Çukurova Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, 31(ÖS 2), ss. ÖS 211-ÖS 220, Ekim 2016
Çukurova University Journal of the Faculty of Engineering and Architecture, 31(SI 2), pp. SI 211-SI 220, October 2016

Design of the Dual–Wideband Monopole Antenna for UMTS, WLAN and WiMAX Applications by using a Novel Hybrid Optimization Algorithm

Deniz ÜSTÜN[*1], Ali AKDAĞLI[2]

[1]*Mersin University, Tarsus Technology Faculty, Department of Software Engineering, Mersin*
[2]*Mersin University, Faculty of Engineering, Department of Electrical–Electronics Engineering, Mersin*

Geliş tarihi: 03.07.2016 *Kabul tarihi: 27.09.2016*

Abstract

In this study, a compact dual–wideband monopole antenna is proposed for the universal mobile telecommunications system (UMTS), wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMAX) applications. In order to obtain the desired operating frequency bands, UMTS (1.9–2.1 GHz), WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.5/3.5/5.5 GHz), a novel integration technique consisting of the HyperLynx® 3D electromagnetic (EM) platform based on the method of moments (MoM) and a new hybrid optimization algorithm (HOA) is utilized. The HOA is developed by integrating powerful mutation and crossover strategies of differential evolution (DE) algorithm with the onlooker bee phase of the artificial bee colony (ABC) algorithm. The monopole antenna is capable of producing two distinct operating bands. First impedance bandwidth of 2.48 GHz is from 1.44 to 3.92 GHz and second band having the bandwidth of 1.58 GHz is between 4.92 and 6.50 GHz. The proposed antenna has been designed, simulated and fabricated on $42\times49.2\times1.6$ mm^3 FR4 substrate with relative permittivity 4.4 and loss tangent 0.02. The better performance in terms of impedance matching is achieved, as compared to the double–or triple–band antennas previously published in the literature. In addition, the design antenna performs the omnidirectional radiation patterns with a good gain performance in the operating bands.

Keywords: Hybrid optimization method, Artificial bee colony (ABC), Differential evolution (DE), Dual–wideband monopole antenna

Yeni Bir Melez Optimizasyon Algoritması Kullanarak UMTS, WLAN ve WiMAX Uygulamaları için Çift–Geniş Bantlı Monopole Anten Tasarımı

Öz

Bu çalışmada, UMTS (universal mobile telecommunications system), WLAN (wireless local area network) ve WiMAX (worldwide interoperability for microwave access) uygulamaları için bir kompakt

[*]Sorumlu yazar (Corresponding author): Deniz ÜSTÜN, *denizustun@mersin.edu.tr*

çift–genişbantlı monopol anten önerilmiştir. UMTS (1,9–2,1 GHz), WLAN (2,4/5,2/5,8 GHz) ve WiMAX (2,5/3,5/5,5 GHz) uygulamalarında arzu edilen çalışma bantlarını elde etmek amacıyla, momentler metoduna dayalı HyperLynx® 3D elektromanyetik platformundan ve yeni bir melez optimizasyon algoritmasından (MOA) oluşan entegre yeni bir teknik kullanılmıştır. MOA, farksal gelişim (FG) algoritmasının güçlü mutasyon ve çaprazlama operatörlerinin, yapay arı kolonisi (YAK) algoritmasının izleyici arı fazına entegre edilmesi ile geliştirilmiştir. Modellenen anten iki ayrı çalışma bandı üretmiştir. Birinci banda ait genişlik, 1,44 GHz'den 3,92 GHz'e kadar toplam 2,48 Ghz'dir ve ikinci çalışma bandı ise 4,92 GHz'den 6,50 GHz'e kadar toplam 1,58 GHz'lik bir genişliğe sahiptir. Önerilen anten tasarımdan sonra benzetimleri gerçekleştirilmiş daha sonra, 4,4 dielektrik sabitli ve 0,02 tanjant kayıplı 42×49,2×1,6 mm^3 boyutlarında FR4 alttaş malzemesi kullanılarak üretilmiştir. Empedans eşlemesi açısından, daha önce literatürde yayınlanan çift ve üç bantlı antenlerle karşılaştırıldığında, önerilen antenin çok daha iyi bir performansa sahip olduğu görülmüştür. Bununla birlikte, çalışma bandları içinde tarsarlanan anten, çok iyi bir kazançla birlikte yönsüz bir radyasyon desenine sahiptir.

