Recognition of OFDM Modulation Method

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Abstract. *This contribution deals with asynchronous noncoherent recognition of modulation types. The main aim is to recognize OFDM modulation method from some other single-carrier analog and digital modulation types in the presence of AWGN noise. The described solution of recognizer uses key features of the received signal. The signal amplitude is observed at the output of the quadrature intermediate-frequency stage. The properties of the recognizer are verified by simulations using Matlab.*

Keywords

Noncoherent asynchronous recognition, OFDM modulation method, AWGN noise, quadrature intermediate-frequency signal, signal key feature, correct recognition, false alarm, simulation.

1. Introduction

Automatic Modulation type Recognition (AMR) could be used as examples for automatic demodulation selection in the software defined radios or in applications of spectra monitoring [1]. It could also improve hybrid receivers dedicated to both digital and analog systems. For example, analog and digital audio broadcasting coexist in the same frequency bands below 30 MHz (amplitude modulation vs. OFDM), analog and digital video broadcasting (special type of amplitude modulation vs. OFDM) and it is supposed that digital audio broadcasting will extend to FM bands, in which analog audio is broadcast (frequency modulation vs. OFDM).

Two main approaches to AMR could be distinguished, firstly maximum likelihood and secondly feature extraction approach [2]. The first one provides optimal solution by minimizing the probability of false classification and the second one is based on the differences of key feature for different modulation types. In this work the latter is used.

OFDM modulation method is based on using a big number of carriers (hundreds, thousands), so it is called Multi-Carrier (MC) modulation method. Each carrier is modulated using quadrature amplitude modulation with randomized modulating data. Applying the central limit theorem, we could claim that OFDM probability law converges to the Gaussian law. The statistical properties of OFDM signal amplitude have to be distinct from the statistical properties of other modulation type signal. The key feature computed on the basis of amplitude signal could be used for OFDM modulation technique recognition. The main goal of this paper is to recognize OFDM from other modulation types; only in addition we deal with the possibility of recognizing each from another (next to OFDM). Many techniques involve recognition of single carrier modulation types, [3]-[5], only a few techniques deal with MC modulation, as example [6]. But techniques involving OFDM and analog and/or digital Single-Carrier (SIC) modulation at the same time are missing.

In this paper the background of a signal processing and key features is described. The study of key feature properties leads to determining of thresholds and these are used for automatic recognition of modulation type. Because we suppose no prior knowledge of signals to be recognized, we call the presented technique as noncoherent and asynchronous. The key feature is computed from samples of the signal at the output of a quadrature mixer for modulation type classification. The influence of the AWGN noise for verification of the properties of recognizer is considered in this work.

2. Background

As an input signal, we consider a number of N_F samples (one frame) of the radio-frequency (RF) signal $s_{rf}[\mathrm{k}]$, which have an expected central frequency fc (we don't know anything about the incoming signal; the exact value is unknown).

Two signals are at the output of quadrature Inter-Mediate (IM) frequency mixer having a useful product in the band around the frequency marked f_{im}

$$r_1'[\mathrm{k}] = \cos(2\pi \frac{f_{osc}}{f_s}\mathrm{k}) \cdot s_{rf}[\mathrm{k}], \tag{1}$$

$$r_2'[\mathrm{k}] = \sin(2\pi \frac{f_{osc}}{f_s}\mathrm{k}) \cdot s_{rf}[\mathrm{k}] \tag{2}$$

where f_{osc} is the frequency of the local oscillator (f_{im}=f_{osc}-f_c) and f_s is the sampling frequency.

Both signals $r_1'[k]$ and $r_2'[k]$ are filtered to suppress useless products of mixing using a FIR (Finite Impulse Response) filter. The frequency amplitude response of the used filter is depicted in Fig. 1. Filtered signals are designated as $r_1[k]$ and $r_2[k]$. It arises from Fig. 1 that system bandwidth is $B_{syst} = 2f_{im}$. Signal $r_1[k]$ is an in-phase component signal and $r_2[k]$ a quadrature component signal of the complex intermediate signal.

