Digital Modulation Recognition Based on Feature, Spectrum and Phase Analysis and its Testing with Disturbed Signals

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Abstract: - The paper describes algorithm for the classification of digital modulations and testing of this algorithm with disturbed signals. 2ASK, 2FSK, 4FSK, MSK, BPSK, QPSK, 8PSK and 16QAM were chosen for recognition as the best-known digital modulations used in modern communication technologies. The algorithm is based on the evaluation of spectral power density of the normalized-centered instantaneous amplitude of the signal, and its spectrum and instantaneous phase analysis. We used multipath fading channel to model signal propagation and disturbed the signal by white Gaussian noise for the purpose of testing the algorithm.

Key-Words: - Classification of modulations, recognition of modulations, channel model, digital modulation.

1 Introduction
Recently a number of different wireless communication standards were proposed and employed in cellular technologies, personal communication services and wireless networks. Each of them has its own unique modulation type, access technique, etc. To realize a seamless intercommunication between these different systems, a multi-band, multi-mode smart radio system, such as software radio, is becoming the focus of commercial and research interests. The automatic modulation classification technique, which is important for the automatic choice of the appropriate demodulator, plays a key role in such a multimode communication system [1]. Automatic identification of the type of digital modulation has found application in many areas, including electronic warfare, surveillance, threat analysis, crisis management, and fight against terrorism [2].

In recent years, various methods for modulation classification have been developed. P. Li, F. Wang, and Z. Wang developed a method that is able to recognize 4ASK, 8ASK, 8QAM, BPSK, QPSK, and 8PSK [3]. Their approach combines high-order cumulants with subspace decomposition. All recognized types of modulation have a correct classification probability of more than 90%, when the SNR is 10dB, 15dB and 20dB. However, when SNR is less than 10dB, this method does not provide satisfactory results.

The algorithm by S. Gangcan, A. Jianping, Y. Jie, and Z. Ronghua utilizes the complexity approach, in which a set of values of Lempel-Ziv complexity for identifying different types of modulations is developed [4]. They recognize 2FSK, 4FSK, BPSK and QPSK modulation types. Their results have been presented for SNR of 10 and 20 dB only.

A. K. Nandi, and E. E. Azzouz introduce two algorithms for analog and digital modulation recognition [5]. The first algorithm utilizes a decision-theoretic approach in which a set of decision criteria for identifying different types of modulations is developed. In the second algorithm the artificial neural network is used as a new approach in the modulation recognition process. They recognize the 2ASK, 4ASK, 2FSK, 4FSK, BPSK, and QPSK digital modulations. Sample results have been presented for SNR of 15 and 20 dB only. In the decision-theoretic algorithm it is found that the overall success rate is over 94% for a SNR of 15 dB while the overall success rate in the artificial neural network algorithm is over 96% for a SNR of 15 dB.

A number of other methods have been published, but they usually rely on the knowledge of some parameters of the received signal, are computationally very intensive, fail with a low SNR, or can distinguish only between amplitude,
phase and frequency modulations [6], [7], [8], [9], [10], and [11].

This paper describes a new method of modulation classification, which is based on a decision-theory approach and spectrum analysis. The method designed is tested with signals passed through a multipath fading channel in order to model signal propagation in a real environment. According to our survey of literature, this kind of testing has not been used by any author, although multipath fading occurs in most cases of real signal propagation and can influence the modulation recognition significantly.

Signals with the 2ASK, 2FSK, 4FSK, MSK, BPSK, QPSK, 8PSK and 16QAM modulations were chosen for the analysis because they belong to the most widely used digital modulations. These modulation types are used in modern radio telecommunication systems (GSM, WiFi, WiMAX, etc.).

### 2 Tested Signal Properties

The techniques of recognition that will be proposed in the next chapter will be illustrated on simulated signals with the above mentioned modulations and the following parameters. Carrier frequency $f_c = 10$ MHz, sampling rate $f_s = 100$ MHz, and symbol rate $r_s = 500$ kHz. The number of samples per symbol duration is $N_b = 200$, which can be determined from the symbol rate and sampling rate. The simulation time $T$ was set to 0.2 ms, which corresponds to 100 symbols. All analyzed signals were simulated as band-limited signals, because every communication system has a definite bandwidth.

After generating these signals they were transmitted through a modeled wireless channel. Its parameters are taken from the Stanford University Interim (SUI) models by IEEE 802.16 Broadband Wireless Access Working Group [12]. This document describes a set of channel models suitable for fixed wireless applications. To be specific we have chosen the SUI – 3 channel model with omnidirectional antenna which simulates three signal paths with a specific attenuation and delay. The model parameters are presented in Tab. 1.

