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A Novel Approach for Polyphase Filter Bank Design Using ABC Algorithm

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***Abstract*—Polyphase filter banks (PFBs) are the most preferred multirate structures for subband coding in Digital Signal Processing (DSP) and communication. For PFB design, there are many important design parameters such as filter length and frequency selectivity. Also, to realize the desired frequency response in designs, stopband and passband attenuation are of considerable importance. In PFB design, researchers and practitioners frequently use iterative and meta-heuristic optimization methods. Heuristic techniques have a significant problem-solving ability in continuous and discrete solution space. Therefore, they give better results than other suggested methods, and their performance depends on the control parameters. In this study, Artificial Bee Colony (ABC) algorithm was employed for suggested design problem of PFB. In the first stage, the control parameters of the ABC algorithm were examined to improve the performance of the proposed PFB problem. In the second stage, the analysis was carried out by changing filter lengths (8-256) and filter band frequencies (0.3-0.7/0.4-0.6). All results obtained were also compared with the Particle Swarm Optimization algorithm (PSO) and the Genetic algorithm (GA). Finally, a DSP application of PFB was carried out according to best results achieved by the ABC algorithm for filter lengths and frequencies.**

***Index Terms*—Channel bank filters; Digital filters; Evolutionary computation; Optimization.**

I. INTRODUCTION

Polyphase filters play an important role in the design of various filter structures, as they reduce the complexity, and therefore, the cost of the filter by decimating before filtering, reducing the number of multipliers for the samples in the filter inputs. Most applications in digital signal processing require variation of the sampling rate. The operations performed to change the sampling rate are interpolation and decimation (sample dilution). One of the most efficient filter bank designs that uses interpolation and decimation processes in practice is the polyphase filter bank structure. Many researchers have designed polyphase filter structures (reducing multiplication and addition numbers) to implement decimation and interpolation operations by fulfilling the requirements of decimation and interpolation operations and using the revaluation filters that perform these operations in ways. As we will show in this study, filters of this structure are full-pass filters with different phase shifts, so we call these structures "polyphase filters" [1]. The structure in (1) shows M-channel polyphase decomposition, and these are the polyphase components of $P_i(z)$ and $H(z)$ [2]

$$H(z) = \sum_{i=0}^{M-1} z^{-i} P_i(z^M). \tag{1}$$

The block diagram of the polyphase filter structure for M = 3 is shown in Fig. 1.

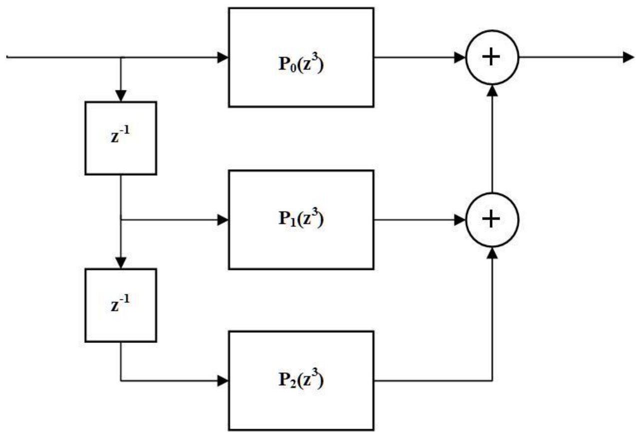

Fig. 1. Block diagram for the polyphase filter structure.

It is obtained by sample reduction of the delayed ("phase shifted") form of the original impulse response. It is obtained by taking the z-transform of the output sequence to get an M-channel polyphase filter structure. There are two main benefits to using a polyphase filter. The first is to

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reduce resource usage, and the second is to reduce computational complexity. Due to these two features, the hardware cost required to implement the design is reduced [3]. Due to the use of polyphase filters, these structures that perform multi-channel operation also reduce the use of system resources. Polyphase filter structures reduce the number of computations per cycle because they remove inputs and data samples that are discarded due to interpolation and sample dilution processes. The polyphase realization process increases the efficiency of the Finite Impulse Response (FIR) filter in terms of the variation in the sampling rate [4]. Polyphase filter banks (PFBs), based on quadrature mirror filters (QMFs), have been successfully used to divide a signal into N subbands and allow resynthesis of the signal arriving from the subbands, creating a very fast signal processing system. The most common applications of PFBs include subband coding of speech signals [5], [6], Time Division Multiplexing (TDM)-Frequency Division Multiplexing (FDM) transmultiplexing systems [7], [8], and short-time spectral analysis takes place [9], [10]. In recent studies, the application of PFBs has been extended to two dimensions, e.g., for subband coding of images [11], [12] and 2D short-time spectral analysis [13]. Most of these methods use direct numerical algorithms to minimize the error measure based on the filter design process.

