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Boolean Particle Swarm Optimization of 3-branch GSM/DCS/UMTS current dividers by using Artificial Immune System

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Abstract: A new binary version of Particle Swarm Optimization called Boolean PSO (BPSO) is applied in order to design current dividers that distribute the current to three output ports and resonate simultaneously at three frequencies. The BPSO is based on the negative selection, which is one of the basic processes in an Artificial Immune System (AIS). The optimizer must satisfy specific requirements at all resonant frequencies, concerning the impedance-matching bandwidth and the distribution of the complex current on unmatched real or complex terminal loads. The dividers are considered to feed mobile communications antenna arrays and are optimized for GSM/DCS/UMTS operation. The optimization is performed by applying both the BPSO and a conventional PSO. The comparison shows that the BPSO is more efficient because it has the ability to produce structures with better frequency response.

Keywords: particle swarm optimization, artificial immune system, mobile communications, multi-frequency dividers

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Dividers are structures of great practical interest [1, 2, 3]. A current divider has to distribute the complex current on the terminal loads according to the desired current-split ratios and the desired phase differences between the currents. Moreover, the divider has to provide impedance matching in the desired bandwidth (BW). However, the main difficulty in designing a multi-frequency current divider results from the fact that all the above requirements must be satisfied simultaneously at all frequencies, taking into account that the terminal loads may have real or complex values and are generally not matched to the main line that feeds the divider.

The present work introduces a new method suitable for the optimization of multi-frequency current dividers. The method makes use of a novel binary version of Particle Swarm Optimization (PSO) called Boolean PSO (BPSO) [4]. The structure of the BPSO algorithm is based on the "negative selection," which is one of the basic processes in an Artificial Immune System (AIS). So far, [4] is the only application of BPSO in electromagnetics.

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2 Boolean PSO using Artificial Immune System

PSO has been studied in several papers [3, 5, 6, 7, 8, 9, 10]. The fundamentals of PSO and the structure of a conventional PSO algorithm are briefly described in [10]. The BPSO is a novel binary version of PSO introduced in [4]. In the BPSO method, the position $X_n = [x_{n1}, \ldots, x_{nd}, \ldots x_{nD}]$ and the velocity $V_n = [v_{n1}, \ldots, v_{nd}, \ldots v_{nD}]$ of each n-th (n=1,...,S) particle are represented by binary strings. After a time step, the d-th bit of V_n and the d-th bit of X_n are respectively updated by using *"and"* ($\cdot$), *"or"* ($+$), and *"xor"* ($\oplus$) operators, as follows:

$$v_{nd} = w \cdot v_{nd} + c_1 \cdot (p_{nd} \oplus x_{nd}) + c_2 \cdot (g_d \oplus x_{nd}) \tag{1}$$

$$x_{nd} = x_{nd} \oplus v_{nd} \tag{2}$$

where p_{nd} is the d-th bit of the best position P_n achieved so far by the n-th particle (pbest position) and g_d is the d-th bit of the best position G achieved so far by all the particles of the swarm (gbest position). In addition, w, c_1, and c_2 are binary digits randomly chosen with probabilities of being '1' determined respectively by the parameters Ω, C_1, and C_2.

An efficient way to control the convergence speed of the optimization process is to determine a maximum allowed velocity V_{max}, which is defined as the maximum allowed number of '1's in V_n. The actual number of '1's in V_n is expressed as L_n. The process of checking L_n is based on a fundamental mechanism in an AIS called "negative selection" (NS). The NS is a basic process of immunity in biology responsible for eliminating T-cells that recognize self antigens in the thymus. Therefore, if $L_n \le V_{max}$, V_n is considered as non-self antigen and is not changed. On the contrary, V_n is considered as self antigen, if $L_n > V_{max}$. In this case, the NS is applied on V_n and thus randomly chosen '1's in V_n must be set equal to zero until $L_n \le V_{max}$.