<table>
<thead>
<tr>
<th>Tap 1</th>
<th>Tap 2</th>
<th>Tap 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>0 dB</td>
<td>-5 dB</td>
</tr>
<tr>
<td>Delay</td>
<td>0 μs</td>
<td>0.5 μs</td>
</tr>
</tbody>
</table>

The Doppler spread was considered zero. We have also disturbed the signals by the additive white Gaussian noise (AWGN).

### 3 Recognition Method

The received real signal $x(t)$ can be represented as the analytic signal $z(t)$, which can be expressed as

$$z(t) = x(t) + jy(t),$$ (1)

where $y(t)$ is the Hilbert transform of $x(t)$, and $j$ is the imaginary unit. From the analytic signal it is easy to determine the instantaneous amplitude, phase, and frequency of the recognized signal [13]. The instantaneous amplitude $a(t)$ is defined as

$$a(t) = \sqrt{x^2(t) + y^2(t)}.$$ (2)

The instantaneous phase $\phi(t)$ is given by

$$\phi(t) = \arg(z(t)).$$ (3)

Finally, the instantaneous frequency $f(t)$ is given by

$$f(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt}.$$ (4)

The maximum value of the spectral power density of the normalized-centered instantaneous amplitude $\gamma_{max}$ of the received signal is used to discriminate between frequency modulations (2FSK, 4FSK and MSK) on one hand, and amplitude and phase modulations (2ASK, MPSK and 16QAM) on the other hand. [7]

$$\gamma_{max} = \max|\text{DFT}(a_{cn}(i))|^2 / N_s,$$ (5)

where $N_s$ is the number of samples per signal and $a_{cn}(i)$ is the value of the normalized-centered instantaneous amplitude at time instants $t = \frac{i}{f_s}$, ($i = 1, 2, ..., N_s$), and it is defined by

$$a_{cn}(i) = a_n(i) - 1,$$ where $a_n(i) = \frac{a(i)}{m_a},$ (6)

where $m_a$ is the average value of the instantaneous amplitude
Normalizing of the instantaneous amplitude is necessary in order to compensate the channel gain.

The dependence of $\gamma_{\text{max}}$ on SNR for each modulated signals is shown in Fig. 1.

![Graph showing the dependence of $\gamma_{\text{max}}$ on SNR](image)

**Fig. 1.** Dependence of $\gamma_{\text{max}}$ on SNR (a), detailed view (b)

For ideal signals (without interferences and noise), the 2FSK, 4FSK, and MSK modulations have no amplitude changes and their $\gamma_{\text{max}}$ is less than at the band-limited MPSK, 2ASK and 16QAM modulations which have amplitude changes. Thus an appropriately chosen threshold value of $\gamma_{\text{max}}$ can separate between these two modulation groups.

But for signals with multipath propagation and noise (which is also the case in Fig. 1), the amplitude of frequency modulations also changes and their $\gamma_{\text{max}}$ increases. This causes that $\gamma_{\text{max}}$ of frequency modulations has similar value as multi-state phase modulations (QPSK and especially 8PSK), which makes the threshold setting more difficult. Let us set the threshold level $tr(\gamma_{\text{max}})$ = 15. Except $\gamma_{\text{max}}$ of frequency modulations, also $\gamma_{\text{max}}$ of 8PSK falls below this value (see Fig. 1).

The spectrum analysis was then used to discriminate between modulations with $\gamma_{\text{max}}$ lower than 15. The power spectrum of MSK, 8PSK (and possibly other phase modulated signals with $\gamma_{\text{max}}$ below threshold) have only one carrier frequency, the spectrum of 2FSK signal has two maxima, which correspond to two carrier frequencies, and the spectrum of 4FSK signal has four maxima which correspond to four carrier frequencies.

To distinguish between MSK and phase modulations whose $\gamma_{\text{max}}$ falls below the threshold $tr(\gamma_{\text{max}})$, another feature is introduced. It is the average value of the normalized absolute centered instantaneous phase deviation $m_{pd}$.

$$m_{pd} = \frac{1}{N_s} \frac{1}{\max_{l} |\phi_{nl}(l) - \phi_{nl}(l-1)|} \sum_{l=1}^{N_s} |\phi_{nl}(l) - \phi_{nl}(l-1)|$$

where $\phi_{nl}$ is the centered non-linear component of the instantaneous phase

$$\phi_{nl}(l) = \phi_{uw}(l) - \frac{2\pi f_{l}}{f_{s}}$$

where $\phi_{uw}(l)$ is the unwrapped phase sequence $\phi(l)$, and $2\pi f_{l}/f_{s}$ is the linear component of the instantaneous phase.

