SNR Estimation and AGC Implementation on USRP

A Project Report

submitted by

A AVADHOOTHA CHAITANYA

in partial fulfilment of the requirements
for the award of the degrees of

BACHELOR OF TECHNOLOGY

and

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS

MAY 2014

THESIS CERTIFICATE

This is to certify that the thesis titled **SNR Estimation and AGC Implementation on USRP**, submitted by **A Avadhootha Chaitanya**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology** and **Master of Technology**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. RadhaKrishna Ganti
Project Guide
Associate Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

Date: 13th June 2014

ACKNOWLEDGEMENTS

First and foremost, I am deeply indebted to my advisor Dr. Radhakrishna Ganti for his guidance and encouragement throughout the course of this project. I would like to thank him profusely for his patient guidance even at times when the project was not going in the right direction.

I would like to thank the Department of Electrical Engineering for providing an excellent laboratory and computational resources for making this project possible. I would like to acknowledge all the professors of the department for their erudition and whose courses instilled my interest in various topics. I would also like to thank my faculty advisor Dr. Srikrishna Bhashyam for his guidance over the past five years.

It is a pleasure to thank all my labmates - Arjun, Praveen, Mali, Reshma, Saikiran, Sourav and others for their wonderful company throughout the year. I would like to thank all my wingmates and friends - Dinesh, Adithya, Suhaas, Vidyasagar, Sandeep, Praveen and others for making my five years of stay at IIT enjoyable. Special thanks are due to my friend Saurabh who helped me in all difficult circumstances.

Finally, since a mere word of thanks would be really insufficient to express my gratitude to my parents and other family members.

ABSTRACT

Orthogonal Frequency Division Multiplexing(OFDM) is a multi-carrier modulation scheme which offers high data rates and provides strong robustness against intersymbol interference (ISI) by dividing the broadband channel into many narrowband subchannels in such a way that attenuation across each subchannel stays flat. A crucial parameter required for adaptive transmission is the signal-to-noise ratio (SNR). It is a standard measure of signal quality for communication systems. SNR Estimators derive estimate by averaging the observable properties of the received signal over a number of symbols. MMSE algorithm for SNR estimation in OFDM system is based on the orthogonality between the estimation error and the estimate of the channel frequency response. This MMSE Estimator is implemented on Universal Software Radio Peripheral (USRP),a computer-hosted software radio to serve as a measuring parameter for the signal quality at the receiver under various circumstances.

Automatic gain control(AGC) is a technique found in many electronic devices, to control the dynamic range of radio receivers. It has a self regulating adaptive mechanism to maintain the output power level constant by varying the gain for different input power levels. Wireless communications(in OFDM scheme) show a wide dynamic range of received power levels necessitating an efficient AGC. So it should work in a way to react to the sudden input variations as would be encountered by the receiver in the case of an obscuration or entering a enclosed area. This AGC is implemented on Universal Software Radio Peripheral (USRP) to overcome the problems mentioned above and achieving the desired results.

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ABBREVIATIONS

OFDM	Orthogonal Frequency Division Multiplexing
AGC	Automatic Gain Control
USRP	Universal Software Radio Peripheral
SNR	Signal-to-noise Ratio
MMSE	Minimum Mean Square Error
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
FFT	Fast Fourier Transform
UHD	USRP Hardware Driver
API	Application Program Interface
dBm	Decibel-milliwatts
dB	Decibel
Tx	Transmitter
Rx	Receiver

CHAPTER 1

BACKGROUND

An important task in the design of future OFDM system is to exploit frequency selective channels by adaptable transmission parameters (bandwidth, coding/data rate, power) to preserve power and bandwidth efficiency according to channel conditions at the receiver. In order to achieve such improvements, efficient and exact signal-to-noise ratio (SNR) estimation algorithm is requisite.

In OFDM scheme, received power levels vary with time necessitating a speedy and efficient AGC response.The main purpose of AGC is to prevent the amplifier output from the saturating the ADC, at the same time enhance SNR of low strength signals. It is implemented using a recursive relation, which continues till the output reaches the reference value.Gain is recursively updated in steps to arrive at a gain corresponding to reference output.

Here we are implementing MMSE Estimator and Automatic Gain Control(in OFDM system) on USRP.

1.1 OFDM

An OFDM signal consists of a number of closely spaced modulated carriers. When modulation of any form - voice, data, etc. is applied to a carrier, then sidebands spread out either side. It is necessary for a receiver to be able to receive the whole signal to be able to successfully demodulate the data. As a result when signals are transmitted close to one another they must be spaced so that the receiver can separate them using a filter and there must be a guard band between them. This is not the case with OFDM. Although the sidebands from each carrier overlap, they can still be received without the interference that might be expected because they are orthogonal to each another. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period($f = \frac{1}{T}$). Multiplexing such hundreds of symbols (BPSK/QPSK/16-QAM) into different sub-carriers in the same time interval is referred to as one OFDM symbol.

