1/2	No
ECC	38.52	QPSK	1/2	Yes
ECC	38.52	QPSK	3/4	No
ECC	38.52	QPSK	3/4	Yes
ECC	5	8PSK	2/3	No
ECC	5	8PSK	2/3	Yes
ECC	38.52	8PSK	2/3	No
ECC	38.52	8PSK	2/3	Yes

The COTS DVB-S2 modems only support rates up to 45 Msym/s. The lower rate modes were sufficient to verify proper implementation of the DVB-S2 protocols. However, they could not verify the fidelity of the higher rate analog conversion. This conversion was verified with an Agilent DSA 90604A, running Agilent’s Vector Signal Analyzer (VSA) software package.

The VSA software package includes the capability to demodulate digital carriers. This was used to verify the signal in space generation of the higher-rate transmissions, whereas Matlab scripts were used to verify the DVB-S2 specific signaling and framing.

SUMMARY

The use of the DVB-S2 commercial standard increases the value of the Ka HDR waveform and reduces risk associated with development and deployment. Our implementation and extension of DVB-S2 meets the requirements for the Ka HDR waveform. The design described in this paper demonstrates the successful implementation of the Ka HDR waveform.

Future development of the Ka HDR waveform will include testing of the waveform over the WGS satellite system, specifically the higher data rates; implementa-

tion of a matching Ka HDR demodulator; and finally testing the waveform in an airborne environment.

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