In this paper, a novel PFB design approach was suggested using the ABC algorithm to optimize filter coefficients. To demonstrate design performance, a PFB reconstruction application was realized according to the results achieved by the ABC algorithm. The motivations and contributions of this paper are given as follows:

- To the best of our knowledge, there is no study describing polyphase filter bank design based on meta-heuristic algorithms in the literature;
- Varying filter lengths and frequencies are analyzed;
- The performance of the ABC algorithm was compared with those of the well-known heuristic algorithms;
- The improvement effect of control parameters on the solution performance of the ABC algorithm was investigated in detail;
- A reconstruction application was performed to assess the suitability and feasibility of the design approach.

II. Related Works

Filter banks are one of the most important structures of multirate systems. In particular, filter bank designs are widely used in rapidly increasing and decreasing the sampling rates of signals and separating the signals into subbands [14]–[16]. It is clear that polyphase filter banks produce effective solutions by implementing fewer multiplication and addition components, especially in the decimation and interpolation processes [17]–[20]. Therefore, the design and implementation of polyphase filter banks, both in simulation and in real time, are of interest to researchers and practitioners. Fiala and Linhart [3] proposed a polyphase FIR filter design that offers high efficiency in Very High Speed Integrated Circuit Hardware Description Language (VHDL) for Register Transfer Level (RTL) synthesis performed with Field Programmable Gate Array (FPGA) in their study. They took advantage of the pipeline structure for filter design. It has been seen that the design they have implemented is successful because of the following three reasons, firstly, the distributed arithmetic algorithm, secondly, polyphase decomposition, and thirdly, it contains filter structures based on interpolation filters. The realized design provides a number of advantages that increase easy portability by optionally using logic sources and Hardware Description Language (HDL) sources. Tecpanecatl-Xihuitl, Aguilar-Ponce, Ismail, and Bayoumi [4] explained the polyphase filter using a new distributed arithmetic algorithm with fewer multipliers. In accordance with the aims of making the filter multiplier less, the new Distributed Arithmetic (DA) algorithm and the designed adder array are used. They also stated that the proposed new DA algorithm in their study further reduces the filter complexity for higher-order filters compared to the traditional methods. Gerek and Cetin [21] used subband decomposition techniques, data coding, and analysis. In many filter bank designs, the goal is to obtain subsampled signals corresponding to different spectral regions of the used signal. However, this approach causes various artifacts in images with spatially varying features, such as images containing text, subtitles, or sharp edges. In their work, the authors present adaptive filter banks with excellent reconstruction for such images. The filters of this linear or nonlinear signal separation structure show changes due to the nature of the signal. These changes result in improved image compression ratios. Deshmukh and Keote [22] designed a multiphase FIR filter using a bypass feed multiplier, add multiplier, and shift elements. They explained that the designs made using the bypass feed multiplier gave better results than the classical designs [22].

III. Optimization Algorithms

Many optimization techniques used in solving optimization problems have been developed in a way that is inspired by some events in nature. Particle Swarm Optimization (PSO) is a population-based optimization algorithm developed by observing the social behavior of bird and fish flocks within the flock. The Artificial Bee Colony algorithm, inspired by the foraging behavior of honey bees, is an up-to-date meta-heuristic algorithm. Karaboga [23], [24] developed the Artificial Bee Colony (ABC) algorithm by modeling the foraging behavior of bees. The ABC optimization algorithm tries to find the place with the most nectar of the food source and tries to find the solution in the solution space that is suitable for the solution of the problem [25], [26]. In this article, the performance analyses of Genetic algorithm (GA), PSO, and Artificial Bee Colony algorithm (ABC) for polyphase filter bank design are compared. From the results obtained, it is seen that ABC produces better solutions than both algorithms in terms of convergence speed and performance.