Anahtar Kelimeler: Melez optimizasyon metodu, Yapay arı kolonisi (YAK), Farksal gelişim (FG), Çift-geniş bant monopol anten

1. INTRODUCTION

The wireless communication technologies which are universal mobile telecommunications system (UMTS), wireless local area network (WLAN), and worldwide interoperability for microwave access (WiMAX) applications have rapidly developed in recent years. At the same time, due to the increasing application areas of multiband frequency microstrip antennas in the modern world, the most of microstrip antenna designs have focused on the structures of antenna integrating various frequencies into a single system. The microstrip antennas have various advantages such as small size, low cost, wide bandwidth, good radiation pattern, simplicity in fabrication and easy integration with microwave devices. Additionally, these antennas have been widely utilized in wireless communication applications to meet the multiband, wideband applications and size reduction operations. So far, numerous microstrip antennas have been proposed to reduce size, enhance bandwidth, obtain multiband characteristic [1–18]. Two different coplanar waveguide (CPW) fed monopole antennas embedded slots into the patch and ground plane have been reported for operating in WLAN [1,2]. The triple–band antennas designed by using defected ground structure were presented for the WLAN and WiMAX, respectively [3,4]. In Ref. [5], a multiband characteristic for WiMAX has been obtained by using a planar inverted L–shaped monopole antenna design with L–shaped parasitic strip. In Ref. [6], a monopole antenna designed by utilizing a modified fork–shaped strip has been reported for the multiple impedance bandwidths covering WLAN and WiMAX. In [7–9], the CPW-fed monopole antennas designed by using different strip geometries have been investigated to achieve the tri–band for WLAN/WiMAX applications. In Ref. [10], a novel, broadband, compact and slot antenna with a parasitic element and a grounded inverted L–shaped strip was reported for WLAN/WiMAX frequencies. In [11,12], the two microstrip antennas which have different geometries for WLAN and WiMAX have been presented to produce dual resonant modes, respectively. The novel microstrip antenna designs [13–16] with different geometric shapes have been investigated to achieve multiband operation covering the frequency bands of WLAN and WiMAX. In Ref. [17], a compact triband square–slot antenna for WLAN and WiMAX applications was reported, while a compact ACS–fed monopole antenna with open–ended have been presented to cover the WLAN and WiMAX operation bands [18]. Unfortunately, although above-mentioned microstrip antennas show good multiband performance, many of these have complex structure [3,11,15–18], large in size [2,10,12,14, 16]. In addition, most of these antennas do not cover whole frequency bands of WLAN and WiMAX. [1,2,4–9,11–17].

In terms of design success, the optimization performance of antenna parameters is one of the important factors in the antenna design process. With the development of the artificial intelligence optimization algorithms, the various methods involving these optimization algorithms have been applied to microstrip antennas [19–22]. In Ref [19], the multiband and wideband patch antennas were designed by using parallel particle swarm optimization and finite difference time domain (FDTD) algorithm. The optimized parameters of a rectangular microstrip antenna (RMSA) have been calculated by particle swarm optimization (PSO) algorithm [20]. The genetic algorithm (GA) based on biological evolution [21] was used to determine the optimum feed position of the probe–feed microstrip antenna. In Ref. [22], the broadband patch antenna was designed by using differential evolution (DE) algorithm and moment of the method (MoM). In addition, the resonant frequency of the microstrip antennas having various geometries has been calculated by using AI optimization methods [23–26].

