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Classification of Radio Communication Signals using Fuzzy Logic

Zuzana Dideková, Beata Mikovičová

***Abstract*—**Characterization of radio communication signals aims at automatic recognition of different characteristics of radio signals in order to detect their modulation type, the central frequency, and the level. Our purpose is to apply techniques used in image processing in order to extract pertinent characteristics. To the single analysis, we add several rules for checking the consistency of hypotheses using fuzzy logic. This allows taking into account ambiguity and uncertainty that may remain after the extraction of individual characteristics. The aim is to improve the process of radio communications characterization.

***Keywords*—**fuzzy classification, fuzzy inference system, radio communication signals, telecommunications

I. Introduction

NOWADAYS, the frequency band dedicated to radio communications is fully occupied. The spectral occupation is governed by an official regulation. Each access and services provider is allocated a number of frequencies. The authorities have to check that providers follow the rules and only authorized users transmit on the allocated band. There is an important interest also for military applications. To achieve these verifications, different tools are used to analyze the radio communication spectrum. Each detected signal must be characterized, i.e. the central frequency, the bandwidth, the level, modulation type, and other characteristics must be evaluated. The most of algorithms for radio communications characterization are based on a level detection, time and bandwidth classification. These algorithms are based on detection and estimation theory [1], [2]. Our aim is to consider the time-frequency representation of signals, called waterfall, as an image and apply image processing techniques in order to detect and recognize signals. Classical image processing methods [3] are used for extraction of characteristics from the image, some pre-processing to de-noise signals and segmentation techniques including mathematic morphology are applied. Afterwards, clustering and labeling allow the classification of signals, i.e. membership of individual signals to some radio communication. But the classification is not sufficiently robust and could be improved by other methods as fuzzy logics. For classification problems, the fuzzy logic is used with a success. There is no need of detail knowledge of mathematical model for the system description and exact mathematic equations. It is used mainly if the rules of classification, which can be formulated by human language, are known.

Z. Dideková is with the Institute of Control and Industrial Informatics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology (FEI STU) in Bratislava, 812 19 Bratislava, Slovakia (phone: +421-918-024-255; fax: +421-265-429-734; e-mail: zuzana.didekova@stuba.sk).

B. Mikovičováiswith the ISEP, 28, rue Notre-Dame des Champs, 75006 Paris, France (e-mail: beata.mikovicova@isep.fr).

Thus, it imitates proceeding of a human at classification. Linguistic variables such as size, width, highness, distance, age, quality, …, and linguistic values (small, great, moderate tall, very large, low quality, …) are used for object classification (human, animal, face, smile, the highest quality, washing mode 1, …) [4]-[6].

In the article we focus on the fuzzy classification part of the proposed system. The article is organized as follows: In section II the problem is formulated, the proposed system is presented in section III, several case studies and results are given in section IV. Finally, conclusions and possible extension of our work are drawn in the section V.

II. Problem Formulation

The aim was to recognize the membership of a signal of certain frequency to aradio communication using its characteristics (relative amplitude, relative time slot duration, and relative bandwidth). The task was realized in Matlab and for fuzzy operations theMatlab Fuzzy toolbox was used.

Signals were available in the matrix form, where the value of each matrix element denotes presence (1) or absence (0) of signal of certain frequency and in the certain time. An example of such signals is depicted on Fig. 1 (0 – signal is absent, black color; 1 – signal is present, white color). Axis Y represents frequency of signal and X axis represents time.

As it can be seen on the figure, there are lots of solid or dashed vertical lines. Each of these lines denotes signal on the certain frequency and it belongs to the certain radio communication. A radio communication can involve 1 or more signals or groups of signals (signals, which occur alongside themselves).Signals are represented on the figure by vertical lines. However for oneradio communicationthey do not necessarily occur on the neighboring frequencies, but they can be distant for lots of frequencies or there can be between them also other radio communications. Radio communication is described in our study by its relative amplitude, relative time slot duration, and relative bandwidth(for groups of signals). Relative amplitude, relative time slot duration, and relative bandwidth denote amplitude, time slot duration, and bandwidth respectively divided by theirmaximum value. Signals (or rather groups of signals), which belong to the same radio communication, have very similar characteristics (but not identical) and the values of these characteristics for individual radio communicationsare not known in advance. Because of this uncertainty, for classification of signals belonging to the same radio communication the fuzzy logic was used.