Baseband equivalent if an OFDM signal is given by

$$x(t) = \sum_{k=0}^{N_c-1} a_m(k) e^{j2\pi\Delta ft} \tag{1.1}$$

defined in the interval $mTs < t < (m+1)Tu$. Where Tu is time period of the OFDM symbol, Nc is number of sub-carriers that are to be multiplexed, $a(m)$ is set of the sub-symbols in mth OFDM symbol and $\Delta f = 1/Tu$. It is important to note that the information that is modulated from an OFDM signal is in frequency domain. The OFDM signal is that it can be implemented easily by using IFFT module. It can be constructed by the following discrete time signal passed through the Digital to Analog Converter (DAC)

$$x(t) = \sum_{k=0}^{N-1} a(k)' e^{j2\pi\Delta kn/N} \tag{1.2}$$

$$a(k)' = a_m(k) for 0 < k < N_c$$

$$a(k)' = 0 for N_c < k < N$$

where N is chosen as a nearest greatest integer to N_c and the sampling rate of the system is $F_s = N\Delta f$.

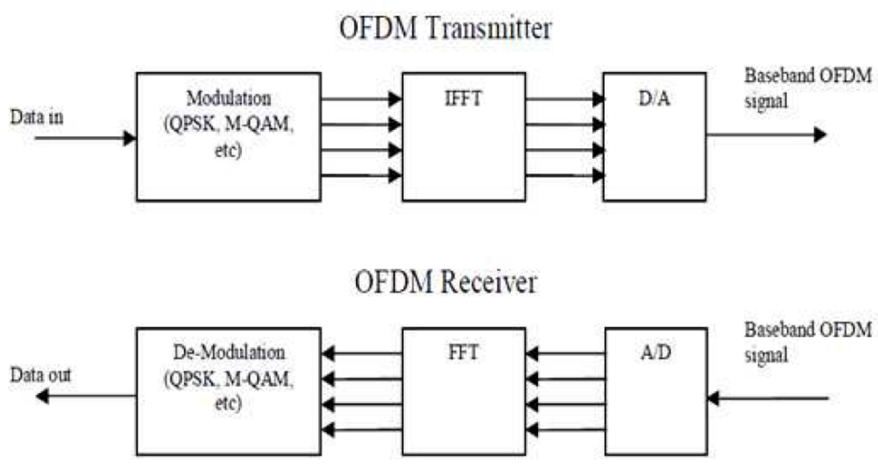

Figure 1.1: General Block Diagram of OFDM

The transmitter first converts the input data from a serial stream to parallel sets. Each set of data contains one information bit for each carrier frequency. Then, parallel data are modulated to the orthogonal carrier frequencies. The IFFT converts the parallel data into time domain waveforms. Finally, these waveforms are combined to create a single time domain signal for transmission.

The receiver basically performs the inverse of the transmitter by first separating the data into parallel streams. Then, the FFT converts these parallel data streams into frequency domain data. The data are now available in modulated form on the orthogonal carriers. Demodulation down-converts this information back to the baseband. Finally, this parallel data are converted back into a serial stream to recover the original signal.

1.2 Universal Software Radio Peripheral

The Universal Software Radio Peripheral (USRP) products are computer-hosted software radios. USRPs connect to a host computer through a high-speed USB or Gigabit Ethernet link, which the host-based software uses to control the USRP hardware and transmit/receive data.The USRP N210 product architecture includes a Xilinx Spartan 3A-DSP 3400 FPGA, 100 MS/s dual 14 bit ADC, 400 MS/s dual 16 bit DAC and Gigabit Ethernet connectivity to stream data to and from host processors. A modular design allows the USRP N210 to operate from DC to 6 GHz.The power output it can typically transmit is 15dBm and noise figure is 5dB.

This USRP has both transmitter(Tx) and receiver(Rx) motherboard, enabling it to transmit and receive at the same time though at different frequencies. It has two antenna slots, one of which can either be used as Tx or Rx, the other one as only Rx. A USRP N210 kit is shown below

Figure 1.2: USRP N210 kit

Implementation on USRP

The device is connected to the computer using either an ethernet cable or a USB 3.0 cable (depending upon the USRP model used), and one can interface it to one's program by using the open source USRP Hardware Driver Application Program Interface(UHD API). UHD API can be used to interface with the USRP from C++(Programming Language) program. This API provides classes and methods to set up the USRP device with the desired frequency, rate and gain settings. The above OFDM system is implemented through the C++ program which allows the USRP to transmit and receive the data at different frequencies. The data is transmitted or received according to the user inputs at a frequency, specified transmit rate, bandwidth and matching antenna of user's choice.

At the transmitter USRP random data is generated and IFFT of the that data is taken as mentioned in the section 1.1 and passed through DAC. Later on it is passed though Variable Attenuator Block with attenuation range of 31.5dB which can be changed with the user input while executing the code to transmit data.

