FPGA Implementation of Automatic Modulation Recognition System for Advanced SATCOM System

Durga Digdarsini, Mahesh Kumar, Gopichand Khot, TVS Ram, VK Tank
Space Applications centre
Indian Space Research Organisation(ISRO)
India
{digdarsini, maheshk, gopik, tvsram, tank}@sac.isro.gov.in

ABSTRACT: *Automatic identification of the digital modulation type of a signal has found applications in many areas, including software defined radio (SDR), surveillance and threat analysis. This paper describes the FPGA based implementation of Automatic Modulation Recognition (AMR) algorithm for advanced communication payload. A wavelet transform based algorithm which involves multi-rate signal processing, is realized to distinguish QAM, PSK and FSK digital modulation signal in noisy environment. The approach is to use wavelet transform to extract the transient characteristics in a digital modulation signal to identify the type of modulation. The optimum thresholds are derived from rigorous simulation in MATLAB/Simulink under the condition that the input noise is Additive White Gaussian (AWGN). The performance of the identification scheme is investigated through simulations. The design is implemented and tested in Xilinx Virtex-4 FPGA based card.*

Keywords: AMR, PSK, FSK, QAM, SDR, AWGN, FPGA, Wavelet, Multi-Rate Signal Processing

Received: 11 November 2013, Revised 10 Decenver 2013, Accepted 17 December 2013

1. Introduction

Advanced communication satellite system will have the capabilities to change the complete receiver configurations according to the communication standards and adaptively demodulate the incoming signal if the Software Defined Radio architecture is employed. Automatic Modulation Recognizer (AMR) is an important subsystem of any Software Defined Radio whose function is to identify unknown modulation at the receiver and to generate appropriate signals for the corresponding demodulator to bring back the baseband data which could be voice, video or data. Satellites with AMR systems will have the capabilities to adaptively demodulate the incoming modulation change from ground station depending upon the channel conditions in real time e.g. if attenuation is more in the channel or bandwidth crunch is there, then it may be required to switch from existing modulation say Quadrature Phase Shift Keying (QPSK) to more bandwidth efficient Quadrature Amplitude Modulation (QAM) modulation. A digital modulation identifier will then be required on-board for detecting the corresponding instantaneous change in the type of modulation. Automatic Modulation Recognition is very useful for regenerative type of payloads where data demodulation and re-modulation is done onboard. There are various algorithms available in the literature to identify the digital modulation [1]. Automatic identification of the digital modulation type of a signal is a rapidly evolving area. A variety of techniques have been proposed to distinguish QAM signal, PSK signal and frequency shift keying FSK signal [5]. Several research groups have developed various modulation identification methods like Decision Theoretic Approach, Statistical

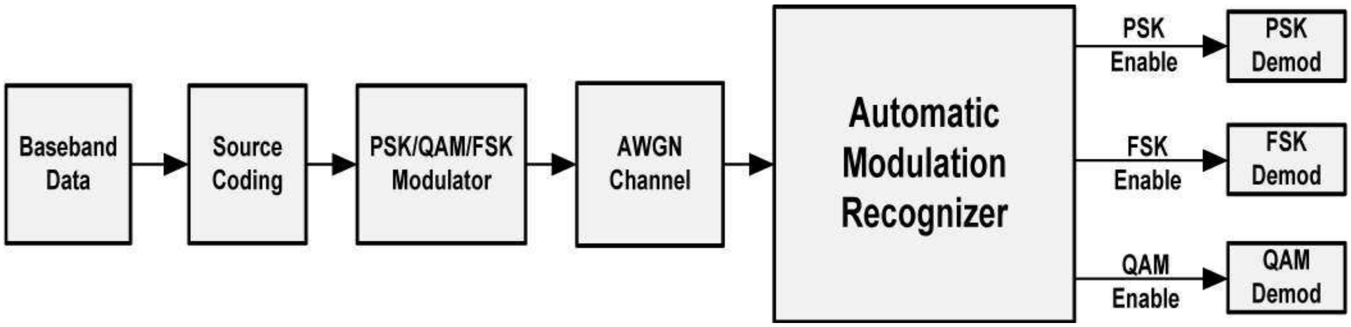

Figure 1. Block Diagram of AMR system

Pattern Recognition and Wavelet Transform based identification in recent past [2-5]. Different digital modulation signals contain different transients in amplitude, frequency or phase. The Wavelet Transform has capability to extract transient information in real time as compared to Decision Theoretic approach and consumes less hardware resources than Pattern Recognition method thereby allowing simple methods to perform modulation identification. FPGA based AMR system is developed which can identify the type of modulation using wavelet transform.

This paper is organized as follows. Section II discusses the basic architecture of AMR system. In section III the discrete wavelet transform of various digital modulations is described briefly. Section IV illustrates the building blocks of Automatic Modulation Recognition system. Section V discusses the Simulink model for the AMR system and the associated simulation results. Section VI describes the FPGA implementation of AMR system for identification of PSK, FSK and QAM signals. Section VII concludes the paper.

2. Basic Architecture of AMR System

Automatic Modulation Recognition is a signal processing technique that automatically detects the type of modulation signal received at the receiver instantaneously and enables the corresponding demodulator for data demodulation and processing. Figure 1 shows Automatic Modulation Recognizer in a general software defined radio system. It consists of source encoding of baseband data which is fed to either PSK or QAM or FSK Modulator for translating the baseband information over the RF carrier.

Parameter	Specification
Modulation Types	BPSK/QPSK/FSK/QAM
Data Rate	2.4Kbps – 2Mbps
Intermediate Frequency	70 MHz ± 120 KHz
Sampling Frequency	40 MHz

Table 1. Specifications of Test Inputs

The modulated signal is passed to AMR system through AWGN channel at the receiver end. AMR system detects the type of modulation during runtime and generates the enable signals for the corresponding demodulator to get the baseband data back at the receiver end. Table I mentions the system specifications for the complete AMR system.

Under sampling is employed here to relax the processing requirements of FPGA.

3. Discrete Wavelet Transform of Digital Modulation

Discrete Wavelet Transform utilizes filters of different cutoff frequencies that are used to analyze the signal at different scales. Haar Wavelet can detect phase, frequency and amplitude changes in the signal in real time and can be implemented in FPGA using FIR filter [7]. It is also symmetric and orthogonal in nature as compared to other wavelets and used for high speed performance of wavelet transform algorithm. Dyadic filter structure is an efficient way to implement Discrete Wavelet Transform

[8]. It decomposes a broadband signal into a collection of sub-bands with smaller bandwidths and slower sample rates. The Dyadic filter structure uses a series of high-pass and low-pass FIR filters to repeatedly divide the input frequency range. The output of each stage contains half the number of coefficients to that input of the stage as the signal is decimated by 2 at every stage. Figure 2 shows the 3-stage Dyadic Filter structure used for the implementation of Discrete Wavelet Transform where $x(n)$ is the signal input to the Dyadic Filter, $g(n)$ and $h(n)$ are the high pass filter and low pass filter impulse responses respectively.