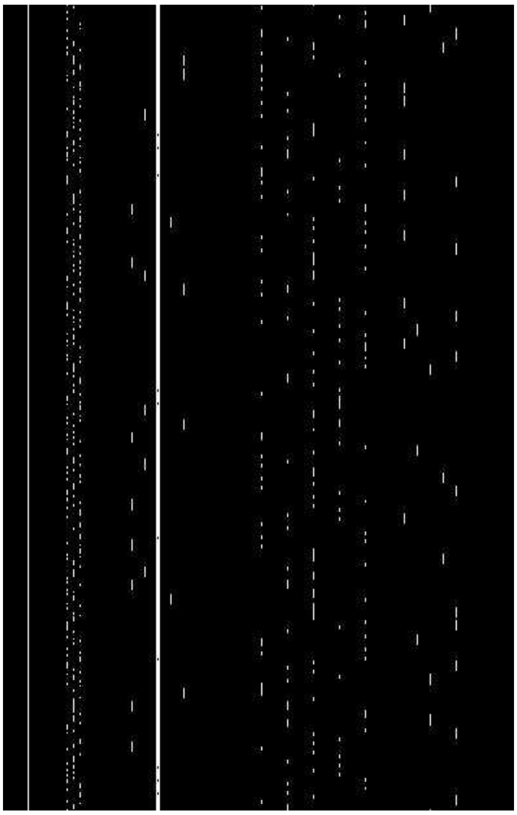

Fig. 1 Presence (white color) or absence (black color) of signal of certain frequency in the certain time

III. Design of Fuzzy Inference System

We designed Mamdani fuzzy inference system with three inputs and one output. For defuzzification the MOM (mean value of maximum) method was used. Presentation of fuzzy inference system (FIS) in Matlab is shown on Fig. 2.

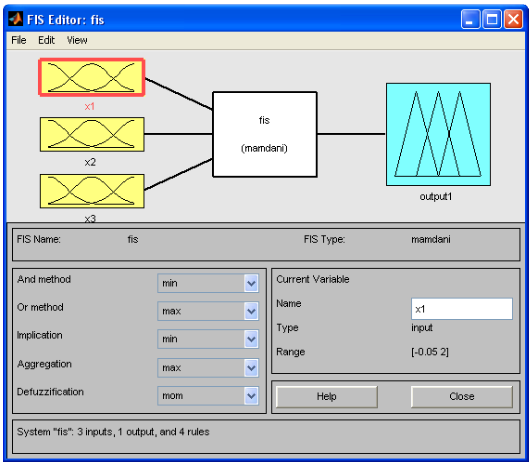

Fig. 2 Presentation of fuzzy inference system in Matlab

Inputs to the FIS are differences of parameters (*x1* - relative amplitude, *x2* - relative time slot duration, *x3* - relative bandwidth) of compared groups of signals and output is a decision whether given two groups of signals belong to the same radio communication (1) or not (0).

Fuzzy sets of all the inputs are designed in like manner (Fig. 3). They can get two values (*small S* and *great G* difference of given parameter), which are represented by triangular membership functions. The input values can vary between 0 and 1. Fuzzy value *small S* starts in the value -0.05 (the range was augmented regarding the computation), peak is in the 0 and end is in the value 0.05. The fuzzy value *great G* starts in the 0, peak is in the value 1 and end is in the 2 (also regarding the computation).

Output from the FIS is decision whether given two groups of signals belong to the same radio communication or not. It can get two values (*Y* – yes, the groups of signals belong to each other; *N* – no, the groups of signals do not belong to each other), which are as well as input values represented by triangular membership functions. Range of the output variable is from -0.5 to 1.5. Fuzzy value *N* starts in value -0.5, peak gets in the value 0 and ends in the value 0.5. Fuzzy value *Y* starts in the value 0.5, peak gets in the value 1 and ends in the value 1.5. As for defuzzification, there was used MOM method, there can be achieved practically only 2 output values: 1 – groups of signals belong to each other or 0 – groups of signals do not belong to each other. Presentation of the fuzzy output variable is shown on Fig. 4.

