Measurement of Error Vector Magnitude (EVM) to Characterize the Impairment of the Tracking and Data Relay Satellite (TDRS) Channel

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Abstract – *A digital signal is transmitted via a carrier wave, it demodulates at a receiver, and locates at an ideal constellation point. However, noise distortion, carrier leakage, and phase noise can force a signal to divert from its ideal position to a new position. Consequently, the performance of the signal is decreased. Bit Error Rate (BER) and Error Vector Magnitude (EVM) measurement techniques are used to enable the analysis and assessment of the extent to which the performance of a signal has been decreased. In this paper, we present the EVM measurement technique as a figure of merit to analyze and evaluate the performance of a User Services Subsystem Component Replacement (USSCR) modem. Also, we demonstrate the use of the EVM measurement technique in a Tracking and Data Relay Satellite (TDRS) system to measure and evaluate channel impairment between a satellite (transmitter) and the ground terminal (receiver) at the White Sands Complex.*

Keywords: Error Vector Magnitude, EVM, Characterizing RF Channel Distortions

1 Introduction

The Bit Error Rate (BER) and Error Vector Magnitude (EVM) techniques have been used to assess the performance of communication systems. For example, BER is used to evaluate the number of erroneous bits per bit of the transmitted signal; EVM is used in Wireless Area Networks (WANs), Universal Mobile Telecommunications Systems (UMTSs), and Enhanced Data Rates (EDRs) for GSM evolution to assess the performance of communication systems [1]. In addition, it evaluates a non-uniform amplitude frequency, non-uniform delay, channel distortion, carrier leakage, IQ mismatch, nonlinearity, local oscillator (L0) phase noise, frequency error, additive and thermal noise, and other distortions in the system [3,4,8]. These distortions include the non-uniform amplitude frequency responses that exist in the bandwidth of the channel.

Furthermore, EVM provides the desired result of a communication performance prior to the demodulation process that starts in the system. In addition, Haussan [4] described that error vector measurements can be made throughout the communication system to determine accurately the location of the source of the error. Also, Lebbink and Peter showed that the Bit Error Rate (BER) performance of a satellite link could be verified by using EVM in satellite integration and testing [6].

Moreover, BER provides a conclusion stating that a single bit has some error in the system. Ahmed [5] described that BER is used to quantify the probability of error based on the number of incorrect bits per bit of transmitted signal, as well as to assess the source of bit error origins from an Additive White Gaussian Noise channel. Also, Hassun [4, 5] explained that BER is a vital tool that can be used to measure the quality of the transmission links. Although using BER requires dedicated equipment and can maximize the cost of testing in communication systems with limited diagnostic value, it does provide accurate results.

2 EVM Analytical Results

EVM is the measurement of the performance of a modulator or demodulator in a communication system, and it also is a viable alternative test method for a transmission link. EVM also can offer insightful information about various imperfections, such as carrier leakage, IQ mismatch, non-linearity, phase noise, thermal noise, and frequency error; it can evaluate the quality of a communication system with a single measurement. As [6,7,8] describes, EVM provides a great deal of insight into the performance of digitally-modulated signals. EVM can be defined mathematically as shown in equation (1):

$$EVM = \sqrt{I_{err}[k]^2 + Q_{err}[k]^2} \quad (1)$$

where k is the symbol index, I_{err} is I_{Ref} - $I_{measure}$, and Q_{err} is Q_{Ref} - $Q_{measure}$. Equation (2) also shows another expression of EVMbased on Root Mean Square (RMS):

$$EVM_{RMS} = \frac{\frac{1}{N}\sum_{k=0}^{N-1} EVM[K]^2}{\sqrt{\frac{1}{N}\sum_{k=0}^{N-1} I_{Ref}[K]^2 + Q_{Ref}[K]^2}} \quad (2)$$

$$EVM_{RMS} = \frac{\frac{1}{N}\sum_{n=1}^{N}\left|S_n - S_{0,n}\right|^2}{\frac{1}{N}\sum_{n=1}^{N}\left|S_{0,n}\right|^2} \quad (3)$$

where $I\text{-}_{Ref}$ is the in-phase reference signal, $Q\text{-}_{Ref}$ is the quadrature reference signal, N is the number of sample points, S_n is the normalized n[th] symbol in the stream of measured symbols, and $S_{0,n}$ is the idealized normalized constellation point of the n[th] symbol. In addition, the phase error can be calculated based on the angle between the measured signal and the reference signal, as shown in equation (4).