The transmitted data sent and constellation can be seen in the below figures

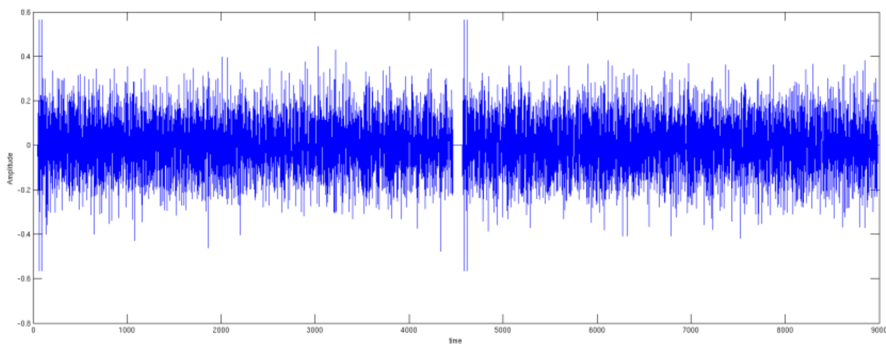

Figure 1.3: Transmitted Data

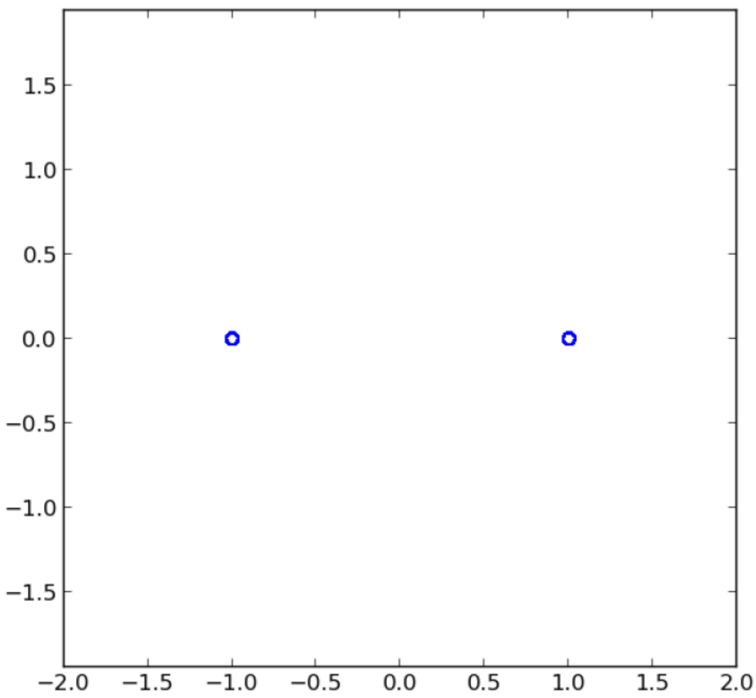

Figure 1.4: Constellation of Transmitted symbols(BPSK)

Similarly at the receiver USRP kit, the receiver code is executed to receive the analogue bit stream which is passed through Variable Attenuator Block. It is passed through ADC and then FFT of the received data is taken and processed.

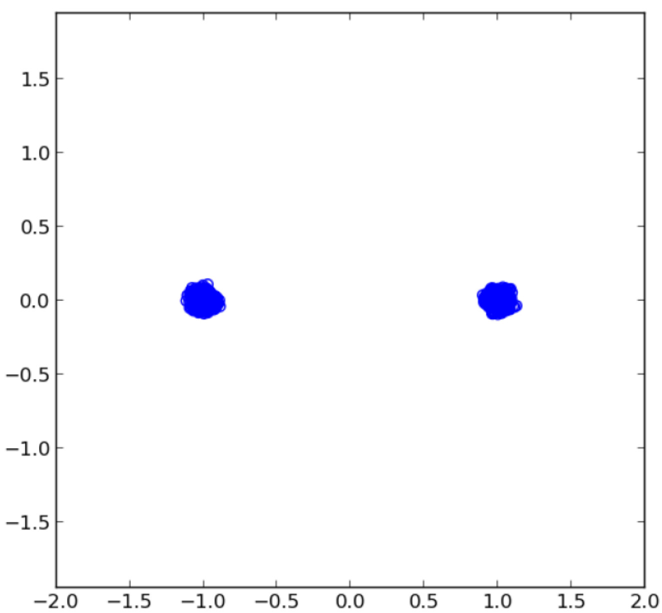

Figure 1.5: Constellation of Received symbols(BPSK)

CHAPTER 2

SNR Estimator

Signal-to-noise ratio (often abbreviated SNR) is a measure that compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power, often expressed in decibels(dB). A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise.
Signal-to-noise ratio is defined as the power ratio between a signal (meaningful information) and the background noise (unwanted signal):

$$SNR = \frac{P_{signal}}{P_{noise}},$$

where P is average power. Both signal and noise power must be measured at the same or equivalent points in a system, and within the same system bandwidth.
SNRs are often expressed using the logarithmic decibel scale. In decibels, the SNR is defined as

$$SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right),$$

2.1 MMSE Algorithm

MMSE algorithm for SNR estimation in OFDM system is based on the orthogonality between the estimation error and the estimate of the channel frequency response expressed as

$$(Y(n) - \hat{H(n)}C(n))(\hat{H(n)}C(n)^*)| = 0 \quad ,n = 1,..,N,$$

where $\hat{H(n)}$ denotes the estimate of $H(n)$, channel frequency response, $C(n)$ denotes the nth complex pilot symbol of the pilot sequence sent, $Y(n)$ denotes the received pilot symbols and $(.)^*$ refers to the conjugation operation.The MMSE average SNR estimate is given by

$$\hat{\rho}_{av} = \frac{\hat{S}_{MMSE}}{\hat{W}_{MMSE}}, \tag{2.1}$$

where S and W are transmitted signal power and noise power respectively.
$\hat{S}_{MMSE}$ and $\hat{W}_{MMSE}$ are defined as below