FIS is using only a few simple rules. If differences of all the signal group parameters are small, then groups of signals belong to each other. If the difference of any parameter of groups of signals is great, then groups of signals do not belong to each other.

Applied rules:
1. If (*x1* is *S*) and (*x2* is *S*) and (*x3* is *S*) then (*output1* is *Y*)
2. If (*x1* is *G*) then (*output1* is *N*)
3. If (*x2* is *G*) then (*output1* is *N*)
4. If (*x3* is *G*) then (*output1* is *N*)

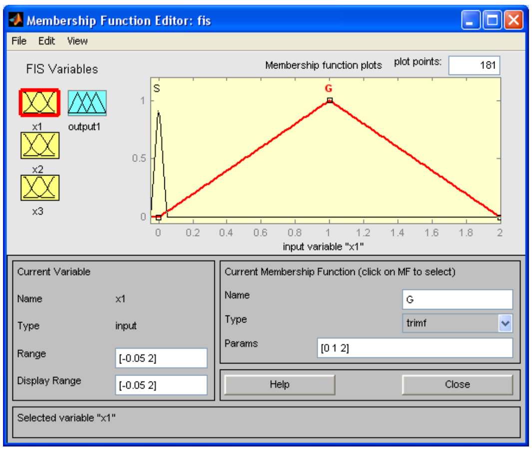

Fig. 3 Presentation of fuzzyinput variable*x1*in Matlab

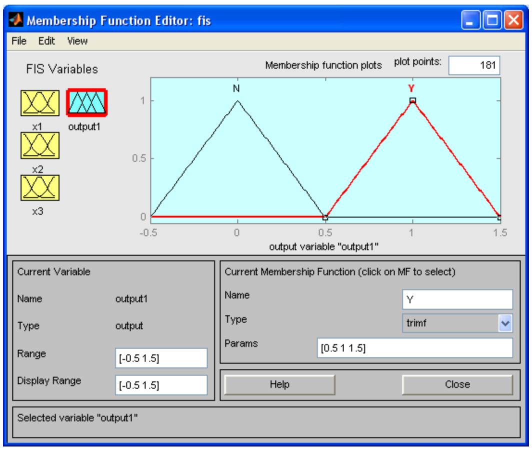

Fig. 4 Presentation of fuzzy output variable in Matlab

IV. Case Studies

Designed fuzzy inference system was tested for some case studies of radio communicationsrecognition.

A. Case Study I

In the first case study, the signals to be classified were from the Fig. 1. On the figure, there can be seen 19 groups of signals. A first group certainly constitutes a complete radio communication (signals are not interrupted). For the groups of signals, which were not interrupted, the fuzzy logic was not applied.This kind of signal was excluded by previous image processing (FM signals). Next 3 groups of signals stay close each other and it is obvious for a human observer, that they are very similar. Fifth, sixth, eighth, and ninth group of signals stay also close each other and they mutually resemble. Among them, there is seventh group of signals, which is not interrupted, like the first group. Tenth to fourteenth groups also resemble one another and fifteenth to nineteenth groups would belong to a same radio communication too.

Using FIS, there have been identified 5 groups (radio communications):

sigs{1}= [1]
sigs{2}= [7]
sigs{3}= [2 3 4]
sigs{4}= [5 6 8 9 15 16 17 18 19]
sigs{5}= [10 11 12 13 14],

where*sigs{i}* denotes radio communication *i* and [j k … l] are groups of signals *j*, *k*, …, *l* numbered according to their occurrence on the figure.

Fuzzy inference system classified groups of signals similarly as a human with his decision-making logic. However, groups of signals 5, 6, 8, 9, and 15 -19 were classified as belonging to the same radio communication. If we better look on the figure, than we can see, that they vastly resemble one another and they would belong to the same radio communication. Human has more limits, than a computer. He cannot compare similarities of patterns, if there is a larger distance between them.These signals were computer-generated in advance and they were classified correctly using designed fuzzy inference system.