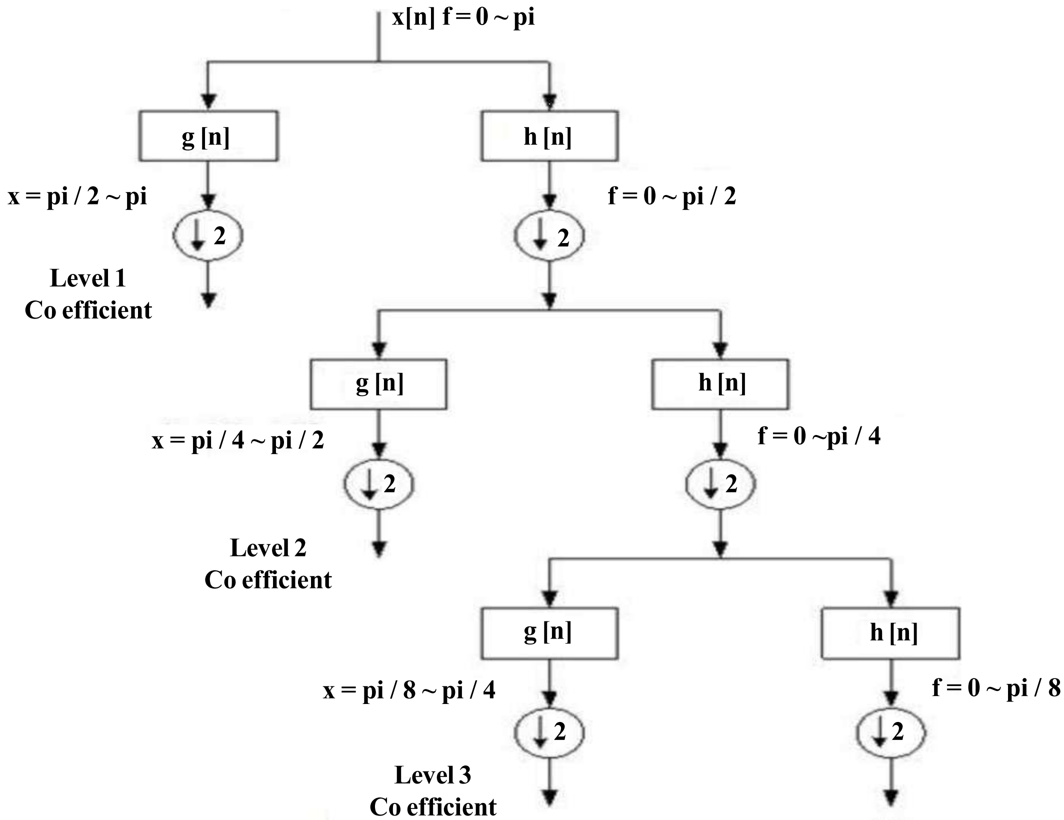

Figure 2. Structure of Discrete Haar Wavelet Transform

3.1 Phase Shift Keying Modulation

Phase Shift Keying (PSK) is a class of digital modulation where change in data polarity is represented by the corresponding change in instantaneous phase states.

PSK signal is mathematically represented by Equation 1 as:

$$S_{PSK}(t) = \sqrt{s}\ \sum_{i=1}^{N} e^{j\varphi i} u\,(t - iT) \tag{1}$$

Where $\varphi_i \in \left\{ \frac{2\pi}{M}(m-1) \right\}_{m=1}^{M}$ is the instantaneous phase, M is the no. of phase states, is the signal power$u\ (t - iT)$ is the step function at the th symbol shifted in time by T intervals and N is the no. of observed symbols.

Equation 2 gives the expression for the magnitude of Haar Wavelet Transform of PSK when T is between the symbol duration [2]

$$|CWT(a,\ \tau)| = \frac{4\sqrt{s}}{\sqrt{a}\, w_c} sin^2\left(wc\,\frac{a}{4}\right) \tag{2}$$

As the carrier frequency remains fixed for a particular communication system and the scaling factor remains constant for a particular type of wavelet. Signal power in PSK class of digital modulation is also constant. Therefore, the magnitude of the Wavelet Transform will remain constant for PSK modulation as clearly stated by Equation 2.

3.2 Frequency Shift Keying Modulation

The FSK signal can be mathematically expressed in Equation 3 as:

$$S_{PSK}(t) = \sqrt{s}\ \sum_{i=1}^{N} e^{j(\omega_i t + \theta_i)}\, u\,(t - i\mathrm{T}) \tag{3}$$

Where $\omega_i \in \{\omega_1 \omega_2, ...\omega_M\}$, $\theta_i \in \{0, 2\pi\}$ is the instantaneous frequency at th symbol

The magnitude of Haar Wavelet Transform of FSK signal is given by [2]:

$$|CWT(a, \tau)| = \frac{4\sqrt{s_i}}{\sqrt{q}\,(\omega_c + \omega_i)}\, sin^2\left[\frac{(\omega_c + \omega_i)^a}{4}\right] \tag{4}$$

Where a is the time scale factor, τ is position of wavelet, s_i is instantaneous amplitude, ω_c is carrier frequency and ω_i is frequency deviation.

Equation 4 shows that WT of M-FSK signal is dependent upon the instantaneous frequency ωi and instantaneous signal power s_i which implies that the magnitude of Wavelet Transform will vary w.r.t. ω_i & s_i and hence will be multistep in nature.

3.3 Quadrature Amplitude Modulation

In Quadrature Amplitude Modulation (QAM), amplitude and phase simultaneously will vary according to the instantaneous data values. The mathematical representation of QAM signal is given by Equation 5 as:

$$S_{QAM}(t) = \sum_{i=1}^{N} (A_i + B_i)\, u\,(t - iT) \tag{5}$$

Where instantaneous carrier amplitudes $A_i + B_i \in \{2m - 1 - m\ M, m = 1, 2, \ldots, M$

M is the no. of phase states.

The magnitude of Haar Wavelet Transform of QAM signal is given by [2]

$$|CWT(a, \tau)| = \frac{4\sqrt{s_i}}{\sqrt{a\omega_c}}\, sin^2\left(\omega_c \frac{a}{4}\right) \tag{6}$$

where is scale, τ is position of wavelet, s_i is instantaneous amplitude and ω*c* is carrier frequency.

Equation 6 shows that the magnitude response of Wavelet Transform is dependent upon the signal amplitude at the ith symbol. Hence, Wavelet Transform of M-QAM signal is also multistep in nature.

4. Automatic Modulation Recognition System

Automatic Modulation Recognition system utilizes Discrete Haar Wavelet Transform (HWT), Averaging Filter, Variance Computation, Mean Computation, and Decision Threshold Logic as major functional element blocks for the identification of modulation signal in real time. Figure 3 shows the internal architecture of AMR system [2]. It consists of two branches. One branch is without amplitude normalization and other branch is with amplitude normalization.

The recognizer first finds the magnitude of HWT on the incoming modulation which will detect the amplitude, phase and frequency transitions present in the signal and produces constant or multistep response depending upon the type of transitions. After smoothing the HWT response through median filter, the recognizer continuously computes the variance on the filtered outputs which depends on modulation parameters like symbol rate, amplitude and carrier frequency. The decision block compares the two variances with the two thresholds for classification between classes of modulation. If the variance of the branch without normalization is greater than the variance produced by the branch with normalization, then the input is classified as QAM modulation. If both variances are lower than the threshold, the input is classified as PSK signal. If both variances are higher than the threshold, the input is classified as FSK signal. Mean over the variance outputs in each arm is calculated and compared in decision block for further sub-classifications of each individual digital modulation. If the digital modulation other than QAM/PSK/FSK classes is input to the AMR system, it will results in zero output.

