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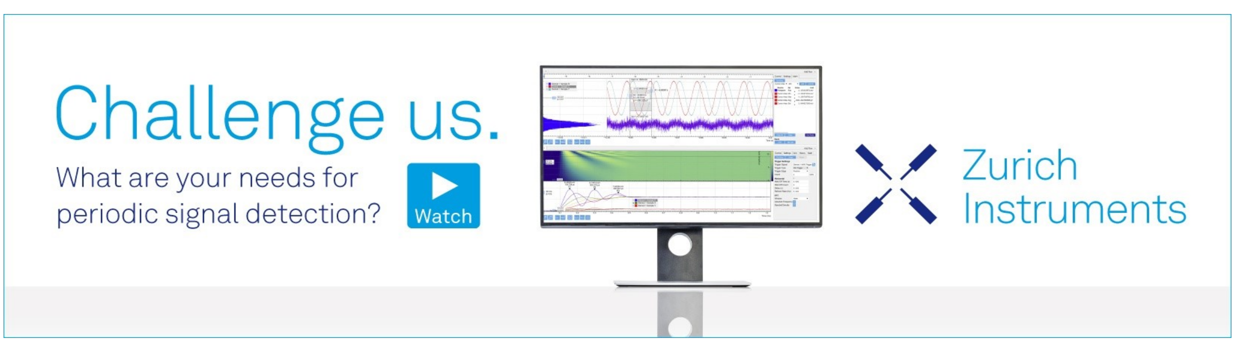

Analysis and Modelling of CMOS Gm-C Filters through Machine Learning

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Abstract. Utilization of machine learning in electronics and in computer-aided design is in progress, giving an opportunity the electronic circuits to be studied in a new way that also contributes to automation of some engineering tasks. In this paper, a novel methodology for analysis and design of Gm-C filters is presented. It is based on applying classification machine learning algorithm Random Forest on theoretically gathered data sets and on published scientific results. The tree-based algorithm is chosen, because of its capability not only to identify the correct class for every training sample and to point out the decision, but also to give explanation related to this decision and to outline a set of rules. The proposed methodology is verified through creation of several data models. Gm-C filters are chosen for exploration because of their extensive usage in computer and communication systems, medical devices and sensors.

INTRODUCTION

The interest to the integrated CMOS continuous time Gm-C filters increases, because of their advantages to operate at high frequency, to consume low power and to possess good performance in a wide frequency band – from several hundred kHz to more than 100MHz. These filters are built through active part that is realized in the form of Operational Transconductance Amplifier (OTA) and passive part that includes capacitors. The OTA's circuit reflects on the filter features and it is designed according to the application area. The OTA is voltage-to-current amplifier and characterizes with high input and output impedance. The Gm-C filters behavior is under extensive investigation striving for higher dynamic range and lower harmonic distortions at lower supply voltage and lower active area on the chip. Some parameters like filters quality factor and cutoff frequency could be electronically determined through transconductance tuning. All these features are reason for Gm-C filters utilization in the fields of computer systems, communication systems, sensor devices, medicine. For example, a Gm-C filter with programmable range of cut off frequency (100-1000 MHz) for reading channels in hard disk drive is proposed in [1], a Gm-C filter with wide tuning range (2-110μS) suitable for wireless receivers is presented in [2], a Gm-C filter with high linear range and less attenuation in pass band for usage in ECG bio-telemetry monitoring system is discussed in [3] a Gm-C filter for processing small amplitude signal (in μV range) from bio-medical and non-bio medical sensors is shown in [4].

The design process allows the filter structure to be obtained considering the required filters' main parameters. Several methods for Gm-C filters design are proposed by different authors. Deliyannis et al. discuss several methods for constructing Gm-C filters: through single OTA and three admittances, single OTA and four admittances, single OTA and five admittances [5], two integrators structure with summed-feedback and two integrator structure with distributed-feedback, Tow-Thomas OTA-C Structure, Feedback lossy integrator OTA-C filter [6]. Ahmed et al. propose a method for transformation op-amp-RC structures into Gm-C filter topology with only grounded capacitors [7]. Sánchez-Gaspariano et al. present a design strategy of CMOS biquad Gm-C filters with improved Q factor through applying signal flow graphs theory [8]. Otin et al. propose a design methodology of analog filters with reduced energy consumption [9]. A structured method for design of fully differential Gm-C filters is shown by Cracan and Cojan Jr. [10].

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During the analysis of Gm-C filters some important characteristics could be received taking into account filters topology. Different techniques and strategies are used for analysis of dynamic range, sensitivity, noise performance. Koziel et al. perform analysis of general Gm-C filter structure through matrix apparatus [11], Sánchez-López and Tlelo-Cuautle apply the theory of symbolic analysis to estimate the filter noise performance [12], Mezher and Bowron use noise block diagrams and noise flow graphs to analyze the noise response in Gm-C filters [13].

It can be seen that several methods for design and analysis of Gm-C filters are used for better understanding their features and characteristics. Machine learning as a part of artificial intelligence could also be applied to learn electronic circuits from data about them with aim behavioral and structural description to be created as well as automatic design and analysis to be achieved. Such strategy is suitable for CAD tools implementation.

The aim of the paper is to present a novel approach for design and analysis of CMOS analog Gm-C filters through utilization of a tree-based machine learning algorithm.

