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Tabu Search for Estimating Optimal Values of Transduction and Reflection Weighing Functions Of SAW Filter

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Abstract: *Surface Acoustic Wave (SAW) filters are used in communication devices due to its small size and relatively superior performance at high frequencies in comparison to other competing filters. However, the design of SAW filter is always a critical issue due to requirement of small size as well as high performance parameters. Single Phase Unidirectional Transducers (SPUDTs) are the key element in design of SAW filters. The most basic challenge in designing with SPUDTs is to estimate both transduction and reflection weighting functions simultaneously that lead to desired frequency response of a SAW filter. As there is internal reflection to the transducer to cancel the effects of regeneration reflections, so the design of SPUDT is a very challenging task. This paper presents a typical local search technique, i.e., Tabu Search for estimation of sequence of transduction weighting coefficients (t) and reflection weighting coefficients (r) for each unit cell in a SPUDT structure to obtain the desired P-matrix and, therefore, a desired frequency response. The measure of closeness between desired P-matrix and obtained P-matrix (computed P-matrix by Tabu Search) is measured by distance. The results obtained with Tabu Search are reasonably improved as compared to existing techniques such as Iterative Local Search Technique.*

I. Introduction

Filters are an essential component in RF signal path. Now-a-days communication devices require very specific filters. So, with desired specifications the design of the filters is becoming more difficult and complex. Moreover, RF spectrum is getting more and more crowded. The reality is that filters using discrete components cannot meet the required performance, cost and size as well. So, Surface Acoustic Wave (SAW) filters were introduced, as these filters are known for its low insertion loss along with low cost, less weight, good performance characteristics and simple manufacturing process. A typical smart phone uses ten or more SAW filters [1]. The performance of SAW filters is based on piezoelectric characteristics of a substrate, geometrical structures of IDTs. Inter-Digital Transducers (IDTs) used in the SAW filter has two interlocking combs of electrodes on one end of the crystal surface, and another two such combs at the opposite end, but on the same crystal surface [2]. Input is connected across input IDTs which set-up electric fields along the surface of the crystal, instead within the bulk of the crystal. The electric fields cause the surface of the crystal to expand and contract. If a sinusoidal voltage is applied across the input electrodes of just the right frequency, a surface wave is created that propagates across the crystal, where it creates a voltage across the output electrodes, which are also interlocking combs. The result is a filtering action. If reflections are not used in the design, IDTs will be bi-directional that lead to very high loss of SAW filter [3]. The SAW IDTs utilizing reflections to obtain unidirectional behaviour is known as Single Phase Uni-Directional Transducers (SPUDT). SPUDT based SAW filters exhibit excellent frequency characteristics [4]. A 3-port p-matrix used to represent the desired specifications or desired response of the SPUDT gives the electro-acoustic behaviour of the transducer [5]. P-matrix can be obtained for any combination of transduction (t) and reflection (r) weighting function. P-matrix for whole SPUDT structure can be obtained by cascading the P-matrix of unit cells.

The paper presents a Tabu Search as optimization technique to find the optimal values of t and r weighting functions for each unit cell in a SPUDT structure in order to obtain the desired P-matrix and, hence, the desired frequency response. Further, a comparison between the results obtained with Tabu Search technique is made with the results obtained with another local search technique, i.e., Iterative Local Search Technique.
The rest of the paper is organized as under:

Section 2 introduces the SAW filter, its modelling and optimization issues and the basic assumptions used to get p-matrix for its unit cell. Section 3 details the local search based optimization technique, i.e., Tabu Search for estimation of sequence of transduction weighting coefficients (t) and reflection weighting coefficients (r) for each unit cell in a SPUDT structure to obtain the desired P-matrix and, therefore, a desired frequency response. The use of Tabu Search for estimation problem of transduction weighting coefficients (t) and reflection weighting coefficients (r) of unit cells in SAW filter is explained in section 4. Section 5 provides the search strategy used in Tabu Search to find the optimized solution. Results are discussed in section 6. Section 7 concludes the paper and gives the future direction of the presented work.