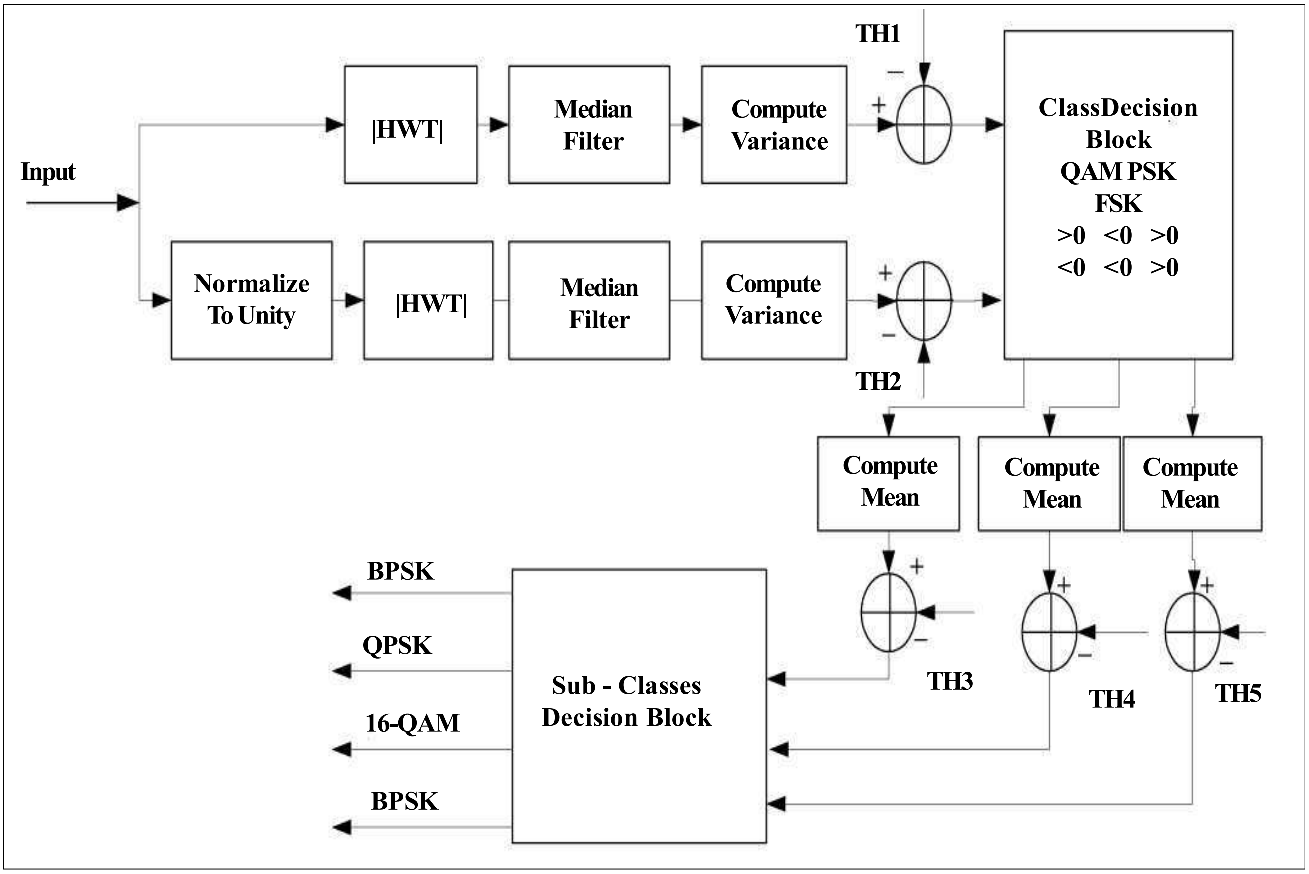

Figure 3. Internal Architecture of Automatic Modulation Recognition System

5. Results and Discussions

A Simulink model is developed using MATLAB/Simulink R2009b for the characterization of complete AMR system as shown in Figure 4. It consists of fixed point PSK, FSK & QAM digital modulator at the transmitter as per the specifications mentioned in Table I. The digital modulated signal is passed through AWGN channel for simulating various SNR considerations. This signal is then applied to Automatic Modulation Recognition (AMR) system which identifies the type of the digital modulation and generates the corresponding enable signals for the respective digital modulation. PSK, FSK and QAM digital modulation classes and their subclasses are targeted as test modulation input for the characterization of AMR System.

The decision thresholds are estimated by simulating the proposed design for 200 ensembles of the transmitted data and computing the variance and mean over the averaged response for a particular type of digital modulation with SNR varying from 5dB to 15 dB.

The magnitude response of the Discrete Haar Wavelet for QAM and FSK will be a multistep as clearly stated in Equation 6 and Equation 4 while for PSK it will be constant as mentioned in Equation 2. Figure 5 &6 shows the magnitude and averaging filter response of 16–QAM and FSK modulation signal at 15 dB SNR.

The magnitude response of DWT for QPSK and BPSK modulation signal at 15 dB of SNR is as shown in Figure7 & Figure 8.

The averaging filter response for the PSK class of digital modulation will also be constant as shown in Figure 9.

The design is simulated under various SNR conditions and the variance of the DWT output is plotted vs. SNR. Figure 10 shows the behavior of variance when SNR is varied from 1dB to 15dB for targeted 16-QAM, QPSK and BPSK type of modulation. The variance curve for 16-QAM shows a steep rise as SNR increases as compared to BPSK and QPSK. This gives enough confi-dence on choosing the proper threshold for distinguishing 16-QAM from QPSK and BPSK. Generally, mid-point between the

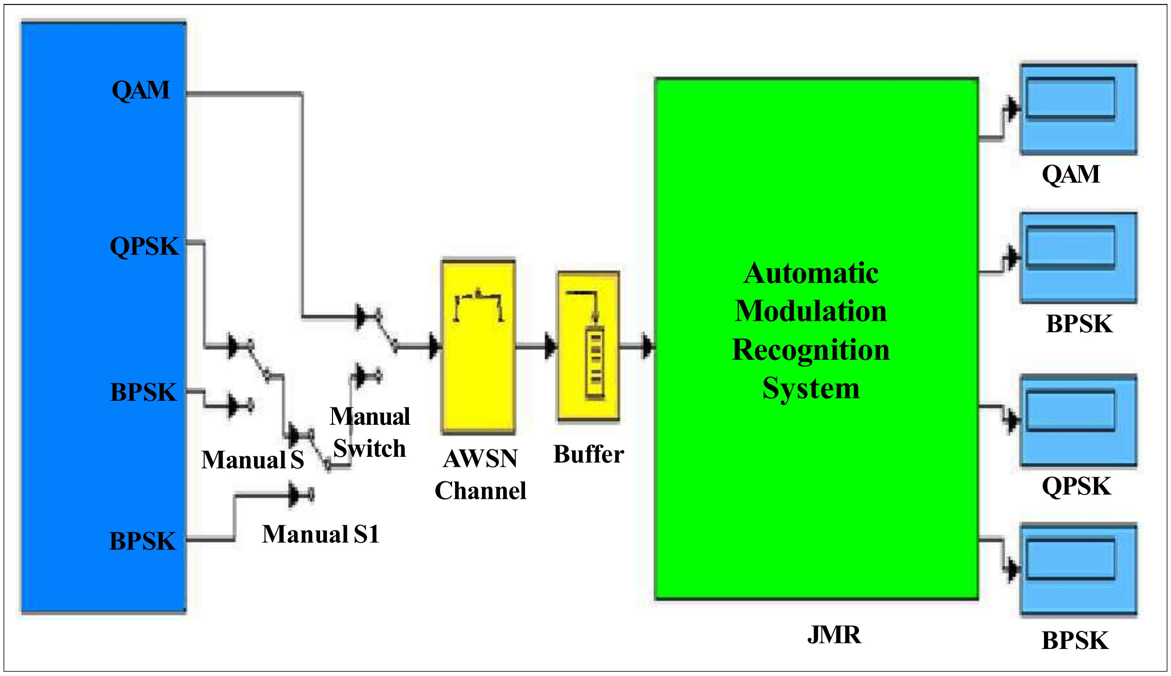

Figure 4. Simulation Model for characterization of Automatic Modulation Recognition System

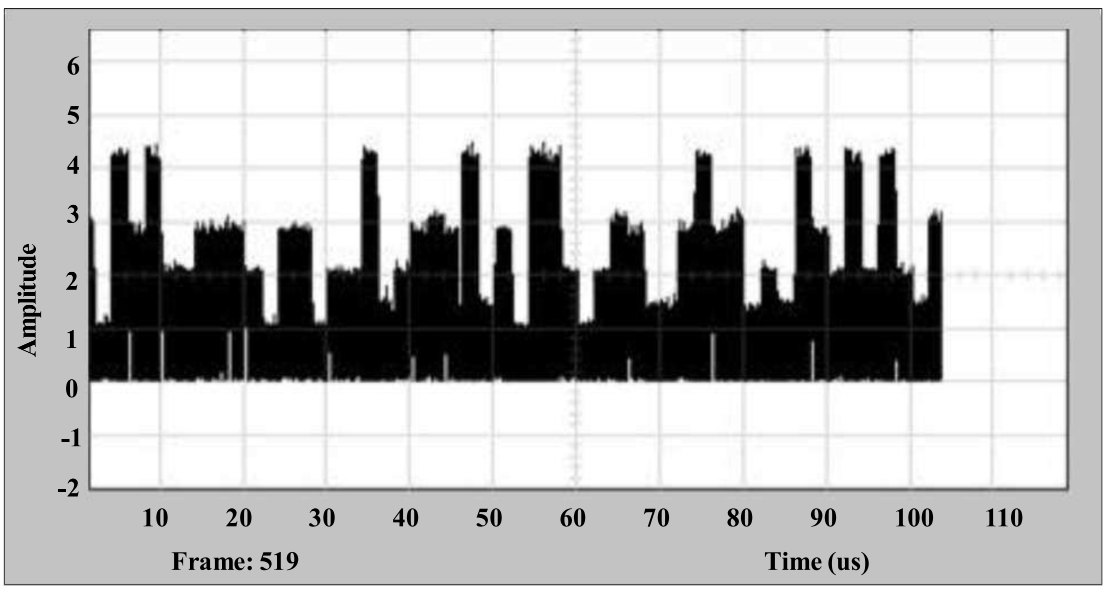

Figure 5. Magnitude Response of DWT for 16-QAM and FSK

variance curve of QAM and PSK is chosen as threshold value for best detection probability.

