A FAST AUTOMATIC MODULATION RECOGNITION ALGORITHM AND ITS IMPLEMENTATION IN A SPECTRUM MONITORING APPLICATION

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ABSTRACT

An algorithm based on an efficient decision-tree approach for performing real-time automatic modulation recognition is presented. The algorithm is computationally efficient and can discriminate between various digital and analog signal modulations, delivering reliable decisions using very short observation times. Communications formats, such as AMPS, GSM and US Digital Cellular, can also be recognized. The implementation of this algorithm in a practical spectrum monitoring system is discussed. Measurements using off-the-air signals, and computer simulations, indicate that the system performs well in different surveillance scenarios.

INTRODUCTION

The problem of quickly and precisely characterizing the radio frequency spectrum is of great practical interest. Important aspects to be determined by the spectrum monitoring process are the occupancy of channels and spectral bands, and the characterization and geo-localization of signals and their sources. For the effective surveillance of communications signals, the information must be extracted and displayed in real-time, and stored efficiently. This goal can be achieved with state-of-the-art software and hardware technology, by using a software radio approach.

This paper presents such an approach, with emphasis on the problem of modulation recognition. Following a brief description of the modulation recognition technique, the hardware and software framework in which the algorithm operates is discussed. Finally, results are presented for the performance of the modulation recognition algorithm with off-the-air signal data.

MODULATION RECOGNITION ALGORITHM [1]

The flowchart of the decision tree proposed in this paper is shown in Figure 1. Its structure is an evolution of the decision tree classifier described in [1], and allows reliable decisions using very short signal segments (less than 30 msec duration for most of the commercial frequency division multiplexed signals). This algorithm is also computationally very efficient, and allows real-time modulation identification for a large variety of signal formats. The operation of this algorithm is briefly described as follows.

The input is first pre-processed in order to determine signal presence, to correct for large carrier frequency offsets and to filter out-of-band noise. This process is performed with the aid of an external noise power estimation module[1] that establishes a power threshold, against which the power spectral density of the observed signal is compared. The noise power module is also used to set another threshold, which is used for computing the centroid frequency of the signal power spectum, and for estimating the signal bandwidth. The carrier frequency error is then mostly corrected, by translating the carrier frequency by an amount equal to the frequency of the spectrum centroid. The out-of-band noise power is removed from the frequency-translated signal, by using a filter corresponding to the estimated signal bandwidth.

The process of detecting and classifying the modulation format embedded in the signal starts by testing for a constant envelope. The feature used to identify the envelope variations is the maximum of the squared Fourier transform of the normalized signal amplitudes [1,2]. This test is insensitive to carrier frequency errors. If it is determined that the signal has a constant envelope, the residual carrier frequency error is estimated and corrected. The frequency error estimation algorithm is based on non-linear processing and uses the knowledge that the input signal has a constant envelope [1]. Then a test to detect significant phase variations is applied to determine if the signal is CW or frequency

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modulated. In the latter case, a series of tests is used for determining specific frequency or spectral characteristics to discriminate between FM and FSK formats. To perform this task, the frequency-uncorrected, constant-envelope signal is used. The instantaneous frequency is obtained by computing the phase derivative of the constant envelope signal in the phase processing stage. This estimated value is required to detect the possible presence of low-modulated commercial FM or AMPS FM signals, which contain a single discrete tone in the modulating signal. It is also required in the computation of the kurtosis coefficient μ^f_{42}, defined in [1]. If this kurtosis coefficient is below 2.5 , a decision is made in favor of FSK. Otherwise, an initial decision is made in favor of FM. A further classification test is required at this point because FSK signals with highly filtered data (such as GMSK signals) may also have a high kurtosis coefficient. The discrimination process is refined by using the FFT of the squared constant envelope signal. If two or more discrete frequency lines are detected, the signal is classified as FSK and an estimate of the number of symbols, *M*, is obtained by counting the number of spectral peaks.

When it is determined that the measured signal has a non-constant envelope, the residual carrier frequency error is estimated, by using non-linear processing specific to the kind of signal expected in the left-hand branch of the decision tree. The signal is frequency corrected, and the result is further examined to determine if it is one-dimensional or two-dimensional. This discrimination is done by determining if any modulation information is carried in the phase of the signal. The feature used to that effect is the absolute phase defined in [1]. If no phase information is present, the signal modulation is one-dimensional, such as AM (transmitted carrier), DSB-SC, or BPSK. A low variance of the unwrapped phase (direct phase) is then used as an indication of an AM signal. If the phase variance is high, the variance of the envelope is used to discriminate between a DSB-SC signal from a BPSK signal.