In this study, a compact dual–band microstrip monopole antenna is proposed for UMTS, WLAN and WiMAX applications. The monopole antenna is designed by using a new and efficient hybrid optimization method based on the ABC [27–29] and DE [30] algorithms In order to obtain more effective search performance, the powerful mutation and crossover strategies of the DE algorithm were integrated to the onlooker bee phase of the ABC algorithm. The usage of the DE' method strategies improved the exploitation ability of the standard ABC algorithm while the kept employed bee phase as the standard ABC' updating strategy retains the exploration ability. In this manner, the between of exploitation and exploration was established a good balance during the search process for the good performance. Finally, the proposed hybrid optimization algorithm was tested on a set of four optimization benchmark functions and also compared with the optimization techniques like DE and ABC algorithms. The obtained results demonstrated that the proposed hybrid optimization technique was superior to both of standard the ABC and DE algorithms on the used benchmark functions. The developed hybrid optimization algorithm was integrated with HyperLynx® 3D electromagnetic (EM) platform [31] based on methods of moment (MoM) [32] and then a monopole antenna having a dual–wideband was designed by using this integrated modality. To this end, a RMSA is chosen as the starting antenna, the proposed method is then utilized to modify some geometrical parameters of this starting antenna to operate in the designed bands. Desired frequency bands are selected in complying with the applications of UMTS (1.9–2.1 GHz), WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.5/3.5/5.5 GHz). The HOA is relatively new and powerful optimization technique based on ABC and DE algorithm is used to find optimal solutions. The mask of desired bandwidth is utilized as an objective function in HOA to find the optimal or near optimal values of the antenna geometric parameters. The designed antenna is then fabricated and measured to evaluate the performance achievable. A successful comparison of the proposed antenna with the antennas previously published in the literature [1–18] is carried out with respect to operating frequency and bandwidth.

2. HYBRID OPTIMIZATION ALGORITHM (HOA) BASED ON ABC AND DE ALGORITHMS

ABC [27–29] algorithm is a swarm based optimization methods discovering near–optimal solutions for the optimization problems by the motivation foraging behavior of honey bees. In this optimization method, the model of the ABC algorithm consists of three different kinds groups of bees: employed bees, onlooker bees and scout bees. The virtual bees in the ABC fly around to search in a multidimensional solution space in order to discover the optimal solution of the optimization problem. The employed bees are assigned to specific food sources depending on experiences of themselves. The onlooker bees decide food source location based on watching the dance of employed bees within the hive and adjust position. Scout bees carry out a random search for determining the new food source. The proposed differential evolution (DE) algorithm by Storn and Price [30] applied to find the optimal solution of numerous optimization problems in different fields is improved by inspiring the natural evolution of species in the world. In the optimization process of a difficult problem, the DEA is obtained an excellent performance using expert knowledge. The hybrid process is performed in the Onlooker bees step of the ABC algorithm. By incorporating the above–mentioned powerful mutation and crossover steps of the DE, an optimization algorithm consisting of ABC and DE has been developed as a hybrid model. The standard DE algorithm has a good exploiting property owing to powerful mutation and crossover strategies and it can easily determine the regions of the desired global minimum or maximum in the search space. On the other hand, the standard ABC algorithm is generally faster at the exploration of the problem solution, however its exploitation ability is comparatively poor. Therefore, an effective hybrid optimization method by integrating mutation and crossover steps of the DE into the onlooker bees step of the ABC algorithm has been developed to provide the improving of the rectangular microstrip antenna bandwidth. Thus, this hybrid optimization technique can explore new possible solutions in the search space with the help of DE mutation and crossover abilities and exploit the population information by the employed bee operator of ABC algorithm. Hence, the exploration and exploitation problems can be overcome by using the powerful hybrid optimization technique consisting of the ABC and DE algorithms.

3. NUMERICAL RESULTS OF HYBRID OPTIMIZATION METHOD

The performance of the developed HOA is compared ABC and DE algorithms. The parameters of the used hybrid and other optimization techniques are given in Table 1.

Table 1. The parameters of optimization algorithms

Parameters	Algorithms		
	Hybrid	ABC	DE
Population Number	100	100	100
Max. Iteration/generation	3000	3000	3000
Evaluation number	300000	300000	300000
Trial number	*NP×D*	*NP×D*	-
Scale factor (*F*)	0.6	-	0.6
Crossover constant (*CR*)	0.4	-	0.4