Further, sub-classification of a particular class of modulation is achieved by the computation of mean on the samples coming averaging filter and then a threshold is selected based on their individual mean curves. Figure 11 shows the mean computation w.r.t. SNR for PSK subclasses. The Optimum threshold for PSK sub-classification between BPSK and QPSK can be set by choosing the threshold in between the BPSK and QPSK mean curves.

The performance of the AMR system is also verified with the frequency offset of 5 KHz, 50 KHz and 120 KHz around the intermediate frequency in order to see the impact of frequency offset due to oscillator inaccuracies on the modulation detection by designed AMR system. Figure 12 shows that there will not be any effect of frequency deviation on modulation identification

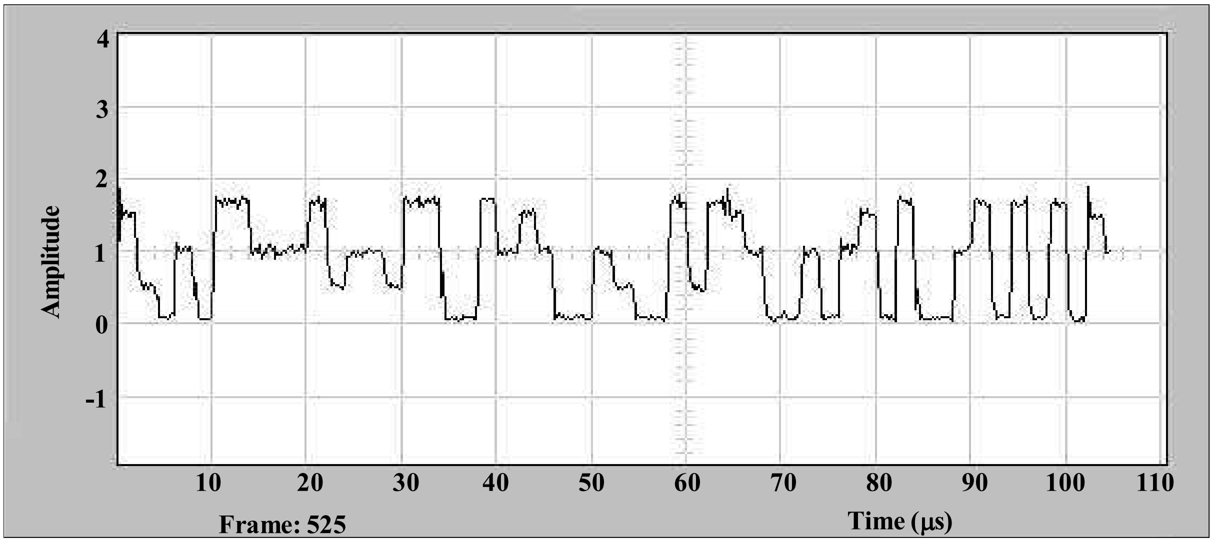

Figure 6. Averaging Filter Response of DWT for 16-QAM and FSK

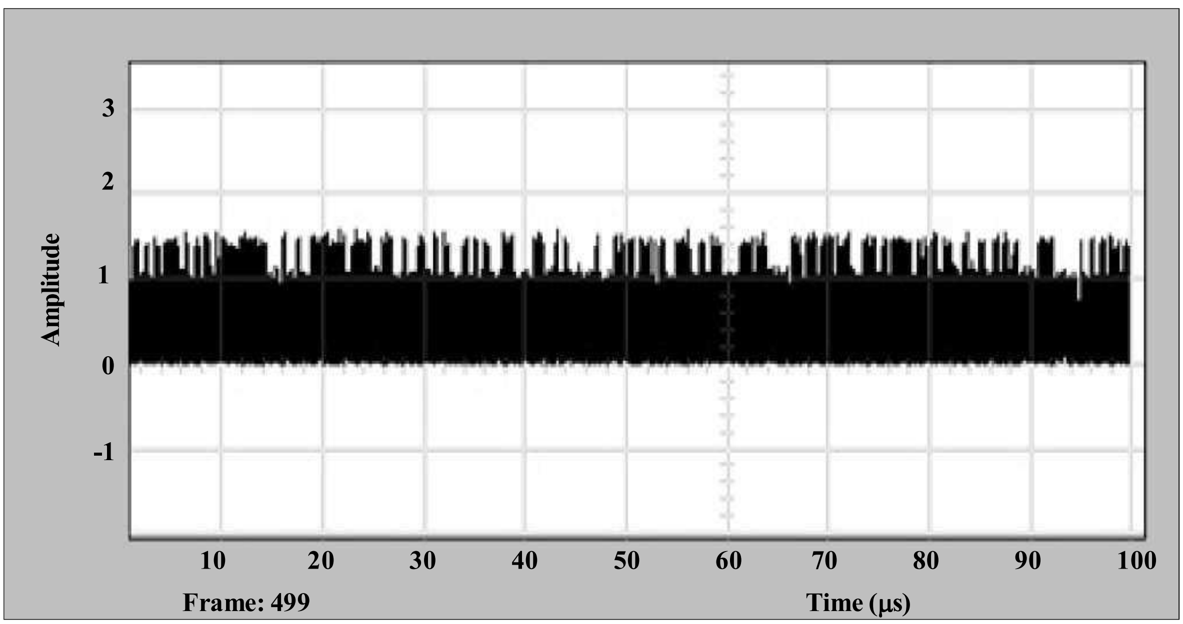

Figure 7. Magnitude Response of DWT for QPSK

by the AMR system. Table 2 shows the performance of AMR algorithm in terms of percentage of probability of correct identifi cation. The results are obtained from the average of 200 independent ensemble runs.

5. Hardware Implementation of AMR System

The complete AMR system consisting of Discrete Wavelet Transform (DWT), Averaging Filter, Variance and mean computation and Decision Threshold logic is implemented using Verilog HDL2001 without the use of any IP core so that design becomes platform independent and can be ported to any FPGA like Xilinx or Actel. However, FPGA implementation is done using XilinxISE-9.2i targeting Xilinx Virtex-II pro xc2vp50-6ff1152 for hardware proof of concept and functional simulation is carried out using QuestaSim 10.0b.

Figure13 shows the hardware test setup for AMR system. Various modulation signals are generated by COMTECH Modem as mentioned in Table I. The modulated signal is mixed with noise generated from noise generator for the required Eb/No and is fed to AMR system for detection of types of modulation.