From component signals $r_1[k]$ and $r_2[k]$ we compute amplitude signal as

$$s_{im\,A}[\mathrm{k}] = \sqrt{(r_1[\mathrm{k}])^2 + (r_2[\mathrm{k}])^2}\,. \tag{3}$$

To compensate signal attenuation caused by the mixing and filtering we divide signal $s_{imA}[k]$ by its standard deviation, which leads to normalized signal (index n means that the signal is normalized, so as not to be confused with noise)

$$s_{im\,A\,n}[\mathrm{k}] = \frac{s_{im\,A}[\mathrm{k}]}{\mathrm{std}\{s_{im\,A}[\mathrm{k}]\}} \qquad \mathrm{k} = 0, 1, \ldots, N_F - 1 \tag{4}$$

where std{} denotes standard deviation.

From component signals we compute the spectrum of the signal as (DFT assigns Discrete Fourier Transform)

$$\begin{aligned} \mathrm{S}_{im}[\mathrm{w}] &= \mathrm{DFT}(r_1[\mathrm{k}] + jr_2[\mathrm{k}]) = \\ &= \mathrm{Real}\{\mathrm{S}_{im}[\mathrm{w}]\} + \mathrm{j}\cdot\mathrm{Imag}\{\mathrm{S}_{im}[\mathrm{w}]\} \\ &\qquad \mathrm{w} = 0, 1, \ldots, N_F - 1 \end{aligned} \tag{5}$$

and amplitude of the spectrum as

$$\mathrm{A}_{S\,r}[\mathrm{w}] = \sqrt{(\mathrm{Real}\{\mathrm{S}_{im}[\mathrm{w}]\})^2 + (\mathrm{Imag}\{\mathrm{S}_{im}[\mathrm{w}]\})^2}\,. \qquad \mathrm{w} = 0, 1, \ldots, N_F - 1 \tag{6}$$

We normalize the spectrum amplitude similarly as before

$$X_{im\,A\,n}[\mathrm{w}] = \frac{\mathrm{A}_{S\,r}[\mathrm{w}]}{\sqrt{\mathrm{E}\{(\mathrm{A}_{S\,r}[\mathrm{w}])^2\}}} \qquad \mathrm{w} = 0, 1, \ldots, N_F - 1 \tag{7}$$

One frame (having N_F samples) of the observed signal represents one realization – assigned by index i.

Three key features are chosen for classification of modulation type, first the 4th order moment (for one realization i)

$$M_{4i} = \frac{1}{N_F}\sum_{k=0}^{N_F-1}(s_{im\,A\,n}[\mathrm{k}])^4\,, \tag{8}$$

key feature A_i (for one realization i)

$$A_i = \frac{1}{N_F}\sum_{k=0}^{N_F-1}\left|s_{im\,A\,n}[\mathrm{k}]\right|, \tag{9}$$

and key feature A_{Si} (for one realization i)

$$A_{S\,i} = \frac{1}{N_F}\sum_{w=0}^{N_F-1}\left|X_{im\,A\,n}[\mathrm{w}]\right|. \tag{10}$$

When finding thresholds we need mean values and standard deviations over N_I realizations. We compute them according to

$$\mathrm{E}\{kf_i\} = \frac{1}{N_I}\sum_{i=1}^{N_I=250} kf_i\,, \tag{11}$$

$$std\{kf_i\} = \sqrt{\frac{1}{N_I}\sum_{i=1}^{N_I=250}(kf_i - \mathrm{E}\{kf_i\})^2} \tag{12}$$

where kf_i stands for M_{4i}, A_i and A_{Si} respectively.