Analyses showed that the suitable threshold $tr(m_{pd})$ is 0.05. The values of $m_{pd}$ for frequency modulations are higher than this threshold and for phase modulations are lower.

The analysis of centered non-linear component of the instantaneous phase ($\phi_{nl}$) was used to discriminate between the 2ASK, BPSK, QPSK, 8PSK and 16QAM modulations. The BPSK signal has two phase values, QPSK has four phase values, 8PSK has eight phase values, and 16QAM has twelve phase values. The 2ASK signal has only one phase value. For the analysis of instantaneous phases, their histograms were calculated. One, two, four, eight and twelve maxima occur in phase histograms, which correspond to the number of phase values in the signals.

The block-diagram of the recognition algorithm is shown in Fig. 2.
4 Testing Results

The results of the method testing in Matlab environment are presented in Tabs. 2 and 3 at SNR of 5 and 0 dB respectively. We have used 200 signal realizations. It is apparent that even at SNR = 0 dB the algorithm recognizes 2FSK, MSK, 2ASK, BPSK, 8PSK and 16QAM modulations with probability at least 95%. 4FSK is recognized with a slightly lower reliability (87.5%). The worst results at SNR = 0 dB are obtained for QPSK signals, but the algorithm still recognizes them correctly in most cases.

![Block-diagram of recognition algorithm](image)

Table 2. Confusion matrix at SNR = 5 dB

<table>
<thead>
<tr>
<th>Generated</th>
<th>Recognized</th>
<th>FSK</th>
<th>FSK4</th>
<th>MSK</th>
<th>2ASK</th>
<th>BPSK</th>
<th>QPSK</th>
<th>PSK8</th>
<th>16QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSK</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSK4</td>
<td>0.5%</td>
<td>95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSK</td>
<td>0.5%</td>
<td>99%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>2ASK</td>
<td>100%</td>
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<td>BPSK</td>
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<td>100%</td>
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<tr>
<td>QPSK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96%</td>
</tr>
<tr>
<td>PSK8</td>
<td>3%</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>2%</td>
<td>95%</td>
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<tr>
<td>16QAM</td>
<td></td>
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<td></td>
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<td></td>
<td>100%</td>
</tr>
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Table 3. Confusion matrix at SNR = 0 dB

<table>
<thead>
<tr>
<th>Generated ↓</th>
<th>Recognized →</th>
<th>FSK</th>
<th>FSK4</th>
<th>MSK</th>
<th>2ASK</th>
<th>BPSK</th>
<th>QPSK</th>
<th>PSK8</th>
<th>16QAM</th>
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<tbody>
<tr>
<td>FSK</td>
<td></td>
<td>97.5%</td>
<td>0.5%</td>
<td>87.5%</td>
<td>0.5%</td>
<td>2%</td>
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<tr>
<td>FSK4</td>
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<td>0.5%</td>
<td>87.5%</td>
<td>12%</td>
<td>9%</td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSK</td>
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<td>96%</td>
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</tr>
<tr>
<td>2ASK</td>
<td></td>
<td>99%</td>
<td>1%</td>
<td>2.5%</td>
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<tr>
<td>BPSK</td>
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<td>97.5%</td>
<td>62.5%</td>
<td>30%</td>
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<tr>
<td>QPSK</td>
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<td>7.5%</td>
<td>3.5%</td>
<td>95%</td>
<td>0.5%</td>
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<td></td>
</tr>
<tr>
<td>PSK8</td>
<td></td>
<td>1%</td>
<td>1%</td>
<td>99%</td>
<td></td>
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<tr>
<td>16QAM</td>
<td></td>
<td>1%</td>
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5 Conclusion
We presented in this paper a new method for noise robust classification of digital modulation types. Our approach utilizes the analysis of the spectral power density of the normalized-centered instantaneous amplitude of the signal, and its spectrum and instantaneous phase. We tested the algorithm with signals transmitted through a multipath fading channel and disturbed by white Gaussian noise to simulate a realistic scenario. The results show that even for very low values of SNR around 0 dB the method recognizes the selected modulations successfully.

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