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Performance Analysis of Automatic Modulation Classification using Time Frequency Transforms under Non-Ideal Channel Conditions

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Abstract*: Classification of different analog and digital modulation classes using Time-Frequency Transforms (TFTs) through MST and MFSWT under ideal channel conditions is presented in this paper. It also deals with performance analysis of proposed Modified S- Transform (MST) and Modified Frequency Slice Wavelet Transform (MFSWT) based Automatic Modulation Classification (AMC) methods under different channel conditions such as Gaussian and fading channels. The performance of the proposed TFT based AMC methods under AWGN (with SNR values varied from -10 dB to 20 dB) and fading channels is examined through simulation. Moreover, the performance of the proposed TFT based AMC is compared with that of the existing techniques in terms of performance metric namely classification accuracy which is also discussed in this paper.

Keywords: S-Transform, Fading Channels, AWGN, FSWT, Cognitive Radio, SDR

I. INTRODUCTION

Recently attention of researchers towards AMC is tremendously increased than ever because of its applications in military security applications, civilian applications, CR, SDR and future wireless networks [1]. Initially, most of the researches in respect of AMC are confined to the military applications to provide security. Further, the attention is also motivated towards commercial applications with the usage of SDR and CR in advanced 4G and 5G data networks. In the past two decades, researchers have developed several multidisciplinary approaches for AMC to improve the classification accuracy under different channel conditions. Early researches in respect of AMC are concentrated only on analog modulations. There after the attention is changed to digital modulations with the evolution of recent communication networks and systems.

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TFTs are used to map time domain signal into time-frequency domain, where the instantaneous amplitude and frequencies are plotted with respect to time. These time-frequency plots are suitable for modulation classification. The combination of Time–Frequency domain investigations has been effectively used for classification and analysis of non-stationary signals such as power quality signals, underwater acoustic[2], biomedical signals [3]-[4], machine condition monitoring [5], speech signals [6], damping vibration signals [7] and seismic signals [8] etc. Ahmad Zuri bin S et. al. [9], have designed a system to analyze ASK and FSK signals. Initially for analysis, TFA based spectrogram is used and thereafter a rules based method is used as a recognizer. Instantaneous frequency is estimated from the TFA and then it recognizes the modulation class and its parameters. These parameters are further applied to rules based classifier for proper classification. The performance analysis is done under AWGN channel with different SNRs. The simulation results show that the system has provided reliable classification accuracy in non-ideal environment. However, analysis is carried out with only BFSK, 4FSK and BASK signals and decisions are made with graphical assumptions.

Next, Tan Jo Lynn et. al. [10], have presented a comparative study of spectrogram and a modified Multi-Window (MW) spectrogram for AMC by considering ASK, M-ary FSK and PSK signals. In place of all the sequences in spectrogram, combination of Slepian sequences is used in MW spectrogram. For the performance comparison, signal features such as peak to side-lobe ratio, main-lobe widths, instantaneous frequency are derived from TFA. However, the analysis is carried out with limited modulation techniques and decision has been taken with graphical assumptions. Then J. L. Tan et. al. [11], have proposed an adaptive smooth-windowed Wigner Ville Bispectrum (SWWVB) for AMC of ASK, FSK and M-ary FSK under fading conditions. However, the accuracy of the proposed accuracy is insufficient for practical applications at lower SNR cases. Followed by them Yun Lin et. al. [12], have developed a new TFA method using S-transform for AMC of LFM, BFSK and BPSK signals. From the S-transform time-frequency distributions of each modulated signal, instantaneous amplitudes and frequencies are extracted. Further, these can be used to distinguish the different modulated signals.

The simulation experiment results show that the S-Transform is capable of recognizing the type of modulation format even with lower SNR. However, the method is not suitable to classify phase modulated signal because, it is unable to extract the instantaneous phase of the signal. T. R. Kishore et. al [13], have developed a new method using the Short Time Fourier Transform (STFT) and Hough Transform (HT) for classification of LFM and nonlinear FM signals.

For classification, time-frequency plot of the each signal is extracted using STFT and applied to HT for further processing. HT finds the number peaks which are existed in the time-frequency plot and takes the further decision about modulation class. The main advantage of the method is that no assumptions have been required about the signal characteristics but it is assumed that the length of the input signal is constant. Compared with traditional methods of TFA such as WVD, this method has provided better performance even at lower SNR. However, the proposed method has not provided any process to classify all signals other than FM. The performance of TFA approaches are significantly affected by length of the window function and selection of window function. TFA is suitable to identify the amplitude and frequency variations effectively. However, the TFTs are unable to track the phase variations accurately. Therefore, TFA is suitable for classification of AM, FM, MASK and MFSK modulated signals but not of MPSK and MQAM signals.