If the test on the absolute phase determines that the signal is two-dimensional, the following decision steps are used to separate PSK signals from QAM and other unidentified modulation types. To perform the classification between QPSK, $\pi/4$-QPSK, *M*PSK and OTHER types of two-dimensional formats, the frequency-uncorrected, constant envelope signal is used. To initiate this classification, a simple test on the variance of the signal amplitude is performed. If the variance of the amplitude is below a given threshold, the signal is assumed to be a PSK signal. Otherwise, it is classified as OTHER. If the test determines that the signal is PSK, the signal is further examined to determine if its embedded modulation is QPSK, $\pi/4$-QPSK or *M*PSK. This test is performed by examining the FFT of the signal after it is raised to the fourth power. QPSK signals produce a single peak in the power spectral density of the resulting signal, while $\pi/4$-QPSK signals produce two peaks separated in frequency by twice the baud rate. Therefore, if this last test results in one peak, the signal is classified as QPSK. The combination of two peaks classifies the modulation as $\pi/4$-QPSK, and the absence of any peak classifies the modulation as MPSK.

SPECTRUM MONITORING

The modulation recognition algorithm discussed above is imbedded in a *Communication Signal Analysis* software, which is itself used in the framework of a wideband spectrum monitoring system called the *Spectrum Explorer.* The system hardware is based on commercially available VXI and personal computer technology, and its architecture is shown in Figure 2. The current receiver is tunable from 20 MHz to 3 GHz, and provides a RF conversion to the center of the band of the analog-to-digital (A/D) circuit. The conversion image rejection of this receiver is better than 95 dB. The A/D converter operates at 20 Msamples/s, with a 23-bit amplitude resolution allowing wide dynamic range operation, with a free spurious level better than -110 dB. The instantaneous bandwidth, including the receiver conversion chain, is greater than 5.0 MHz (from 2.5 MHz to 8.0 MHz). The A/D output data is transferred, via a fast serial bus, to a personal computer. The latter performs several functions, serving as a digital signal processing engine, supporting a graphical user interface and providing a capability for storing data summarizing the results of the spectrum monitoring processing and, if desired, raw signal data. Sufficient processing capability for real-time operation is obtained by using dual processors, in a symmetrical multi-processing configuration under the Windows NT operating system.

A FFT or polyphase-FFT based channelizer provides a fast signal detection capability by allowing simultaneous detection of narrowband signals within the system bandwidth. Provisions are made for synchronized operation of two or more sets of tuners and A/Ds, to support direction finding (DF) techniques based on relative phase measurement. Since the phase information needed for direction finding is obtained directly from the channelizer, direction finding is performed for each detected signal. Channel occupancy/DF measurements can be made at a rate exceeding 20,000 channels/s, and the results used to quickly cue a dedicated receiver to perform detailed analysis of the individual occupied channels.

The user interface enables the system to be easily reconfigured to address the specific requirements of the signal environment of interest. The *Spectrum Explorer* measures, in addition to the modulation type of individual channels, technical parameters such as power, carrier frequency, S/N ratio, channel and band noise level, modulation level, baud rate and signal bandwidth. The PC also controls one or more drop-down receivers for narrowband processing such as demodulation of specific formats.

CLASSIFICATION RESULTS

The modulation recognition algorithm of Figure 1 has first been tested by using computer simulated signals, as described in [1]. On a simulated additive white Gaussian noise channel, the results show a classification success rate higher than 90%, for a signal-to-noise (SNR) ratio of 5 dB, and significant carrier frequency and symbol timing errors. The SNR is defined over the analysis bandwidth as

$$\mathrm{SNR} = \frac{S}{N_0 \cdot F_s} \qquad (1)$$

where S is the signal power, N_0 is the white noise power spectral density and F_s is the sampling frequency.

In order to characterize the practical performance of the algorithm, the *Spectrum Explorer* has been used to monitor off-the-air transmissions, and collect signals in different frequency bands. A set of collected signals has been assembled and used to evaluate the modulation recognition algorithm. This set is described in Table 1. The channel bandwidth and the bit rate indicated in Table 1 correspond to either the known system characteristics, or to estimated values. The sampling rate is also indicated (F_s in equation (1)). The observation period corresponds to the length of the signal segments provided to the modulation recognition algorithm. For most cases, it corresponds to a block of 1024 complex samples. Note that the signals were passed directly to the modulation recognition software, without any processing to cancel carrier frequency errors, or, in the cases of digital modulations, to recover the symbol timing.