MACHINE LEARNING IN ELECTRONIC CIRCUITS DESIGN AND ANALYSIS

The exploration about application of machine learning in electronic circuits design and analysis is performed through construction of bibliometric network in support of VOSviewer software [14]. The bibliographical and citation information as well as information about abstract and keywords of scientific articles indexed in Scopus database is extracted. The search query includes the keywords *machine learning* and *electronic circuit*. The returned documents on 10 July 2020 are 1652 and they are used to draw the mainframe regarding the machine learning role in electronic circuits' domain as it is shown on figure 1.

The analysis of keywords occurrences (**O**) and total link strength (**TLS**) among the terms in scientific publications points out that the term *machine learning* is most often connected to the terms like *fault diagnosis*, *electronic design automation*, *features extraction*, *circuit design*, *integrated circuits modeling*, *analog processing circuit*, *PCB fabrication*, *product failure detection*. The most utilized machine learning algorithms are: support vector machine, artificial neural networks, Random forest, k-Means, J48, Naive Bayes and Regression (Table 1).

TABLE 1. Connection of the term *machine learning* to the term *electronic circuit*

Connection of the term machine learning to terms related to the application areas – O/TLS		**Connection of the terms machine learning to the terms concerning algorithms – O/TLS**
Fault diagnosis (7/29)	Memory capacity (2/11)	Support vector machine (7/29)
Electronic design automation (5/19)	Liquid crystal display (1/16)	Artificial neural networks (5/23)
Feature extraction (5/27)	Integrated circuits modeling (1/10)	Random forest (4/22)
Circuit design (2/7)	Medical devices (1/8)	k-means (2/10)
ATmega32 microcontroller (1/16)	PCB fabrication (1/8)	J48 (1/6)
Autonomous intelligent robot (1/16)	Wearable device (2/24)	Naïve Bayes (1/6)
(infrared) (bio) sensor (2/32)	Product failure detection (1/7)	Regression (3/12)
Power electronic circuits (2/6)	Analog processing circuits (1/6)	

The statistics regarding the number of scientific articles indexed in Scopus during a ten year period (from 2009 to 2019 year) is presented on figure 2. It can be seen that the number of published articles is not big, but the graphical curve has almost exponential form that highlight the increased research interests recently to the topic. For example, the indexed in Scopus scientific papers are 503 for 2019 year, 280 for 2018 year, 154 for 2017 year, 107 for 2016 year, 78 for 2015 year, etc.

Then, a detailed literature analysis is performed and it is points out that just a few articles about machine learning usage in support of automated design and analysis of electronic circuits are published. Beerel and Pedram discuss the contribution of machine learning to computer-aided design (CAD) in the context of very-large-scale integration (VLSI) process [15]. The authors propose the well-known CAD algorithms to be improved through applying machine learning techniques. Rosenbaum outlines the drawbacks of contemporary software for electronic design automation (EDA) as the roots for failures in testing are seen in inaccurate modeling possibilities and limitations in simulation-driven design optimization [16]. The author highlights the important role of machine learning for avoiding the pitfalls in design and optimization of microelectronics circuits. Moradi and Mizaei propose a new method for automated CMOS analog circuits design through usage of an evolutionary algorithm [17]. The method is tested on different circuits of operational amplifiers and it is verified through comparison with similar algorithms. An article by Metcalfe reveals the importance of machine learning for performance of fast and accurate electronic blocks placement and tracing [18]. The author concludes that the developed timing model will improve the design time and design performance.

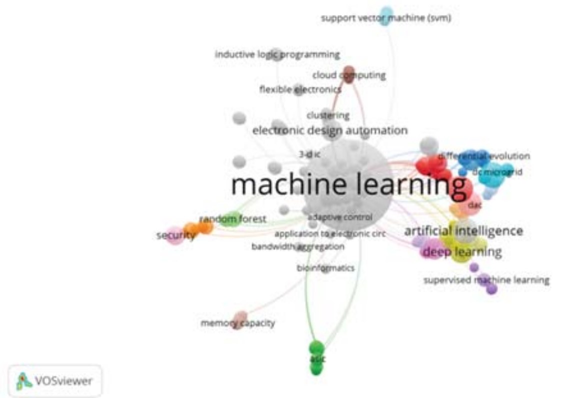


FIGURE 1. Constructed bibliometric network about the connection between the terms *machine learning* and *electronic circuit*

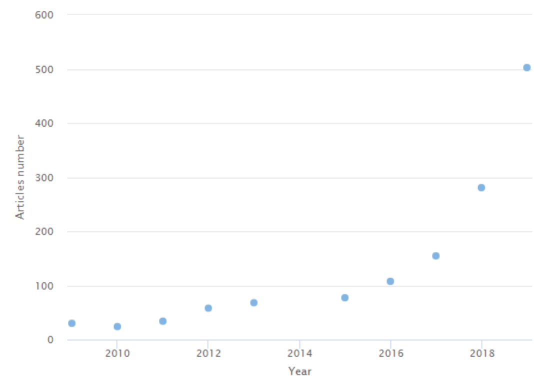


FIGURE 2. Scientific production related to the terms *machine learning* and *electronic circuit*

PROPOSED METHODOLOGY

The previous sections reveal the importance of machine learning algorithms usage in order to facilitate analysis and design of electronic circuits and also outline that such research is just at the beginning stage.