The BPSO algorithm is briefly described as follows:

1. Randomly initialize X_n (n=1,...,S) inside the search space.
2. Randomly initialize V_n (n=1,...,S), so that $L_n \le V_{max}$.
3. Evaluate the fitness function $F(X_n)$ for n=1,...,S.
4. Set P_n=X_n and $F(P_n) = F(X_n)$ for n=1,...,S (the first position of each particle is considered as pbest position).
5. Find the maximum fitness value F_{max} among $F(P_n)$ (n=1,...,S). F_{max} corresponds to the gbest position G, so that F_{max}= $F(G)$.
6. Update the particle velocities V_n (n=1,...,S) using Eq. (1).
7. Correct V_n (n=1,...,S) by applying the NS process.
8. Update the particle positions X_n (n=1,...,S) using Eq. (2).
9. Evaluate the fitness function $F(X_n)$ for n=1,...,S.
10. For n=1,...,S, if $F(X_n) > F(P_n)$ then P_n=X_n (the new position becomes pbest position of the n-th particle).
11. For n=1,...,S, if $F(P_n) > F(G)$ then G=P_n (the pbest position with the maximum fitness value in the swarm becomes gbest position).
12. If the predefined maximum number of iterations is not reached, repeat the procedure from step (6), or else report results and terminate.

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3 Formulation

The proposed structure of the divider is shown in Fig. 1. The divider consists of three branches that feed three corresponding terminal loads Z_{AT}, Z_{BT}, and Z_{CT}. Each branch consists of four tandem transmission line sections of different length and of different characteristic impedance. In total, the divider is composed of 12 sections, and thus there are 24 structure parameters (12 lengths and 12 characteristic impedances) available to optimize the divider.

A well-designed divider must obtain the desired impedance matching BW, which is the frequency range where the Return Loss (RL) at the input of the divider is below −10 dB. A way of calculating the RL is given below. Given the value of Z_{AT} (Z_{AT}=Z_{A0}) and using transmission line theory [11], the input impedances at the positions A_i(i=1, . . . , 4) of branch A are calculated recursively by the expression:

$$Z_{Ai} = Z_{oai}\frac{Z_{A(i-1)} + jZ_{oai}\tan(\beta D_{ai})}{Z_{oai} + jZ_{A(i-1)}\tan(\beta D_{ai})} \qquad (3)$$

where β is the phase constant inside the structure of the divider and $Z_{A(i-1)}$ is the input impedance at the position A_{i-1}. The input impedances at the positions B_i and C_i (i=1,. . . ,4) of the other two branches are calculated in the same way. The positions A_4, B_4, and C_4 are identical and coincide with the input of the divider. Thus, the input impedance Z_{in} of the divider is derived by the parallel combination of Z_{A4}, Z_{B4}, and Z_{C4}. Considering that the main transmission line that feeds the divider has a characteristic impedance of 50 Ω, the RL at the input of the divider is calculated in decibels by:

$$RL = 20\log|(Z_{in} - 50)/(Z_{in} + 50)|\ \ [dB] \qquad (4)$$

A way of calculating the current-split ratios is given below. The input power of the divider is expressed in terms of the complex input voltage V_{in} as follows:

$$P_{in} = 0.5\ |V_{in}|^2\ \mathrm{Real}\,[1/Z_{in}^*] \qquad (5)$$

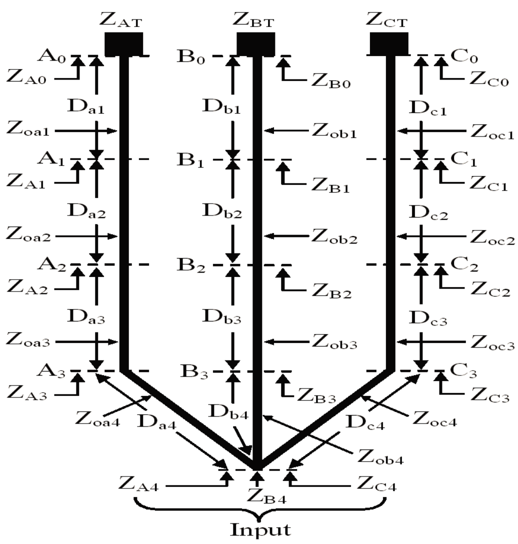

Fig. 1. The proposed structure of the three-branch current divider.