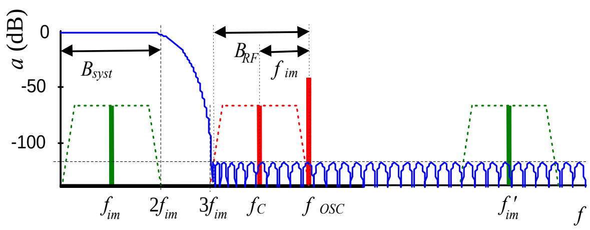

Fig. 1. The frequency amplitude characteristic (marked blue) of the FIR filter to suppress undesirable products of mixing (note: output products of mixing are colored green, input signals are colored red; even if no leakage of the input signal is considered theoretically, the characteristic reflects a real situation with possible leakage of the input signal).

3. Simulation

We use simulation to verify capabilities of the above mentioned key features to recognize (mainly) the OFDM modulation technique.

Nine types of modulation are chosen:

- AM-SC (Amplitude Modulation-Suppressed Carrier)
- AM (Amplitude Modulation)
- FM-NB (Frequency Modulation-Narrow Band)
- FM-WB (Frequency Modulation-Wide Band)
- PM (PM, Phase Modulation)
- 4FSK (4-states Frequency Shift Keying)
- 4PSK (4-states Phase Shift Keying)
- 16QAM (16-states Quadrature Amplitude Modulation)
- and as a matter of course OFDM – two cases of OFDM signal are simulated; the first with bandwidth of approx. 9.5 kHz (marked as OFDM n – “narrow”) and the other with bandwidth of approx. 77 kHz (marked as OFDM w – “wide”).

It is worth noting, the OFDM n signal corresponds to the DRM (Digital Radio Mondiale) signal (Mode A) and the bandwidth value for OFDM w is chosen almost between 50 kHz and 100 kHz – these range is expected for an extended system of DRM (DRM+).

Modulating parameters for the OFDM signal are shown in Tab. 1. The modulating signal for other modulation types is generated randomly, the maximal frequency and symbol rate are respectively 15 kHz and 14980 Bd, except of AM and FM-NB, both with maximal frequency of 4.5 kHz.

OFDM	number of carriers	modulation on sub-carriers	OFDM symbol rate (Bd)	signal bandwidth (Hz)
n	229	64-QAM	41,7	9542
w	1853	64-QAM	41,7	77208

Tab. 1. Modulating parameters for OFDM signal.

The carrier frequency f_c has the value of 80 kHz and the sampling frequency f_s is 524288 Hz. Minimally 73000 samples of each modulated signal are generated, corresponding to the time duration of approx. 139 ms (exact values in the case of digital modulation are influenced by the symbol rate). $N_I = 250$ realizations of each signal are generated.

We use a channel with additive Gaussian noise to examine the properties of the key features and later on for the verification of the recognition technique. To compensate unknown signal attenuation caused by a radio channel we use normalization. Samples of the RF signal $s_{rf}[\mathrm{k}]$ could be described as

$$s_{rf}[\mathrm{k}] = \frac{s_{mod}[\mathrm{k}]}{\sqrt{\frac{1}{N_F}\sum_{k=0}^{N_F-1}\left(s_{mod}[\mathrm{k}]\right)^2}} + n[\mathrm{k}] \qquad (13)$$

$$\mathrm{k} = 0, 1, \ldots, N_F - 1$$

where $s_{mod}[\mathrm{k}]$ stands for the modulated signal and, as a result of the channel influence, samples of Gaussian noise $n[\mathrm{k}]$ are added to it.

For Signal-to-Noise Ratio (SNR) we use the definition according to the deviations

$$\mathrm{SNR} = 10 \cdot \log_{10} \frac{\sigma_u^{\ 2}}{\sigma_n^{\ 2}} \qquad (14)$$

where $\sigma_u^{\ 2}$ corresponds to the deviation of the useful signal and $\sigma_n^{\ 2}$ corresponds to the deviation of the noise signal. Because of normalization in (13) we obtain $\sigma_u^{\ 2}$=1. The amount of the noise signal could be determined from