NP: Number of population, D: Problem dimension

In order to evaluate performance of the hybrid optimization algorithm, four benchmark functions are used. All experiments are repeated 30 times independently for each test function. These functions are given in Table 2. In the Table 2, the search range of functions indicates a subset of SR, D is the dimensions of the benchmark functions and it is equal of 30 for all functions. C column is denoted characteristic of these functions. The minimum value of the chosen four benchmark functions for evaluating the performance of the algorithms is equal of zero. The functions 1, 2 are unimodal a high–dimensional functions while the benchmark functions 3, 4 are multimodal and high dimensional–functions. The mean results of thirty independent runs obtained in the experiment are shown in Table 3. It can be clearly seen from the experimental results that the HOA is significantly better than the DE algorithm. The multimodal functions have many local minimums. The HOA obtained the best results for the f_3, f_4 functions having multimodal property. The results show that the improved HOA can determine better optimal solutions than DE algorithms within the maximum number of the evolution number. Additionally, the HOA has a powerful ability to avoid from poor local optima and find a good near–global optimum. On the other hand, compared with ABC algorithm, the HOA is reached better solutions than ABC. It is oblivious that the performance of the proposed HOA is more effective than DE and ABC for the high–dimensional benchmark functions. Figure 1 shows the average convergence graphs of the used HOA, ABC and DE algorithms for the used some benchmark functions in the performance test. It is clear that the HOA has better performance than the ABC and DE algorithm for all functions. Especially, compared with the convergence of the ABC and DE algorithm, our hybrid technique is better fast and stable.

Table 2. The benchmark function used in the experiment

Functions	SR	C	Formulations
f_1 *Sumsquares*	[-10, 10]	US	$f_1 = \sum_{i=1}^{n} i x_i^2$
f_2 *Powell*	[-4, 5]	UN	$f_2 = \sum_{i=1}^{n/4} \left[\begin{array}{l} (x_{4i-3} + 10x_{4i-2})^2 \\ + 5(x_{4i-1} - x_{4i})^2 \\ + (x_{4i-2} - 2x_{4i-1})^4 \\ + 10(x_{4i-3} - x_{4i})^4 \end{array} \right]$
f_3 *Schwefel2.26*	[-500, 500]	MS	$f_3 = \sum_{i=1}^{n} - x_i \sin\left(\sqrt{\lvert x_i \rvert}\right)$
f_4 *Penalized1*	[-50, 50]	MN	$f_4 = \frac{\pi}{n} \left\{ \begin{array}{l} 10\sin^2(\pi y_1) \\ + \sum_{i=1}^{n-1} (y_i - 1)^2 \\ \times \left[1 + 10\sin^2(\pi y_{i+1})\right] \\ + (y_n - 1)^2 \end{array} \right\}$ $+ \sum_{i=1}^{n} u(x_i, 10, 100, 4)$ $y_i = 1 + \frac{1}{4}(x_i + 1)$

U: Unimodal, M: Multimodal, S: Separable, N: Non-Separable

Table 3. The comparative experimental results of HOA, ABC and DE algorithms

Functions	Algorithms	Mean	Standard deviation
f_1	ABC	4.95E-016	6.62E-017
	DE	1.41E-024	6.51E-025
	HOA	**1.74E-032**	**9.50E-033**
f_2	ABC	3.16E-003	4.26E-004
	DE	4.78E-011	2.16E-011
	HOA	**1.75E-014**	**1.06E-014**
f_3	**ABC**	-12569.5	2.87E-012
	DE	-10882.4	693.105
	HOA	**-12569.5**	**1.85E-012**
f_4	ABC	4.44E-016	7.84E-017
	DE	9.20E-024	5.08E-024
	HOA	**8.22E-032**	**4.63E-032**