$$\hat{S}_{MMSE} = \frac{1}{N} \left| \sum_{n=0}^{N-1} Y(n)C(n)^* \right|^2$$

$$\hat{W}_{MMSE} = \frac{1}{N} \sum_{n=0}^{N-1} |Y(n)|^2 - \hat{S}_{MMSE}$$

2.2 Implementation of MMSE Estimator

Analysis of this MMSE estimator is clearly mentioned in [1]. This is implemented at the receiver side, using the pilot symbols. A pilot sequence of 40 symbols,and their location which are known to both receiver and transmitter is inserted at the transmitter side and IFFT of the data is taken and further transmitted. FFT of the received data stream is taken and pilot symbols are extracted using the pilot locations. This received pilot symbols and the data has the channel effects on it which are to be equalized to further use it for calculating the estimate of SNR. $\hat{S}_{MMSE}$ and $\hat{W}_{MMSE}$ would be as below

$$\hat{S}_{MMSE} = \frac{1}{40} \left| \sum_{n=0}^{39} ReceivedData(PilotLocations[n])PilotSequence(n)^* \right|^2$$

$$\hat{W}_{MMSE} = \frac{1}{40} \sum_{n=0}^{39} ReceivedData(PilotLocations[n])|^2 - \hat{S}_{MMSE}$$

Thus the SNR(in dB) is calculated from the expression $10 \log_{10} \left(\frac{\hat{S}_{MMSE}}{\hat{W}_{MMSE}} \right)$.
When the transmitter gain is increased, the Variable Attenuator comes into act in reducing the attenuation and thus increasing the signal power. Therefore an increase in SNR can be noticed. USRP N210 and USRP B210 has a maximum output power of 15dBm(15dBM - 30 = -15dB) and 10dBm(10dBm - 30 = -20dBm) respectively. Increase in the transmitter gain after reaching the maximum output of the USRP wouldn't

have any impact on the transmitted signal power.

SNR increases with the increase in transmitted power and comes to a saturation when it reaches the USRP's maximum output power limit. This can be seen in the Fig. 2.1 and Fig. 2.2.

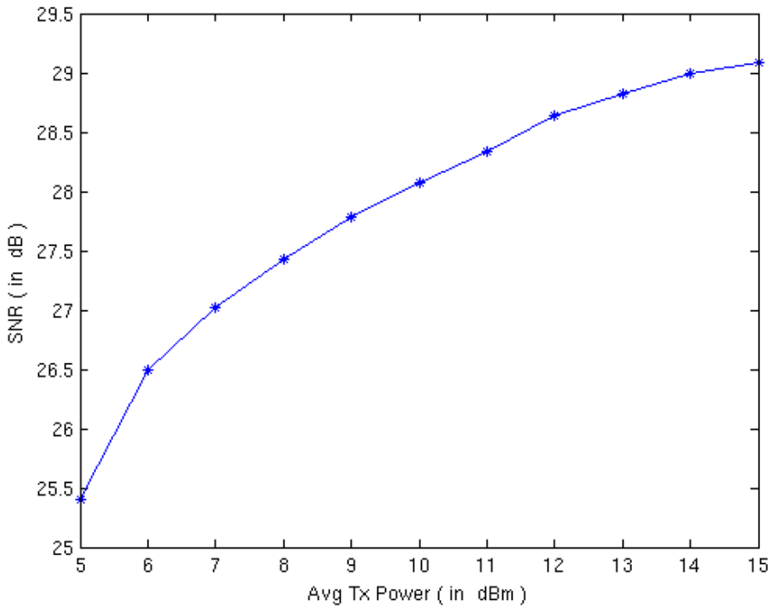

Figure 2.1: SNR with the Transmitted Power on USRP N210

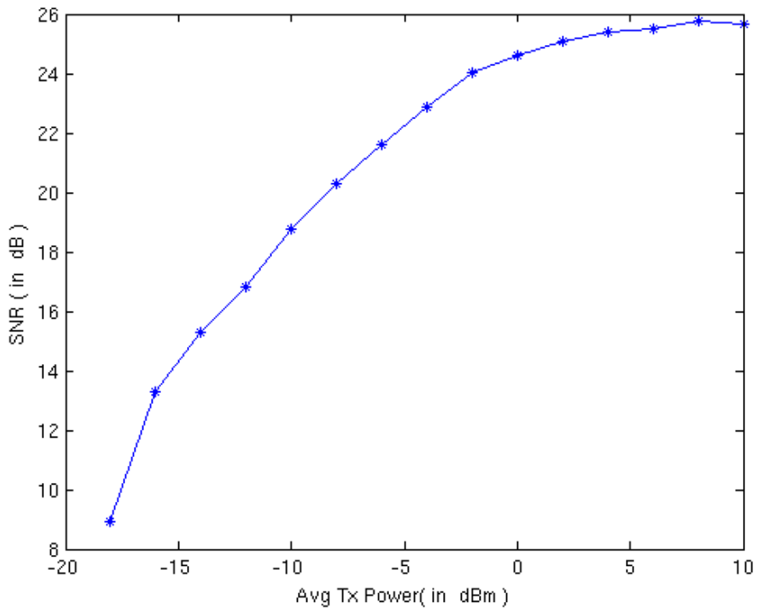

Figure 2.2: SNR with the Transmitted Power on USRP B210

CHAPTER 3

Automatic Gain Control

Orthogonal Frequency Division Multiplexing (OFDM) is a special multi carrier modulation technique in which all the sub-carriers are orthogonal, it can combat multi path fading and has high spectral utilization. In OFDM systems, the random addition of multiple sub-carriers in time-domain makes a higher peak to average power ratio of transmitting signal. Therefore, a good Automatic Gain Control (AGC) algorithm is critical for OFDM system. The main purpose of AGC is to prevent amplifier output from saturating the ADC, at the same time enhance SQNR of low strength signals, maintaining the output power level constant.