In this work a methodology for design and analysis of Gm-C filters is proposed that includes utilization of a machine learning algorithm.

Figure 3a presents the analysis process that consists of several steps: choice of filter topology that will be analysed, data collection about filter structure and its functionality (through theoretical description or through experimentation), data processing and data model preparation, choice of machine learning algorithm to train data and to learn the data model, achieving the results that lead to the analysis, optimization or prediction the filter features.

The design process is depicted on figure 3b and it includes the following steps: forming a specification with filter parameters (according to the customer requirements), data collection related to these parameters (theoretically or through experiments), data processing and data model preparation, choice of a machine learning algorithm that is capable to train data and to learn the data model, obtaining the filter topology.

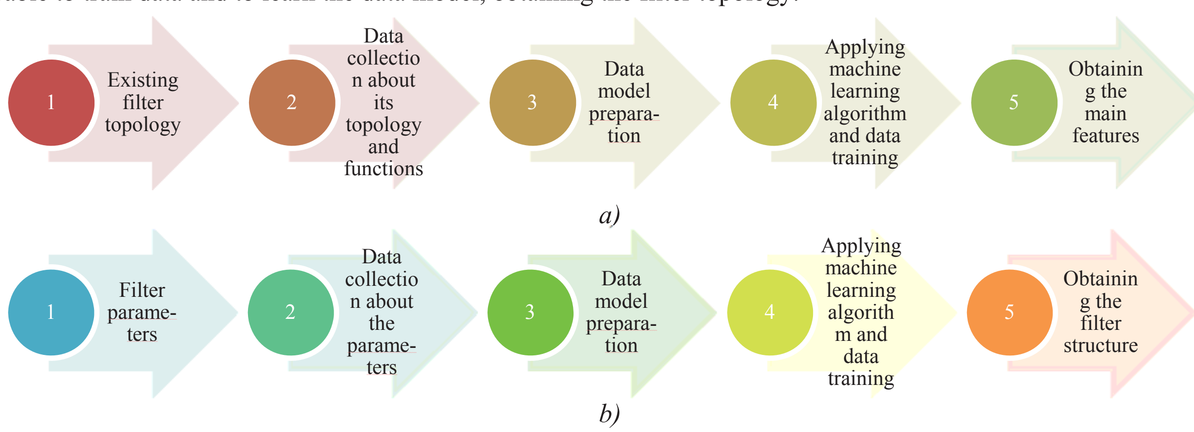


FIGURE 3. Methodology for: a) analysis of Gm-C filters; b) design of Gm-C filters

METHODOLOGY VERIFICATION

Analysis of Gm-C filters

The first step is related to a choice about the filter topology that will be analyzed. The main researched filter structure in this work is based on single OTA and three-admittance model, where Y can be capacitor sC, transconductor $g = 1/R$, $g + sC$, open circuit or short circuit (figure 4a) [5]. The general transfer function of the three-admittance filter structure is presented through the following equation:

$$H(s) = \frac{U_o}{U_i} = \frac{g_m Y_2}{Y_1Y_2+Y_1Y_3+Y_2Y_3+g_mY_2} \quad (1)$$

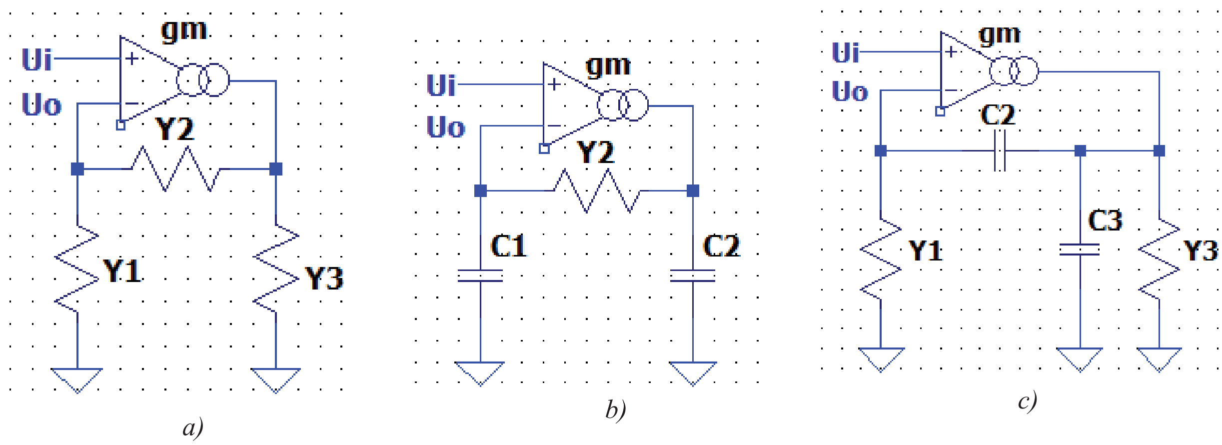


FIGURE 4. Gm-C filter: a) single OTA and three-admittance structure; b) second order low pass filter; c) second order band pass filter

If the admittance type is specified, then different filter topologies with corresponding transfer functions and characteristics could be achieved (Table 2). Two examples of Gm-C filters are presented on figure 4b and 4c (taken from [5]): the first one is second order low pass filter with transfer function $H(s) = \frac{g_m g_2}{s^2C_1C_3+sg_2(C_1+C_3)+g_mg_2}$ and the second one is second order band pass filter with transfer function $H(s) = \frac{sg_mC_2}{s^2(C_2C_3)+s[(g_m+g_1+g_3)C_2+g_1C_3]+g_1g_3}$.