$$Phase\ Error = arctan\frac{Q_{meas}}{I_{meas}} - arctan\frac{Q_{ref}}{I_{ref}} \quad (4)$$

I_m = I_{meas} and Q_m = Q_{meas}. The magnitude of the error vector is described in Figure 1 and defined in equation (5).

$$EVM = \sqrt{(I_{meas} - I_{ref})^2 + (Q_{meas} - Q_{ref})^2} \quad (5)$$

Figure 1 also shows a signal that was diverted from its ideal position (blue color) to a new position (red color) due to noise and carrier leakage.

3 Measurement of EVM

As Figure 2 shows, a baseband information sequence (bits) was added to a sinusoidal wave to produce a modulated signal. Later, phase and thermal noise were added into the modulated signal and transmitted via an Additive White Gaussian Noise (AWGN) channel. Then, this signal was demodulated, and the EVM measurement was calculated. To further analyze the EVM measurement, we used Thermal Noise (TN), Noise Spectral Density (NSD), White Gaussian Noise (WGN), and Pseudorandom noise (PN).

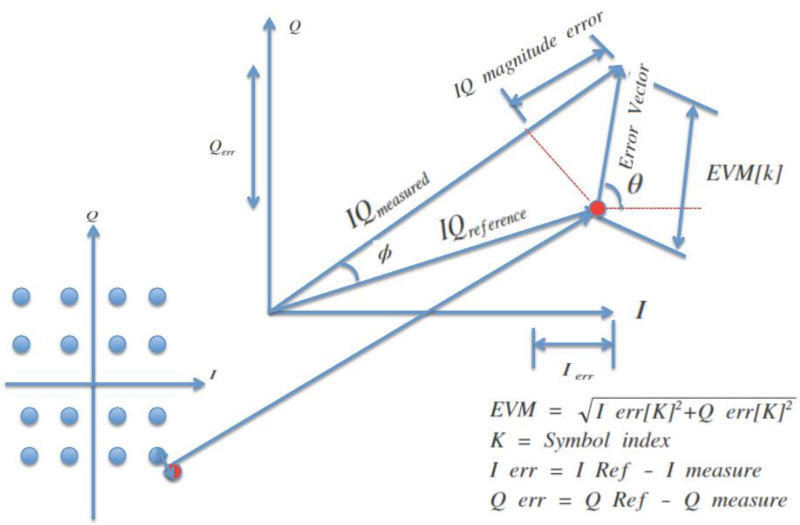

Figure 1. Measurement of the magnitude of the error vector and related quantities

Figure 2. Block diagram of the measurement of EVM in the modulated and demodulated signals

A baseband information sequence (bits), represented as $c_k(t) = c_0, c_1, c_2, \ldots$ consisting of a pulse, such as $c_k(t)$, is +1 or -1 or binary number 0 or 1, which can be divided into a phase stream by equations (6) and (7).

$$c_I(t) = c_{1,}c_{3,}c_{5,} \ldots (odd\ bits) \quad (6)$$

$$c_Q(t) = c_{0,}c_{2,}c_{4,} \ldots (even\ bits) \quad (7)$$

Moreover, an orthogonal realization of an 8-PSK waveform has in-phase and quadrature input, added with a cosine and sine function, and produced a modulated signal that can be described by equation (8).

$$S(t) = \frac{1}{\sqrt{2}}c_I(t)cos\left(2\pi f_o t + \frac{\pi}{4}\right) + \frac{1}{\sqrt{2}}c_Q(t)sin\left(2\pi f_o t + \frac{\pi}{4}\right) \quad (8)$$