Simulated white Gaussian noise was then added to the collected signals, and the resulting noisy signals processed by the modulation recognition algorithm, using segments of size equal to the observation period indicated in Table 1. For each of the 14 signals described in Table 1, a minimum of 500 data segments was processed. The classification results are shown in Table 2, for a SNR of 5 dB. The boldface figures indicate where the ideal result (100%) should appear. Except for the case of AM voice, these figures all indicate a success rate higher than 80%, with only three cases under 90%. The AM voice signal is often classified as CW, because of the silence periods typically observed in the modulating signal, which produce a pure carrier at the modulator output. Since the software was operated on a signal segment basis, this case is not considered as an error. The military Jaguar V radio (signal 7) and the burst radio (signal 11) signals present special issues requiring further development of the algorithm. Note that signal 14 is made of four 16-QAM subcarriers, and is therefore classified as OTHER in a majority of cases.

CONCLUSIONS

In this paper, a fast and computationally efficient modulation recognition algorithm has been presented. This algorithm has been implemented in a spectrum monitoring system, which allows real-time modulation recognition and signal analysis at SNRs as low as 5 dB, even in the presence of carrier frequency errors and other impairments. This system can identify, with high confidence, modulation types in the set {CW, AM, DSB-SC, FM, FSK, BPSK, QPSK, $\pi/4$-QPSK, *M*PSK, NOISE}. It can also identify signals associated with commercial system formats, such as AM, FM, AMPS and US digital cellular, with an accuracy as in Table 2. This algorithm is commercially available in the *Spectrum Explorer* suite of software. Future work will extend the classifier to handle additional types of signals.

REFERENCES

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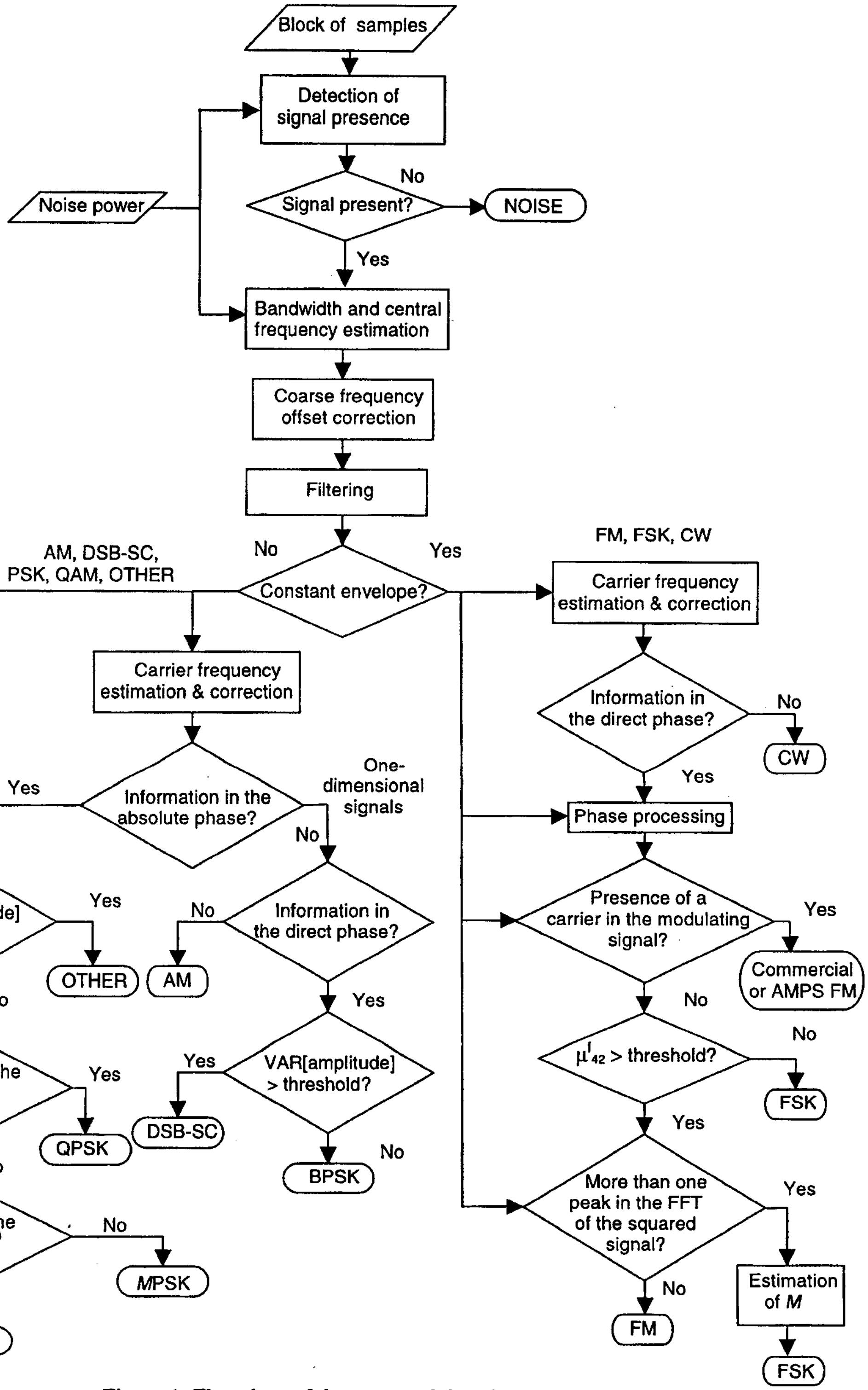