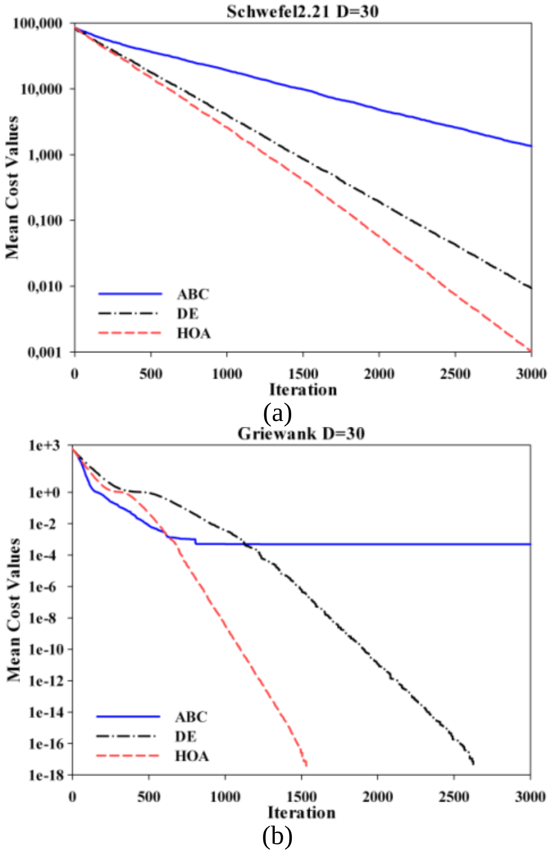


Figure 1. Average convergence performance of ABC, DE algorithms and HOA

4. ANTENNA DESIGN AND OPTIMIZATION

The antenna is constructed on a volume of 42 × 49.2 × 1.59 mm^3 FR4 substrate with dielectric constant 4.4 and loss tangent 0.02. Also, the antenna is excited by a microstrip line with 50 Ω impedance and signal strip width of 3 mm. The simulation process is performed by using packaged software named HyperLynx® [31] depended on the MoM [32]. Firstly, the design process has been started by using a monopole rectangular microstrip antenna. In order to obtain the desired bands corresponding UMTS, WLAN and WiMAX, the performance of impedance matching of the antenna has been improved by embedding slots into the patch and the ground. In this study, the aim is to design a compact dual–band microstrip antenna by using a novel efficient method consisting of the MoM technique with the HOA. HOA uses the fitness evaluation to find well a solution. Each mathematical expression used to evaluate the fitness is referred to as a fitness factor. In order to optimize the geometry of the last antenna structure with respect to the desired performance of impedance matching of the antenna, the mathematical formula given in (1) is used as fitness function which having fitness factors.

$$fitness\ function = \left\{ 1 - \left[\sum_{n=1}^{N} \frac{S_{11}(f(n))}{D(n)} + \sum_{n=1}^{N} G(n) \right] \right\} \qquad (1)$$

$$D(n) = \begin{cases} -40, & if\ f(n)=2.4,\ f(n)=3.5,\ f(n)=5.5\,GHz \\ -20, & other \end{cases} \qquad (2)$$

$$G(n) = \begin{cases} 1, & if\ S_{11}(f(n)) \le -10\ dB \\ 0, & if\ S_{11}(f(n)) > -10\ dB \end{cases} \qquad (3)$$

Here, n=1, 2, …, N for $f(n)$ = {1.7, 1.8, 1.9, 2.0, 2.1, 2.4, 2.5, 3.5, 5.2, 5.5, 5.8} GHz frequencies and N is the number of the fitness factor and is equal of value 11. The methodology of the used method combining HyperLynx® 3D electromagnetic (EM) platform [31] based on the method of moments (MoM) [32] and HOA is illustrated in Figure 2. At first, the initial parameters such as colony size, trial and iteration numbers of the HOA was set, and the possible solutions of the antenna geometric parameters are randomly determined as defined in the initial phase of the HOA. The geometry of the antenna is then simulated for those of each solution points by using HyperLynx® 3D electromagnetic (EM) platform [31] based on the method of moments (MoM) [32]. The fitness function is evaluated by considering the results of MoM. Eventually, the best solution which is closest to the desired performance of impedance matching of the antenna is memorized for every iteration. The solutions are being recursively enhanced by a specified iteration number.

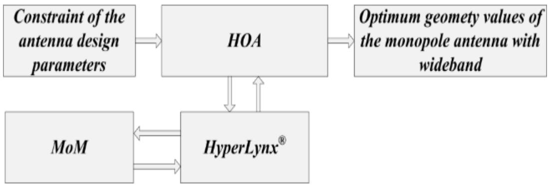


Figure 2. The antenna design and optimization methodology

Design parameters of the proposed antenna were given in Figure 3. The design parameters for a compact dual–band microstrip antenna are tabulated in Table 4. The values of optimization algorithmic parameters in the HOA are chosen as follows: population size (NP) = 100, food number = 50, F=0.6 (scale factor), CR=0.4 (Crossover rate), trial value = $NP \times D$. D is the number of the antenna design parameter. The maximum iteration number is set to 2000. The optimum values of the antenna are found by using the proposed optimization method. The optimized values of geometric parameters are listed in Table 5.