B. Case Study II

In the second case study, there were 48 groups of signals. Signals are shown on Fig. 5. Values of parameters (relative amplitude, relative time slot duration, and relative bandwidth) of first 15 groups of signals are noted in Table I.

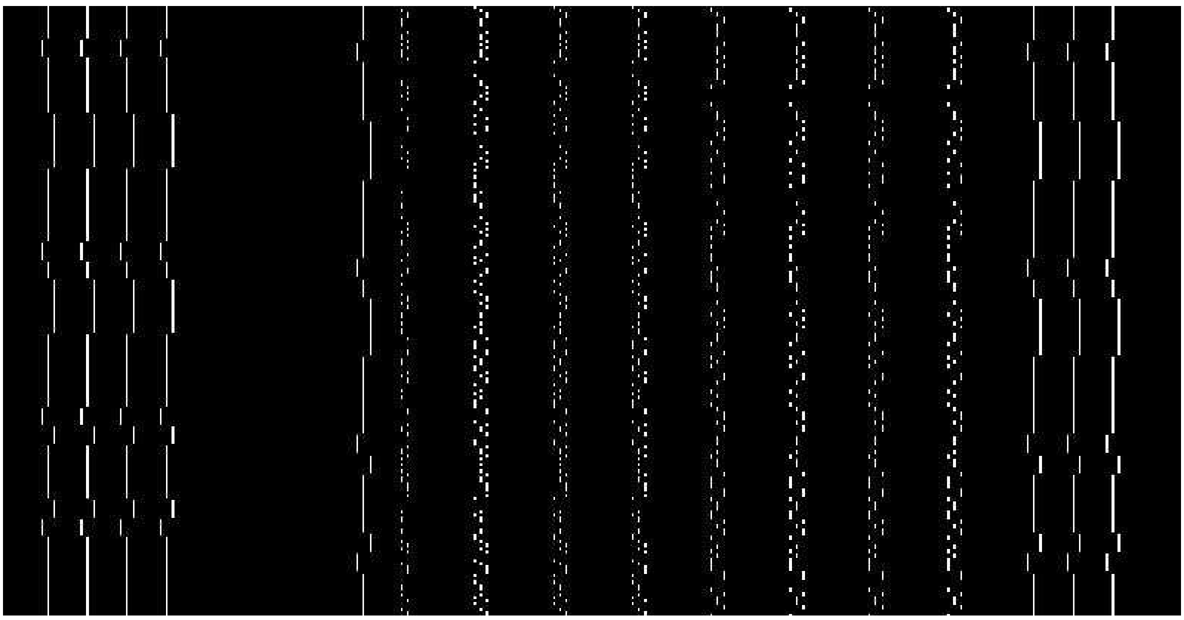
Fig. 5 Presence (white color) or absence (black color) of signal of certain frequency in the certain time – Case study II

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Correct classification of radio communications using FIS:
sigs{1}= [1 2 3], *sigs{2}*= [4 5 6],
sigs{3}= [7 8 9], *sigs{4}*= [10 11 12],
sigs{5}= [13 14 15], *sigs{6}*= [16 17 18],
sigs{7}= [19 20 21], *sigs{8}*= [22 23 24],
sigs{9}= [25 26 27], *sigs{10}*= [28 29 30],
sigs{11}= [31 32 33], *sigs{12}*= [34 35 36]
sigs{13}= [37 38 39], *sigs{14}*= [40 41 42],
sigs{15}= [43 44 45], *sigs{16}*= [46 47 48]

The proposed fuzzy classification method was compared with a standard classification method.