In addition, in [9,10,11], a simulator was used to calculate phase noise based on unnormalized spectral density.

$$L(f) = \frac{Power\ density(one\ phase\ modulation\ sideband)}{carrier\ power} \quad (9)$$

$$S_u(f) = 2\left[\frac{10\exp(L(f)+10logB)}{10}\right] \quad (10)$$

The integrated phase noise over the band is:

$$S_B(a,b) = \int_a^b S_u\,(f)df \quad (11)$$

4 EVM Results in the Simulation

After a simulator added a phase noise into a modulated signal, it transmitted the signal via the Additive White Gaussian Noise (AWGN) channel. Later, the signal is demodulated and EVM is calculated. Figure 3 shows, in the top two graphs, that the EVM measurement increased when a simulator added a thermal noise into a modulated signal. In contrast, the EVM measurement decreased when a simulator added a pseudorandom noise. The bottom two graphs show that the EVM measurement increased when the simulator added a power spectral density noise in a modulated signal. Conversely, the EVM measurement decreased when a simulator added a white Gaussian noise.

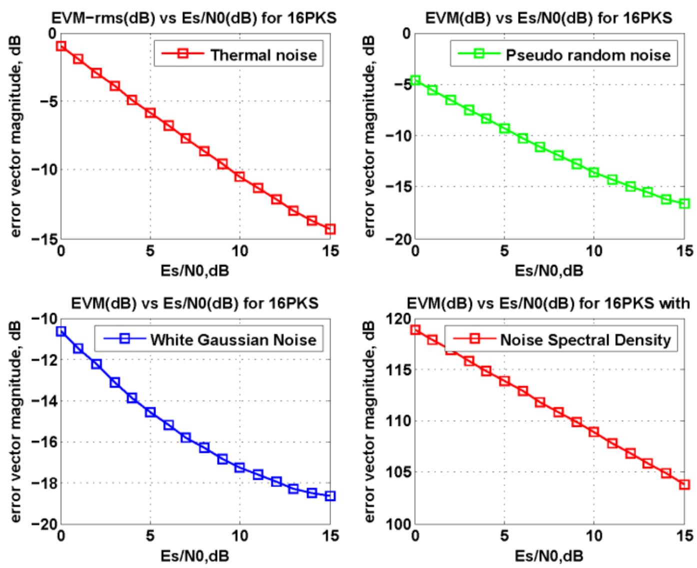

Figure 3. Measurement of the magnitude of the error vector and related quantities

5 EVM Measurement in Simulink

We used Simulink's simulation tool to measure EVM in the 8-PSK modulated and de-modulated baseband. The simulator generated an integer, changed the integer to a baseband information sequence (bits), added a sinusoidal wave, and produced a carrier wave modulated signal. Secondly, it added phase and thermal noise into the modulated signal; converted the modulated signal's frequency from 1 GHz to 14 GHz using a Raised Cosine Transmit Filter (RCTF); and transmitted the signal via the AWGN channel. In addition, the simulator converted the modulated signal's frequency from 2 to 32.5 GHz using a Raised Cosine Receiver Filter (RCRF). Finally, it demodulated a signal and calculated EVM and the Bit Error Rate (BER). In addition, we analyzed further how the value of EVM changed in terms of increasing and decreasing noise and the frequencies of the up converter and down converter. For example, when we increased the thermal noise in the system, the value of EVM increased. However, when we increased the frequency of the up-converter and the down-converter, the value of EVM decreased.