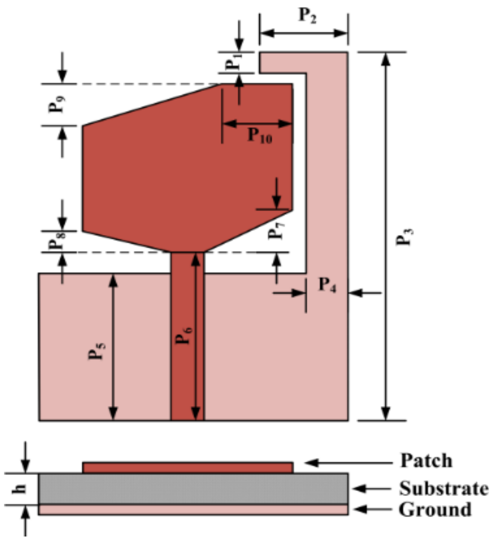


Figure 3. The last structure and design parameters of the proposed antenna

Table 4. Lower and upper bounds of the design Parameters (in mm) for compact dual–band monopole antenna

Bounds	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
Lower	10	35	55	7	20	20	8	8	10	15
Upper	1	0	0	1	10	10	0	0	0	0

Table 5. Values of the geometric parameters (in mm) for optimized compact dual–band monopole antenna

P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
2.7	3	49.2	3.1	13.4	16.2	4.3	1.9	8.2	11.5

The simulated and measured return loss curves of the final (optimized) and the antenna are given in Figure 4. The final antenna has two different operating bandwidths with S_{11}<-10 dB. The first operating frequency interval having a bandwidth of 2.1 GHz is between 1.74 and 3.84 GHz and second operation band which has between 4.85 and 6.5 GHz have a bandwidth of 1.65 GHz. Finally, the desired performance of the proposed antenna is reached by using optimization technique based on HOA integrated in MoM method. The optimized antenna with the dimensions given in Table 5 has been successfully fabricated to test the accuracy of the optimization method in practical patch antenna designs. The return loss of the development antenna was measured with an Agilent E5071B ENA Series RF network analyzer. It can be clearly seen that there is a good agreement between the measured and simulated results. Some discrepancies between the measured and simulated results can be attributed to the substrate variations, fabrication tolerances, and feed connector misalignment. The photographs of the fabricated antenna are shown in Figure 5.

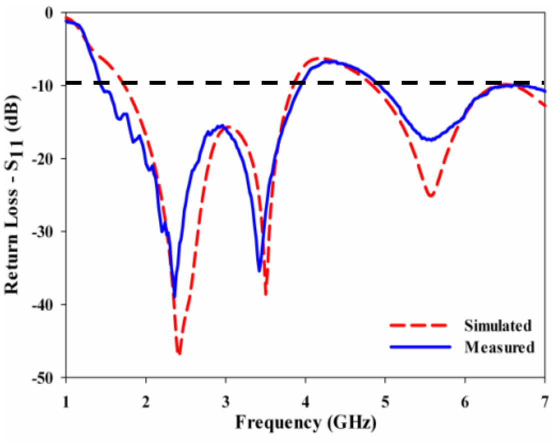
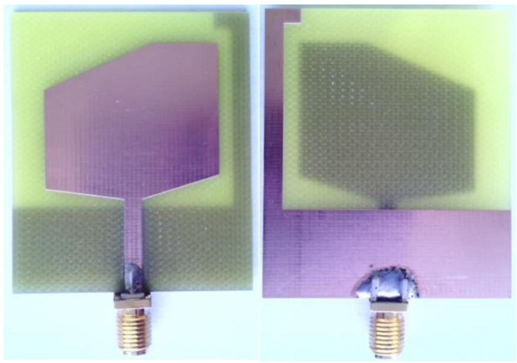


Figure 4. The measured and simulated return loss curves for the antenna

Table 6. Reported multiband antennas in the literature

References	UMTS (1.9–2.1) GHz	WLAN (2.4/5.2/5.8) GHz	WiMAX (2.5/3.5/5.5) GHz
[1]	-	(2.4/5.2/5.8)	-
[5]	-	-	(2.5/3.5/5.5)
[11]	-	(2.4/5.2/5.8)	(2.5/3.5/5.5)
[12]	-	(5.2/5.8)	(3.5/5.5)
[17]	-	(2.4/5.2)	(2.5/3.5)
Proposed Antenna	**(1.9–2.1)**	**(2.4/5.2/5.8)**	**(2.5/3.5/5.5)**



(a) (b)

Figure 5. The photographs of the fabricated antenna : (a) Top plane and (b) Bottom plane