3.1 Basic Structure

AGC in its basic structure contains a Variable Gain Amplifier(VGA), whose gain is controlled by the control voltage ,which in turn generated by difference operation of estimated output power and desired reference value. As a design requirement VGA gain should have sufficient dynamic range to handle variations in input power. Usually VGA has linear in dB response and its settling time is far smaller than the sampling time. The ADC digitizes the output of VGA and the power of the output is estimated.

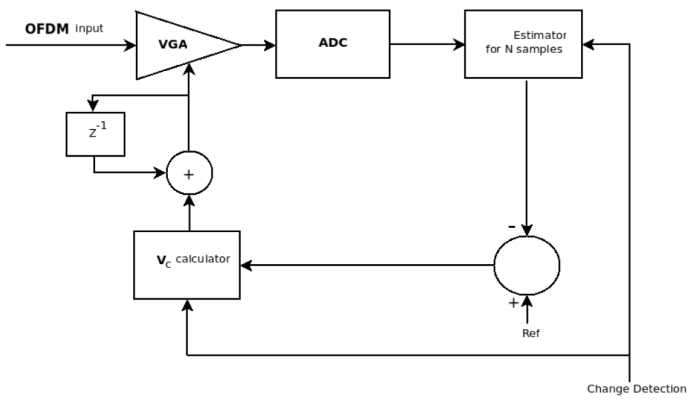

Figure 3.1: Block Diagram of AGC

3.2 Working of AGC

As mentioned in [2], AGC is implemented using recursive relation, which continues till the output reaches reference value. Gain is recursively updated in steps to arrive at a gain corresponding to reference output. The estimated output power is compared with reference output value and the difference is applied in turn to variable gain amplifier. According to recursive formula new gain update is proportional to difference between previous estimated output and reference output ,multiplied by step factor. Higher the step factor larger is gain change and faster is the convergence. But higher step size creates more error in steady state. Where as for smaller step factors gain changes will be smaller and take longer time to converge.

The Automatic Gain control will respond to the changed input based on feed back estimated output. Gain is increased iteratively in steps so that error in steady state is reduced. In a basic Iterative process for applying gain represented as

$$Gain_i = Gain_{i-1} + stepfactor(Reference\ output - Estimated\ output) \quad (3.1)$$

Reference Output

There are two types of errors induced due to ADC. One is because of clipping of saturating signals and other is due to mere quantization of signals in linear region of ADC.Lower Strength signals get worse affected by quantization noise, where as higher strength saturating signals suffer due to clipping(This can be seen in the Fig. 3.2). So there is always a need to scale the received input so to maximize the SQNR.This output level of ADC when the maximum SQNR is found is taken as the reference output.

To find out input corresponding to maximum SQNR ADC output, experiment is repeated varying the transmitter gain spanning the dynamic range of ADC and in each case average SQNR is noted.The output power of ADC at which SQNR is maximum is taken to be the reference output power. The received signal corresponding to reference output power is shown in Fig. 3.3