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where $|V_{in}|$ is the amplitude of V_{in} and Z^*_{in} is the complex conjugate value of Z_{in}. Normalizing all quantities with respect to P_{in} (P_{in}=1Watt) and regarding the phase of V_{in} as reference phase, we get:

$$V_{in} = V_{A4} = V_{B4} = V_{C4} = \sqrt{2/\text{Real}\left[1/Z^*_{in}\right]} \tag{6}$$

Using transmission line theory [11], the voltages at the positions A_i (i = 3,. . .,0) are calculated recursively by:

$$V_{Ai} = V_{A(i+1)}\left[\cos\left(\beta D_{a(i+1)}\right) - j\frac{Z_{oa(i+1)}}{Z_{A(i+1)}}\sin\left(\beta D_{a(i+1)}\right)\right] \tag{7}$$

The voltages at the positions B_i and C_i (i=3,. . .,0) are calculated by similar expressions. The complex current applied on the load Z_{AT} is given by:

$$I_{AT} = V_{A0}/Z_{AT} \tag{8}$$

The currents I_{BT} and I_{CT} are calculated in the same way. Regarding I_{AT} as reference current, two current-split ratios can be derived as follows:

$$R_1 = |I_{BT}|/|I_{AT}| \;\; \& \;\; R_2 = |I_{CT}|/|I_{AT}| \tag{9}$$

The phase difference p_1 between I_{BT} and I_{AT} and the phase difference p_2 between I_{CT} and I_{AT} can be derived as well.

The BPSO algorithm is applied using 30 particles (S=30). Also, Ω=0.1, C_1=C_2=0.5, and V_{max}=5. The objective of the algorithm is to find the values of the 24 above-mentioned parameters of the divider structure that make the fitness function F reach the global maximum F_{max}. Since BPSO is based on binary logic, the 24 real-valued structure parameters must be converted to binary strings. F is defined as follows:

$$F = \sum_{m=1}^{M}\sum_{k=1}^{2}\left[c^R_{mk}\cdot\left|R_k(f_m) - R^d_k(f_m)\right| + c^p_{mk}\cdot\left|p_k(f_m) - p^d_k(f_m)\right|\right] + \sum_{m=1}^{M}\left[c^{BW}_m\cdot BW(f_m) + c^{RL}_m\cdot RL(f_m)\right] \tag{10}$$

f_m (m=1,. . .,M) are the resonant frequencies and the superscript "d" denotes the desired values of R_1, R_2, p_1, and p_2. The use of $RL(f_m)$ in Eq. (10) ensures a deep resonance at f_m. Provided that the weight factors c^R_{mk}, c^p_{mk}, c^{RL}_m (m=1,. . .,M & k=1,2) have negative values and c^{BW}_m (m=1,. . .,M) have positive values, the fitness function tends to be maximized when the requirements concerning R_1, R_2, p_1, p_2, BW, and RL tend to be satisfied.

4 Numerical Results

The proposed technique has been applied to optimize three-branch current dividers for GSM/DCS/UMTS operation. The loads Z_{AT}, Z_{BT}, Z_{CT} are assumed to be the first three elements of a six-element antenna array excited by a Dolph-Chebyshev current distribution in order to be used in mobile communications and to produce a broadside radiation pattern with side lobe level

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equal to −20 dB [12]. Therefore, $R_1{}^d$=0.777, $R_2{}^d$=0.541, and $p_1{}^d$=$p_2{}^d$=0 at each of the three resonant frequencies. The best results derived by the BPSO are compared with the best results derived by a conventional PSO. Both methods are executed 30 times with 10000 iterations per execution. Two cases are studied concerning (a) real loads Z_{AT}=60 Ω, Z_{BT}=72 Ω, and Z_{CT}=150 Ω, and (b) complex loads Z_{AT}=100+j15 Ω, Z_{BT}=200−j40 Ω, and Z_{CT}=150+j50 Ω. The characteristic impedances and the lengths of the sections of the optimized dividers are given in Table I. All the lengths are measured in terms of the wavelength λ_0 inside the structure of the divider at 900 MHz. The desired values of R_1, R_2, p_1, and p_2 are achieved at all resonant frequencies by both algorithms. However, Fig. 2 (especially in case a) indicates that BPSO results in structures with better frequency response.