Measured return loss of the proposed antenna shown that the impedance bandwidth of the two distinct operating bands with –10 dB return loss were about 2.48 GHz (1.44–3.54 GHz) and 1.58 GHz (4.92–6.50 GHz) which are wide enough to cover the desired bandwidths of UMTS, WLAN and WiMAX applications. It is clearly seen that the proposed antenna obtained better results, when the obtained measurement result compared to previously proposed multiband antennas results in the Table 6 in terms of operation bands covering the frequencies of UMTS, WLAN and WiMAX applications. Figure 6 demonstrates the antenna radiation patterns at 2.4, 3.5 and 5.5 GHz. The symmetrical radiation patterns are seen in the *x–z* and *y–z* planes as depicted in the Figure 6. In addition, the radiation patterns with nearly omnidirectional radiation pattern are observed for these frequencies.

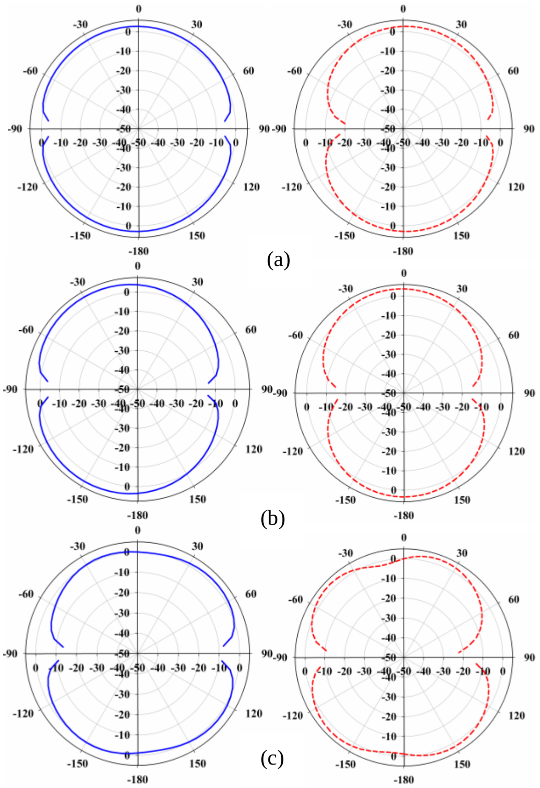


Figure 6. Radiation patterns of the proposed antenna for different frequencies: (a) 2.4 GHz, (b) 3.5 GHz and (c) 5.5 GHz *x–y* plane (▬▬▬), *y–z* plane (- - - - -)

The gain of the antenna is illustrated in Figure 7. It has been observed from Figure 6 that the gain at 2.4, 3.5 and 5.5 GHz are 1.84, 2.6 and 0.7 dBi, respectively. According to the gain curve, there is gain reduction at 5.5 GHz compared to the other frequency bands because of current is distributed in more than one frequency.

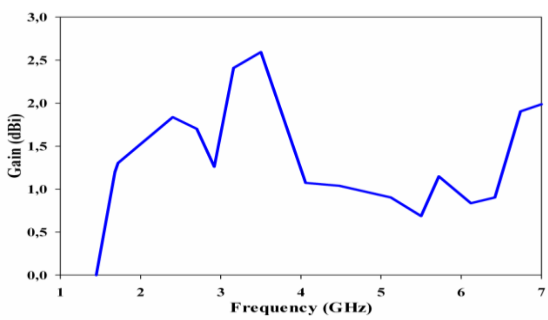


Figure 7. Gain of the proposed antenna

5. CONCLUSION

A novel dual–band microstrip antenna design based on the patch monopole for UMTS, WLAN and WiMAX applications has been proposed with simulated and measured results. In this antenna design, in order to achieve the required bands of the UMTS, WLAN and WiMAX applications, the different methods which are the cutting the patch and embedding slots into the ground has been applied to the geometry of the antenna. According to obtained results, there is close agreement between the measurement and simulation results. The proposed antenna has the capable of producing two distinct operating bands with –10 dB return loss. The operating bands were about 2.48 GHz (1.44–3.54 GHz) and 1.58 GHz (4.92–6.50 GHz). In addition, it also ensures the gain of 1.84, 2.6 and 0.7 dBi for 2.4, 3.5 and 5.5 GHz, respectively. The antenna radiation pattern with nearly omnidirectional has been obtained. As a result, the proposed design can be a suitable antenna for using in UMTS, WLAN and WiMAX applications.