II. SAW Filter And Optimization Problem:

2.1 SAW Filter

SAW is one of the most advance technology that is used to perform signal processing. SAW filters are electromechanical devices used in wide range of radio frequency applications providing frequency control, frequency selection and signal processing capabilities. SAW filters are useful due to small size and relatively superior performance at high frequencies in comparison to other competing filters. The performance is based on piezoelectric characteristics of a substrate. The electrical signal is converted to the mechanical one and back again to the electrical domain at the output. After propagating through the piezoelectric element the output is recombined to produce a direct analogue implementation of finite impulse response filter.

The basic structure of a SAW filter consists of one input and one output IDTs deposited on a piezoelectric substrate [19]. A basic IDT is a device consists of two interlocking comb shaped metallic coatings which are applied to piezoelectric substrate. The combination of two strips with opposite sign is called finger pairs. These IDTs function as a transmitter and receiver for the surface acoustic waves. The IDTs can be designed to give the SAW device various characteristics and functions, the filtering function being among the most important. The shape and spacing of the electrodes determine the centre frequency and the band shape of the acoustic waves produced by the input transducer. In fact, the signal processing & frequency response characteristics of a SAW device are primarily governed by 3 interrelated factors; the geometry of two IDTs, the piezoelectric substrate and the wave propagation type. The IDT characteristics are also determined by 3 factors; the number of finger pairs, finger geometry in the period and the substrate material. The typical response of a SAW filter is given by:

$H(f) = H_1(f).H_2^*(f)$ ... (1)

Where $H_1(f)$ = frequency response of input IDT,

$H_2(f)$ = frequency response of output IDT

Internal reflections do exist in SAW filters for structural reasons. The reflection is used in SAW IDTs to achieve unidirectional behaviour. The unidirectional SAW IDTs are called SPUDTs. However, the analysis of SAW filters using reflections is relatively complex. A 3-port Reflecting Cell Model (RCM) is used to calculate P-parameters of a SAW structure utilizing electrode reflections. Many design methods [3, 4, 5] have been proposed for SPUDTs. Most of the design methods considered the reflection and transduction weighting functions separately. The optimization algorithm for the design of SPUDT, which presents simultaneous control of transduction and reflection functions, was first given by Ventura et al. [6]. After that the basics of optimization algorithm were extended to a complete filter structure, including multiple reflections between two transducers [4]. The optimum excitation and reflection functions are determined using mathematical optimization. Withdrawal weighted implementation is used order to obtain both the functions of SPUDTs, i.e., excitation and reflection [8]. The possible values of normalized t and r are +1, 0, −1. Corresponding to these values of r and t, there will be nine distinct unit cells. One needs to have P-matrices corresponding to these nine distinct unit cells. The single cells as well as the whole transducer are described by three port admittance-matrix [9]. This three-port has one electrical and two acoustical ports. To describe a whole transducer, the standard-cell 3-ports have to be cascaded acoustically, whereas the electrical ports must be connected in parallel. Cells as well as the whole transducer are described by three port admittance-matrix [9].

2.1 p-matrices for unit cells:

The coupling-of-modes (COM) method is most commonly used for modelling SAW filter. The equations used in COM model given by Abbott et. al. [7] and to give solution to COM equations p-matrix representation is used given by Tobolka [5]. The p-matrix representation of a single unit cell of a SPUDT is having 3-port (two acoustic ports and one electric).

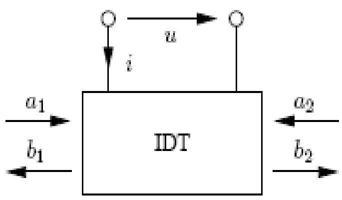


Fig. 1: p-matrix representation of a single unit SPUDT cell [7].

