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Design and implementation of analog modulated signals radio monitoring receiver based on SDR technology

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Abstract. *Modern radio monitoring receivers can be used in a variety of applications, including spectrum monitoring, radio reconnaissance, jamming signals identification, and RF signals direction finding. Recently, the high developing rate in Software Defined Radio (SDR) technology provides a programmable communication system, where functional changes can be made by simply updating the software. The paper aim is to emulate SDR monitoring receiver model that can recognize the modulation type of the intercepted signals based on LABVIEW graphical programming language and deploying this model on NI-USRP-2920 platform. The designed SDR receiver model has been fully implemented and successfully recognized the modulation type of common analogue modulated signals (AM, DSB, FM/PM, USB, LSB, VSB). The obtained experimental results were compared with the reference guide ones that based only on MATLAB simulation for evaluating the proposed implemented model. Experimental results showed that by using multi-features at the same time to discriminate analogue modulated signals with decision tree recognition algorithm, Nandi and Azzouz model, average recognition rate reached 88.3% when SNR=5dB , 96% at SNR=10dB, and 100% at SNR=30dB. The implemented model results were 3dB less than reference ones, where the effects of real hardware and over the air channel interference signal sources were considered.*
Keywords: SDR; Radio monitoring; Modulation recognition; LABVIEW.

1. **Introduction.** Radio Monitoring Receiver (RMR) forms a basic subsystem in any radio monitoring station for various civilian and military applications. Contrary to normal receivers, RMR is not tuned to a particular frequency or mode; but it detects the signal within a wide frequency band and also identifies its mode of operation. Further, upon the classification of the modulation type of the intercepted signal, it demodulates the signal accordingly for extracting noncipherd information [1–4].
Over the last few years, the digital implementation of analog radio systems, which are widely used for various radio applications in military, civilian and commercial aspects, has a high developing rate synchronized with that of technology.Software Defined Radio (SDR) technology enables designing and implementation of a transceiver that can be programmed through a software according to the requirements of the application [5, 6]. However, the SDR receiver concept has additional demands from its architecture side in order to be able to provide multi-band, multi-mode operations with re-configurability, which are needed to be matched with a set of air interface standards [4–7]. the objectives of this paper are to design and implement a proposed model of software defined RMR

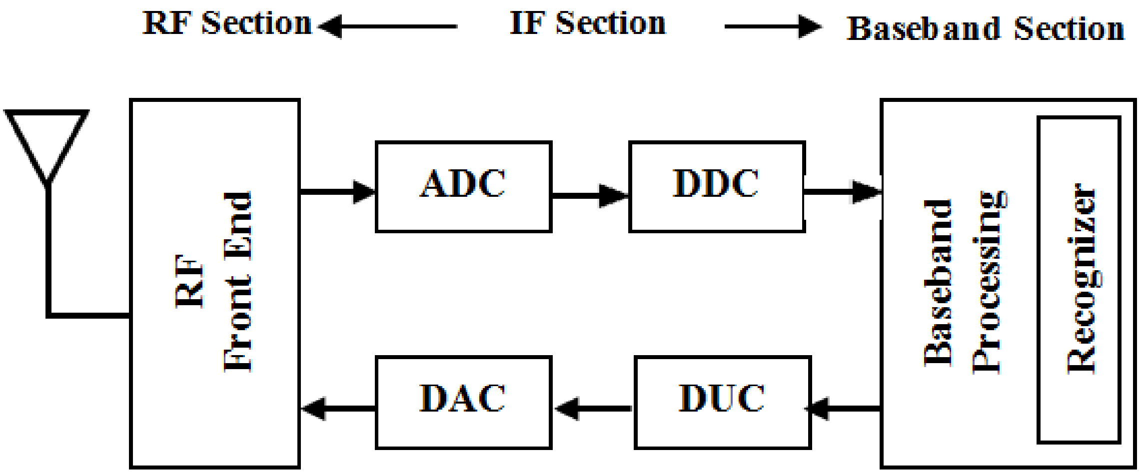


FIGURE 1. SDR architecture for working as monitoring [1,10]

with modulation recognition ability using Laboratory Virtual Instrumentation Engineering Workbench (LABVIEW) graphical programming language and deploy this model on a Universal Software defined Radio Peripheral (USRP) platform of type NI-USRP -2920 [7]. Section 2 introduces the basic software defined RMR architecture and briefly mentions the functionality of its modules. The considered signal models that can be recognized by the proposed RMR receiver are considered in section 3. Recognition processes and the used modulation recognition algorithm are discussed in section 4. Section 5 presents the LABVIEW baesd implementation of the proposed RMR using NI-USRP 2920 platform. The experimental results and analysis arediscussed in section 6. Finally, the conclusions of this paper are mentioned in section 7.

2. **Radio Monitoring Receiver.** Software defined receiver is a radio communications receiving system in which some or all the typical components of a communication system such as mixers, modulators, demodulators, detectors are implemented and controlled through software programming [1,4].Functions of a typical digital communication system can be divided into three main functional blocks: RF section, IF section, and baseband section. SDR architecture for working as monitoring receiver [4] is shown in Fig. 1.

The RF section ,also called RF front end, consists of essentially analog hardware modules. It is responsible for transmitting/receiving the radio frequency (RF) signal from the antenna via a coupler and converting it to a lower center frequency such that the new frequency range is compatible with the following ADC blocks. It also filters out noise and communication channel undesired signals and amplifies the desired signals to a suitable level for the ADC block. On the transmition path, RF front-end performs analog up conversion and RF power amplification. The IF section contains ADC/DAC and DDC/DUC blocks. The ADC blocks perform analog -to-digital conversion (on receiving path) while DAC performs the opposite function of it i.e. digital-to-analog conversion (on transmitting path). ADC/DAC blocks interface between the analog and digital sections of the radio system [1–4].The DDC/DUC blocks perform digital Down / UP conversion of sampling rates on receive path and the opposite operation on the transmit path for matching sampling rates between various interconnected blocks. DDC/DUC blocks and base band processing operations require large computing power and these modules are

generally implemented using ASICs or stock DSPs [1–4].
Digital processing stage is the key part of any software defined radio. It enables the radio to be re-configured to any air interface conditions. The baseband section performs base band operations such as connection setup, equalization, frequency hopping, timing recovery, and correlation and also implements the various demodulation schemes according to the modulation recognizer decision, which is a part of the baseband operations [1, 2].