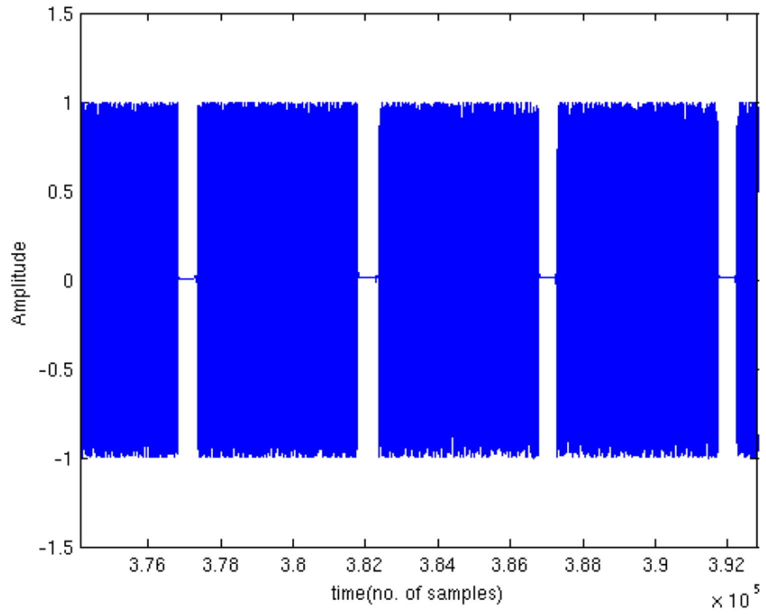

Figure 3.2: Received signal getting clipped after passing through ADC

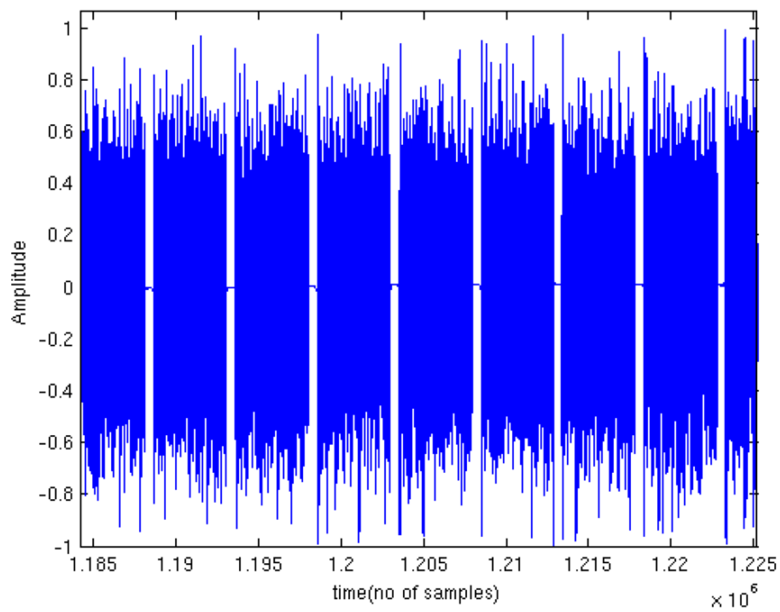

Figure 3.3: Received signal when the reference output power is reached

3.2.1 Convergence Delay

Convergence delay is the time taken, from instance of change in the input to the time till the AGC settles down to 5% of the reference output value. An overshoot is seen at the instance of change in the input, the extent of it depending on previous gain and the present input. For a situation when the receiver is set to high gain, to overcome the low input power levels, a sudden change in the input power level from low to high will result in an larger overshoot. Therefore difference term (reference output power - estimated output power) used to calculate the updated gain will also be higher introducing a gain change of larger amount resulting in faster convergence. In case of smaller output changes gain changes will be slower.But the controllable parameters which can be adjusted so that the convergence delay can be reduced, are the integration length and step factor.

Step Factor

Step factor is the parameter which multiplies to difference term in gain updating relation controlling the amount of gain change. For a given RMS output value for higher step factor faster would be the convergence delay. But higher step factor would cause large steady state error. It is to be chosen in such a way that would result in low steady state error with acceptable accuracy level of the estimate.

Integration Length

Integration length is the number of samples utilized in deriving the output strength value. Output estimation can be done in terms of average absolute value or an RMS value giving the estimate of output power. Trade off affecting the convergence delay is the number of samples utilized in calculating the estimate. Lesser number of samples will yield into faster convergence delay. But lesser number of samples will result in poor estimation accuracy.

3.2.2 Implementation of AGC

This adaptive AGC is implemented at the receiver side, using the continuous samples received. The reference output power for the USRP N210(14 bit ADC) is found to be -13.5dB. A higher integration length is used to get a better accuracy of estimate. To reduce the convergence delay that can be caused by the integration, the step factor is chosen in such a way that it ensure the faster convergence.

The integration length is around 4500 samples(about a length of a frame). The step factor takes the value 1 normally and 0.12 when the absolute value of difference term is 1.5. The iteration mentioned in equation 2.2 is triggered whenever the change in estimated output and reference output is detected. The USRP N210 has the receiver gain that can be varied from 0 to 38. So the AGC works in increasing or decreasing the gain in the above range resulting in the convergence of the estimated output and the reference output. The iteration stops when the difference term reaches around 5% of the reference output as mentioned in the section 3.2.1.

The Step factor is chosen to be 1 based on experimental observations at different input levels. The convergence happens faster at this step factor as shown in the following figures. Received signal comes out of clipping region sooner when the step factor is 1 and any value greater than 1 gives unstable results (the received signal might get saturated due to larger change in the gain)