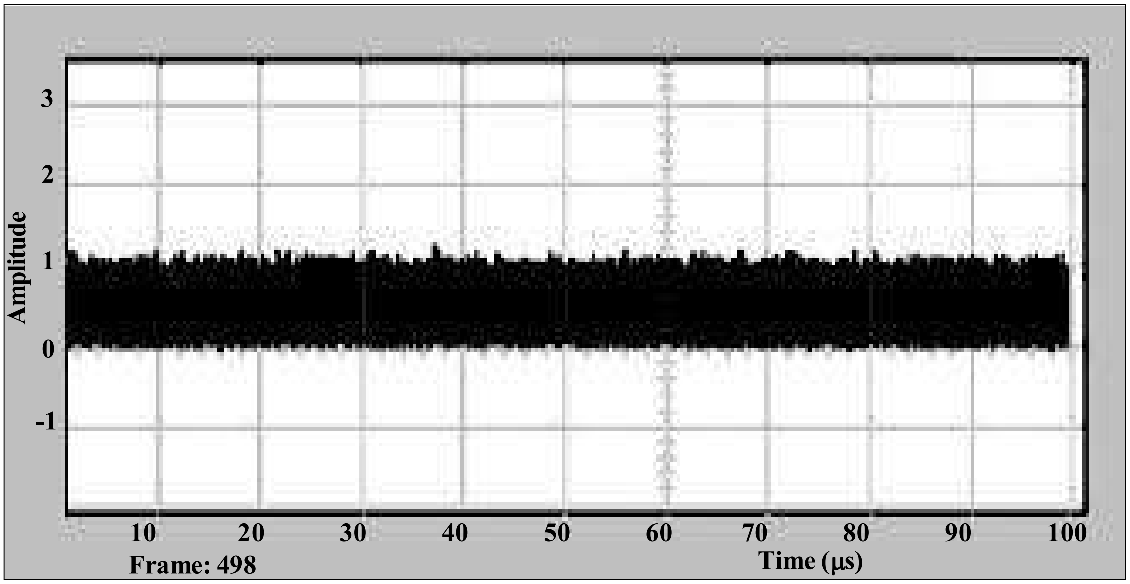

Figure 8. Magnitude Response of DWT for BPSK

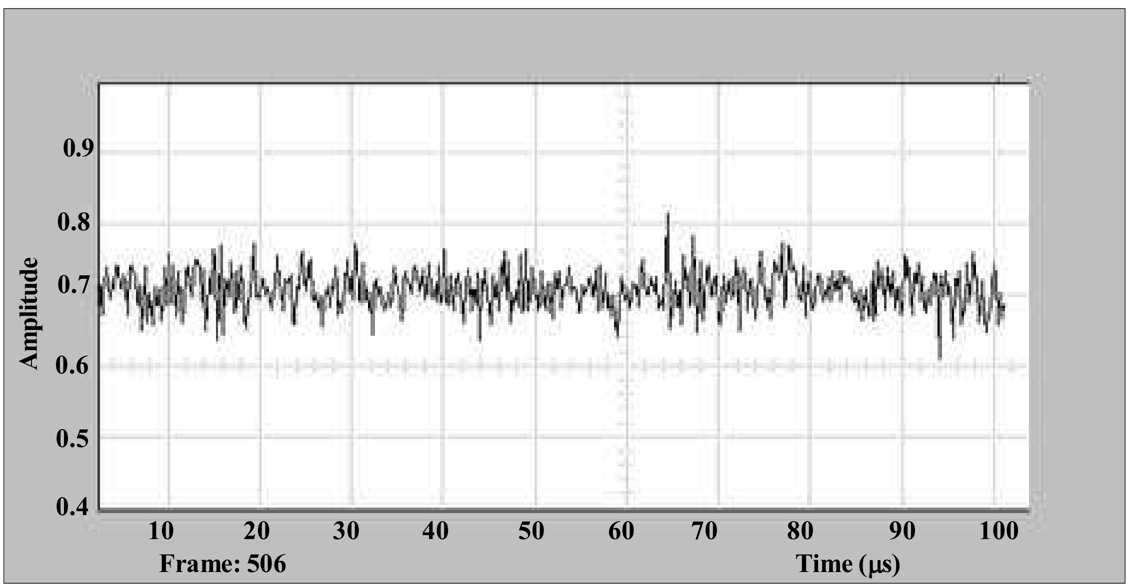

Figure 9. Averaging Filter Response of DWT for PSK

The modulated signal is passed through ADC AD9054A of Analog Devices mounted on the Xilinx virtex-II pro FPGA development board and output is captured in Logic Analyzer. This data is stored in ROM of FPGA which is used as a stimulant for the functional simulation of the entire design. Results from QuestaSim 10.0b are presented in Figure 14 which shows output signals from various stages of AMR system. The simulation results include 16-QAM modulated data input, output of DWT which is multistep here showing response for QAM modulation input, variance and mean computed on DWT output samples, QAM and PSK enable signals.

The 16-QAM and PSK modulation are generated from COMTECH modem as per the specifications mentioned in Table 2 and their SNR is varied, corresponding variance is captured in Logic Analyzer and ported to MATAB for plotting variance vs. SNR for these modulations. Figure 15 and Figure 16 shows the PSK modulation spectrum and its constellation while Figure 17 and Figure 18 shows the spectrum and constellation for 16-QAM modulation used as test input for characterizing AMR system in hardware.