TABLE 2. Gm-C filters dataset

№	Type	Y_1	Y_2	Y_3	Transfer function $H(s)$	Gain K	Cutoff frequency ω_c
First order topologies							
1	Low pass	sC_1	∞	0	$\frac{g_m}{sC_1 + g_m}$	1	$\frac{g_m}{C_1}$
2	Low pass	∞	g_2	sC_3	$\frac{g_m}{sC_3 + g_2}$	$\frac{g_m}{g_2}$	$\frac{g_2}{C_3}$
3	Low pass	sC_1	∞	g_3	$\frac{g_m}{sC_1 + (g_m + g_3)}$	$\frac{g_m}{g_m + g_3}$	$\frac{g_m + g_3}{C_1}$
4	Low pass	sC_1	g_2	g_3	$\frac{g_m g_2}{sC_1(g_2 + g_3) + g_2(g_m + g_3)}$	$\frac{g_m}{g_m + g_3}$	$\frac{g_2(g_m + g_3)}{C_1(g_2 + g_3)}$
5	High pass	g_1	sC_2	g_3	$\frac{sC_2 g_m}{sC_2(g_m + g_1 + g_3) + g_1g_3}$	$\frac{g_m}{g_m + g_1+g_3}$	$\frac{g_1g_3}{C_2(g_m + g_1 + g_3)}$
6	Low pass	g_1	g_2	sC_3	$\frac{g_m g_2}{sC_3(g_1 + g_2) + g_2(g_1+g_m)}$	$\frac{g_m}{g_m + g_1}$	$\frac{g_2(g_1+g_m)}{C_3(g_1 + g_2)}$
Second order topologies							
7	Low pass	sC_1	g_2	sC_3	$\frac{g_m g_2}{s^2(C_1C_3) + sg_2(C_1 + C_3) + g_mg_2}$	1	$\sqrt{\frac{g_mg_2}{C_1C_3}}$
8	Low pass	sC_1	g_2	$g_3 + sC_3$	$\frac{g_m g_2}{s^2(C_1C_3) + s[(g_2 + g_3)C_1 + g_2C_3] + g_2(g_m + g_3}$	$\frac{g_m}{g_m + g_3}$	$\sqrt{\frac{g_2(g_m + g_3)}{C_1C_3}}$

TABLE 2 (Continued). Gm-C filters dataset

№	Type	Y_1	Y_2	Y_3	Transfer function $H(s)$	Gain K	Cutoff frequency ω_c
9	Band pass	g_1	sC_2	$g_3 + sC_3$	$\frac{sg_mC_2}{s^2(C_2C_3) + s[(g_m + g_1 + g_3)C_2 + g_1C_3] + g_1g_3}$	$\frac{g_mC_2}{(g_m + g_1 + g_3)C_2 + g_1C_3}$	$\sqrt{\frac{g_1g_3}{C_2C_3}}$
10	Band pass	$g_1 + sC_1$	sC_2	g_3	$\frac{sg_mC_2}{s^2C_1C_2 + s[g_3C_1 + (g_m + g_1 + g_3)C_2] + g_1g_3}$	$\frac{g_mC_2}{(g_m + g_1 + g_3)C_2 + g_3C_1}$	$\sqrt{\frac{g_1g_3}{C_1C_2}}$

Data for filters analysis is taken from Table 2 where the building filter components are given: sC, g, $g + sC$, open circuit (infinite admittance) and short circuit (zero admittance) as well as the corresponding transfer functions $H(s)$, DC gains K, cut off frequency ω_c, the filter order and the filter type.

The first created data model aims to analyze the type of components and to propose a decision regarding the filter type and its order. The created data file is in the .arff format and it is simulated in the environment of RapidMiner Studio software:

```
@relation automatedanalysis

@attribute component1 {sc1, g1, inf, zero, g1+sc1}
@attribute component2 {sc2, g2, inf, zero, g2+sc2}
@attribute component3 {sc3, g3, inf, zero, g3+sc3}
@attribute filterorder {first, second}
@attribute filtertype {lp, hp, bp}

@data
sc1, inf, zero, first, lp
inf, g2, sc3, first, lp
sc1, inf, g3, first, lp
sc1, g2, g3, first, lp
g1, sc2, g3, first, hp
g1, g2, sc3, first, lp
sc1, g2, sc3, second, lp
sc1, g2, g3+sc3, second, lp
g1+sc1, g2, sc3, second, lp
g1, sc2, g3+sc3, second, bp
g1+sc1, sc2, g3, second, bp
```

For topology analysis of Gm-C filters a decision trees machine learning algorithm is chosen, because the tree-based algorithms are capable not only to identify the correct class for every training sample and to point out the decision, but also there is possibility the decision to be explained, a set of rules to be formed and the tree model to be improved.