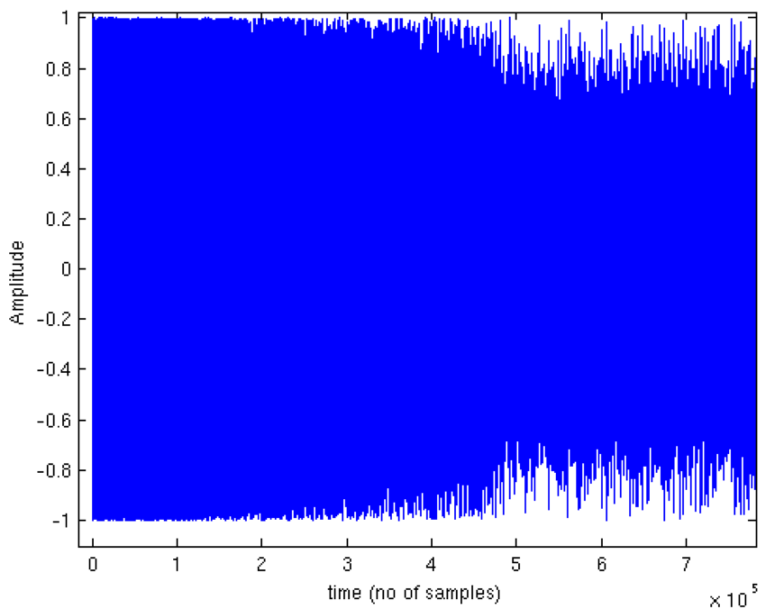

Figure 3.4: Received signal at a step factor 12x10^{-3}

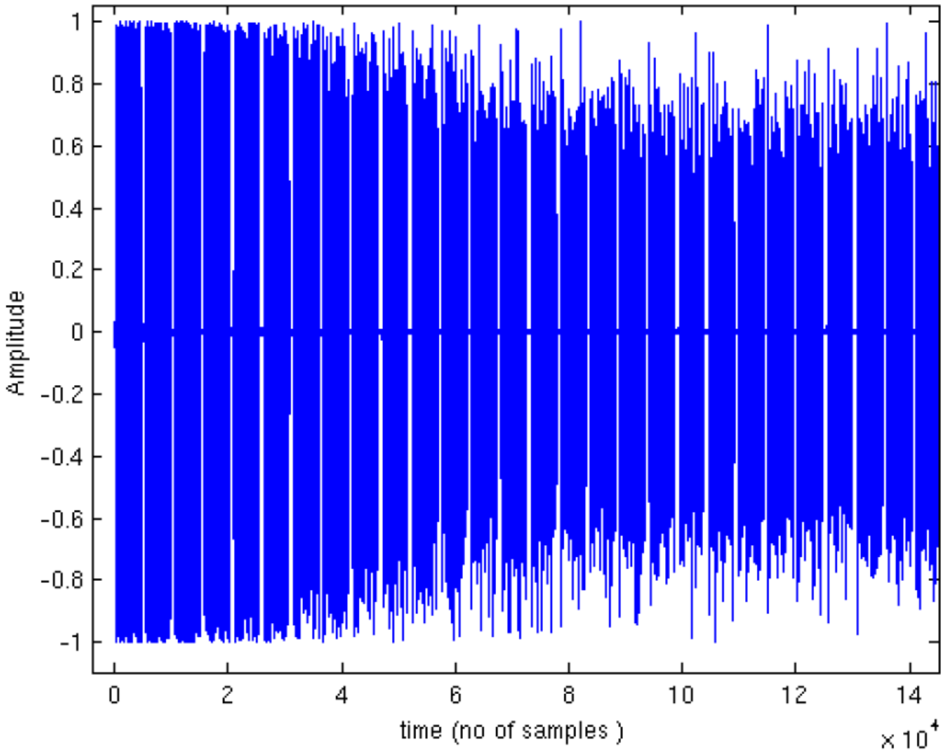

Figure 3.5: Received signal at a step factor $12 \text{x} 10^{-2}$

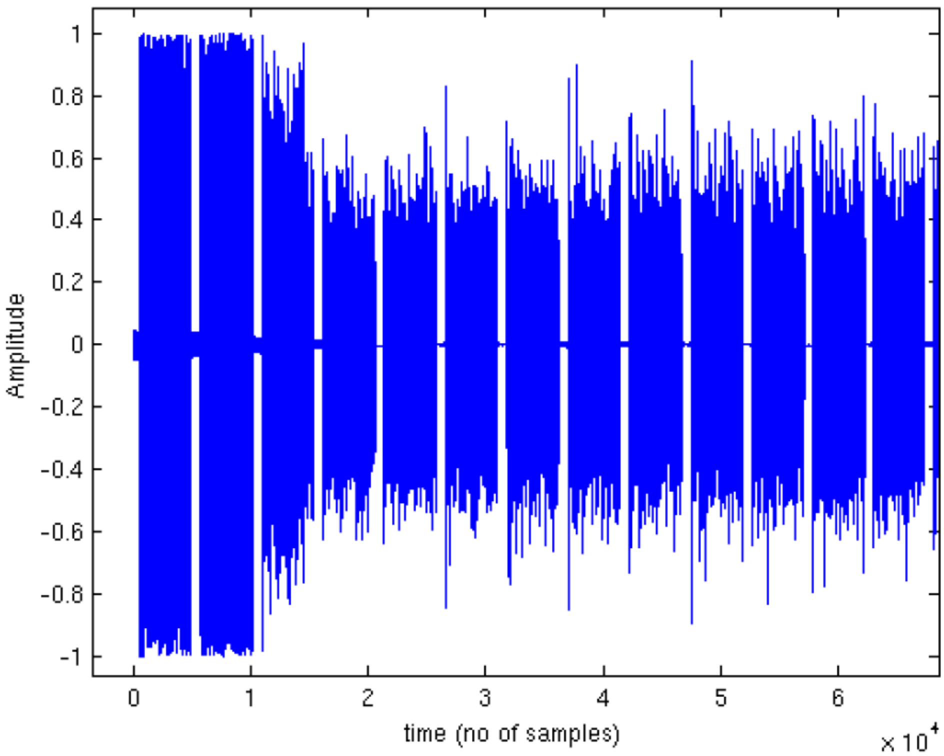

Figure 3.6: Received signal at a step factor 1

It can be seen that, in the case of ADC saturation, AGC works efficiently to come out of the clipping region and maintains the output power level constant. It also has to enhance the signal and maintain the desired reference power for low strength input signals. The same can be observed in Fig. 3.7, thus ensuring the other objective of AGC From the Fig. 2.1 and Fig. 2.2, it is observed that the SNR is low when the transmitter