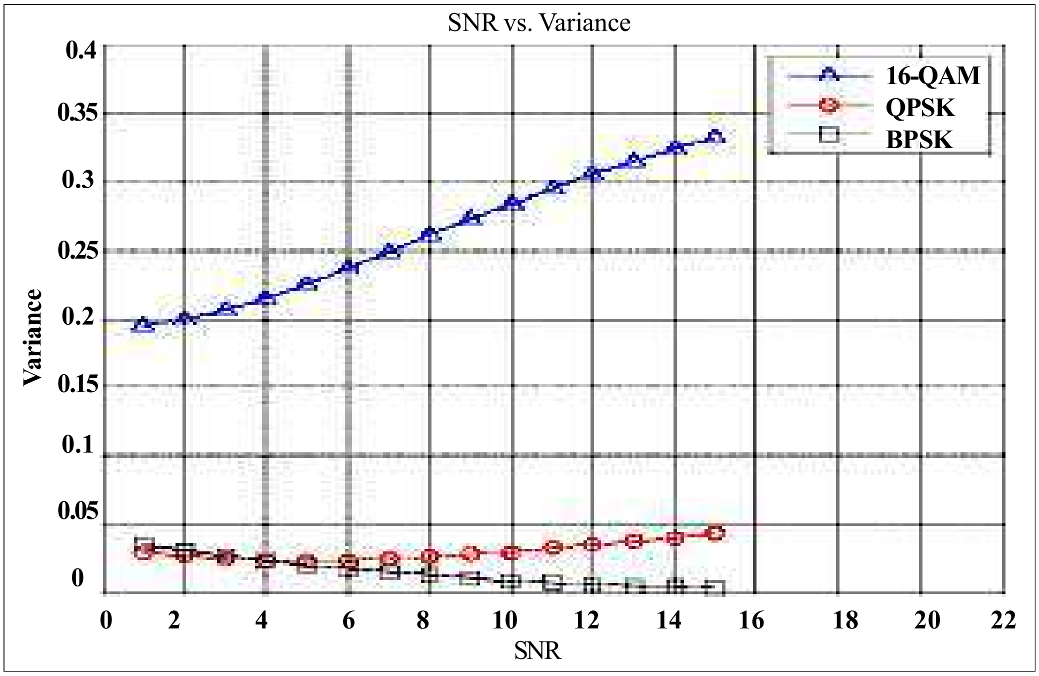

Figure 10. Variance vs. SNR to identify PSK and QAM Modulation

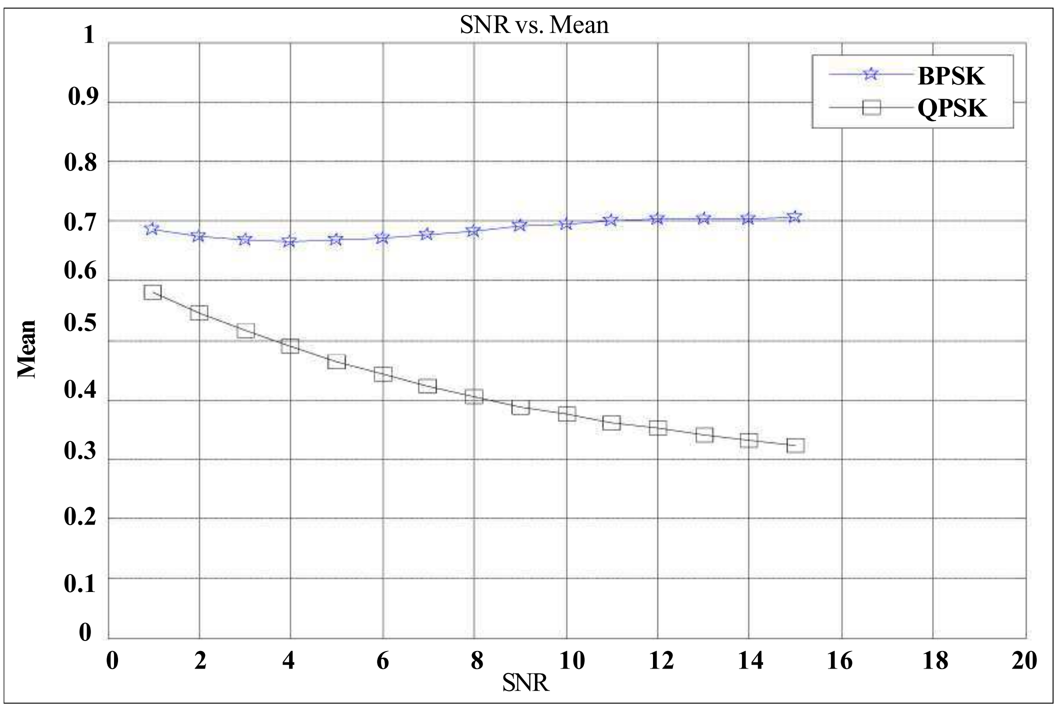

Figure 11. Mean vs. SNR to identify BPSK and QPSK Modulation

SNR	PSK	QAM	FSK
15	100	100	100
10	98.2	99.5	99
6	97.5	98.6	98.6
5	97.1	98.2	98.2

Table 2. Performance of AMR Algorithm

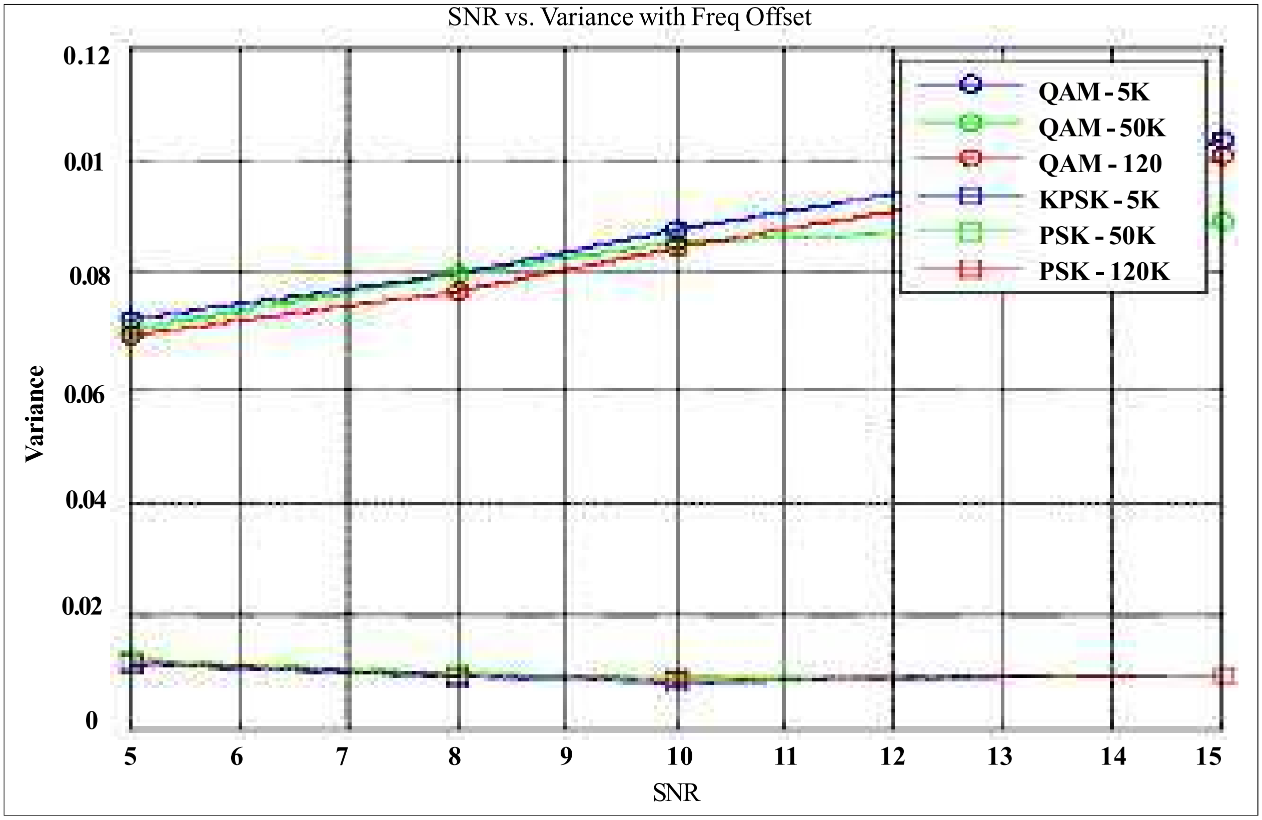

Figure 12. SNR vs. Variance with Freq Offset

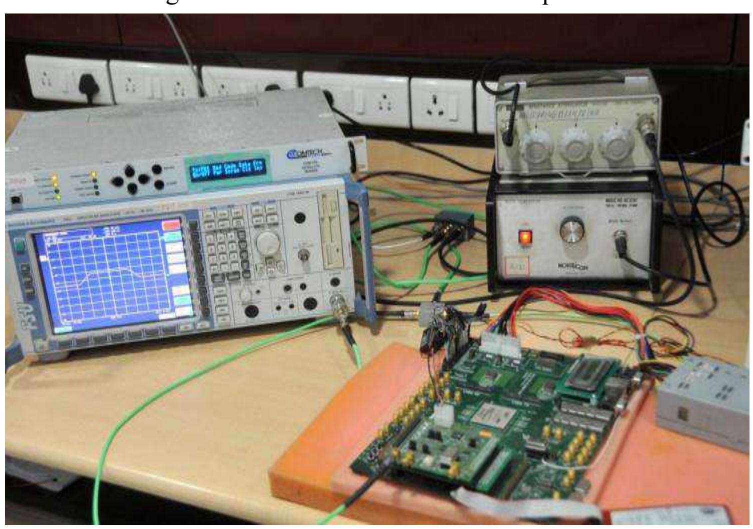

Figure 13. Hardware Test Setup for AMR System

Type of Modulation	**16-QAM**	**QPSK**	**BPSK**
Type of Coding	TPC	Viterbi	Uncoded
Code Rate	¾	½	1
Data Rate (Mbps)	2	2	2
Carrier Frequency (MHz)	70	70	70