$$\sigma_n^{\ 2} = 10^{-\frac{\mathrm{SNR}}{10}} \qquad (15)$$

It is worth noting that the system bandwidth and the value of sampling frequency are taken into account when SNR is computed and samples of noise are generated by a random generator with Gaussian probability law with zero mean value and the unit deviation (marked as $\mathrm{norm}_{(0;1)}[\mathrm{k}]$)

$$n[\mathrm{k}] = \sqrt{\frac{f_s}{2B_{syst}} \cdot \frac{1}{10^{\frac{SNR}{10}}}} \cdot \mathrm{norm}_{(0;1)}[\mathrm{k}] \qquad (16)$$

$$\mathrm{k} = 0, 1, \ldots, N_F - 1$$

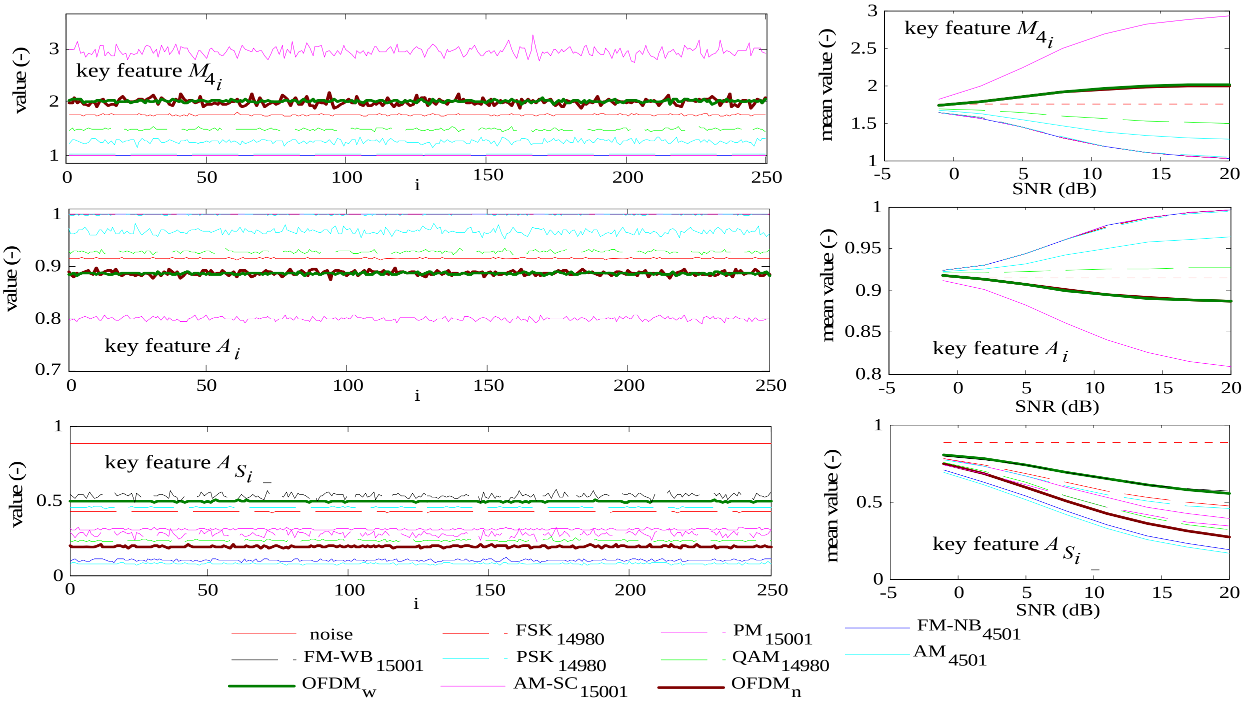

Fig. 2. Values of key features in dependence on realization; Mean value of key features in dependence on SNR.

The frequency of IM signal f_{im} is supposed to be 60000 Hz. To be precise, we decimate sequence of the samples after the intermediate FIR filtering (each second sample is used), so that the new sampling frequency is f_{s2} ($f_{s2} = f_s/2$). The number of samples N_F in one frame is 20000 and 36000.