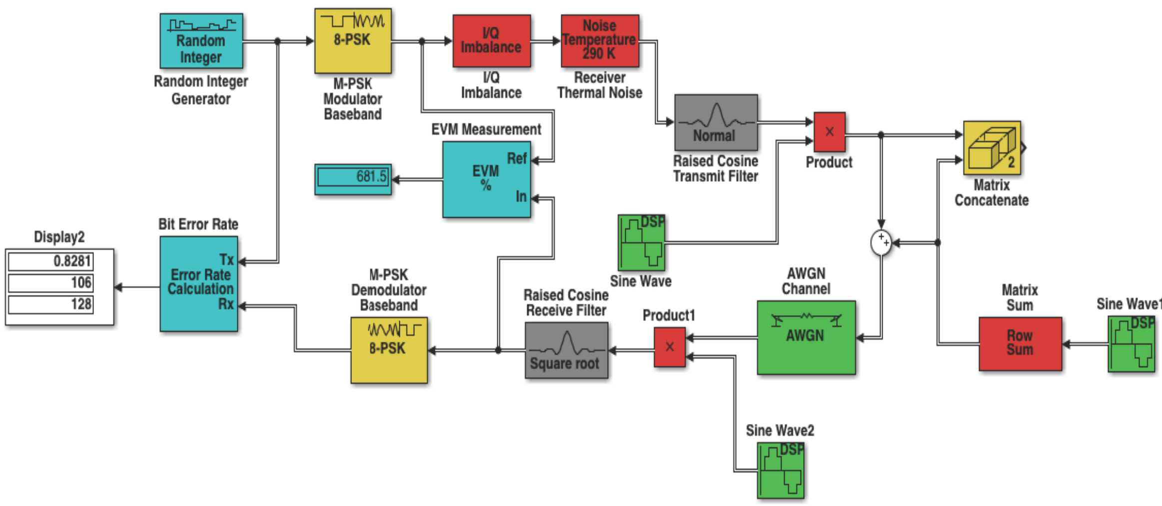

Figure 4. Measurement of EVM in modulated and demodulated basebands

6 Measurement of EVM in the USSCR Modem

USCCR modems have a Narrowband (NB) modulator, a Wideband (WB) demodulator, and an input and output signal distribution card, and they provide advanced modulation and coding techniques, such as Low Density Parity Check (LDPC) code, Turbo Product Code (TPC), and 8-PSK modulation; they also support a Single Network Mail Protocol (SNMP), which allows users to connect and monitor the modem remotely [12].

Figure 5 illustrates a modulated QPSK narrowband signal mixed with a phase noise transmitted to a VSA86000 signal analyzer. Subsequently, the signal analyzer demodulated the narrowband signal and calculated EVM.

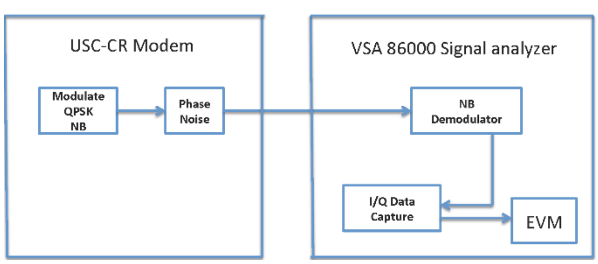

Figure 5. Block diagram of EVM measurement in a USS CR modem

In addition, by adding a thermal, pseudorandom, power spectral density noise in the USCCR modem, the communication performance of the modem can be measured.

Figure 6 shows that the measurement of the spanning frequency for a BPSK-modulated signal without adding phase noise in the modem.

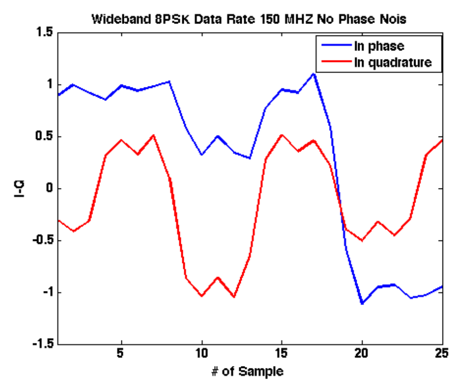

Figure 6. Measurement of wideband 8PSK IQ with no phase noise

In order to measure EVM, the input data rate was set as 1 KHz, 1 MHz, and 25 MHz, and the symbol rate 25 MHz. As the results show, when the data rate increased from 1 KHz to 1 MHz, the spanning frequency increased from 15 KHz to 160 MHz, and the EVM value also increased. In addition, the input data rates were set as 2 KHz, 1 KHz, and 25 MHz, and symbol rates were 1 KHz, 0.5 KHz, and 12.5 MHz. When the data rate decreased from 2 to 1 KHz, there were no changes in either the spanning frequency or the value of EVM. In addition, since there no phase noise was added into the modem, then I and Q measurements in Figure 6 moved in the same direction. However, when a phase noise was added into the modem, the I and Q measurements in Figure 7 moved in different directions.