In this Fig.1 at port 1, a_1 and b_1 are input and output acoustic signal at port 1. Similarly a_2 and b_2 input and output acoustic signal at port 2. Third port in fig.1 is electric port whose electric signals are I (current) and v (voltage). Mathematically a p-matrix basically relates the input and output signal at three ports of a single unit cell. P_{13} and p_{23} can be interpreted as IDT transfer function [4] as under:

$$\begin{bmatrix} b1 \\ b2 \\ i \end{bmatrix} = \begin{bmatrix} p11 & p12 & p13 \\ p21 & p22 & p23 \\ p31 & p32 & p33 \end{bmatrix} \begin{bmatrix} a1 \\ a2 \\ v \end{bmatrix} \quad \text{... (2)}$$

Basically relationship exists between various parameters of this p-matrix that can be derived from reciprocity and energy conservation theory. The objective of the paper is to estimate both the weighting functions (*t* and *r*) simultaneously that lead to desired specifications (the desired P-matrix). In a basic unit cell the *t* and *r* weighting functions can have any of three values, expressed in normalized form as 1, 0, or –1 [8]. Corresponding to these values of both *t* and *r*, there will be 9 possible distinct unit cells. The p-matrices for these 9 distinct unit cells are generated using COM model [6].

Cascading formulas of unit cells:

The P-matrix for complete SAW structure is obtained by cascading the P-matrices for the unit cells. All the P-matrix elements give reflection strength, transduction strength, and transmission strength. In order to obtain P-matrix for SAW structure, it is needed to first get P-matrices for its unit cells and then cascade these p–matrices using cascading formulas as given by Abbott et. al. [7, 8].

Optimization problem and objective function:

Two p-matrices are said to be closer if the distance between these two matrices is lesser. As the weighting function coefficients *t* and *r* for each unit cell in a SPUDT structure can have any value out of +1, 0, -1. So, the possible number of distinct unit cells will be 3×3=9. If we take two unit cells together then number of possible distinct structures will be 9^2=81. If we can take more unit cells together and correspondingly the number of possible distinct structures will increase as if we take n unit cell together then total possible number of distinct structures will be 9^n. So, to choose the combination for which obtained p-matrix is closest to desired p-matrix p_d, the optimization techniques need to be applied to find out specific combination of unit cells, which have minimum distance.

The objective of present technique is to find the combination of basic unit cells (*t* and *r*) cascaded in some specific order to minimize the distance between the obtained P-matrix (p_o) and desired P-matrix (p_d). Frobenius norm is used for measuring distance between two P-matrices. If *X* and *Y* are two matrices as under:

$$X=\begin{bmatrix} x11 & x12 & x13 \\ x21 & x22 & x23 \\ x31 & x32 & x33 \end{bmatrix} \text{ and } Y=\begin{bmatrix} y11 & y12 & y13 \\ y21 & y22 & y23 \\ y31 & y32 & y33 \end{bmatrix} \quad \text{... (3)}$$

Then, the Frobenius norm *d(X, Y)* [9] defining the distance between matrices *X* and *Y* is given as:

$d(X,Y)= ||X\text{-}Y|| = d(X,Y)= ||X\text{-}Y|| = |a_{ij} – b_{ij}|^{½}$ ... (4)

The minimization of Frobenius norm distance is the objective function of the current problem and the present work explores the issue of estimation of *t* and *r* for each unit cell in a SPUDT structure to obtain the desired P-matrix and hence a desired frequency response. The existing papers have mainly used Iterative technique to estimate the sequence of transduction weighting coefficients (*t*) and reflection weighting coefficients (*r*) for each unit cell in a SPUDT structure to obtain the desired P-matrix. In the present work P-matrices P_o and P_d are defined over frequency range of desired response, so that distance between P_d and P_o is minimized for all the frequency points in the frequency range of desired response.

III. Tabu Search

Glover proposed a new approach in 1986, named as Tabu Search (TS) and formalized in 1989 [11, 12, 18, 20], is a meta heuristic search method employing Local Search (LS) methods used for mathematical optimization to allow LS methods to overcome local optima. The basic concept of TS is an extension of steepest descent by incorporating adaptive memory and responsive exploration [11]. The word Tabu (or taboo) comes from Tongan, a language of Polynesia, where it was used by the aborigines of Tonga Island to indicate things that cannot be touched because they are sacred. Tabu means “a prohibition Tabu Search starts with an initial solution and stores it as the current and best solution. The neighbors of the current solution are then created by neighborhood structure. These are candidate solutions (possible solutions). They are evaluated according to given objective function and a candidates of which is not a Tabu or satisfies the aspiration criterion is selected as a new current solution. This selection is called move and added to Tabu list [11, 12]. The new current solution is compared with the earlier best solution. If fitness function improved, it is saved in Tabu list as new best solution. Iterations are repeated until a stop criterion is satisfied.