Dependences of values on realizations and dependences of mean values on SNR are shown in Fig. 2 for all three key features. It is very visual, how values of key feature could be used for the recognition of modulation types. The study of these dependences, and here not presented standard deviations of key features, leads to the determination of thresholds. It's not possible to describe this determination in this paper in detail. We can see the values of threshold in Tabs. 2-4.

			N_F			
			20000		36000	
			from	to	from	to
group	1	AM-SC	2,350	-	2,252	-
	2	OFDM	1,800	2,350	1,788	2,252
	3	noise	1,714	1,800	1,726	1,788
	4	QAM	1,376	1,714	1,388	1,726
	5	AM	1,113	1,376	1,116	1,388
	6	FM-NB, FM-WB, FSK, PM, PSK	-	1,113	-	1,116

Tab. 2. Thresholds of the key feature M_{4i}.

			N_F			
			20000		36000	
			from	to	from	to
group	1	FM-NB, FM-WB, FSK, PM, PSK	0,986	-	0,986	-
	2	AM	0,943	0,986	0,939	0,986
	3	QAM	0,917	0,943	0,916	0,939
	4	noise	0,911	0,917	0,912	0,916
	5	OFDM	0,863	0,911	0,869	0,912
	6	AM-SC	-	0,863	-	0,869

Tab. 3. Thresholds of the key feature A_i.

			N_F			
			20000		36000	
			from	to	from	to
group	1	noise	0,878	-	0,880	-
	2	mod. signal	-	0,878	-	0,880

Tab. 4. Thresholds of the key feature A_{Si}.

It is evident that the so-called angle modulations (for M_{4i} in group 6 and for in A_i group 1) could not be recognized each from other by the proposed technique (as example FM-NB could not be recognized from PSK and so on). Another key feature (derived from a frequency or a phase) must be used for this purpose if we need it. But it has no impact on recognition OFDM from each of these angle modulations and it satisfies to the main aim.

When using key features M_{4i} and A_i (as clear from Tab. 2 and 3) it is possible to recognize 5 groups of modulation types and noise signal. We can recognize only between a noise signal and a modulated signal (2 groups) with the help of key feature A_{Si} (see Tab. 4).

4. Results

As results of simulation, probabilities of the correct recognitions P_r, probabilities of the false alarms P_a and the confusion matrix for some SNR ratio values between -1 dB and 20 dB are presented in Tabs. 5-9 and Figs. 3-6.

Confusion matrixes are tools for the demonstration of the properties of the recognizer. Types of used modulation are aligned in rows, meanwhile recognized groups of modulation types are in columns (usually one group means one type, but not always, see Tabs. 2-4). The probability of the correct recognitions P_r is computed as a number of realizations with correct classifications; it means that the signal is modulated by the same type of modulation as recognized (the best value is 1). The probability of the false alarm P_a is computed as number of realizations with the wrong classifications; it means that a signal is modulated by a different type of modulation than recognized (the best value is 0).

We can start with the key feature M_{4i} (Tab. 5 and 6, Fig. 3 and 4). We found out from the presented results, that the described recognizer has very good results in the OFDM modulation technique recognition. OFDM (group 2) is recognized already for SNR = 5 dB (and higher) and no false alarm is for SNR = 8 dB (and higher). The results are not satisfactory for the modulation in group 5 and 6. But the main aim is discrimination of OFDM modulation technique. The described recognizer is useful for modulation types AM-SC, OFDM, QAM and noise (note that only AWGN noise is tested). For other AM and angle modulation types another known technique must be used for recognition. There is no chance to recognize particular modulation types in group of angle modulation.

The results are almost the same for the $N_F = 20000$ and $N_F = 36000$.

When we compare the results for the key feature A_i and M_{4i} we can say that they are very similar.

The key feature A_S seems to be very good for the classification of a noise signal (but only AWGN is tested). Only good classifications and no false alarm are for all the tested cases. That is the reason why only one confusion matrix for SNR = -1 dB is presented and no other probabilities are computed.