Decision trees algorithms use divide-and-conquer technique and are based on entropy $H(X)$, probability $P(X)$ and information gain $I(X,Y)$ calculation [19]. The entropy

$$H(X) = \sum_{i=1}^{n} -p_i log_2 \, p_i \tag{2}$$

shows the amount of information related to an attribute. Its value is maximum e.g. $H(X) = 1$ when $P(X) = 0.5$ and its value is minimum e.g. $H(X) = 0$ when $P(X) = 0$ or 1. The probability is

$$P(X) = \frac{X_i}{X}, \tag{3}$$

where X_i is a fraction of samples from a given class and X is the number of samples in the whole training set. The information gain presents the entropy change $H(X)$ from a prior state to another state that provides some information regarding the attribute Y:

$$I(X,Y) = H(X) - H(X,Y) \tag{4}$$

Decision tree algorithms construct trees, finding the attributes with maximum information gain and minimum entropy. These attributes are used for dividing the training data set into data subsets and tree branches formation. When in a data subset all samples are from the same class, then a leaf with the label of this class is created. The leaf contains the decision.

Data is trained in RapidMiner Studio and Random Forest algorithm is applied. Figure 5 presents two trees that are constructed when the attribute filtertype is chosen with the role *label*. The extracted rules have the following form:

IF the component2 is sC2 **AND** the component1 is g1 **AND** the component3 is g3+sC3 **THEN** the filter type is band pass;

IF the component3 is g3 **AND** the component2 is g2 **THEN** the filter type is low pass.

Figure 6 shows two generated trees when the attribute filterorder is used as *label*. The extracted rules are in the same form:

IF the component2 is g2 **AND** the component1 is inf **THEN** the filter is from first order;

IF the component3 is sC3 **AND** the component1 is g1+SC1 **THEN** the filter is from second order.

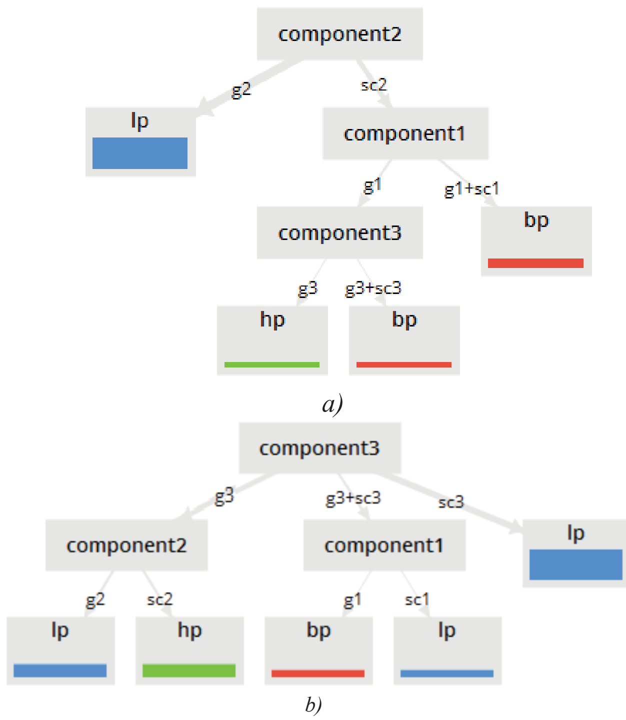


FIGURE 5. Constructed trees with the label *filter type*

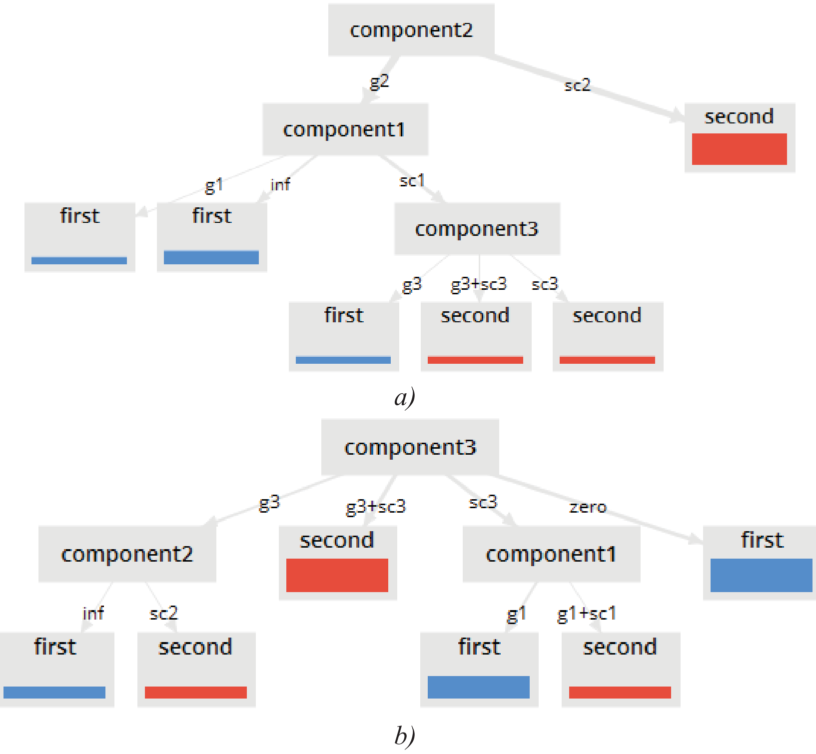


FIGURE 6. Constructed trees with the label *filter order*

Analysis of Gm-C filters with CMOS transconductor cell is performed through data, published in scientific papers which results are summarized in Table 3. The aim is the filter performance to be evaluated through parameters like: supply voltage V_{dd}, threshold voltage V_{th}, total harmonic distortion thd, dynamic range dr, active $area$ and filter $order$. The data model is created in .arff format:

@relation performancecmos

@attribute vdd {1.5, 1.35, 1, 1.8}
@attribute order {1, 2, 5, 6, 3}
@attribute vth {0.5, 0.43, 0.6, 0.9, 0.8}
@attribute thd {50, 45, 49.5, 48.6, 40, 44}
@attribute dr {60, 70.5, 57, 50, 45, 68}
@attribute area {1, 0.06, 0.25, 0.13, 0.159}

@attribute performance {good, verygood, excellent}

@data
1.5, 6, 0.8, 50, 60, 1, good
1.35, 2, 0.9, 45, 70.5, 0.06, excellent
1.5, 5, 0.6, 49.5, 57, 0.25, verygood
….

TABLE 3. Dataset about Gm-C filters with CMOS transconductor

	Lee and Cheng 2009 [20]	Zhang and El-Masry, 2007 [21]	Qian et al., 2005 [22]	Veeravalli et al., 2002 [23]	Solis-Bustos et al., 2000 [24]	Ramasamy and Venkataramani, 2018 [25]	Karami and Atarodi, 2019 [26]
Supply voltage	±1V	±1.8V	±1.5V	±1.35V	±1.5V	1.8V	1.5V
Filter order	5	3	5	2	6	2	1
Threshold voltage	0.5V	0.43V	0.6V	0.9V	0.8V	-	-
Total Harmonic Distortion	48.6dB	45dB	49.5dB	45dB	50dB	40dB	44dB
Dynamic range	50dB	45dB	57dB	70.5dB	60dB	50dB	68dB
Area	0.13 mm^2	0.159 mm^2	0.25 mm^2	0.06 mm^2	1mm^2	0.3 mm^2	-

From the constructed trees (figure 7) several rules could be extracted:

IF vdd is 1.5V **AND** thd is 49.5dB **THEN** the filter performance is verygood;
IF dr is 70.5dB **THEN** the filter performance is excellent;
IF thd is 49.5dB **THEN** the filter performance is verygood;
IF area is 0.06 mm^2 **THEN** the filter performance is excellent.