II. SIGNAL MODEL

A. Signal Model in Gaussian Channel

The received signal of CR adaptive modulation system *r(n)* is given by

$$r(n) = m(n) + f(n) \tag{1}$$

where *m(n)* is transmitted signal and *f(n)* is fading and AWGN noise added in the channel. For transmission of binary data, the received signal *r(n)* is given by [14]

$$r(n) = Ae^{i(2\pi nTfo+\theta n)} \sum_{k=-\infty}^{\infty} m(k)h((n - k + \in)T) \tag{2}$$

Here *m(k)* is input binary stream, *h(.)* is channel effects, *A* is the amplitude, *T* is symbol time, θn is phase jitter and $\in$ is time shifts occurred in channel.

B. Signal Model in Multipath Fading Channel

If *s(t)* is the transmitted signal and is given by $Re\{u(t)e^{j2\pi f_c t}\}$ where *u(t)* is the complex low pass signal, then received signal *r(t)* in a multipath channel is given by

$$r(t) = \sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi[(f_c + f_{D,n}(t))\tau_n(t) - f_{D,n}(t)t]} u(t - \tau_n(t)) \tag{3}$$

where f_c is the carrier frequency, N is the total number of received paths and $\alpha_n(t)$ and $\tau_n(t)$ are the amplitude and time delay of n[th] path. Doppler shift introduced in the incident wave is given by

$$f_{D,n}(t) = f_d \cos(\theta_n(t)) \tag{4}$$

where $f_d = v/\lambda_c$ and λ_c is the wavelength of the transmitted signal. $\theta_n(t)$ phase shift of the n[th] wave.

III. PROPOSED TRANSFORMS

To overcome the limitations of STFT and WT, two new TFTs namely MST and FSWT with modified window are developed for AMC of both analog and digital modulation signals. ST and FSWT are used only for classification of different power quality and ECG signals as well as for analysis [15]-[19] not for AMC. In this section, the window functions of ST and FSWT are considered and modified to obtain MST and MFSWT for tracking the variations in modulated signals such as amplitude and frequency to identify the modulation format.

A. Modified S-Transform

Modified S-Transform (MST) is given by [18]

$$S(\tau, f) = \int_{-\infty}^{\infty} R(\alpha + f) e^{(-2\pi^2\alpha^2K^2)/\left(l+m\sqrt{|f|}\right)^2} e^{2i\pi\alpha\tau} d\alpha \tag{5}$$

The discrete MST of a signal is

$$S[k,n] = \sum_{k=0}^{N-1} R(k+n) e^{\left(-2\pi^2k^2K^2/l+m\sqrt{|f|}^2\right)} e^{i\frac{2\pi mk}{N}} \tag{6}$$

The suitable variation of the window width can give superior control on energy concentration for the ST. This can be achieved by incorporating the extra parameters *l*, *m* and *K* in the window function, which changes with instantaneous frequency of the signal and thereby MST acquires good time and frequency resolutions.

B. MFSWT

Modified FSWT for a signal r(t) is given by [19]

$$F_f(t,\omega,\sigma) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R(v) e^{\frac{-2K^2\pi^2(v-\omega)^2}{\sigma^2(l+m\sqrt{|w|})^2}} e^{jvt} dv \tag{7}$$

where *K,l and m* are positive integers, *w* is signal fundamental frequency and *K* is chosen from the condition

The discrete MFSWT for a signal r(n) is given by

$$F_f(a,b,\sigma) = \frac{1}{N} \sum_{k=0}^{N-1} R(k) e^{\frac{-2\pi^2K^2(k-b)^2}{\sigma^2(l+m\sqrt{|w|})^2}} e^{\frac{i2\pi ka}{N}} \tag{8}$$

where, N is the length of the signal spectrum, *R(k)* is DFT of *r(n)*.

In proposed research, the MST and MFSWT are used to for extracting the local spectrum of the analog and digital modulated signals for the purpose of AMC. The proposed MST and MFSWT provide a better time and frequency resolution. Hence, MST and MFSWT are useful for analysis of all non-stationary signals such as power quality, speech, RADAR, seismic, Biomedical, communication signals etc.