3. **Representation of analog Modulated Signals.** A modulated signal s(t) can be expressed by a function of the form [5, 6]:

$$S(t) = A_c a(t)\cos(2\pi f_c t + \varphi(t) + \theta_0) \tag{1}$$

where $a(t)$ is the signal envelope, f_c is the carrier frequency, $\varphi(t)$ is the phase, θ_0 is the initial phase and Ac controls the carrier power. Particular modulation types are obtained by encoding the base band message into $a(t)$ and $\varphi(t)$. The mathematical expressions for different types of analog modulated signals (AM, DSB, SSB, VSB, FM/PM) are given together with their amplitude and phase relationships, which will later help to classify these modulation types.

3.1. **Amplitude Modulated Signals.** The expression describing Amplitude Modulated (AM) signal is given by [5, 6]:

$$S_{AM}(t) = [1 + mx(t)\ \cos(2\pi f_c t\ )] \tag{2}$$

where m is the modulation index, $x(t)$ is the modulating signal and f_c is the carrier frequency. The instantaneous amplitude $a(t)$ and phase for this signal is [5, 6]:

$$a(t) = |1 + mx(t)| \tag{3}$$

and the instantaneous phase $\varphi(t)$ is [5, 6]:

$$\varphi(t) = 2\pi f_c\, t \tag{4}$$

3.2. **Double side-band Modulated Signals.** Double side-band modulated (DSB) signals can be expressed as [5, 6]:

$$S_{DSB}(t) =\ x(t)\ \cos(2\pi f_c\, t) \tag{5}$$

The instantaneous amplitude and phase are given by [5, 6]:

$$a(t) =\ |x(t)| \tag{6}$$

$$\varphi(t) = \begin{cases} 2\pi f_c t & \text{if } x(t) \geq\ 0, \\ 2\pi f_c t\ +\ \pi & \text{if } x(t) \prec\ 0 \end{cases} \tag{7}$$

3.3. **Single Side-band Modulated Signals.** Single side-band (SSB) modulated signals can be expressed as [5, 6]:

$$S_{sss}(t) =\ x(t)\cos(2\pi f_c t)\ \mp\ y(t)\ \sin(2\pi f_c t) \tag{8}$$

where $x(t)$ is the modulating signal, $y(t)$ is the Hilbert transform. Using the harmonic analysis, SSB signal can be expanded as [5, 6]:

$$S_{sss}(t) = \sum\nolimits_{i=1}^{N} x_i\ \cos[2\pi(f_c\ \pm\ f_i\,)t\ +\ \psi_i] \tag{9}$$

The negative sign is used for upper side-band (USB) signal generation and the positive sign is used for lower side-band (LSB) signal generation. The instantaneous amplitude and phase is given by [5, 6]:

$$a(t) = \sum\nolimits_{i=1}^{N} x_i^2\ +\ 2\sum\nolimits_{i=1}^{N}\sum\nolimits_{j=1}^{N} x_i x_j\ \cos\left[2\pi(f_i\ -\ f_j\,)t\right]^{\frac{1}{2}} \tag{10}$$

$$\varphi(t) = \tan^{-1}\frac{\sum_{i=1}^{N} x_i \sin[2\pi(f_c + f_i)t + \psi_i]}{\sum_{i=1}^{N} x_i \cos[2\pi(f_c + f_i)t + \psi_i]} \tag{11}$$

3.4. **Frequency Modulated Signals.** In frequency modulation the instantaneous frequency is varied linearly with the modulating signal$x(t)$. The frequency modulated signal is written as [5, 6]:

$$S_{FM}(t) = \cos[2\pi f_c t + K_f \int_{-\infty}^{t} x(\tau)\, d\tau] \tag{12}$$

where $K_f$is the frequency deviation coefficient.

3.5. **Phase Modulated Signals.** In phase Modulated (PM) signals, the instantaneous phase is varied linearly with the modulating signal$x(t)$. The phase modulated signal is written as [5, 6]:

$$S_{PM}(t) = \cos[2\pi f_c t + K_p x(t)] \tag{13}$$

where $K_p$is the phase deviation coefficient.

3.6. **Vestigial Side Band Modulated Signals.** Generally, the Vestigial Side Band (VSB) Modulated signal is derived from AM signals by filtering through a vestigial side band filter unit [5,6].The analytic expression of the magnitude and phase response of VSB filter are given by [5, 6]:

$$|H_{VSB}(f)| = \begin{cases} (\frac{1}{2\alpha})[f - (f_c - \alpha)] & \text{if } f_c - \alpha \leq f \prec f_c + \alpha \\ 1 & \text{if } f_c + \alpha \leq f \prec f_c + f_x \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$|\phi_{VSB}(f)| = \begin{cases} (\frac{-\pi}{2\alpha})[f - (f_c - \alpha)] + \pi & if\ f_c - \alpha \leq f \prec f_c + \alpha \\ (\frac{-2\pi}{f_x - \alpha})[f - (f_c - \alpha)] + \pi & if\ f_c + \alpha \leq f \prec f_c + f_x \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

Where f_x is the maximum frequency of modulating signal, andα is chosen such that $(2\alpha/ f_c) \geq 0.01$ [5,6].

4. **analog Modulated Signals Recognizer.**

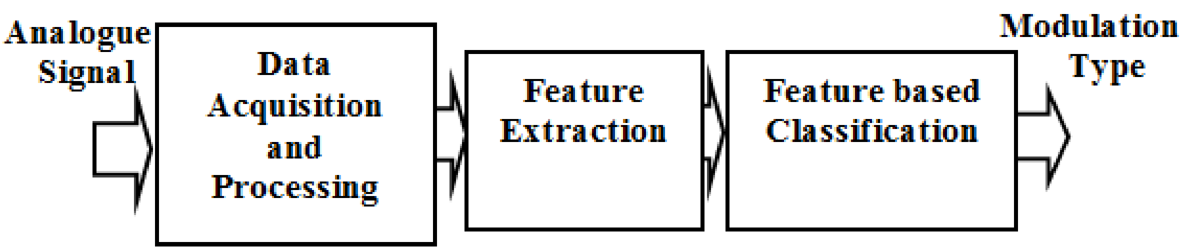


FIGURE 2. SDR architecture for working as monitoring [1, 10]