A. Artificial Bee Colony Algorithms

Since heuristic algorithms give results in a shorter time than other classical algorithms, they are frequently used to solve different types of problems in many fields such as engineering, finance, and economics [27]. Along with the effective use of fuzzy logic in nonlinear problems, many methods inspired by systems in nature were also used to solve such problems. Especially, swarm-based heuristic search algorithms are fast in problem solving and can give more accurate results. In general, the common feature of these heuristic search algorithms is that they are concerned with the interaction of individuals with their environment and with other individuals. This is called "herd intelligence". The most important action for the survival of the herd is finding food. It has been observed that living things in nature are constantly divided into labors in search of food sources. Artificial Bee Colony algorithm (ABC) is considered to be one of the most up-to-date algorithms of this type. This algorithm is inspired by natural events such as sending a lookout to the environment, identifying areas with flower nectar and returning to the hive, and giving information about the distance and productivity of the nectar source to the worker bees in the hive, by modeling the different dance styles of honey bees to find rich flower nectars. The ABC algorithm was presented to the scientific community in 2005 with a study published by Karaboga [23]. The purpose of the ABC algorithm, in short, is to find the best in the shortest time and with the least energy. This feature of ABC has created different areas of use in a short time and continues to do so. The swarm intelligence approach, as a new branch of algorithms originating from real nature, focuses on modeling insect behavior to develop effective metaheuristic methods that use the problem-solving skills of insects in nature. The most basic feature of swarm intelligence is the interactive behavior of colony members with each other. An example of this behavior is the three types of dance, in which real honey bees in nature show information about the quality of the food source they find in the hive. Because of these movements, the bees that find a quality food source share the direction, distance, and nectar amount information of the food source with other bees in the hive. Thanks to this successful system, the other bees in the hive can easily be directed to regions with high-quality food sources. As Karaboga [23] stated, three types of bee classes were defined in bee colony-based algorithms: worker, onlooker, and scout bees.

1. Worker bees

In the algorithm, the task of these bees is to bring nectar from some predetermined sources to the hive. Additionally, the worker bees also share information such as the quality of the source they visit and the distance to the hive with other bees waiting in the hive.

2. Onlooker bees

These bees in the algorithm are in search of a food source according to the dance of the worker bees in the hive. New sources are determined by listening to and analyzing the previous observations of worker bees.

3. Scout bees

Scout bees search for new honey sources by wandering around randomly and relying only on their own observations. In the model based on the artificial bee colony algorithm, some assumptions are made to simplify [23]. The model only has one companion bee that takes nectar from each source. In addition, the total number of food sources and the number of bees employed are equal. The number of onlooker bees is equal to the number of employed bees. The locations of the food sources correspond to the feasible solutions to the optimization problem, and the amounts of the nectar from the sources correspond to the quality of the solutions related to these sources. Therefore, this algorithm tries to find the point that gives the minimum or maximum of the problem from the solutions in space and to find the place with the most nectar of the source. The main steps of the ABC algorithm are given in [23]:

– Send the pioneers to the first food sources. Send the worker bees back to the food sources and determine the nectar amounts.

– Calculate the probability value of the sources identified by the onlooker bees.

– Stop the process of using resources that the bees do not use.

– Send scouts to the search area to randomly discover new food sources

– Memorize the best food source ever found.

Until (requirements are met).

Between the lower and upper limits of the optimization problem parameters, the random generation of the nutrient source region is performed

$$x_{ij} = x_j^{\min} + rand(0,1)\left(x_j^{\max} - x_j^{\min}\right). \tag{2}$$

In (2), j represents the number of food sources produced and i represents the number of optimization parameters. In the second stage, the worker bee collects nectar from the previously determined food source. At the same time, it evaluates the quality of the new source by analyzing another nectar source located near its source. ϕ_{ij} is the random real number in the range [-1, 1] and the calculation of the new nectar source search v_{ij} is given in (3)

$$v_{ij} = x_{ij} + \phi_{ij}\left(x_{ij} - x_{kj}\right). \tag{3}$$

While evaluating the value of the new solution resource found for the problem, if v_{ij} goes outside the parameter limits previously determined, a translation is made according to (4) and the suitability of the solution cost is calculated according to (5):

$$v_{ij} = \begin{Bmatrix} x_j^{\min},\ v_{ij} < x_j^{\min} \\ v_{ij},\ x_j^{\min} \le v_{ij} \le x_j^{\max} \\ x_j^{\max},\ v_{ij} \ge x_j^{\max} \end{Bmatrix}, \tag{4}$$

$$fitness_i = \begin{Bmatrix} 1/(1+f_i),\ f_i \ge 0 \\ 1+abs(f_i),\ f_i < 0 \end{Bmatrix}. \tag{5}$$

The food sources, whose fitness values are calculated using (5), are transferred to the onlooker bees through a probabilistic selection process called "greedy selection" after the worker bee cycle is completed. The final part of the algorithm is to determine of the nectar-depleted food source. The algorithm's ability to identify a depleted food source occurs as a result of a cycle formed by the completion of the search process of worker and onlooker bees. Counters updated during the search process are used for this process. These counters should be given at the start of the program.