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The flow chart for AMC of analog and digital modulated signals is shown in Fig. 1. The classification procedure involves two stages. In first stage, the MST and MFSWT is applied to an unknown received signal for extraction of joint time-frequency contour and magnitude plots. In the next stage, the decision making circuit checks the variations of the signal in terms of amplitude and frequency for proper recognition of modulation format based on the time-frequency contour and magnitude variations.

The main advantage of TFT based AMC approach does not require prior information about the channel characteristics and signal characteristics.

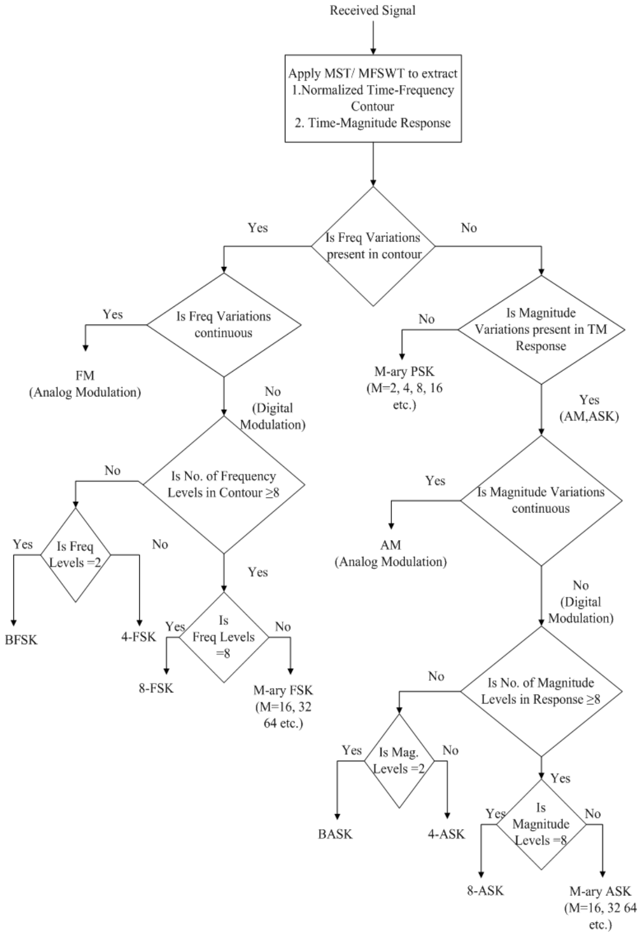

Fig. 1. AMC using proposed MST/ MFSWT

IV. SIMULATION RESULTS AND DISCUSSIONS

The performance analysis of proposed MST and MFSWT for AMC is carried out under different channel conditions such as AWGN and multipath fading. Different types of analog and digital modulated signals such as AM, FM, Binary ASK, FSK, PSK, 4ASK, 4FSK, 8ASK, 8FSK, BPSK and QPSK are considered for the simulation to validate the efficiency of proposed TFT based AMC algorithms. To classify the signals, joint TFC and Magnitude vs Time plots are extracted for every signal and based on the local spectra, the modulation format of the signal is identified. The performance analysis is carried out under SNR from -10dB to 20dB.

A. Performance Analysis under Gaussian Channel

The TFA of continuous wave analog modulation schemes such as AM and FM under AWGN channel condition with different SNR values are shown from Fig. 2 to Fig. 5. Fig. 2 and Fig. 3 illustrate the TFA of AM signal with MST under AWGN channel with SNR of 0dB and -10dB respectively. From Fig. 2 and Fig. 3, it is depicted that no frequency variations are present in the TFCs. In the magnitude response, it is observed that continuous amplitude variations are present in the signals. Therefore the signals which are illustrated in Fig. 2 and 3 are recognized as continuous AM signals.