Figure 1: Flowchart of the proposed decision tree.

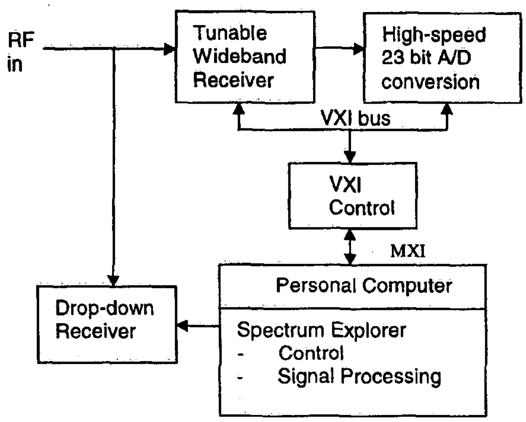

Figure 2: Spectrum Monitoring Hardware architecture.

Signals		Signal Description	Modulation/Bit rate	Channel Bandwidth (kHz)	Sampling rate F_s (ksamples/sec)	Observation period (msec)
1	CW	Continuous wave	--	--	40	25.6
2	AM Music	Commercial AM	AM	10	40	25.6
3	AM Voice	Commercial AM	AM	10	40	25.6
4	Analog AMPS	US Analog Cellular	FM	30	40	25.6
5	FM Music	Commercial FM	FM	200	320	3.2
6	FM Voice	Commercial FM	FM	200	320	3.2
7	FSK Jaguar V	Military hopping radio	binary FSK, 19.2 kbps	25 (single hop)	93.75	2.73
8	FSK Pager	Binary FSK pager	binary FSK, 1.6 kbps	15	50	20.48
9	FSK Trunk	Trunk Radio	binary FSK, 1.9 kbps	5	30	34.1
10	FSK OPP	Police radio	binary FSK, 1.8 kbps	10	50	10.24
11	FSK Traffic	Burst radio	binary FSK, 2.5 kbps	5	30	17.06
12	FSK AMPS	AMPS - Data signaling	binary FSK, 10 kbps	30	80	12.8
13	USDC	US Digital Cellular	$\pi/4$-DQPSK, 48.6 kbps	30	80	12.8
14	DMCA/16-QAM	Clearnet Cellular	4 X 16-QAM, 64 kbps	20	40	25.6

Table 1: Off-the-air collected signals used in the classification

		Classified as (%)									
Signals		CW	AM	DSB-SC	BPSK	QPSK	FM	FSK	$\pi/4$-QPSK	MPSK	OTHER
1	CW	**98.2**	0.2				1.0	0.6			
2	AM Music		**100**								
3	AM Voice	27.3	**71.7**				0.4	0.6			
4	Analog AMPS		0.8				**97.5**	1.0		0.7	
5	FM Music						**97.7**	1.4		0.9	
6	FM Voice						**95.3**	4.5		0.2	
7	FSK Jaguar V						17.0	**83.0**			
8	FSK Pager					0.2	0.4	**99.2**	0.2		
9	FSK Trunk						6.5	**93.1**		0.4	
10	FSK OPP						3.5	**94.9**		1.6	
11	FSK Traffic						13.0	**86.8**		0.2	
12	FSK AMPS						5.7	**93.8**		0.5	
13	USDC					2.9	1.4	5.9	**89.6**		0.2
14	DMCA/16-QAM						0.2	7.6			**92.2**

Table 2: Classification results of off-the-air signals, SNR = 5 dB