Any food source that is larger than the control parameter known as the limit set by the algorithm is exhausted and abandoned by looking at the counter. The worker bee that belongs to the abandoned area is excluded from the algorithm. The onlooker bee that finds the new source turns into a worker bee and collects honey from the source it finds, and the limit value for that source is reset. The worker bee, whose task is completed, turns into a scout bee.

B. Particle Swarm Optimization Algorithm

Algorithms based on herd intelligence emerged because of the interaction of the individuals in the herd with their environment and other individuals and the modeling of common behaviors. Particle Swarm Optimization is a swarm-based heuristic algorithm based on the behavior of flocks of fish and birds. It was developed by Kennedy and Eberhart [28] and made available to the scientific community. The PSO algorithm was first described by Kennedy [29] as the social adaptation of knowledge. The first variant of PSO was developed by adding a new parameter called "inertia weight" to the original algorithm [30]. In the following process, researchers in the world of science have produced many variants with initialization, mutation operators, and other parameters to increase the success of the algorithm [31]. The control parameters of the PSO algorithm are listed below:

– Swarm (Population) size: a value between 10 and 50 particles can be selected and determined;
– Maximum number of iterations.

The inertia weight, which is the control parameter of the first variant of PSO, is used in many applications. The basic steps of the PSO algorithm are given by the authors in [28]–[32]:

– Initialize Population.
– Repeat.
– Calculate fitness values of particles.
– Modify the best particles in the swarm.
– Choose the best particle.
– Calculate the velocities of particles.
– Update the particle positions.
Until (requirements are met).

C. Genetic Algorithm

The genetic algorithm, which imitates the evolutionary processes in nature as a computer program, was first developed by Holland *et al.* in the 1970s [33]. The book examining developments in genetic algorithms was published by Holland [34] in 1975. GA is an abstraction-oriented search method that is based on Darwin's theory of evolution and natural selection of biological systems and represents them in mathematical operators such as crossover or recombination, mutation, selection of the fittest individual, and reproduction. There are thousands of research papers and hundreds of books on GA because GA is so successful in solving a wide variety of optimization problems [35], [36]. The basic algorithm is summarized below [33]–[37]:

– Initialize Population.
– Repeat.
– Evaluation.
– Reproduction.
– Crossover.
– Mutation.
Until (requirements are met).

IV. PROPOSED MODEL

In this study, a novel approach to PFB design was suggested using the ABC algorithm to optimize filter coefficients. In particular, the ABC algorithm was effectively used in the prototype FIR filter design. In addition to the ABC algorithm, the PSO algorithm and the GA algorithm are used in the design of the polyphase filter bank. The proposed model approach is briefly shown in Fig. 2.

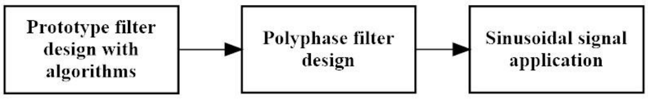

Fig. 2. The scheme of the proposed model.

First, a specially designed frequency response is used for the FIR filter design. The frequency response of the FIR filter coefficients optimized using the optimization algorithms is aimed at obtaining the desired and predefined frequency response. In Fig. 3, the predefined frequency response of the prototype filter is presented.

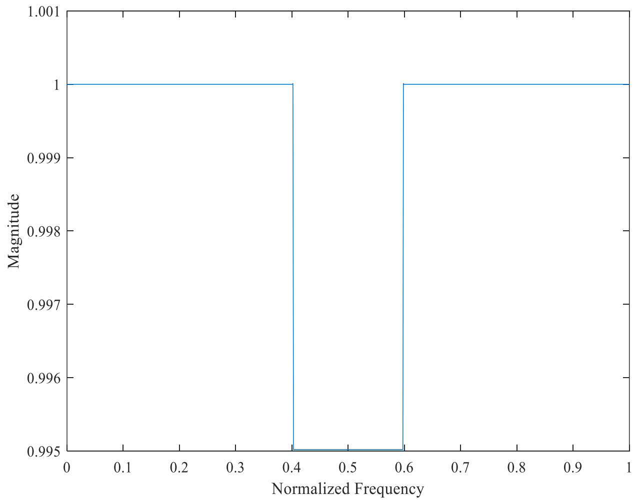

Fig. 3. Predefined frequency response of the prototype filter.