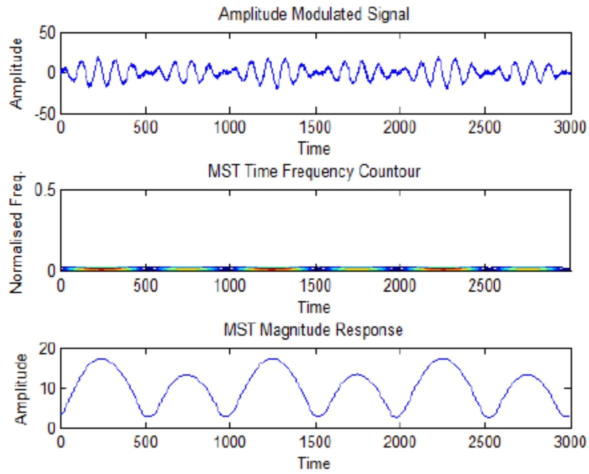

Fig. 2. TFA of AM signal with MST at 0dB SNR

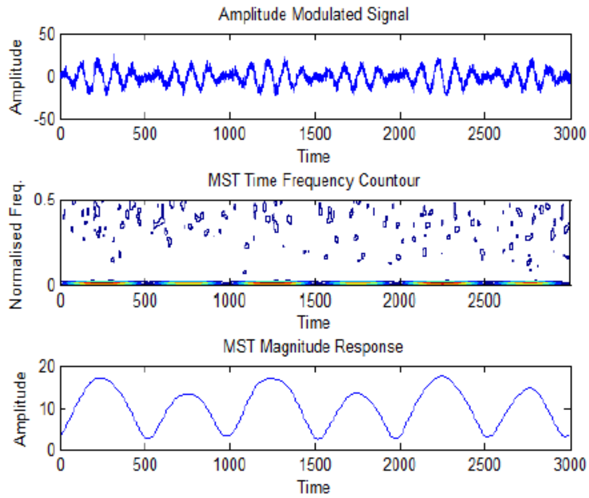

Fig. 3. TFA of AM signal with MST at -10dB SNR

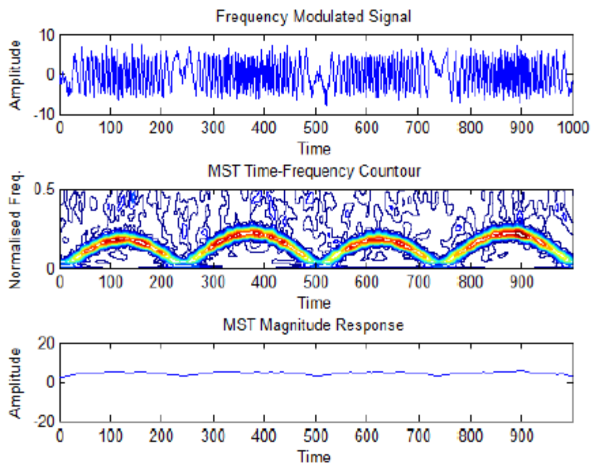

Fig. 4. TFA of FM signal with MST at 0dB SNR

Fig. 4 and Fig. 5 illustrate the TFA of FM signal with MST under AWGN channel with SNR of 0dB and -10dB respectively. From Fig. 4 and Fig. 5, it is depicted that no amplitude variations are present in the magnitude response. But the frequency of the signals is linearly varying with time. Therefore the signals which are shown in Fig. 4 and 5 are recognized as continuous FM signals.