4.1. **Modulation recognition system.** analog modulation recognition system consists of three main subsystems: acquisition and pre-processing of the intercepted signals, feature extraction and classification subsystems as shown in Fig.2. In order to process the analog signals in computers, the information carried by the analog signal should be represented in a digital form, which is done through the data acquisition and processing subsystem. The feature extraction block gives the feature vectors, which are different for various modulation types, is the most important block of the overall system. Modulation

Table 1. Key Spectral Features for Modulation Classification [5-9]

Key Feature	Definition
$\gamma_{\max}$ is the Maximum value of PSD of the normalized centered instantaneous amplitude	$\gamma_{\max} = \frac{\max\left\|DFT(A_{cn(i)}\right\|^2}{N_s}$ **Where DFT is the discrete Fourier transform of the modulated signal,N_s is the sample number,$A_{cn} = \frac{A_i}{\mu_A} - 1$, A_i is the i^{th}instantaneous amplitude and $\mu_A$is the sample mean.**
σ_{dp} is standard deviation of the direct value of the centered nonlinear component of the direct instantaneous phase in non-weak segment dp	$\sigma_{dp} = \left(\frac{1}{N_c}\left(\sum_{A_{n(i)}\succ\tau_{th}} \varphi_{NL}^2(i)\right) - \frac{1}{N_c}\sum_{A_n(i)\succ\tau_{th}} \varphi_{NL}(i)\right)^{\frac{1}{2}}$ **Where all parameters are similar to σ_{ap} but differs in the absence of the absolute operator in the nonlinear component of the instantaneous phase**
Standard deviation of the absolute values of the centered nonlinear components of instantaneous σ_{ap}	$\sigma_{ap} = \left(\frac{1}{N_c}\left(\sum_{A_{n(i)}\succ\tau_{th}} \varphi_{NL}^2(i)\right) - \frac{1}{N_c}\sum_{A_n(i)\succ\tau_{th}} \|rphi_{NL}(i)\|^2\right)^{\frac{1}{2}}$ **where N_c is the number of sample(s) in φ_{NL} for $A_n(i) \succ \tau_{th}$, where $A^{th}$is the threshold value of $A_n(i)$ when the filter provides the minimum amplitude of the signal sample due to high noise sensitivity and φ_{NL} is the nonlinear component of the i^{th} instantaneous phase of the sample.**
P- value measures the signal spectrum symmetry around the carrier frequency (known)	$P = \frac{p_L - p_U}{p_U + p_L}$ **where** $p_L = \sum_{i=1}^{f_{cn}} \|X_c(i)\|^2$, $p_U = \sum_{i=1}^{f_{cn}} \|X_c(i + f_{cn} + 1)\|^2$**where,** $X_c(i)$ **is the Fourier transform of the intercepted signal**$X_c(i)$, $(f_c + 1)$ **is the sample number corresponding to the carrier frequency,** f_c **and**f_{cn}**is defined as;** $f_{cn} = \frac{f_c N_s}{f_s} - 1$

recognition of an intercepted signal is finally realized by the classification subsystem which recognizes the type of the modulation based on the classification algorithm [5–8].

4.2. **Feature extraction of analog modulated signals.** The implemented modulation recognition algorithm is based on extracting four key features, which are typical those used in reference sources [5–8]. The key feature $\gamma_{\max}$ represents the spectral density maximum and is zero for FM and large for all types of AM modulated signals. σ_{dp} is a measure of standard deviation of the centered non-linear component of direct instantaneous phase and can be used to discriminate AM and DSB signals. The key feature P-value represents the spectrum symmetry and is used to separate the USB and LSB signals from the other analog modulated signals even at very low SNR. The calculation equations of the four key spectral features are listed on Table 1.

4.3. **Feature Based Classification Algorithm.** A decision theoretic algorithm, based on using four key spectral features, for modulation classification of common analog modulated signals is executed through a flowchart, which indicates the sequence order of selecting the features to discriminate between signals of interest in the form of an algorithm. The selected algorithm to be implemented based on LABVIEW platform is Nandi and Azzouz algorithm [8], which is shown in Fig.3.

The first key feature, $\gamma_{\max}$, is used to differentiate the FM/PM signals because in

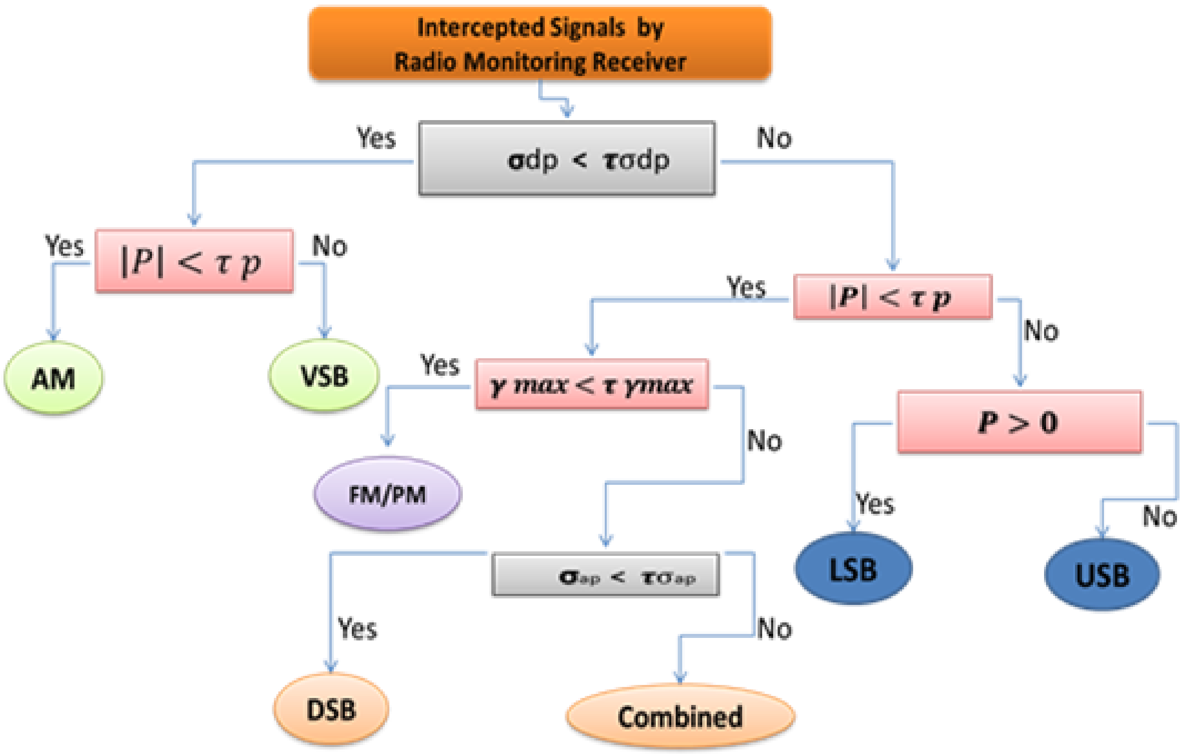


FIGURE 3. Modulation recognition algorithm flow chart for analog modulated signal [8]