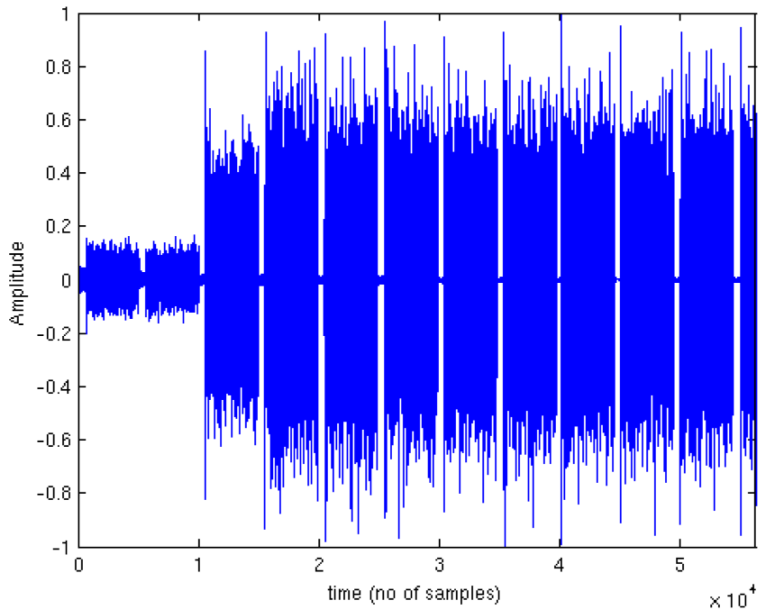

Figure 3.7: Received signal in the case of low strength input

power is low and increases with the increase in transmitter power. An efficient AGC would prevent ADC saturation and maintains the received signal power level constant, therefore the Signal to Noise Ratio.

SNR levels are improved with the introduction of AGC into the OFDM system. In the case of low strength inputs, it enhances the output strength and prevents saturation of ADC to maintain desired output level by adjusting the gain at the receiver USRP. From the Fig. 3.8 and Fig. 3.9, it can be seen that the SNR levels without the AGC followed a increasing pattern with the increase in transmitter power levels. When the AGC is present, SNR levels are maintained around 29.5 at all transmitted power levels.

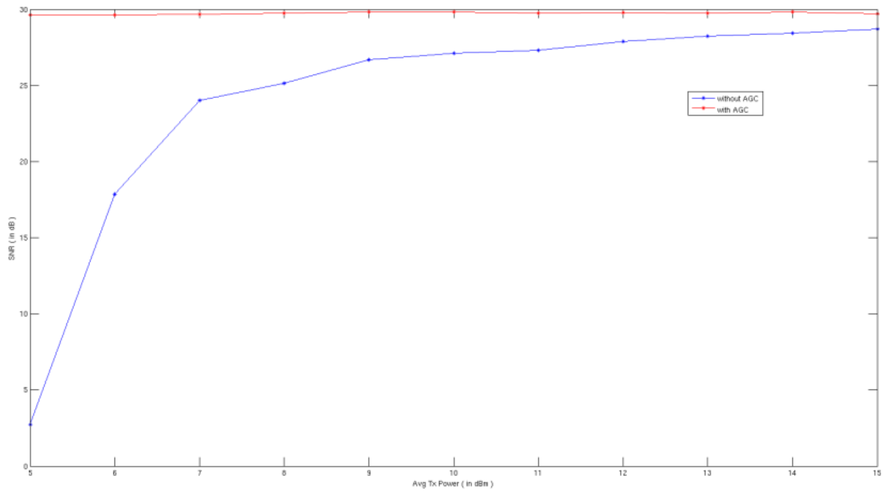

Figure 3.8: SNR levels in presence of AGC on USRP N210

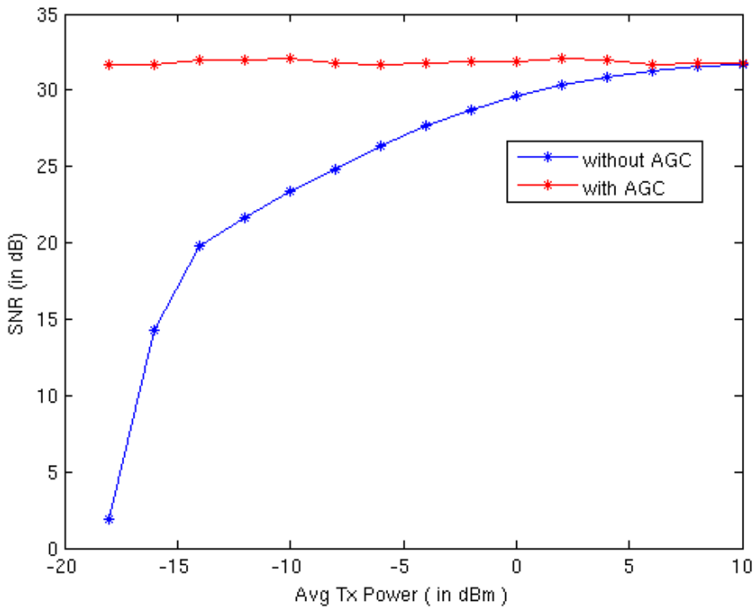

Figure 3.9: SNR levels in presence of AGC on USRP B210

CHAPTER 4

Conclusion

The MMSE Estimator proved to be an efficient estimate of Signal to Noise ratio, a standard measure of signal strength. It increases with the increase in the input strength of the signal and goes to a saturation limit when the transmit power touches the USRP's maximum output power level.

The Automatic gain Control modifies the gain at the receiver to prevent saturation at the ADC and enhance the SQNR levels in case of low strength input signals. It keeps the output power level constant and thus the SNR levels are improved ensuring the quality of the signal at all circumstances.

This Estimator and AGC are tested in OFDM scheme on USRP B210 and USRP N210 which successfully gave the desired results

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