SNR (dB)		recognized group 1	2	3	4	5	6
-1	P_r	0	0	1	1	0	0
	P_a	0	0,0933	0,1848	0,6312	0	0
2	P_r	0	0,098	1	1	0	0
	P_a	0	0,1111	0,1804	0,6	0	0
5	P_r	0,004	0,982	1	1	0	0
	P_a	0	0,1107	0,0036	0,6	0	0
8	P_r	1	1	1	1	0	0
	P_a	0	0	0	0,1	0,5	0
11	P_r	1	1	1	1	0,468	0
	P_a	0	0	0	0,0532	0,5	0
14	P_r	1	1	1	1	0,952	0,9552
	P_a	0	0	0	0,0048	0,0224	0
17	P_r	1	1	1	1	0,996	1
	P_a	0	0	0	0,0004	0	0
20	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0

Tab. 5. Probabilities of correct detection P_r and probabilities of false alarm P_a vs. SNR using key feature M_{4i} for N_F = 20000.

SNR (dB)		recognized group 1	2	3	4	5	6
-1	P_r	0	0	1	1	0	0
	P_a	0	0,1084	0,1052	0,6972	0	0
2	P_r	0	0,22	1	1	0	0
	P_a	0	0,1111	0,156	0,6	0	0
5	P_r	0,26	0,998	1	1	0	0
	P_a	0	0,0822	0,0004	0,6	0	0
8	P_r	1	1	1	1	0	0
	P_a	0	0	0	0,1	0,5	0
11	P_r	1	1	1	1	0,608	0
	P_a	0	0	0	0,0392	0,5	0
14	P_r	1	1	1	1	0,984	1
	P_a	0	0	0	0,0016	0	0
17	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0
20	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0

Tab. 6. Probabilities of correct detection P_r and probabilities of false alarm P_a vs. SNR using key feature M_{4i} for N_F =36000.

SNR (dB)		recognized group 1	2	3	4	5	6
-1	P_r	0	0	1	1	0	0
	P_a	0	0	0,682	0,1988	0,0213	0
2	P_r	0	0	1	1	0,036	0
	P_a	0	0	0,6	0,1928	0,1111	0
5	P_r	0	0	1	1	0,998	0
	P_a	0	0,4104	0,1896	0,0004	0,1111	0
8	P_r	0	0,296	1	1	1	0,912
	P_a	0	0,5	0,0704	0	0,0098	0
11	P_r	0	0,98	1	1	1	1
	P_a	0	0,5	0,002	0	0	0
14	P_r	0,8176	1	1	1	1	1
	P_a	0	0,0912	0	0	0	0
17	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0
20	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0

Tab. 7. Probabilities of correct detection P_r and probabilities of false alarm P_a vs. SNR using key feature Ai for NF = 20000.

SNR (dB)		recognized group 1	2	3	4	5	6
-1	P_r	0	0	1	1	0	0
	P_a	0	0	0,7924	0,0576	0,0556	0
2	P_r	0	0	1	1	0,074	0
	P_a	0	0	0,6	0,1852	0,1111	0
5	P_r	0	0	1	1	1	0
	P_a	0	0,5	0,1	0	0,1111	0
8	P_r	0	0,8	1	1	1	1
	P_a	0	0,5	0,02	0	0	0
11	P_r	0	1	1	1	1	1
	P_a	0	0,5	0	0	0	0
14	P_r	0,928	1	1	1	1	1
	P_a	0	0,036	0	0	0	0
17	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0
20	P_r	1	1	1	1	1	1
	P_a	0	0	0	0	0	0

Tab. 8. Probabilities of correct detection P_r and probabilities of false alarm P_a vs. SNR using key feature A_i for N_F = 36000.