FM/PM signals, the amplitude is always constant and the normalized centered instantaneous amplitude is zero. So the value of $\gamma_{\max}$ is less than the threshold value ,$\tau_{\gamma\max}$, and for the remaining signal types, the amplitude of the carrier signal changes according to the message signal, and exceeds the threshold value. The second key feature, σ_{dp}, is used to differentiate the AM and VSB signal from the other signal types.

Since VSB signal is also like an AM signal and the only difference between them is that, in VSB signal, one sideband is completely present with some part of the other sideband . So for both signals, there is no direct phase information . Hence its σ_{dp} value is less than the threshold value, $\tau_{\sigma ap}$,and for the other signal types, there is some direct phase information. For DSB signal type, the phase value is either 0 or π, which means a direct phase value exists, hence the σ_{dp} of this signal is more than the threshold value $\tau_{\sigma dp}$. Hence σ_{dp} can differentiate the AM-VSB signal from the other signal types. The third key feature, σ_{ap}, is used to differentiate the combined AM-FM signal from the DSB signals,where it contains only two side bands without carrier signal component and constant centered phase value $\pi/2$,which indicates no phase variation. But in the combined AM-FM signal, the phase is constantly changes according to the message signal, which means that σ_{ap} value is greater than the threshold value $\tau_{\sigma_{ap}}$.The fourth key feature , Pvalue, is considered with the power of the lower sideband and upper sideband in order to differentiate the signals whose lower and upper side bands have different amplitudes.

The P value can differentiate the AM signal from the VSB signal. In AM signal, the lower sideband and upper side band have the same power values, hence the P has zero value. Also, VSB signal contains one complete sideband and some portion of the other

side band. So the amplitudes of the two sidebands are different, hence the power of upper and lower sidebands are also different. So the P value is not zero.
Moreover, in FM/PM and DSB signals,the power of lower and upper sidebands are the same, so the P value is zero. Hence the threshold value τ_p value can differentiate the AM signal from the VSB signal and also can differentiate the SSB signal from all other signal types.

5. **LABVIEW Based Implementation of Radio Monitoring Receiver.** LABVIEW program has two major windows: Front Panel (FP) and Block Diagram (BD). A Front panel window provides a graphical user interface while BD one contains building blocks for resembling a functional block diagram of various software defined designs. The proposed receiver unit simplified block diagram is shown in Fig.4. and its FP is shown in Fig.5.
The proposed model of radio monitoring receiver is divided into three main parts: signal acquisition, signal processing (recognizer, demodulation), and data transfer. As shown in Fig.4., signal acquisition part includes all related USRP Virtual Instruments (VIs): Open Rx Session VI, Configuration VI, Initiate VI, Fetch Rx Data VI, Abort VI, and Close Session VI, where the details of all their operations.
are listed in USRP technical sheet [7]. These common operations have been used for acquiring the intercepted signals by the USRP front end. As shown in Fig.5., the proposed designed front panel provides a guide user interface in order to control and assign the hardware parameters : center frequency, antenna gain, IQ rate, used antenna, .etc. Also, the proposed front panel displays time domain and frequency domain windows and the control pattern to display modulation recognizer front panel. Acquired signals are

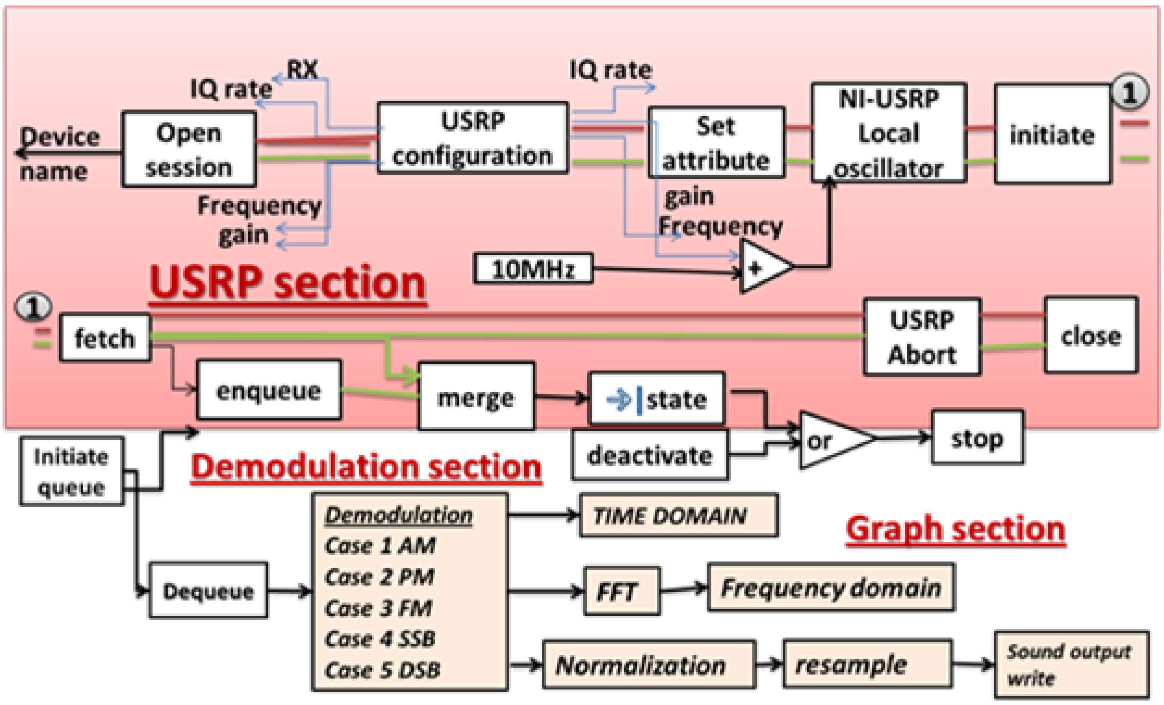


Figure 4. The proposed receiver unit simplified BD

transferred for being processed as the follows:

- Recognize its modulation type ,as shown on Fig.6(a),
- Demodulate the acquired signal according to its modulation type, and

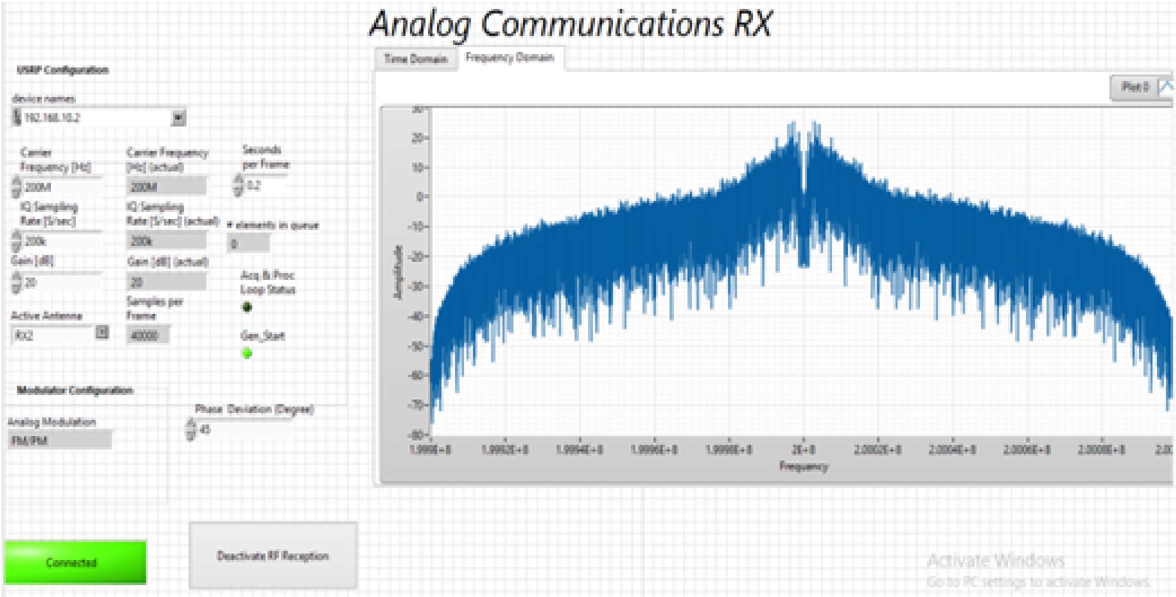


FIGURE 5. The proposed receiver unit simplified BD

- Displaying the time domain output after normalization process, as shown on Fig.6(b).

The proposed modulation recognizer simplified block diagram is shown in Fig.7. and its FP is shown in Fig.8. Acquired signals are transferred for being processed through modulation recognition processes. The simplified block diagram contains the basic procedures for getting the modulation type decision as follows:

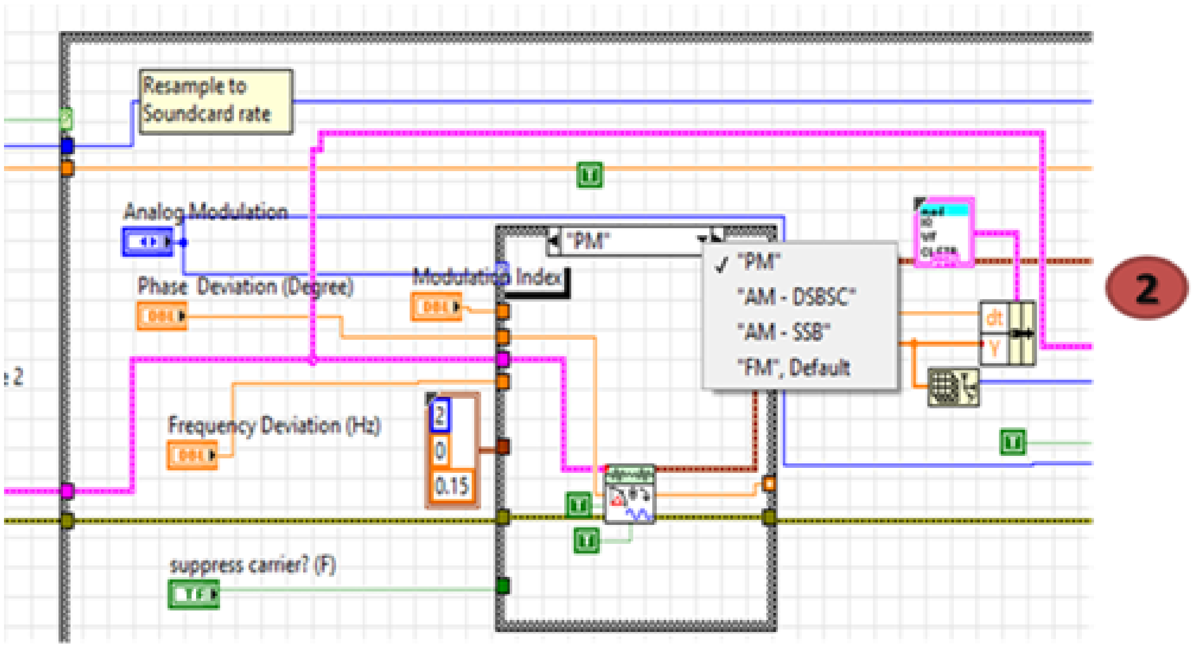
- Pre-processing the acquired signal samples instantaneous amplitude, instantaneous phase, FFT, and extracting non-weak samples,
- Calculating the four key features$\gamma_{\max}$, σ_{dp},σ_{ap} and P-value, and
- Applying the recognition decision tree algorithm on the previously calculated key features.

The decision about the modulation type appears by lighting lamp indicating this type on FP as shown in Fig.8.and selecting the appropriate demodulator in receiver side. According to the four key feature equations , as listed in table 1. , Labview BD of the key features extraction $\gamma_{\max}$, , σ_{ap},σ_{dp} , and P-value are shown in Fig.9. and Fig.10.