3.1 Elements of TS Algorithms:

The basic philosophy of the presented technique is to find the combination of unit cells in some specific order so that the distance between the obtained P-matrix for obtained combination of unit cells and desired P- matrix is minimized. The elements of the TS algorithm [2] in connection with designing a SAW filter having desired response are defined as follows.

- **Initial solution**: A population of solutions are randomly generated covering the entire range of possible solutions that can be visited during search. The population size depends on the nature of the problem, but typically contains several hundreds or thousands of possible solutions. In local search based techniques such as Tabu Search, out of this population one solution is picked randomly as current solution.
- **Neighborhood Structure**: A neighborhood structure is a mechanism, which contain new set of neighbor solutions by applying a single local transformation to current solution [13]. Each neighbor solution is reached from a given solution by an operation called move. Pairwise exchange of individuals unit cells are used to define neighborhood in this problem. It systematically organizes the way in which the space is explored by making use of special memory structures which serve to determine neighbourhood effectively.
- **Move or local modification**: At each iteration, the search moves to an improving feasible solution (solution with improved objective function) called neighbors. Neighbors differ slightly from the current solution. By applying local modification to previous solution, we get current solution. New current solution becomes the best solution found so far.
- **Tabu list:** Tabu list is short term memory of search, only limited quantity of information can be stored in this. The main objective of the Tabu list is to prevent the search from tracking back to visited solutions from where it comes. In Tabu list, the elements added on the list are attributive. The main purpose of using an attributive representation is to save computer memory. Tabu list is automatically updated after each move. If the solution is labelled Tabu, then search will disallow that move. The Tabu list size (S) is an important parameter in guiding the search in the short term. There are usually three approaches for deciding size of Tabu list [14]; any predetermined value can be set, randomly chosen by considering any specific range, or dynamically changing by adjusting the value. In the presented work, third approach is used which is more challenging and more informative.
- **Aspiration criterion**: The aim of the aspiration criterion is allowing a move, if the move gives a solution better than the best obtained so far then the move, even if it is Tabu. If a move that satisfies a given aspiration criterion is selected, then the solution selected as new current solution. If the entire neighbor is labelled Tabu or no neighbor satisfies the aspiration criterion then the oldest neighbor entering the Tabu list at first, is selected as new current solution.
- **Termination criterion:** When the objective function reaches a pre-specified value or a fixed number of iterations can be considered as termination criterion.

IV. Tabu Search For Estimation Of *T* And *R*

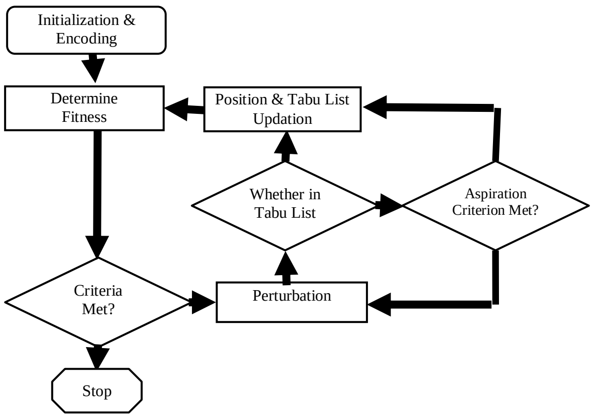


Fig. 2: Basic Tabu Search (TS) Steps.

As the given desired p-matrix is P_d and obtained P-matrix is P_o. Tabu Search is used to find the combination of unit cells in some specific order so that the distance between P_o for obtained combination of unit cells and P_d is minimized. As the optimization problem (deciding suitable structures of SAW filters based on estimation of sequence of *t* and *r* for each unit cell in a SPUDT structure to obtain P_d, Tabu Search approach is used to explore the large solution space (large number of possible solutions). Tabu search is a meta-heuristic that is proved successful in finding good solutions to difficult combinatorial problems and also successfully avoid being trapped at local optimal that were hard to find otherwise [16,17]. It uses memory not only to keep track of the current best solution but it also stores information related to the exploration process. To explore every possibility of this large solution space, presented work employ a search strategy that is Tabu Search approach:

Step 1: Choose an initial solution i in solution space S. Set i* = i and x=0.