Table 2. Specifications of the Modulation Input Generated from Comtech Modem

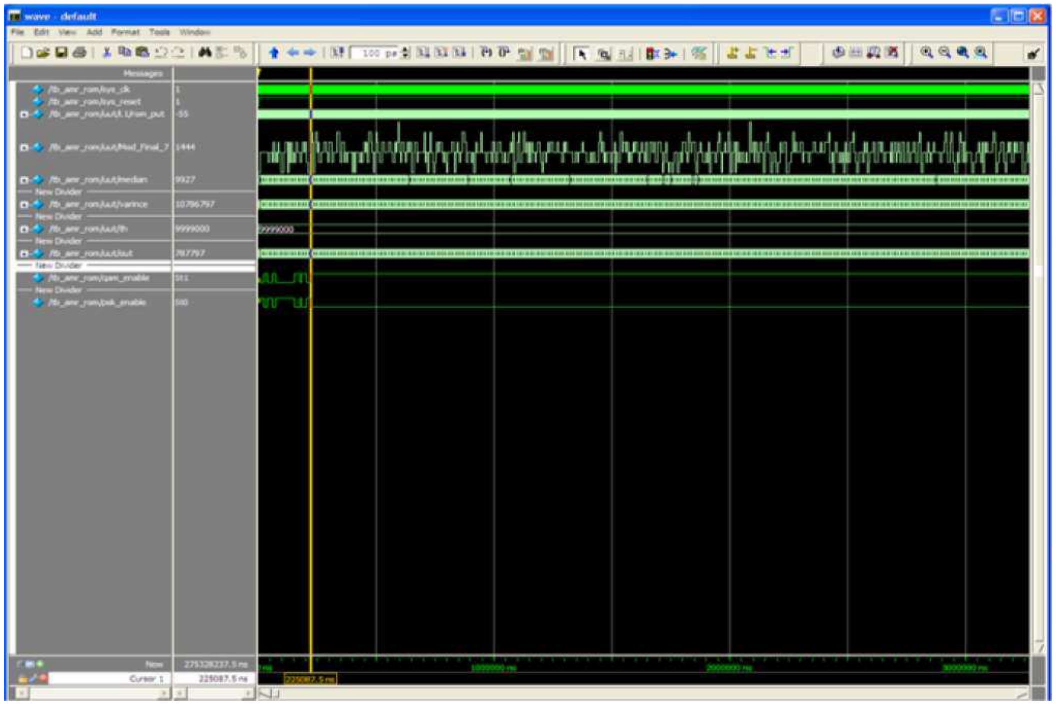

Figure 14. Functional Simulation of AMR system using QuestaSim 10.0b

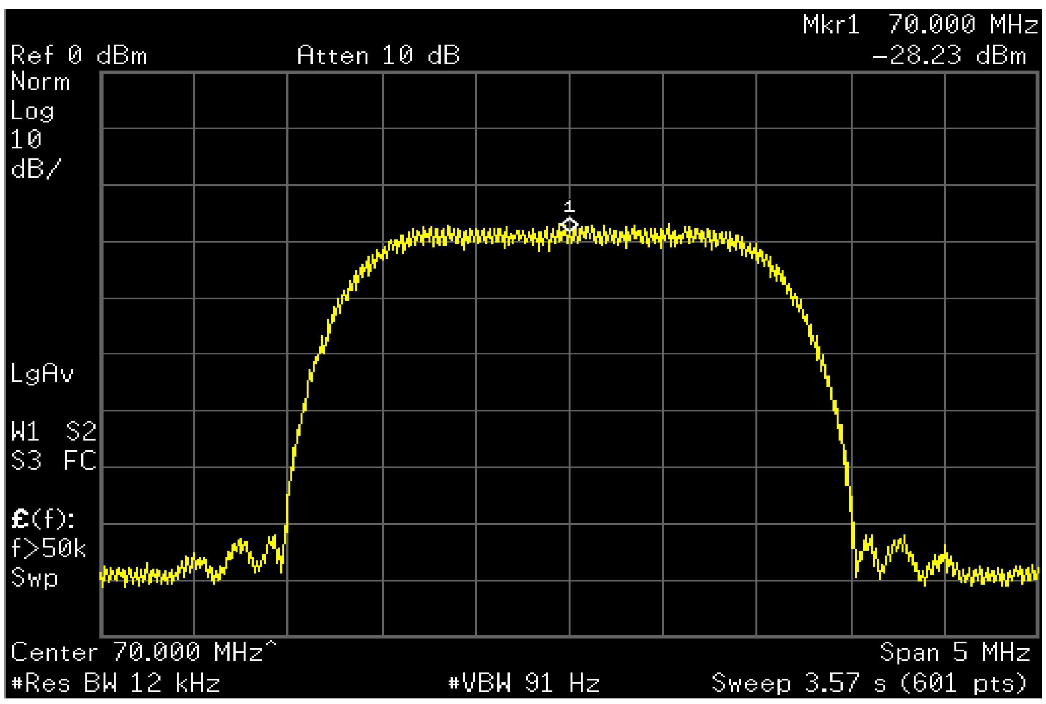

Figure 15. PSK Modulation Spectrum

Figure 19 shows the variance curve in AMR system implemented on FPGA for various SNR conditions. It shows the similar response as obtained from the software simulation model. A slight deviation between hardware and software simulation results for 16 QAM modulation because of limited ADC dynamic range which can be improved by using high bit resolution ADC having high dynamic range.

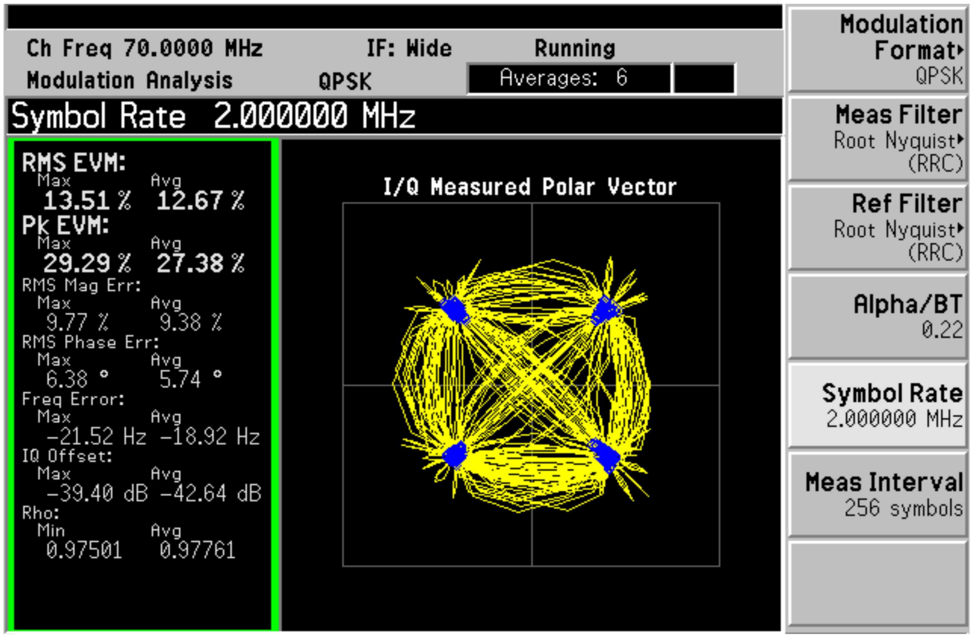

Figure 16. PSK Constellation

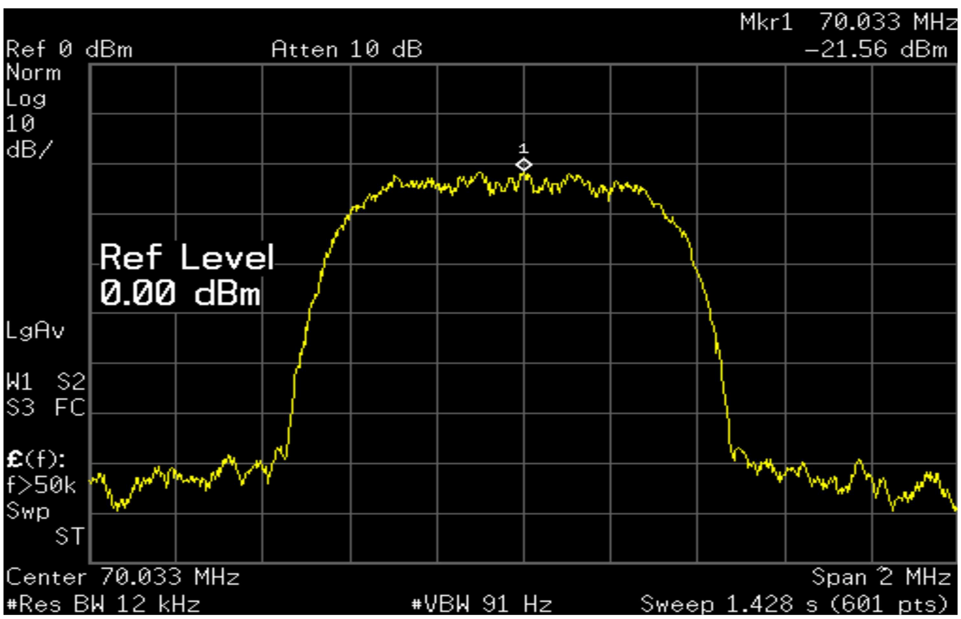

Figure 17. 16-QAM Modulation Spectrum

7. Conclusion

A hardware efficient architecture of FPGA based AMR system for Advanced SATCOM Payload is presented in this paper. Entire design is carried with single edge of the clock so that static timing analysis could be performed successfully. The design is made portable and platform independent because IP cores are not used. The total occupancy of the optimized entity in Xilinx Virtex–II Pro XC2VP50 is only 15%. Future scope of this work lies in implementation of various algorithms for the estimation of the necessary modulation parameters like symbol rate, channel coding, bandwidth etc. at the receiver end. Advance Communication Satellite will have the capabilities to change the complete receiver configurations according to the communication standards and adaptively demodulate the incoming signal if the Software Defined Radio architecture is employed. This will be very useful in 4th generation communication system where a receiver can receive more than one type of modulation with single receiver.