The FIR digital filter is given as

$$y(k)=\sum_{m=0}^{M-1} w_m x(k-m), \tag{6}$$

where $x(k)$ is the input signal, $y(k)$ is the output signal, w_m is a vector that comprises filter coefficients, and M specifies the order of the FIR digital filter. The filter coefficient vector can be presented as

$$w=\left[b_0\ b_1\ \ldots b_{M-1}\right]. \tag{7}$$

In the following equation, $e(k)$ is the error signal and fed back to the ABC algorithm. The coefficient vector of the FIR digital filter is adjusted by the ABC algorithm and minimization of the objective function is realized. The objective function, which is used in the ABC algorithm, is the mean square error (MSE) and is represented as

$$J(w)=\frac{1}{K}\sum_{k=1}^{K}\left[d(k)-y(k)\right]=E\left[\left|e(k)\right|^{2}\right], \quad (8)$$

where E represents the expected value. $H_d(e^{jw})$ and $H_{out}(e^{jw})$ are predefined frequency response and output frequency response of prototype FIR filter designed by optimization algorithm, respectively.

Finally, the designed prototype FIR filter is applied to the polyphase filter bank structure described in the previous section, according to the determined channel numbers and filter taps.

V. DISCUSSION OF DESIGN RESULTS

In this study, the effects of the control parameter changes of the Artificial Bee Colony algorithm on the polyphase filter bank design were investigated. Determining the control parameters of the algorithm is one of the most important factors that directly affects the working performance of heuristic algorithms. In the first study investigating the algorithm control parameters, the filter length was taken as 32 in the polyphase filter design problem; by giving different values of control parameters such as population size, limit value, and maximum number of cycles, the algorithm was run 50 times and the lowest mean square error values were obtained. The parameters and changed values of the ABC, PSO, and GA algorithms are shown in Table I. In this study, control parameters such as population size and maximum number of iterations were taken at the same values for ABC, PSO, and GA, and a comparison was made so that performance analyzes could be performed under equal conditions [32]–[38].

The study of the stopband and passband frequency range used in the filter design performed with the ABC algorithm is given in Table II. In the two different frequency range studies, where w_p-w_s = 0.4-0.6, the filter output gave results closer to the ideal.

TABLE I. PARAMETER VALUES OF ABC, PSO, AND GA ALGORITHMS.

Meta-heuristic algorithm	Control parameter values
ABC	Population size = 10 Limit = 320 Max. number of iterations = 1200
PSO	Population size = 10 Cognitive parameter = 1.8 Social parameter = 1.8 Max. number of iterations = 1200
GA	Population size = 10 Generation gap = 0.9 Max. number of iterations = 1200

TABLE II. PERFORMANCE OF ALGORITHMS DEPENDING ON PASSBAND AND STOPBAND FREQUENCIES.

Algorithms and Results		w_p-w_s	
		0,3-0,7	0,4-0,6
ABC	Mean	0,0565	0,0633
	Standard Deviation	0,0078	0,0070
	Best Value	0,0385	0,0433
PSO	Mean	0,0437	0,0510
	Standard Deviation	0,0122	0,0144
	Best Value	0,0293	0,0327
GA	Mean	0,1211	0,1228
	Standard Deviation	0,0317	0,0341
	Best Value	0,0707	0,0808

The parameter analysis study for the ABC algorithm is shown in Table III.

In cases where the population number is 10, better results were obtained in the population number search in the algorithm. Figure 4 shows the convergence curves for the filter length value 32 of the ABC, PSO, and GA algorithms. As seen in this graph, the ABC and PSO algorithms converged faster than the GA algorithm.

TABLE III. PARAMETER ANALYSIS FOR ABC ALGORITHM.