Step 2: Set x=x+1 and generate a subset V* of solution in neighborhood N (i, x).

Step 3: Choose a best j (that minimizes Frobenius distance) in V* and set i=j. When a Tabu move would result in a solution better than any visited so far, its Tabu classification will be overridden (an aspiration criterion).

Step 4: If f (i) < f (i*) then set i* = i.

Step 5: Update Tabu and aspiration conditions.

Step 6: If a chosen iteration cut-off rule is met then stop. Else return to Step 2.

The stopping conditions are as under [14]:

- No feasible solution in the neighborhood of solution i, i.e., (i, x+1)=0;
- x is larger than the maximum number of iterations allowed.
- The number of iterations since the last improvement of i* is larger than a specified number.

The success of Tabu Search in finding good solutions depends on several control parameters, these are listed as under:

1. Size of the Tabu list.
2. Strategy with which Tabu status can be bypassed.
3. The definition of the neighbourhood.
4. The way the diversification schemes are developed and employed.
5. The way previous solutions are identified systematically and the way in which the space is explored by using special memory structures which serve to determine N (x) effectively.

V. Experimental Results And Discussion:

The pseudo-code for Iterative Local Search is under:

```
procedure IterativeLocalSearch_Routine
    GenerateInitialSolution()
    EvaluateFitness()
    while (termination condition not met) do
        Pertubation()
        Update_Position();
        EvaluateFitness();
    end-while
end-procedure
```

Fig. 3: Pseudo-code for Iterative Local Search (ILS)

The pseudo-code for the Tabu Search is as under:

```
procedure TabuSearch_Routine
    GenerateInitialSolution()
    EvaluateFitness()
    while (termination condition not met) do
        Pertubation()
        while (not in Tabu_List or meeting Aspiration Criterion) do
            Update_Position();
            EvaluateFitness();
            Update_Tabu_List();
        end-while
    end-while
end-procedure
```

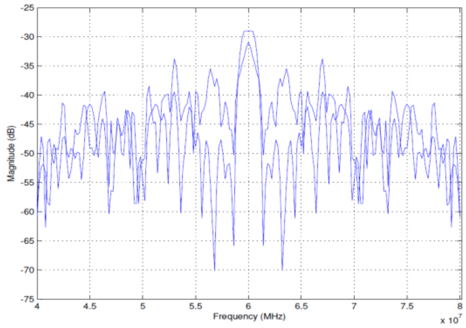
Fig. 4: Pseudo-code for Tabu Search (TS)

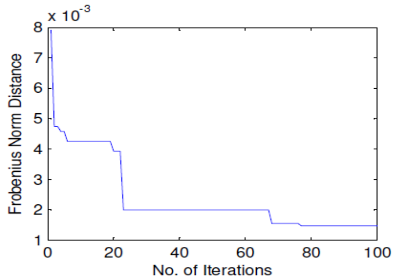
In the present work, P-matrices P_o and P_d are defined over frequency range of desired response, so that distance between P_d and P_o is minimized for all the frequency points in the frequency range of desired response. Tabu Search Technique is used to estimate the weighting functions, i.e, *t* and *r*. The various parameters of SAW chosen for the undertaken problem are detailed as under:

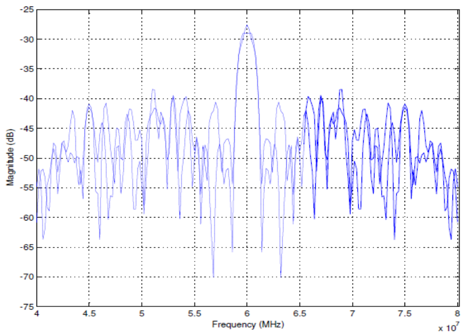
Normalized pass-band cut-off frequency = 0.908,
Normalized stop-band cut-off frequency = 0.998,
Maximum ripples allowable in pass-band = 0.02,
Maximum ripples allowable in stop-band = 0.029,
Number of unit cells cascaded in SPUDT1 = 62,
Number of unit cells cascaded in SPUDT2 = 68.