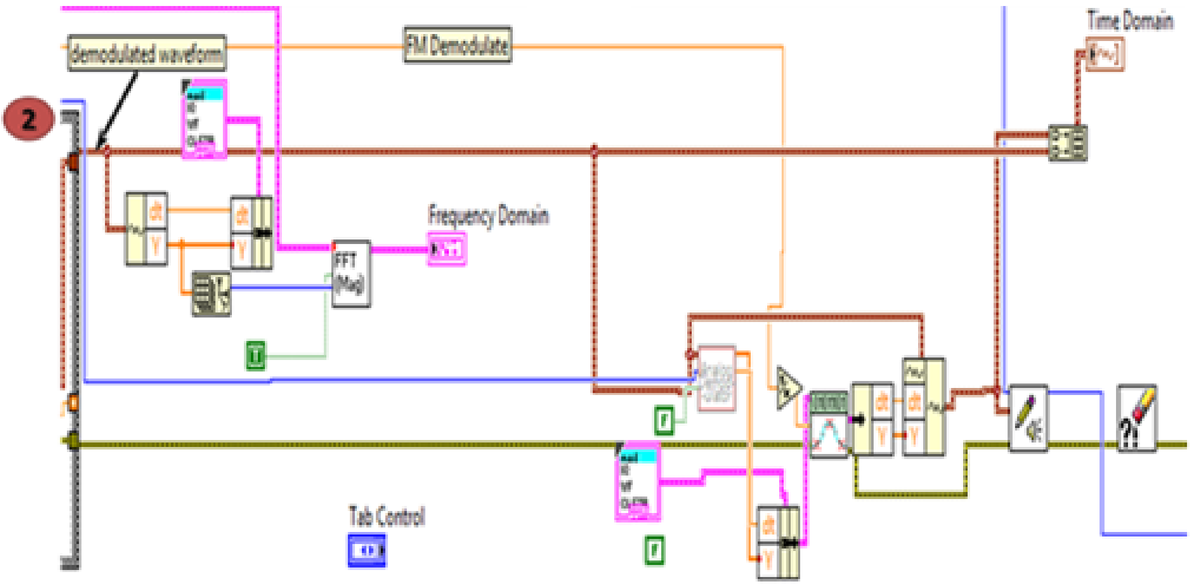
6. Experimental Evaluation.

6.1. **Experimental Hardware Setup.** As shown in Fig.11., the experimental setup consists of two host PCs and two USRP 2920, which are used as receiver (RX) and transmitter (TX) units. A single USRP 2920 is used as a transmitter and it is placed at a distance of 50ft from the receiver unit. The host PC interfaces with the USRP 2920 through a Gigabit Ethernet (GigE) connection cabel. USRP 2920 provides up to 40MHz of instantaneous analog bandwidth. The analog to digital and digital-to-analog converters on the motherboard use a 100MHz master clock and sample at 100MS/s and 400MS/s respectively. The on-board Xilinx Spartan 3A-DSP 3400 FPGA performs the required digital interpolation or decimation to provide the required sampling rate [7].

6.2. **Experimental results and analysis.** The correct modulation recognition results are based on 1000 iterations averages. Table 2. shows the performance of the proposed modulation recognition algorithm at specific SNR levels at SNR = 5 dB, 10 dB, and 30 dBin the form of confusion matrix.



(a)



(b)

FIGURE 6. LABVIEW block diagram:(a) Modulation type control to choose correct demodulator,(b) Normalization process before write function and plot the time domain.

Table 3. demonstrates that by using decision tree feature based algorithms to discriminate the proposed common analog modulated signals, the average recognition rate can reach 88.3From Tabel 4. , it is clear that MATLB based simulated Nandi and Azzouz algorithm [11] has overall recognition rate 99.2These obtained results are less than previous published results that used the same modulation recognition algorithm [8–11].
The interpretation of this difference is that published results were based on simulation results for verifying the algorithm design model without taking into consideration the