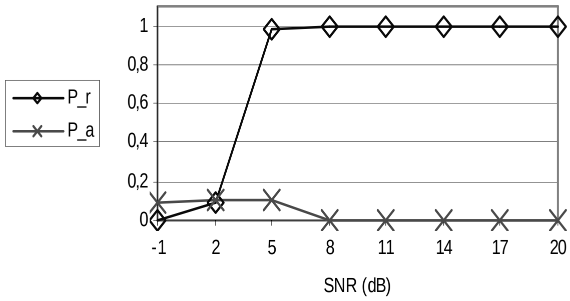

Fig. 3. Probability P_r and probability P_a vs. SNR for OFDM modulation, using M_{4i}, N_F = 20000.

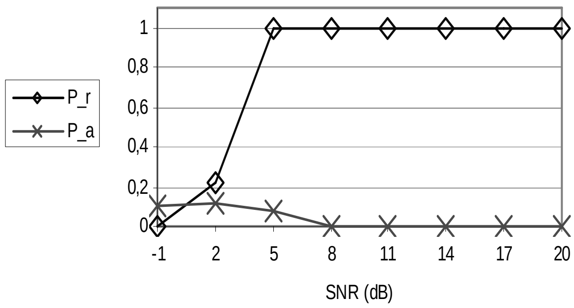

Fig. 4. Probability P_r and probability P_a vs. SNR for OFDM modulation, using M_{4i},, N_F = 36000.

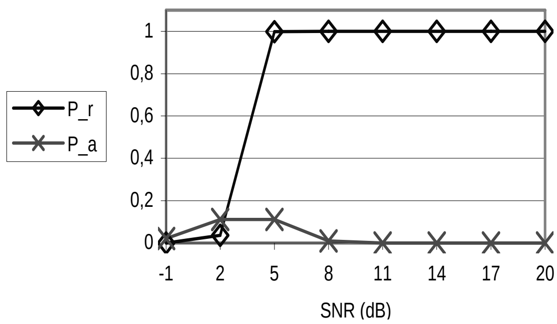

Fig. 5. Probability P_r and probability P_a vs. SNR for OFDM modulation, using A_i, N_F = 20000.

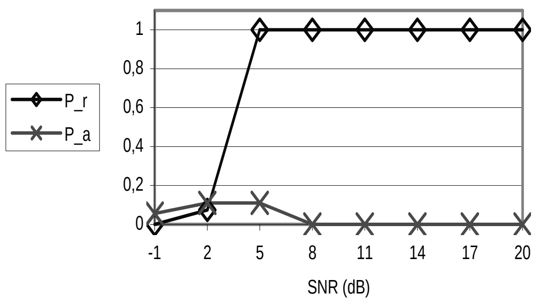

Fig. 6. Probability P_r and probability P_a vs. SNR for OFDM modulation, using A_i, N_F = 36000.

		recognize group	
		1	2
modulated	noise	250	0
	OFDM_3	0	250
	OFDM_9	0	250
	AM-SC	0	250
	QAM	0	250
	AM	0	250
	FM-NB	0	250
	FM-WB	0	250
	FSK	0	250
	PM	0	250
	PSK	0	250
P_r		1	1
P_a		0	0

Tab. 9. Confusion matrix of modulation vs. noise recognition using A_{Si} (the same results for all tested cases).

5. Conclusion

In this paper the noncoherent asynchronous recognition technique for classification of the modulation types involving all analog and digital single-carrier and OFDM is described. The solution uses key features computed on the basis of amplitude signal and its spectrum at the output of quadrature intermediate frequency stage.

The described method seems to be sufficient for the recognition of the multi-carrier modulation technique OFDM in the presence of the Gaussian noise for low value of SNR (8 dB). As the technique is noncoherent and asynchronous, we don’t need to know anything about the receiving signal, which could be interesting for practical applications.

Nowadays some results from this work are verified using software defined radio (SDR) and it seems that the results are applicable as an example for the recognition of analog AM, FM broadcasting and digital audio broadcasting Digital Radio Mondiale. But no extensive tests have been done with the SDR reception yet. It is planned for future work.

Acknowledgements

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