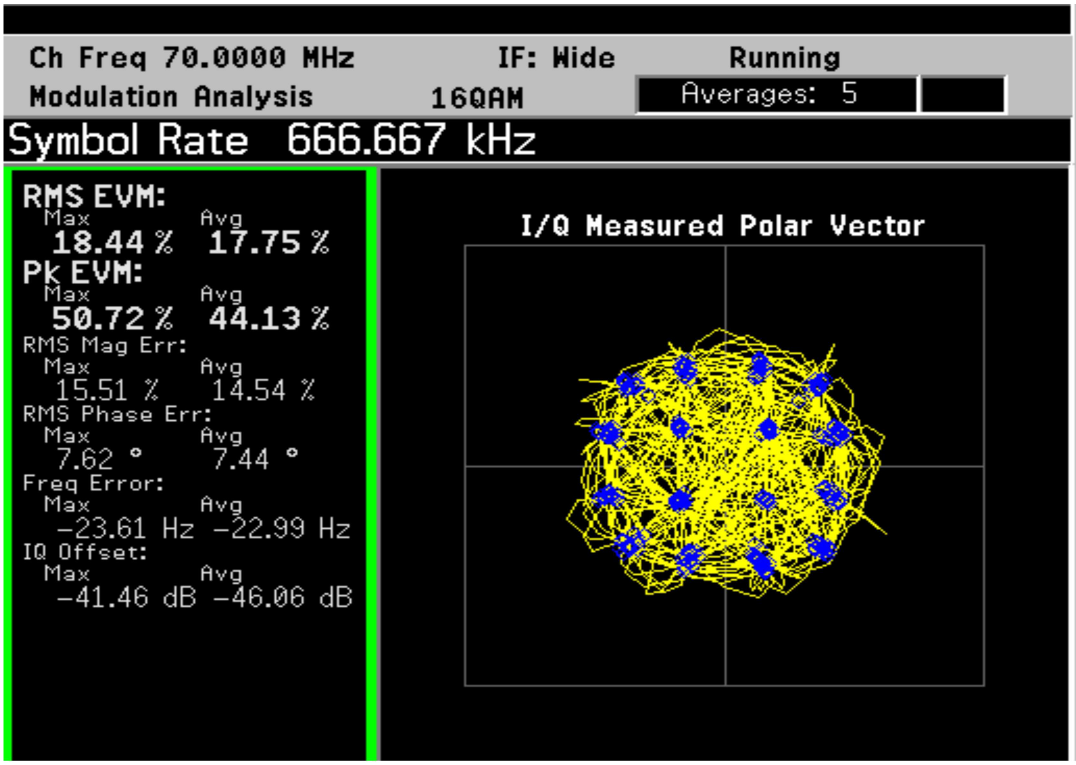

Figure 18. 16- QAM Modulation Constellation

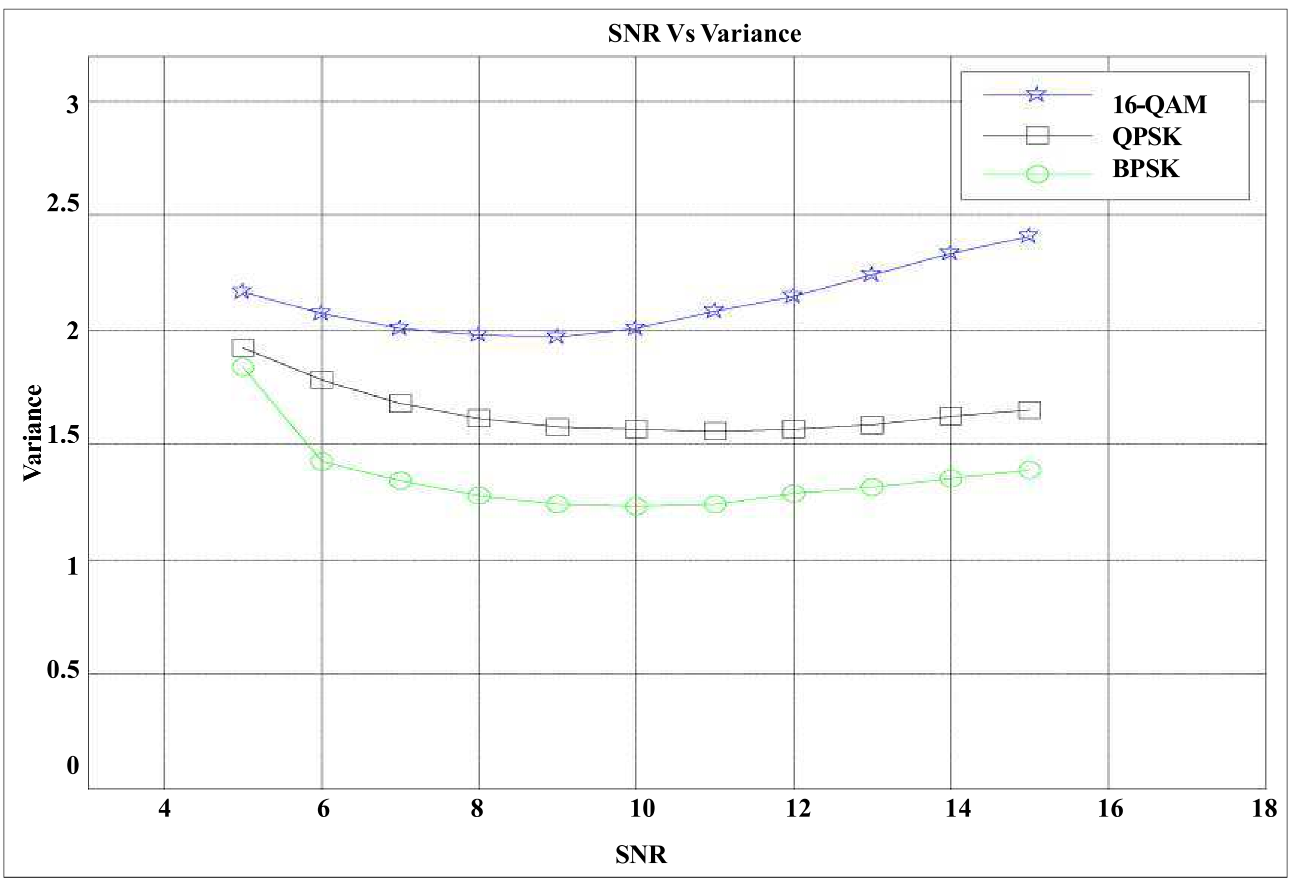

Figure 19. Variance vs. SNR curve to identify PSK and QAM Modulation in Hardware

References

[1] Azzouz, E. E., Nandi, A. K. (1996). Automatic Modulation Recognition of Communication Signals, Kluwer Academic Publishers.

[2] Liang Hong, K. C. Ho. (1999). Identification of digital modulation types using the wavelet transform, IEEE.

[3] Prakasam, P., Madheswaran, M. (2009). Modulation Identification Algorithm for Adaptive Demodulator in Software Defined Radios Using Wavelet Transform, *International Journal of Signal Processing*.

[4] Jae-Do Jin, Young-Jin Kwak, Kwang-Wook Lee, Kyung HoonLee, Sung-JeaKo. (2004). Modulation type classification method using wavelet Transform for adaptive modulator, IEEE.

[5] Jaspal Bagga, Neeta Tripathi. (2012). Study and Comparison of Various Modulation Classification Techniques under Noisy Channel Conditions, *International Journal of Emerging Technology and Advanced Engineering* (IJETAE), 2, (4) 216 221, April.

[6] Polikar, R. (1994). The Wavelet Tutorial.

[7] Mohamed I. Mahmoud, Moawad I. M. Dessouky, Salah Deyab, Fatma H. Elfouly, Comparison between Haar and Daubechies Wavelet Transformations on FPGA Technology, World Academy of Science, Engineering and Technology, p. 26.

[8] MathWorks India: www.mathworks.in.