Table I. Geometry of the optimized dividers

	Case a (Real loads)		Case b (Complex loads)	
	Boolean PSO	Conventional PSO	Boolean PSO	Conventional PSO
Z_{oa1}/D_{a1}	77.40 Ω/0.137 λ_0	67.27 Ω/0.284 λ_0	92.69 Ω/0.424 λ_0	115.09 Ω/0.234 λ_0
Z_{oa2}/D_{a2}	86.92 Ω/0.199 λ_0	75.84 Ω/0.311 λ_0	85.73 Ω/0.309 λ_0	98.54 Ω/0.252 λ_0
Z_{oa3}/D_{a3}	111.92 Ω/0.345 λ_0	91.98 Ω/0.305 λ_0	94.69 Ω/0.228 λ_0	91.79 Ω/0.258 λ_0
Z_{oa4}/D_{a4}	125.91 Ω/0.192 λ_0	109.39 Ω/0.282 λ_0	110.26 Ω/0.089 λ_0	113.30 Ω/0.343 λ_0
Z_{ob1}/D_{b1}	77.41 Ω/0.282 λ_0	95.69 Ω/0.218 λ_0	144.30 Ω/0.343 λ_0	181.10 Ω/0.320 λ_0
Z_{ob2}/D_{b2}	65.97 Ω/0.278 λ_0	86.78 Ω/0.395 λ_0	92.71 Ω/0.323 λ_0	133.19 Ω/0.350 λ_0
Z_{ob3}/D_{b3}	83.62 Ω/0.171 λ_0	86.67 Ω/0.215 λ_0	80.27 Ω/0.213 λ_0	110.26 Ω/0.201 λ_0
Z_{ob4}/D_{b4}	123.31 Ω/0.145 λ_0	118.33 Ω/0.361 λ_0	118.91 Ω/0.206 λ_0	127.06 Ω/0.232 λ_0
Z_{oc1}/D_{c1}	135.16 Ω/0.212 λ_0	155.97 Ω/0.140 λ_0	120.75 Ω/0.405 λ_0	127.13 Ω/0.226 λ_0
Z_{oc2}/D_{c2}	154.13 Ω/0.297 λ_0	157.70 Ω/0.294 λ_0	92.05 Ω/0.313 λ_0	101.18 Ω/0.369 λ_0
Z_{oc3}/D_{c3}	172.81 Ω/0.191 λ_0	159.36 Ω/0.344 λ_0	121.51 Ω/0.206 λ_0	74.70 Ω/0.135 λ_0
Z_{oc4}/D_{c4}	159.23 Ω/0.174 λ_0	165.71 Ω/0.408 λ_0	175.72 Ω/0.106 λ_0	137.30 Ω/0.360 λ_0

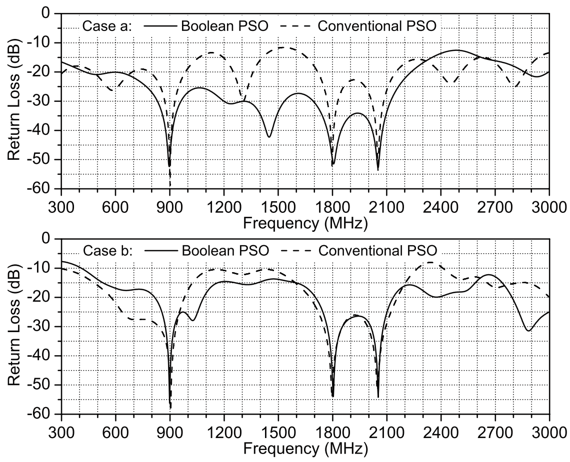

Fig. 2. Frequency response of the optimized dividers.

5 Conclusions

By applying BPSO, the requirements concerning the frequency response, the current-split ratios and the phase differences between the currents can be satisfied simultaneously at the operation frequencies of GSM, DCS and UMTS

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applications, despite the use of unequal real or complex terminal loads. For a given number of iterations, the BPSO results in dividers with better frequency response than a conventional PSO. Moreover, the proposed method is generic and can be used to optimize dividers at any three frequencies.

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