Classification using standard method:
sigs{1}= [1], *sigs{2}*= [2 3],
sigs{3}= [4], *sigs{4}*= [5 6],
sigs{5}= [7], *sigs{6}*= [8 9],
sigs{7}= [10], *sigs{8}*= [11 12],
sigs{9}= [13], *sigs{10}*= [14 15],
sigs{11}=[16 17 18], *sigs{12}*= [19 20 21],
sigs{13}= [22 23 24], *sigs{14}*= [25 26 27],
sigs{15}= [28 29 30], *sigs{16}*= [31 32 33],
sigs{17}= [34 35 36], *sigs{18}*= [37 38 39],
sigs{19}= [40], *sigs{20}*= [41 42],
sigs{21}= [43], *sigs{22}*= [44 45],
sigs{23}= [46], *sigs{24}*= [47 48]

We can see that fuzzy classification method is more efficient. Standard classification method cannot successfully classify groups of signals if there is a greater difference in some of parameters.A specific value must be adjusted in order to classify groups of signals in the rightradio communications. On the contrary, fuzzy classification do not use specific values of boundary-lines, hence the classification is more robust.

C. Case Study III

In the third case study, there were 48 groups of signals as well. The presentation of the signals was similar as in the second case study, but parameter values of the groups were different, with smaller variance in the same radio communication and smaller difference between 2 individual ones. Signals are depicted on Fig. 6 and values of parameters (relative amplitude, relative time slot duration, and relative bandwidth) of first 15 groups of signals are noted in Table I, together with the values from the second case study.

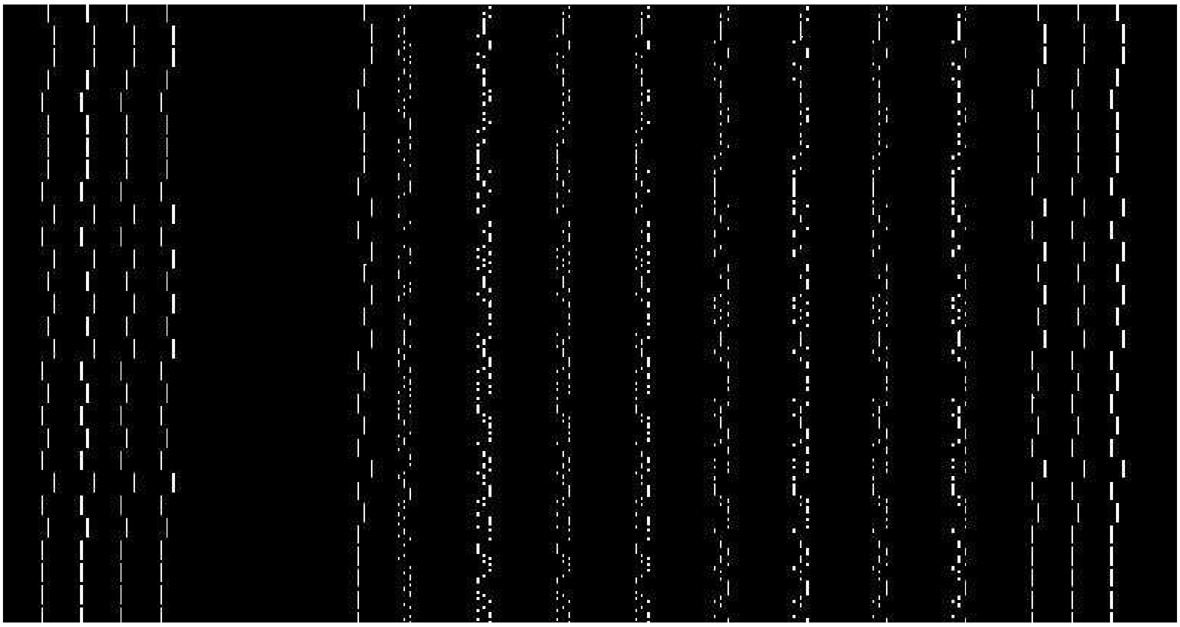

Fig. 6Presence (white color) or absence (black color) of signal of certain frequency in the certain time – Case study III

Standard method classified groups of signals to the next classes (radio communications):
sigs{1}=[1 2 3 13 14 15], *sigs{2}*=[4 5 6 40 41 42],
sigs{3}=[7 8 9 43 44 45], *sigs{4}*=[10 11 12 46 47 48],
sigs{5}=[16 17 18 28 29 30], *sigs{6}*=[19 20 21 31 32 33],
sigs{7}=[22 23 24 34 35 36], *sigs{8}*=[25 26 27 37 38 39].