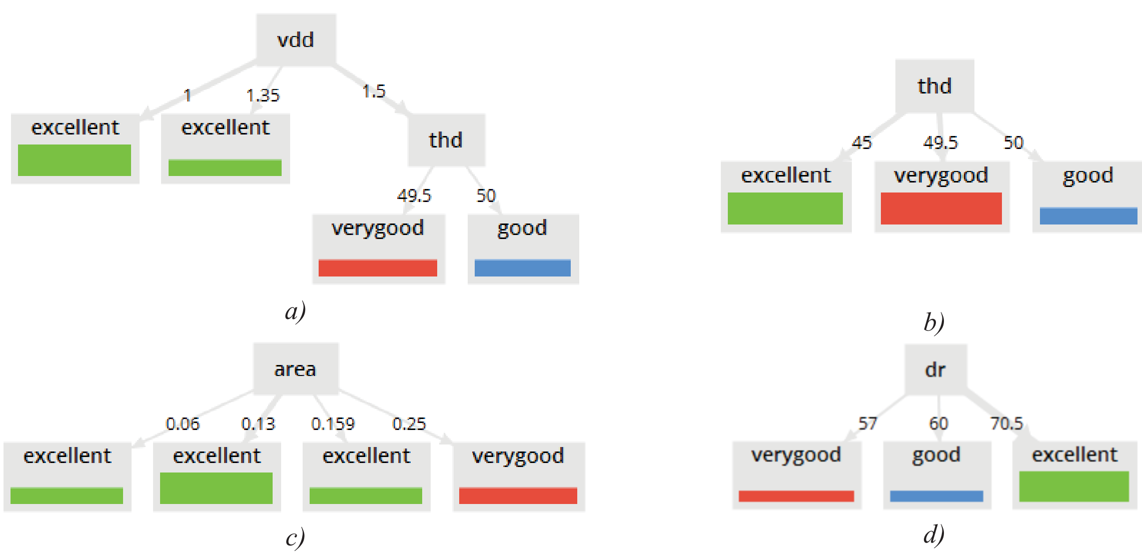
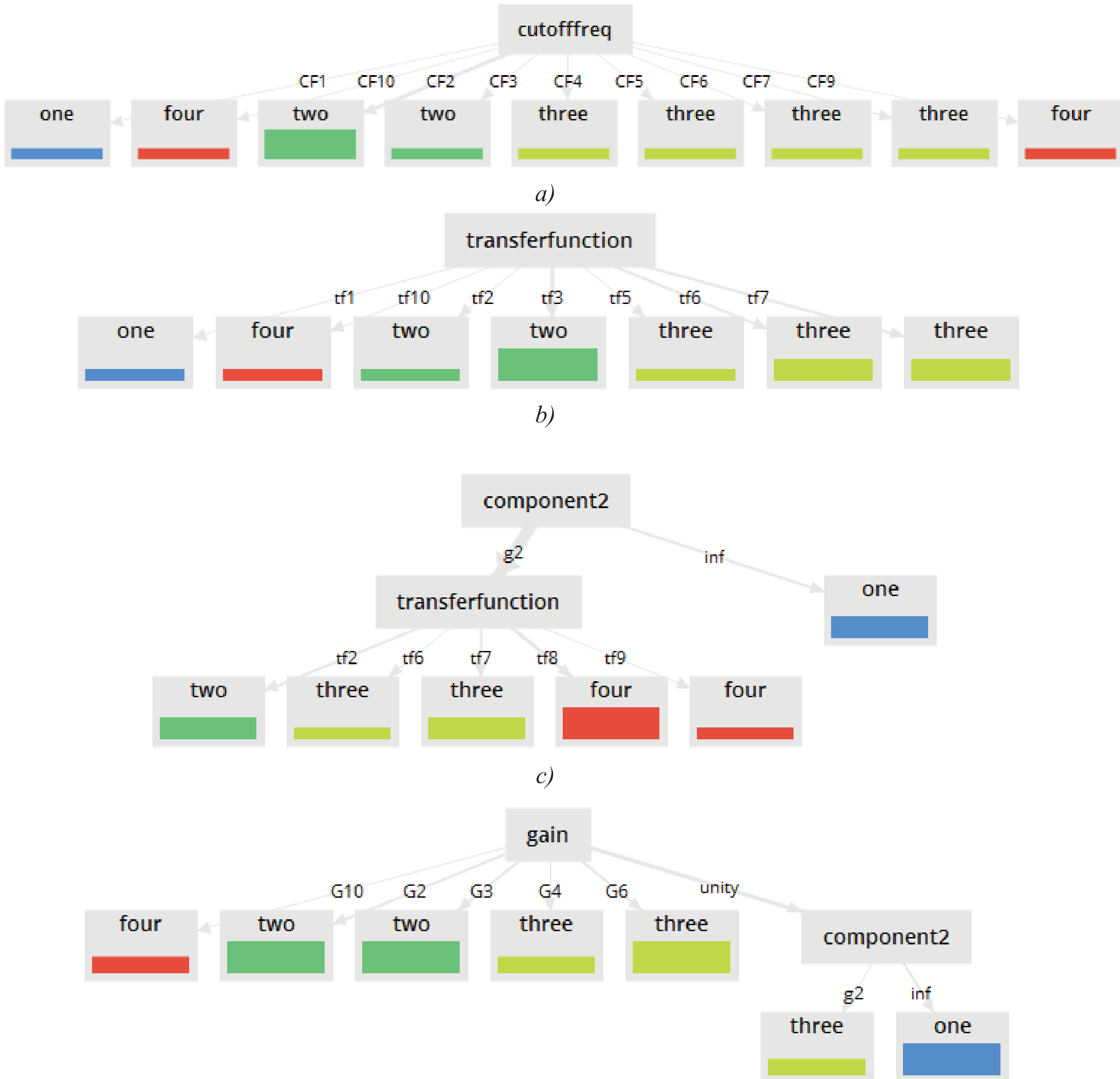


FIGURE 7. Constructed trees with the label *filter performance*

Design of Gm-C filters

During the design process the filter parameters: transfer function, DC gain, cut off frequency are specified and its structure has to be obtained. The dataset is formed through data from Table 2 as the transfer functions, DC gains and cut off frequencies are numbered from 1 to 10. Then, the data model is created in .arff format, the data is trained in RapidMiner Studio environment and classification algorithm Random Forest is applied. Figure 8 presents four constructed trees when the label is chosen to be *number of components*. The extracted rules have the following form:

IF the cut off frequency is CF1 **THEN** the filter has to contain one passive component;
IF the transfer function is tf1 **THEN** the filter has to contain one passive component;
IF the component2 is g2 **AND** the transfer function is tf2 **THEN** the filter has to contain two passive components;
IF the gain is G10 **THEN** the filter has contain four passive components.



d)

FIGURE 8. Constructed trees with the label *number of components*

CONCLUSIONS

This work proposes a methodology for design and analysis of Gm-C filters through usage of a tree-based machine learning algorithm. Several data models are developed to verify the methodology - datasets are prepared according to mathematical formulas or taking into account published scientific results, data is trained in RapidMiner Studio environment and Random Forest algorithm is applied. During the process of analysis the three-admittance model of Gm-C filters is used to identify the filters type and order, considering the filter topology and its building components. Also, the Gm-C filters performance is classified into three groups: good, very good and excellent in the case when the transconductor is manufactured through CMOS technology. During the design process the number of building components is outlined as well as their type, taking into account the required filter parameters.

The results point out that the classification machine learning algorithms like Random Forest precisely performs the tasks related to the design and analysis of Gm-C filters, supporting the decision making process.