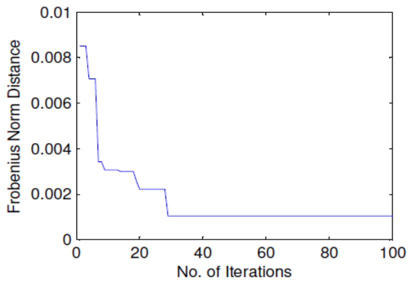
Fig. 5: Different parameters of SAW filter

The results obtained with Tabu Seach are as shown in Fig. 6 to Fig. 8. In the left hand side figures, X-axis represents the frequency in Mega-Hertz and the Y-axis represents normalized amplitude in decibels for different SPUDT frequency responses. In the right hand side figures, X-axis represents the number of iterations and the Y-axis represents the Frobenius norm distance. In these figures, the top left is the plot of the response of desired filter and filter by obtained by Iterative Technique. Top right is the plot of Frobenius norm distance obtained by Iterative Technique. Bottom left is the plot of the response of desired filter and filter by obtained by Tabu Search Technique. Bottom right is the plot of Frobenius norm distance obtained by Tabu Search Technique. A comparison of the result obtained for 100, 200 and 500 iterations. The experimental results show that while taking in to account two parameters, i.e., Frobenius norm distance and no. of generations required for convergence to the optimal solution, the performance of Tabu Search Technique is quite better as compared with the Iterative Local Search Technique.