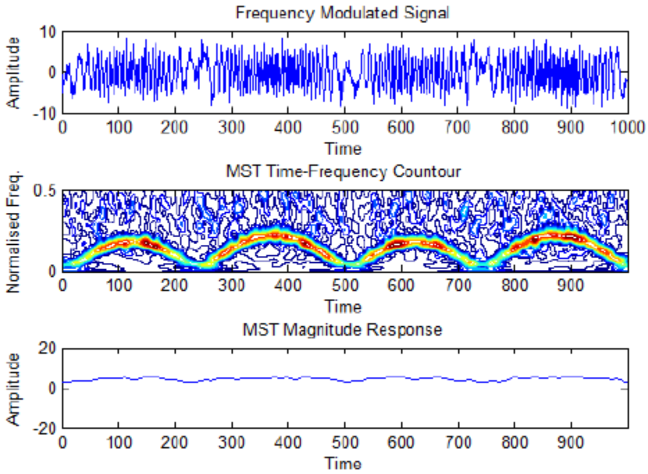

Fig. 5. TFA of FM signal with MST at -10dB SNR

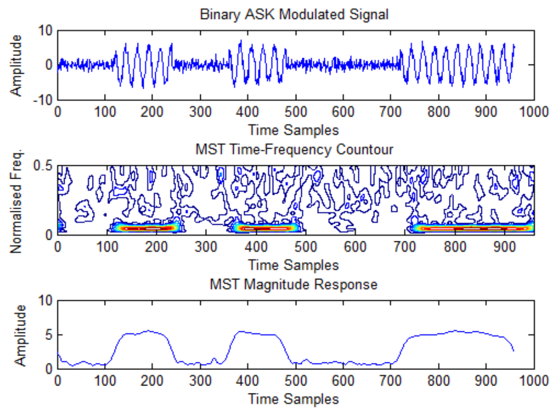

Fig. 6. TFA of BASK signal with MST at 0dB SNR

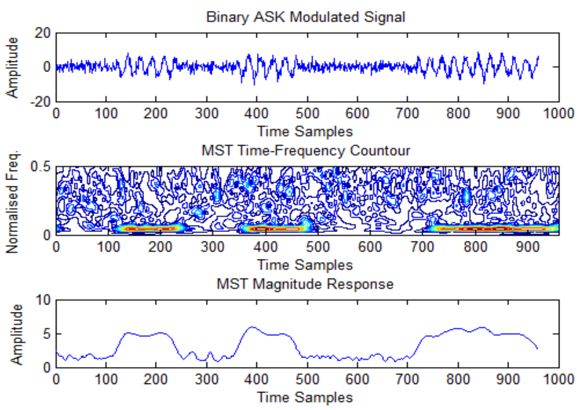

Fig. 7. TFA of BASK signal with MST at -10dB SNR

Fig. 6 and Fig. 7 illustrate the TFA of BASK signal with MST under AWGN channel with SNR of 0dB and -10dB respectively. From the TFC and magnitude plots, it is observed that the signal is present/ ON in some intervals and absent/OFF for another intervals. The variations in amplitude are discrete in nature. Hence, the signal is classified as OOK. Fig. 8 and Fig. 9 illustrate the TFA of BFSK signal with MST under AWGN channel with SNR of 0dB and -10dB respectively. From the TFC and magnitude plots, it is verified that the signal has two discrete frequencies. Hence the signal is classified as BFSK.

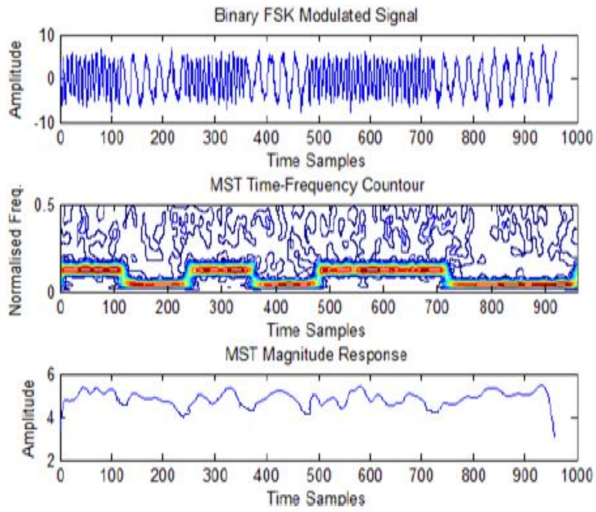

Fig. 8. TFA of BFSK signal with MST at 0dB SNR

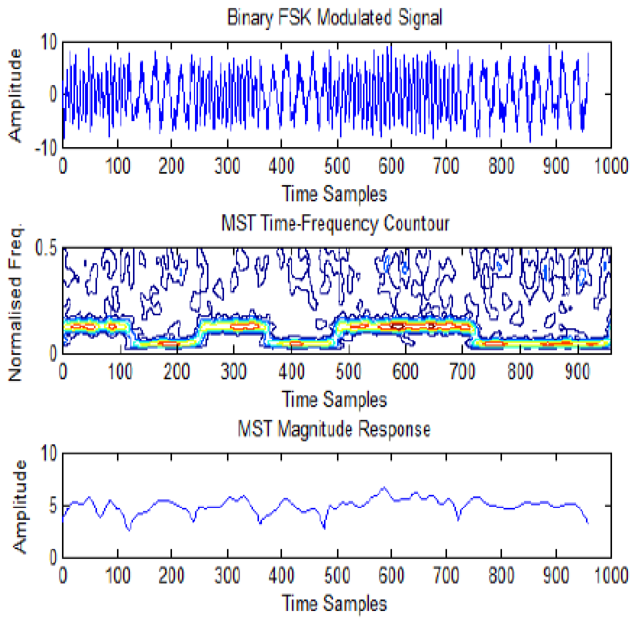

Fig. 9. TFA of BFSK signal with MST at -10dB SNR

Fig. 10 and Fig. 11 illustrate the TFA of 4FSK signal with MST under AWGN channel with SNR of 0dB and -10dB respectively. From the TFC and magnitude plots, it is portrayed that the signal has four discrete frequencies. Hence the signal is classified as 4FSK.