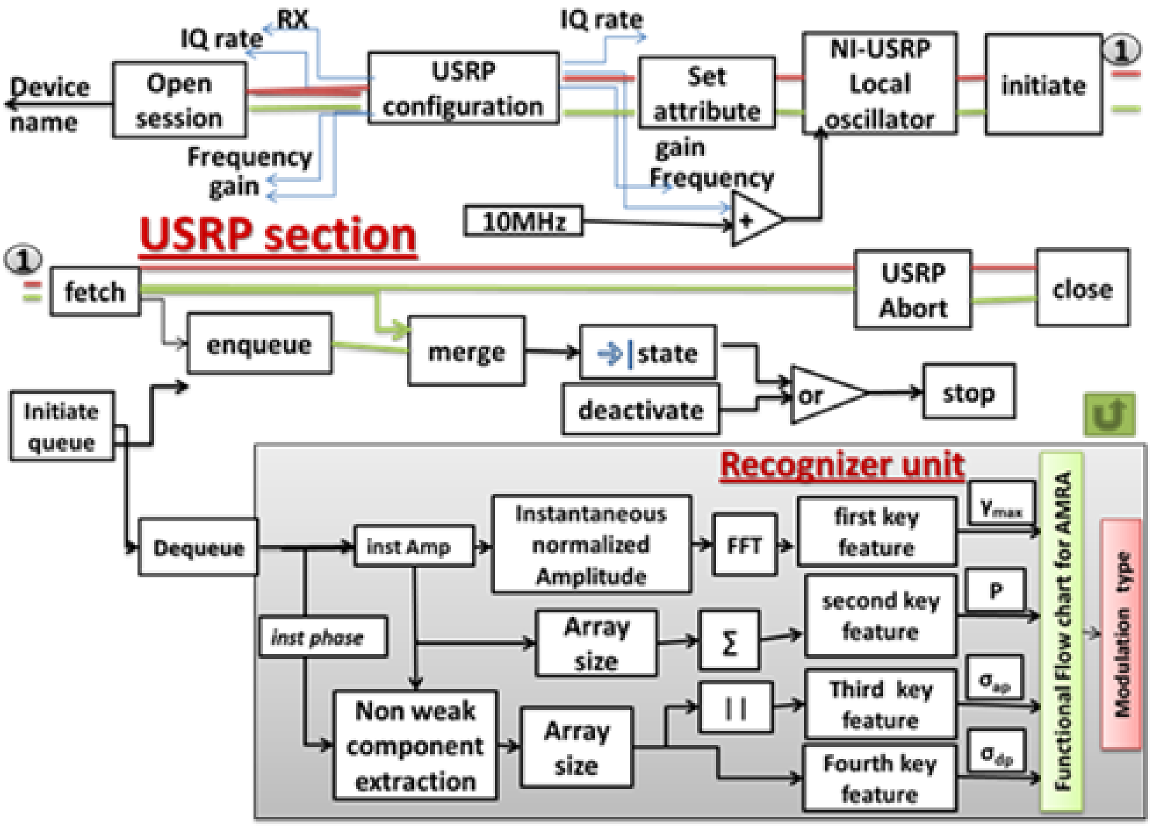


FIGURE 7. The proposed modulation recognizer simplified block diagram

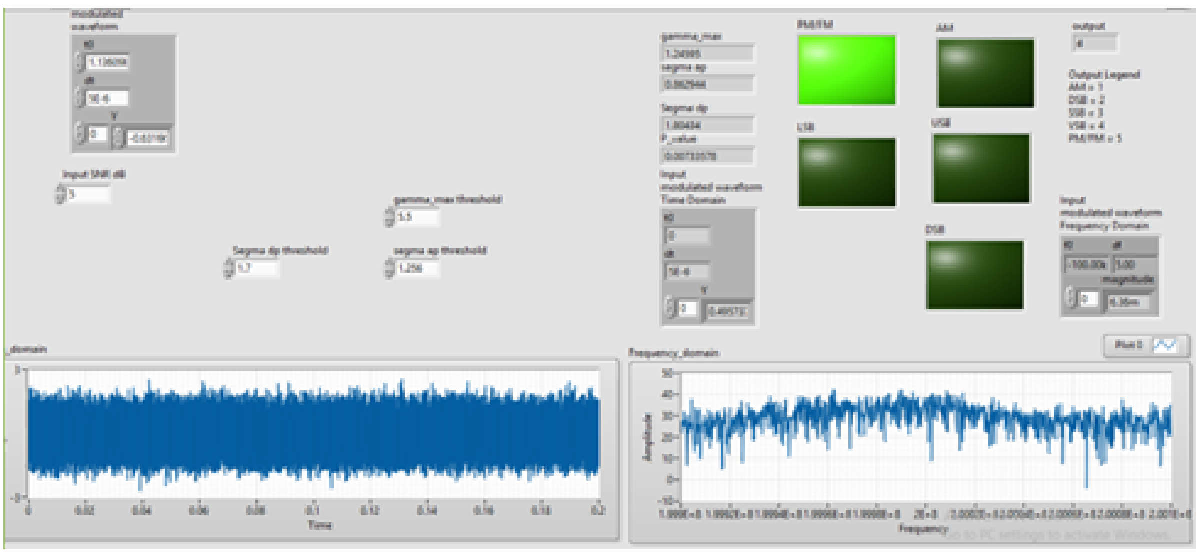


FIGURE 8. The proposed modulation recognizer unit front panel

hardware and wireless channel impairments effects either from internal or external interference signal sources, which are considered in SDR based implementation results.

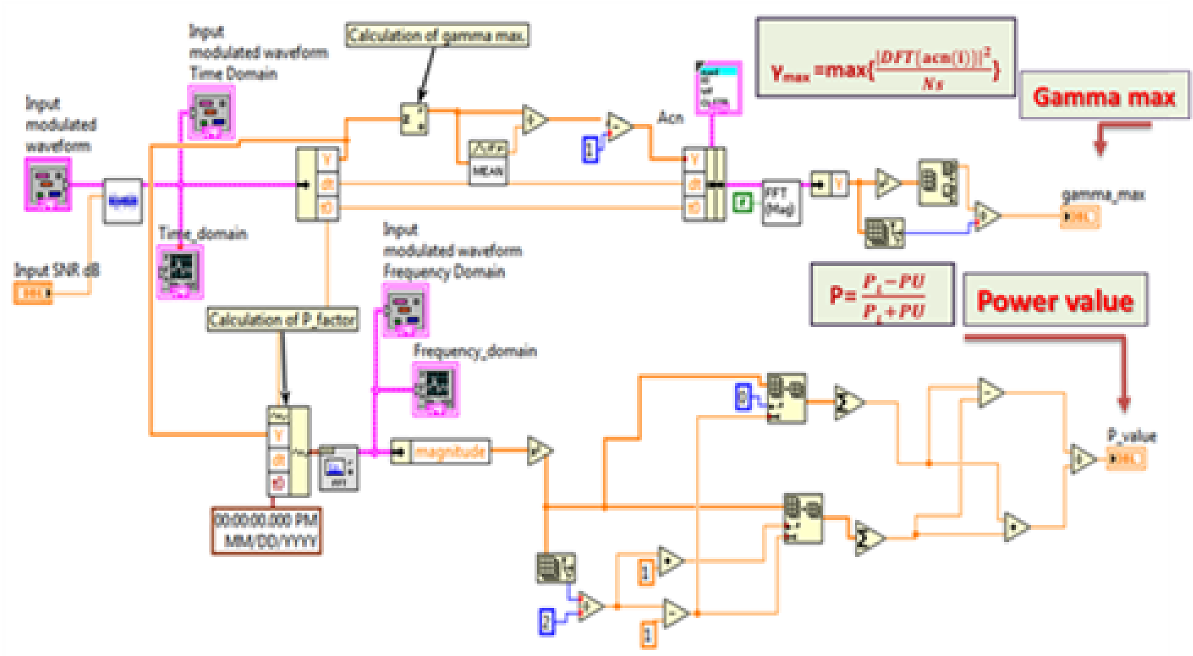


FIGURE 9. Labview implementation of $\gamma_{\max}$ and P value key features extraction