REFERENCES

1. T. Terada et al., "100–1000 MHz cutoff frequency, 0–12 dB boost programmable Gm-C filter with digital calibration for HDD read channel", in *Proceedings of ESSCIRC*, Athens, Greece, 2009, 108-111.
2. T.-Y. Lo et al., "A Wide Tuning Range Gm–C Filter for Multi-Mode CMOS Direct-Conversion Wireless Receivers", *IEEE Journal of Solid-State Circuits*, 44(9), 2009, 2515-2524.
3. D. Jihai et al., "An OTA-C filter for ECG acquisition systems with highly linear range and less passband attenuation", *Journal of Semiconductors*, 36(5), 2015, doi: 10.1088/1674-4926/36/5/055006.
4. R. Arya and J. P. Oliveira, "Gm-C biquad filter for low signal sensor applications", In *Proceedings of MIXDES*, Lodz, Poland, 2016, 207-210.
5. T. L. Deliyannis, et al., "Single Operational Transconductance Amplifier (OTA) Filters", *Continuous-Time Active Filter Design*, Boca Raton: CRC Press LLC, 1999.
6. T. L. Deliyannis, et al., "Two Integrator Loop OTA-C Filters", *Continuous-Time Active Filter Design*, Boca Raton: CRC Press LLC, 1999.
7. R. F. Ahmed et al., "New op-amp-RC to Gm-C transformation method", *Analog Integrated Circuits Signal Process*, 49(1), 2006, 79–86, doi: 10.1007/s10470-006-8696-2.
8. L. A. Sánchez-Gaspariano et al., "CMOS Analog Filter Design for Very High Frequency Applications", *Electronics*, 9(2), 2020, https://doi.org/10.3390/electronics9020362.
9. A. Otin et al., "A Design Methodology for Low-Power Active Analog Filters for Wireless Communications", 2008, http://bioelectronics.tudelft.nl/~wout/documents/DCIS2008_Otin_Serdijn.pdf.
10. A. Cracan and N. Cojan Jr., "A structured approach to designing fully differential Gm – C filters", in *Buletinul Institutului Politehnic Din Iaşi*, Publicat de Universitatea Tehnică „Gheorghe Asachi" din Iaşi,Tomul LVII (LXI), Fasc. 1, 2011, 67-80.
11. S. Koziel1 et al., "Dynamic Range, Noise and Linearity Optimization of Continuous-Time OTA-C Filters", in *Proceedings of the ICECS*, Tel Aviv, Israel, 2004, 41-44, doi: 10.1109/ICECS.2004.1399609.
12. C. Sánchez-López and E. Tlelo-Cuautle, "Symbolic Noise Analysis in Gm-C Filters", in *Proceedings of the CERMA*, Cuernavaca, 2006, 49-53, doi: 10.1109/CERMA.2006.88.
13. K. A. Mezher and P. Bowron, "Noise-flow-graph analysis of OTA-C filters",In Proceedings of IEEE ISCAS, vol. 1, Sydney, 2001, 695-698, doi: 10.1109/ISCAS.2001.921951.
14. A. Perianes-Rodriguez et al., "Constructing bibliometric networks: A comparison between full and fractional counting", *Journal of Informetrics*, 10(4), 2016, 1178-1195.
15. P. A. Beerel and M. Pedram, "Opportunities for Machine Learning in Electronic Design Automation", in *Proceedings of IEEE ISCAS*, Florence, 2018, 1-5, doi: 10.1109/ISCAS.2018.8351731.
16. E. Rosenbaum, "Machine Learning for Electronic Design Automation", 2018, https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/images/events/matlabexpo/us/2018/machine-learning-for-electronic-design-automation.pdf
17. B. Moradi and A. Mizaei, "A New Automated Design Method Based on Machine Learning for CMOS Analog Circuits", *International Journal of Electronics*, 103(11), 2016, 1868-1881.
18. R. Metcalfe, "Machine learning in EDA accelerates the design cycle", 2020, https://www.edn.com/machine-learning-in-eda-accelerates-the-design-cycle/.
19. L. Rokach and O. Maimon, "Decision Trees", In: Maimon O., Rokach L. (eds), *Data Mining and Knowledge Discovery Handbook*, 2005, Springer, Boston, MA.
20. S.-Y. Lee and C.-J. Cheng, "Systematic Design and Modeling of a OTA-C Filter for Portable ECG Detection", *IEEE Transactions on Biomedical Circuits and Systems*, 3(1), 2009, 53-64.
21. X. Zhang and E. I. El-Masry, "A Novel CMOS OTA Based on Body-Driven MOSFETs and its Applications in OTA-C Filters", in *IEEE Transactions on Circuits and Systems I*, 54(6), 2007, 1204-1212, doi: 10.1109/TCSI.2007.897765.
22. X. Qian et al., "ACMOScontinuous-time lowpass notch filter for EEG systems", Analog Integrated Circuits Signal Process., 44, 2005, 231–238.
23. A. Veeravalli et al., "Transconductance amplifier structures with very small transconductances: A comparative design approach", *IEEE Journal Solid-State Circuits*, 37(6), 2002, 770–775.
24. S. Solís-Bustos et al., "A 60 db dynamic-range CMOS sixth-order 2.4 Hz lowpass filter for medical applications", *IEEE Transaction Circuits Systems II*, 47, 2000, 1391–1398.

25. S. Ramasamy and B. Venkataramani, “A low power programmable bandpass filter for digital radio mondiale, *Journal on Microelectronics*, 4(3), 2018, 634-640.