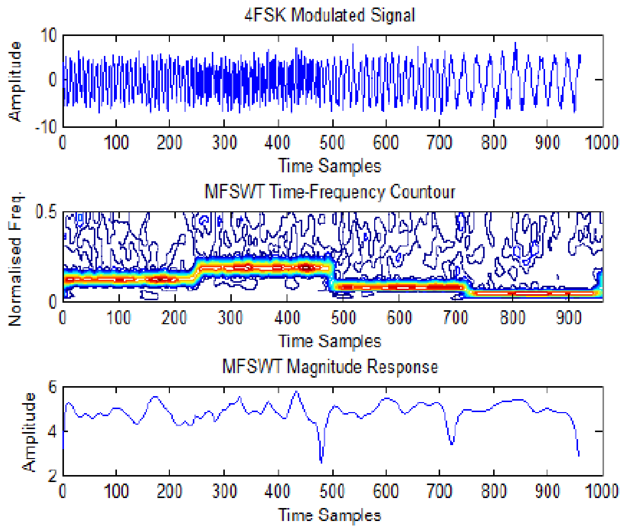

Fig. 10. TFA of 4FSK signal with MST at 0dB SNR

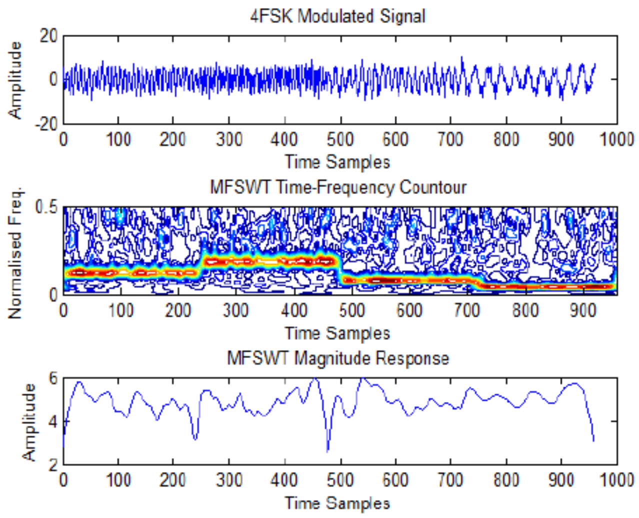

Fig. 11. TFA of 4FSK signal with MST at -10dB SNR

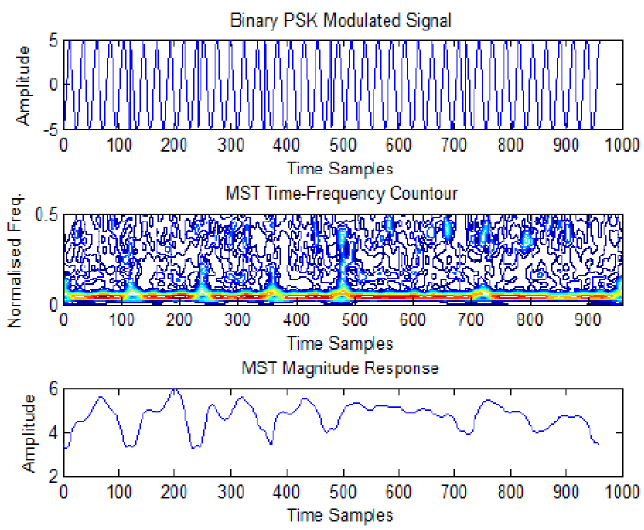

Fig. 12 TFA of BPSK signal with MST of 0dB SNR

Fig. 12 illustrates the TFA of BPSK signal with MST under AWGN channel with SNR of 0dB. From the TFC and magnitude plots, it is not possible to classify the signal based on frequency and magnitude. Hence, it is proved that TFA is not suitable for classification of MPSK and MQAM signals.