Fuzzy inference system with primarily proposed parameters classified radio communicationsas follows:
sigs{1}=[1 2 3 7 8 9 13 14 15 43 44 45],
sigs{2}=[4 5 6 10 11 12 40 41 42 46 47 48],
sigs{3}=[16 17 18 22 23 24 28 29 30 34 35 36],
sigs{4}=[19 20 21 25 26 27 31 32 33 37 38 39].

None from these methods did classify groups of signals correctly. Seeing that individual radio communications have, compared to second case study, smaller variance of their parameter values (relative amplitude, relative time slot duration, and relative bandwidth), parameters of fuzzy inference system were modified in order to reflect this situation.

The range of fuzzy values *small S* was reduced. The values were modified so that they start in the value -0.02,the peak is got in the value 0 and the end in the value 0.02. Modified fuzzy inference system classified radio communications correctly:

sigs{1}=[1 2 3], *sigs{2}*=[4 5 6],
sigs{3}=[7 8 9], *sigs{4}*=[10 11 12],
sigs{5}=[13 14 15], *sigs{6}*=[16 17 18],
sigs{7}=[19 20 21], *sigs{8}*=[22 23 24],
sigs{9}=[25 26 27], *sigs{10}*=[28 29 30],
sigs{11}=[31 32 33], *sigs{12}*=[34 35 36],
sigs{13}=[37 38 39], *sigs{14}*=[40 41 42],
sigs{15}=[43 44 45], *sigs{16}*=[46 47 48].

TABLE I
VALUES OF PARAMETERS OF FIRST 15 GROUPS OF SIGNALS IN CASE STUDY IIAND CASE STUDY III

GS	RC	Case study II			Case study III		
		RA	RTSD	RB	RA	RTSD	RB
1	1	0.9938	0.9444	0.4286	0.9956	1.0000	0.6000
2	1	0.9557	0.9444	0.4286	0.9956	1.0000	0.6000
3	1	0.9697	0.9444	0.4286	0.9956	1.0000	0.6000
4	2	0.9938	0.9444	0.7143	0.9956	1.0000	1.0000
5	2	0.9557	0.9444	0.7143	0.9956	1.0000	1.0000
6	2	0.9697	0.9444	0.7143	0.9956	1.0000	1.0000
7	3	0.9217	0.9444	0.4286	0.9556	1.0000	0.6000
8	3	0.8870	0.9444	0.4286	0.9556	1.0000	0.6000
9	3	0.8998	0.9444	0.4286	0.9556	1.0000	0.6000
10	4	0.9217	0.9444	0.7143	0.9556	1.0000	1.0000
11	4	0.8870	0.9444	0.7143	0.9556	1.0000	1.0000
12	4	0.8998	0.9444	0.7143	0.9556	1.0000	1.0000
13	5	0.8998	1.0000	0.4286	0.9938	0.9737	0.6000
14	5	0.9583	1.0000	0.4286	0.9939	0.9737	0.6000
15	5	0.9739	1.0000	0.4286	0.9939	0.9737	0.6000

GS – group of signals, RC – radio communication, RA – relative amplitude, RTSD –relative time slot duration, RB – relative bandwidth.

V. CONCLUSION

The new method of classification of radio communications (membership of groups of signals to an individual radio communication) using fuzzy logic,has been proposed. The method has been verified on some case studies.

Fuzzy classification imitates proceeding of a human at object classification. It employs already obtained human knowledge. In comparison with standard classification method, the proposed one is more robust to changes in parameters of groups of signals (relative amplitude, relative time slot duration, and relative bandwidth) and it is adjustable more easily.

This method is intuitive and in Matlab also easy applicable. In case of need, the parameters of fuzzy inference system can be simply modified. The spread of membership functions can be adjusted considering the known variance of parameters of classified groups of signals and linguistic values or decision-making rules can be alsosimply added or removed.

The method would be applied also to classification of individual radio communications to the classes of radio communication (TDMA - time division multiple access, FM - frequency modulation, FHSS - frequency-hopping spread spectrum) if the characteristics of recognition are known.

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