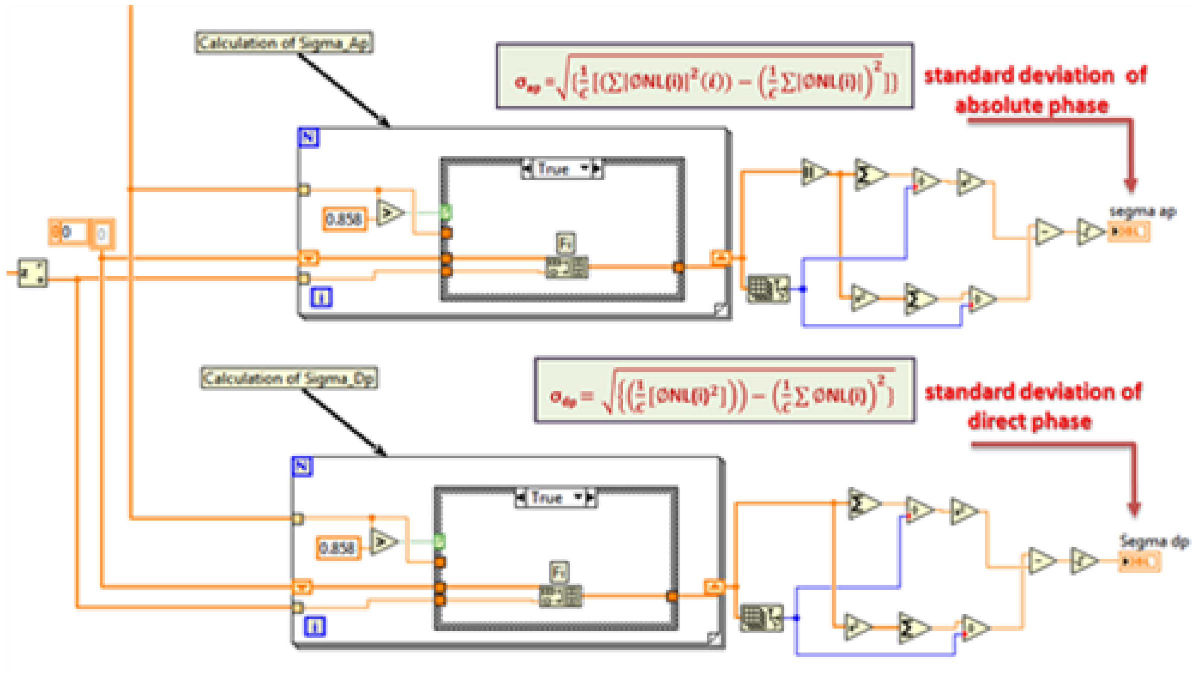


FIGURE 10. Labview implementation of σ_{dp} and σ_{ap} key features extraction

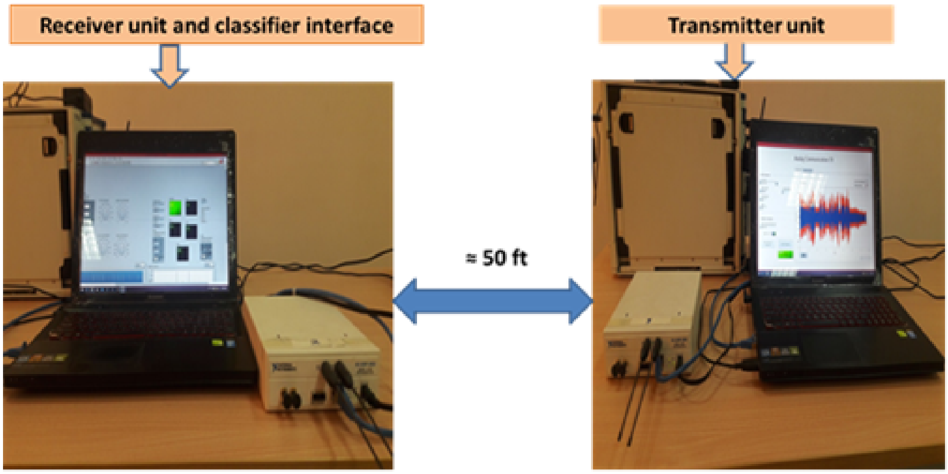


FIGURE 11. Experimental setup for testing and analysis the proposed RMR model

TABLE 2. Confusion matrix for AMRA (based on 1000 realization at SNR = 5 dB,10 dB, and 30 dB

O/P		I/P	AM	DSB	FM/PM	USB	LSB	VSB	Total%
AM	SNR (dB)	5	87	3	1	0	0	9	100
		10	95	2	0	0	0	3	100
		30	100	0	0	0	0	0	100
DSB	SNR (dB)	5	3	90	1	0	0	6	100
		10	1	97	0	0	0	2	100
		30	0	100	0	0	0	0	100
FM/PM	SNR (dB)	5	2	1	90	1	1	5	100
		10	0	1	98	0	0	1	100
		30	0	0	100	0	0	0	100
USB	SNR (dB)	5	0	0	0	89	4	7	100
		10	0	0	0	95	1	4	100
		30	0	0	0	100	0	0	100
LSB	SNR (dB)	5	0	0	0	5	88	7	100
		10	0	0	0	1	95	4	100
		30	0	0	0	0	100	0	100
VSB	SNR (dB)	5	0	0	0	5	6	89	100
		10	0	0	0	2	2	96	100
		30	0	0	0	0	0	100	100

7. **Conclusion.** In this paper, a proposed RMR model had been designed using LABVIEW graphical programming language and implemented throgh deploying it on SDR platform, NI-USRP 2920 device. The emulated RMR model used a reference guide feature based modulation recognition algorithm, Nandi and Azzouz algorithm, which depends on extracting four key spectral features of the common analog modulated signal

Table 3. Comparison of the implemented RMR results with its simulated based results

	Nandi and Azouz algorithms [12]	Our work
SNR	10 dB	10 dB
Overall recognition	99.2%	96%
Number of features	4	4
AM	100%	95%
DSB	100%	97%
FM/PM	100%	98%
USB	97%	95%
LSB	99%	95%
VSB	98%	96%

Table 4. The performance of the implemented RMR system

Modulated signals	**Recognition rate at SNR (dB)**		
SNR	5	10	30
AM	87%	95%	100%
DSB	90%	97%	100%
FM/PM	90%	98%	100%
USB	89%	95%	100%
LSB	88%	95%	100%
VSB	89%	96%	100%
Overall recognition	88.3%	96%	100%

types (AM, AM-DSB, FM/PM, USB, LSB, VSB). The experimental Labview based results achieved overall success rate 88.3 % when SNR=5dB, 96 % at SNR=10dB, and 100 % at SNR=30dB. The obtained results affected by hardware and over the air channel interference signal sources, which in turn had been taken as a reason to interpret the decreasing difference in overall success rate w.r.t. the Matlab simulation based results by approximately 3dB.
Nowadays, most signals in communication and radar systems have digital modulation types. So our trend in research will be directed to design digital modulation recognizers in RMR systems based on SDR technology.

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