Table I: Classification Accuracy of Proposed TFT based AMC under AWGN channel

SNR dB	AM	FM	BASK	4ASK	8ASK	2FSK	4FSK	8FSK
20	100	100	100	100	100	100	100	100
15	100	100	100	100	100	100	100	100
10	100	100	100	100	100	100	100	100
5	100	100	100	100	100	100	100	100
0	100	100	100	100	100	100	100	100
-5	100	100	100	99	97	100	98	96
-10	100	100	97	95	91	100	94	89

Table I depicts the classification accuracy of proposed TFT based AMC approaches using MST and MFSWT. Both these TFTs are accurate than the Spectrogram [9], WVD [11], and STFT [13] based approaches. The performance is measured by extracting the instantaneous amplitude and frequency of the signal from the TFCs of MST and MFSWT and further the decision is taken based on the algorithm represented in Fig. 1. From all the simulation results it is proved that AWGN conditions don't affect the performance of AMC with TFTs. From this, it is depicted that TFA based AMC is immune to noisy conditions present in the channel.

B. Performance Analysis under Multipath Fading

The AMC with proposed MFSWT under multipath fading channel along with additive noise are illustrated from Fig. 13 to Fig. 17. Fig. 13 depicts the AMC using proposed MFSWT approach of BFSK under fading channel along with -10dB SNR. For simulation, four paths are chosen with random path gains and doppler shifts. From the simulation result, it is observed that fading doesn't affect the modulation classification accuracy.

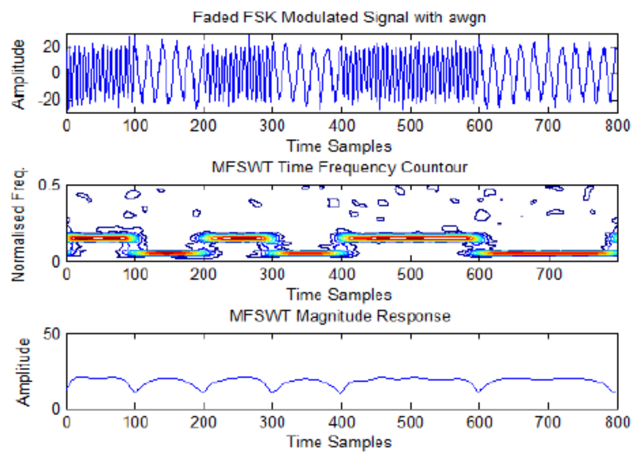

Fig. 13. TFA of BFSK signal with MFSWT under fading conditions

Fig. 14 illustrates the AMC of BASK under fading channel with -10dB of SNR using proposed MFSWT approach. From the simulation result, it is observed that even with more number of paths and AWGN with lower SNR, proposed approach is able to detect the correct modulation class.