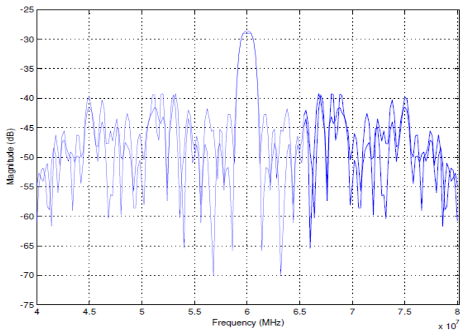


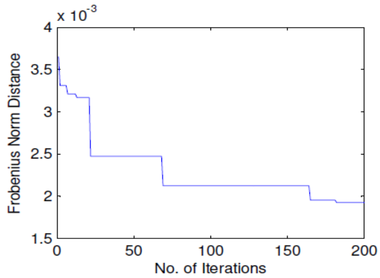


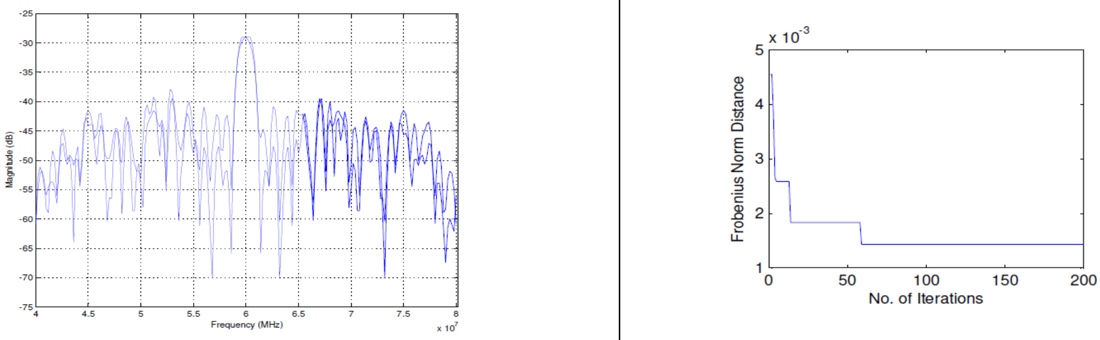




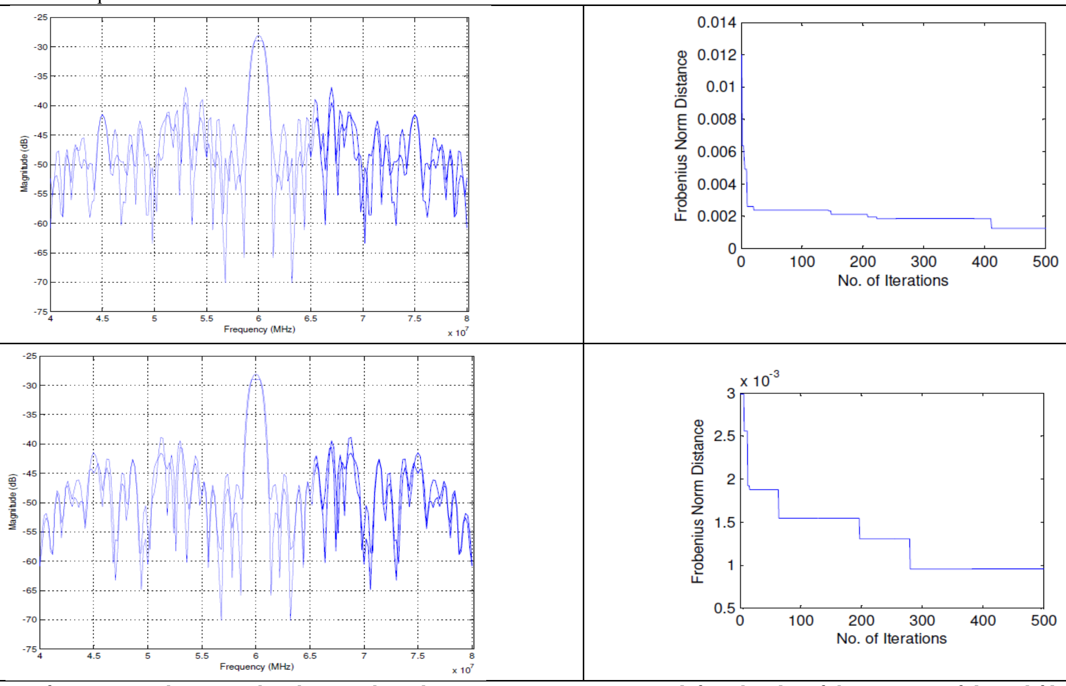
6: Comparison of Iterative Technique with Tabu Search Technique in 100 iterations. Top left is the plot of the response of desired filter and filter by obtained by Iterative Technique. Top right is the plot of Frobenius norm distance obtained by Iterative Technique. Bottom left is the plot of the response of desired filter and filter by obtained by Tabu Search Technique. Bottom right is the plot of Frobenius norm distance obtained by Tabu Search Technique.







: Comparison of Iterative Technique with Tabu Search Technique in 200 iterations. Top left is the plot of the response of desired filter and filter by obtained by Iterative Technique. Top right is the plot of Frobenius norm distance obtained by Iterative Technique. Bottom left is the plot of the response of desired filter and filter by obtained by Tabu Search Technique. Bottom right is the plot of Frobenius norm distance obtained by Tabu Search Technique.



Comparison of Iterative Technique with Tabu Search Technique in 500 iterations. Top left is the plot of the response of desired filter and filter by obtained by Iterative Technique. Top right is the plot of Frobenius norm distance obtained by Iterative Technique. Bottom left is the plot of the response of desired filter and filter by obtained by Tabu Search Technique. Bottom right is the plot of Frobenius norm distance obtained by Tabu Search Technique.

VI. Conclusion And Future Directions

In the present work, Tabu Search technique is used to estimate transduction weighting function (t) and reflection weighting function (r), simultaneously, to achieve a desired SPUDT response. As desired SPUDT response is given in terms of P-matrix and search space is explored by Tabu Search. So, out of different possible combinations (solutions), a single specific combination of unit cell is searched whose cascaded P-matrix closely approximates the desired P-matrix. While looking at the results obtained, it is quite evident that Tabu Search Technique has clear-cut edge over Iterative Technique not only in terms of faster convergence (obtained in lesser number of generations) but also in terms of optimal solutions (minimum Frobenius norm distance). As a future work, some population-based techniques need to be tried and compared with Tabu Search Technique.

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