Run Order	1	2	3	4	5	6
Pop. Size	10	20	30	40	50	100
Max. Cycle	600	300	200	150	120	60
Mean	0,0923	0,1355	0,1915	0,2636	0,3305	0,7908
Standard Deviation	0,012	0,0219	0,0276	0,0432	0,0671	0,1555
Min	0,0666	0,0715	0,137	0,1962	0,1893	0,4928
Max	0,1306	0,1965	0,2636	0,4099	0,4715	1,3041
MSE	0,0087	0,0183	0,0374	0,0713	0,1136	0,6491

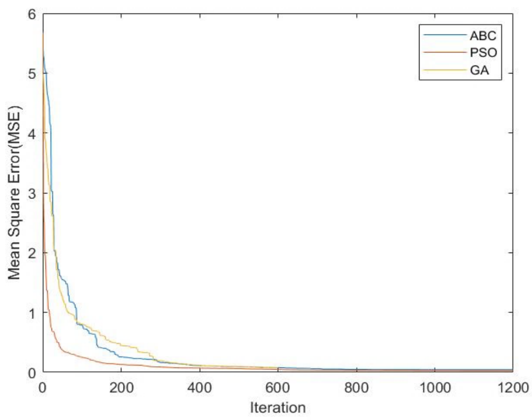

Fig. 4. The convergence curves for the filter length value 32 of the ABC, PSO, and GA algorithms.

When the filter length is 8 and 16, the lowest standard deviation values are obtained in the ABC Algorithm (Table IV). It was concluded that the standard deviation values obtained by the ABC algorithm are better in case the filter length increases. While the filter length is 8, 16, 32, and 64 in terms of the best values, the lowest best values are obtained in the PSO algorithm, while the lower best values are obtained in the ABC algorithm when the filter length is 128 and 256. After the algorithms were run under equal conditions for 6 different filter lengths depending on the filter length, it was seen that the smallest standard deviation values for each filter length were obtained in the ABC algorithm.

In Figs. 5–7, the graphs of the filter input and output signals in the polyphase filter bank design realized with the

ABC algorithm are given for filter lengths 8, 16, and 32. As can be seen from the graphs, the overlap of the input and output signals is quite the truth. In this case, it shows the success of the designed filters.

TABLE IV. PERFORMANCE ANALYSIS OF ALGORITHMS ACCORDING TO FILTER LENGTHS

Filter Length		ABC	PSO	GA
8	Mean	0,0906	0,0880	0,1263
	Std	0,0055	0,0157	0,0226
	Best Value	0,0816	0,0793	0,0838
16	Mean	0,0707	0,0583	0,1378
	Std	0,0073	0,0083	0,0316
	Best Value	0,0551	0,0476	0,0881
32	Mean	0,0633	0,0664	0,2679
	Std	0,0070	0,1134	0,0613
	Best Value	0,0433	0,0318	0,1283
64	Mean	0,0921	0,1707	0,2509
	Std	0,0103	0,1533	0,0531
	Best Value	0,0711	0,0692	0,1616
128	Mean	0,2013	1,0946	1,0972
	Std	0,0358	0,5729	0,2515
	Best Value	0,1358	0,2777	0,6994
256	Mean	1,9369	6,5348	6,2444
	Std	0,6466	1,3681	0,7326
	Best Value	0,6209	3,5657	4,5867

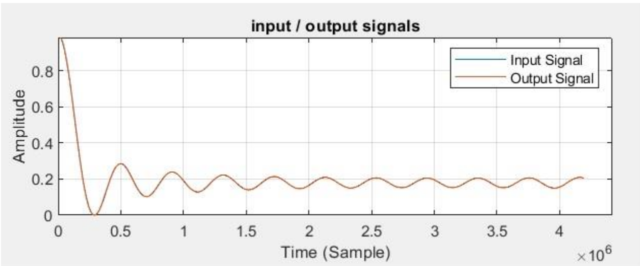

Fig. 5. Polyphase filter bank input and output signals designed with the ABC algorithm for filter length 8.

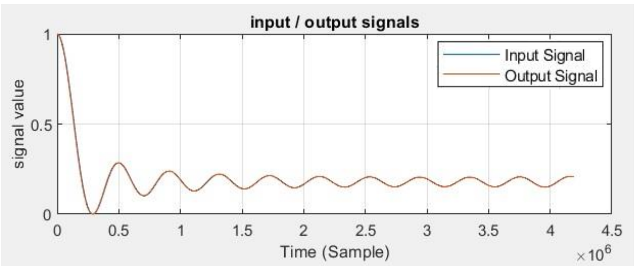

Fig. 6. Polyphase filter bank input and output signals designed with the ABC algorithm for filter length 16.