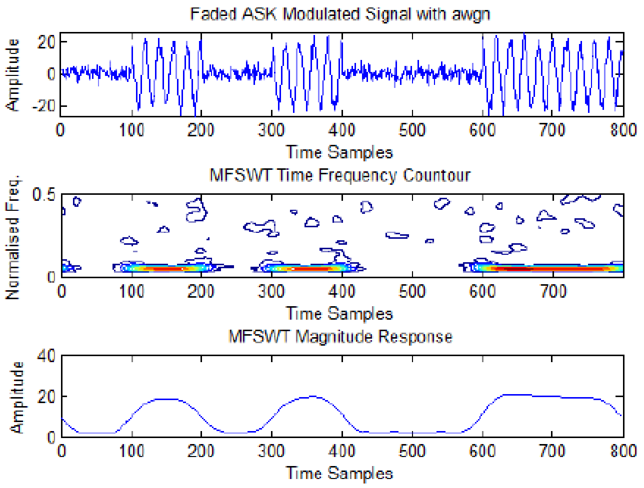

Fig. 14. TFA of BASK signal with MFSWT under fading

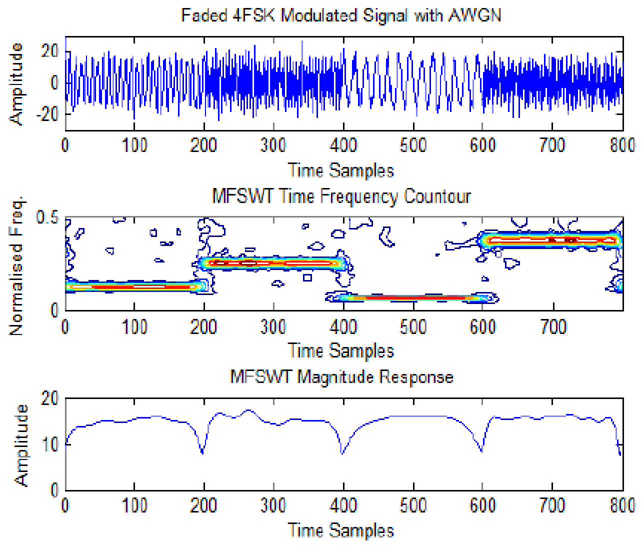

Fig. 15. TFA of 4FSK signal with MFSWT under fading

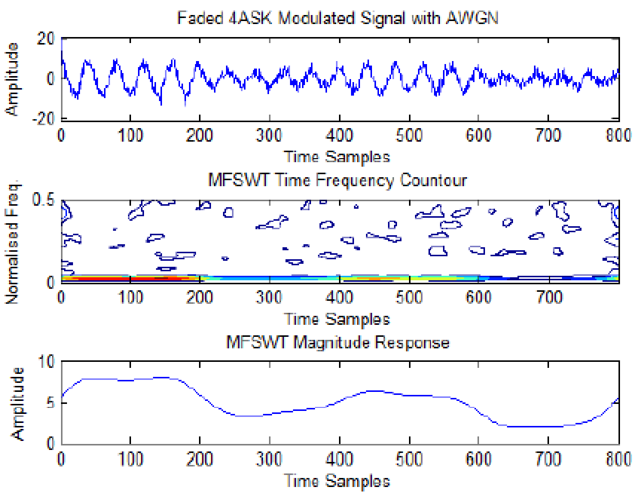

Fig. 16. TFA of 4ASK signal with MFSWT under fading

Fig. 15 and Fig. 16 illustrate the AMC of 4FSK and 4ASK signals under fading channel conditions along with -10dB SNR using proposed MFSWT approach. From the simulation result it is observed that even with more number of paths and AWGN with lower SNR proposed approach is able to detect the correct modulation class.

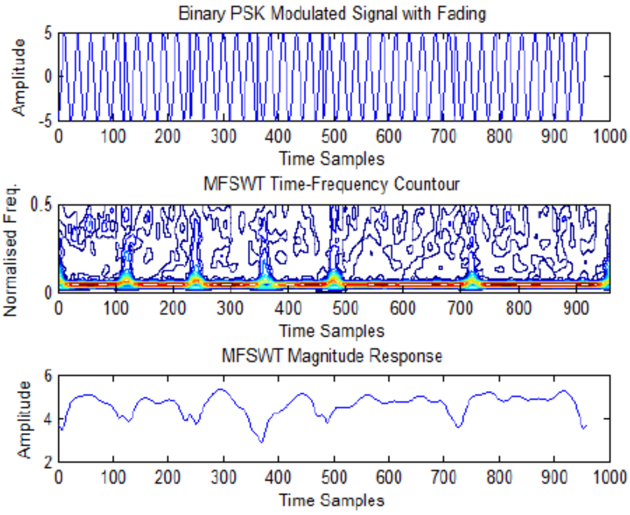

Fig. 17. TFA of BPSK signal with MFSWT under fading

Fig. 17 illustrates the AMC of BPSK under fading channel with 0dB of SNR using proposed MFSWT approach. From the TFC and magnitude plots, it is not possible to classify the signal based on frequency and magnitude. Hence, it is proved that TFA is not suitable for classification of MPSK and MQAM signals.

From all the simulation results it is proved that multipath fading along with AWGN doesn't affect the performance of AMC using proposed TFTs except MPSK. From the simulations it is depicted that proposed TFT based AMC is immune to noisy conditions present in the channel.

V. CONCLUSION

In this paper, the performance analysis of the proposed TFTs such as MST and FSWT are verified through simulation for AMC under non-ideal conditions. The performance analysis is carried out in two cases. In the first case, the channel is assumed as AWGN, and the investigations are carried out by varying the SNR value from -10 dB to 20 dB. In the second case, channel is assumed as multipath fading channel, and the analysis is carried out by varying number paths, path gains, frequency offsets and phase shifts. To understand the effectiveness of the proposed TFT algorithms for AMC, the performance analysis in terms of detection accuracy is carried out for different classes of analog and digital modulated signals such as AM, FM, M-ary ASK, M-ary FSK signals (with M=2, 4 and 8) and BPSK. It is depicted through the simulation that the proposed TFTs provides better classification accuracy than the existing approaches even under multipath fading conditions. Even though the performance of proposed TFTs is good for MASK and MFSK modulation classes, but it is poor for MPSK modulation classes.

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