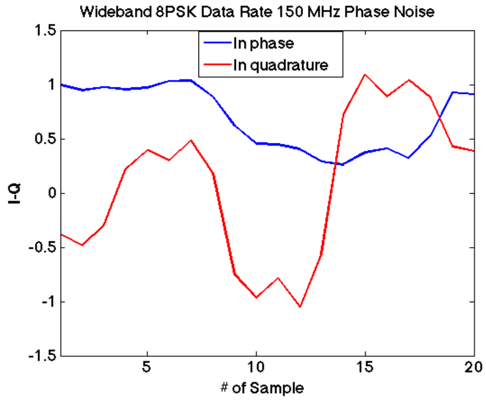

Figure 7. Measurement of wideband 8PSK IQ with phase noise

7 Conclusions

We used a software simulation and VSA86000 signal analyzer software to study and analyze the EVM measurement techniques in wireless communication. EVM-based software was used in MATLAB and Simulink. We calculated error vector and phase error by adding noises, such as thermal, additive white Gaussian, and phase noise in the simulation. In the VSA86000 signal analyzer, we measured a magnitude error and phase error for different modulated signal schemes by adding phase noise in USS-CR modem. Our experiment showed that the value of EVM increased when we added phase noise into the modem.

Furthermore, we were not able to use a channel emulator, and we implemented a down converter and up converter in the modem; consequently, we could not analyze how channel impairment changed the measurement of the value of EVM in this case. However, in the Simulink simulation, we added a down converter, white Gaussian additive channel, and an up converter in the simulator; as a result, we analyzed the quality of the communication channel in a Simulink simulation.

In summary, Error Vector Magnitude (EVM) measurements provide the overall performance of wireless communication. These measurements are used extensively in many different telecommunication systems to analyze carrier leakage, phase noise, intermodulation distortion, and noise distortion.

Future research work

Tracking and Data Relay Satellites (TDRSs) are used for Communication between NASA's ground terminal (White Sands Complex) and various spacecraft, including the International Space Station, Space Shuttles, and the Hubble Space Telescope. According to NASA [14], TDRS can transmit and receive data from the spacecraft over at least 85% of the spacecraft's orbit. In addition, the BER measurement technique is used to evaluate the communication system between the customer's transmitter, TDRSs, and the ground terminal.

For example, Figure 8 shows that the customer transmits a signal, the distortion of which includes gain imbalance, phase non-linearity, and phase noise. The signal is transmitted via the AWGN channel. The TDRS Spacecraft transmits a signal with linear and non-linear distortions via the AWGN channel to a ground terminal. Then, BER evaluates the number of bit errors per unit time received from the transmitter and the ground terminal. However, BER cannot offer insightful information of noise distoration, gain imbalance, or phase noise. Instead, it only checks whether a single bit has some error. However, EVM can offer insightful information on the various imperfections.

In summary, EVM can evaluate the quality of USSCR modem communication systems with a single measurement. Therefore, applying the EVM measurement technique into a customer's transmitter, TDRS Spacecraft and the ground terminal (receiver) can assess and evaluate any impairments of the channel and the performance of the communication system.

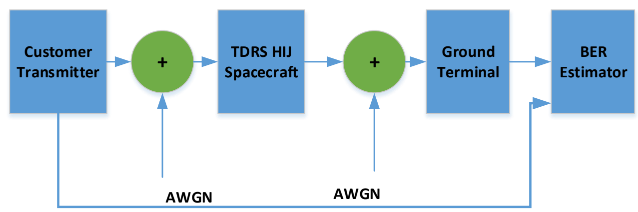

Figure 8. End-to-end linkage of the customer, TDRS, and NASA's White Sands Complex

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