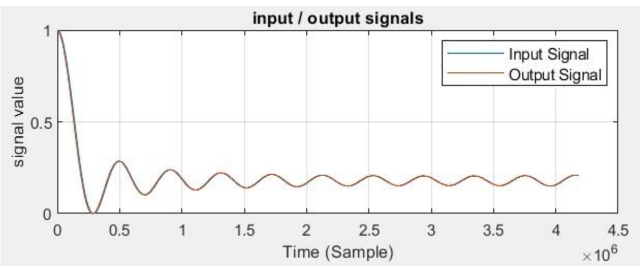

Fig. 7. Polyphase filter bank input and output signals designed with the ABC algorithm for filter length 32.

In addition, the obtained results showed that the designed polyphase filter bank can be used in applications. The coefficients of the polyphase filters designed for filter lengths 8, 16, and 32, respectively, are given as follows.

h(8) =	0.0178838877053427	0.417675932488215
	0.0118564401940498	0.846819549059568
	-0.0380649301769743	-0.305552668080392
	0.00948624926784254	0.0881373380621081

h(16) =	0.158521314446805	0.528748468546029
	0.489877503983286	-0.0216564110748927
	-0.178818852759353	0.0342402050354916
	0.166828137672670	-0.361540153512452
	0.423632560552408	-0.257556869330310
	0.0253202302685653	0.0781870553893945
	-0.0724767793650063	0.0317343122410023
	0.0281803617753145	-0.0456170989915066

h(32) =	-0.0444845220155277 -	0.0226898677219153
	0.0633106885826592	0.0899909411699788
	-0.155178235709356	0.0465604237887962
	-0.00128499852450455	0.133719257615825
	-0.0566605133299175	0.0148291209378902
	-6.70501213784519e-05	0.0132240654170025
	-0.479556691848363	0.476835837471769
	-0.102158187333724	-0.197126842429550
	-0.0513264944778494	-0.138126137807327
	0.311926196867722	0.397408340436380
	0.376438802584474	0.0575235490305800
	0.110216490120762	0.0594976242363078
	-0.0659396341670633	0.0375922301404361
	0.0202329654546419	0.0731046532115891
	0.0922381088966494	0.0741314259541506
	-0.0199017442060139	-0.0421109191992474

In the next study, algorithm performances for polyphase filter bank output will be examined in terms of reconstruction error and spectrogram. The filter bank design will be tested with different filter lengths and algorithm parameters to be compared, and the results will be evaluated. It is foreseen that the designed polyphase filter bank can be developed thanks to future studies.

VI. CONCLUSIONS

In this paper, the polyphase filter bank design was performed for the first time with the ABC algorithm. In addition to this, a novel approach for polyphase filter bank design using the ABC algorithm was suggested, and to the best of our knowledge, there is no study describing polyphase filter bank design based on meta-heuristic algorithms in the literature. The varying filter length and frequency are studied in detail. The results obtained were compared with the results obtained with well-known optimization algorithms such as PSO and GA.

In this article, first, filter design was made with the ABC algorithm, and the limit, population size, and filter frequency ranges of the algorithm were studied. Parameter analysis was performed for the ABC, PSO, and GA algorithms in terms of mean, standard deviation, and best value. Also, for 8, 16, 32, 64, 128 and 256 filter lengths in this study; In terms of filter length, the best results were obtained with 32 filter length. The best mean value for filter length 32 was 0.0633 and the ABC algorithm was used. Likewise, when the filter length is 32, the best standard deviation value is 0.0070 when the ABC algorithm is used.

While the filter length is 32, the best result in terms of the best value was obtained as 0.0318 when the PSO algorithm was used. Later, the design was compared with other algorithms such as PSO and GA and it was seen that the ABC algorithm gave better results. Second, after optimizing the designed filter, polyphase filter application was realized, and input-output signal analysis was performed for different filter lengths.

As can be seen from the results, a successful and effective design has been realized with the ABC algorithm. In this paper, the best results were obtained in the range of w_p-w_s = 0.4-0.6 in the study of the stopband algorithm and passband frequency range used in the prototype filter design performed with the ABC algorithm. In our future studies, the analysis of the designed filter bank will be carried out in real-time systems.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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