6. ACKNOWLEDGEMENTS

The authors are thankful to Dr. Abdurrahim Toktas for his precious help and performing antenna simulations through the HyperLynx® 3D EM platform in Karamanoglu Mehmetbey University.

7. REFERENCES

1. Liu, W.C., Wu, C.M., Chu, N.C., 2010. A Compact CPW–fed Slotted Patch Antenna for Dual-band Operation, IEEE Antennas Wireless Propag Lett., 9, 110–113.

2. Huang, C.Y., Yu, E.Z., 2011. A Slot–monopole Antenna for Dual–band WLAN Applications, IEEE Antennas Wireless Propag Lett., 10, 500–502.

3. Pei, J., Wang, A., Gao, S., Leng, W., 2011. Miniaturized Triple–band Antenna with a Defected Ground Plane for WLAN/WiMAX Applications, IEEE Antennas Wireless Propag Lett., 10, 298–302.

4. Liu, W.Ch., Wu, Ch, M., Dai, Y., 2011. Design of Triple–frequency Microstrip–fed Monopole Antenna using Defected Ground Structure, IEEE Trans Antennas Propag, 10, 2457–2463.
5. Lu, J.H., Huang, B.J., 2010. Planar Multi–band Monopole Antenna with L–shaped Parasitic Strip for WiMAX Application, Electron Lett., 47, 671–672.
6. Xu, P., Yan, Z.H., Wang, C., 2011. Multi–band Modified Fork–shaped Monopole Antenna with Dual L–shaped Parasitic Plane, Electron Lett., 47, 364–365.
7. Liu, P., Zou, Y., Xie, B., Liu, X., Sun, B., 2012. Compact CPW–fed Tri–band Printed Antenna with Meandering Split–ring Slot for WLAN/WiMAX Applications, IEEE Antennas Wireless Propag Lett., 11, 1242–1244.
8. Xu, Y., Jiao, Y.C., Luan, Y.C., 2012. Compact CPW–fed Printed Monopole Antenna with Triple–band Characteristics for WLAN/WiMAX Applications, Electron Lett., 48, 1519–1520.
9. Iddi, H.U., Kamaruddin, M.R., Rahman, T.A., Abdulrahman, A.Y., Khalily, M., Jamlos, M.F., 2013. Triple–band CPW–fed Planar Monopole Antenna for WLAN/WiMAX Application, Microwave Opt Technol Lett., 55, 2209–2214.
10. Pouyanfar, N., 2014. Broadband CPW–fed Square Slot Antenna Loaded with Parasitic Element for WLAN/WiMAX Applications, Microwave Opt Technol Lett., 56, 338–340.
11. Yoon, J.H., Kil, G.S., 2012. Compact Monopole Antenna with Two Strips and a Rectangular–slit Ground Plane for Dual–band WLAN/WiMAX Application, Microwave Opt Technol Lett., 54, 1559–1566.
12. Kaur, J., Khanna, R., 2014. Development of Dual–band Microstrip Patch Antenna for WLAN/MIMO/WiMAX/AMSAT/WAVE Applications, Microwave Opt Technol Lett., 56, 988–993.
13. Huang, H.F., Zhang, S.F., 2014. Compact Multiband Monopole Antenna for WLAN/WiMAX Applications, Microwave Opt Technol Lett., 56, 1809–1812.
14. Malekpoor, H., Jam, S., 2013. Design of Multi–band Asymmetric Patch Antenna for Wireless Applications, Microwave Opt Technol Lett., vol. 55, pp. 730–734.
15. Hu, W., Yin, Y.Z., Yang, X., Fei, P., 2013. Compact Multi Resonator–loaded Planar Antenna for Multiband Operation, IEEE Trans. Antennas Propag, 61, 2838–2841.
16. Yuan, Z.X., Yin, Y.Z., Ding, Y., Li, B., Xie, J.J., 2012. Multiband Printed and Double–sided Dipole Antenna for WLAN/WiMAX Applications, Microwave Opt Technol Lett., 54, 1019–1022.
17. Hu, W., Yin, Y.Z., Fei, P., Yang, X., 2011. Compact Triband Square–slot Antenna with Symmetrical L–strips for WLAN/WiMAX Applications, IEEE Antennas Wireless Propag Lett., 10, 462–465.
18. Li, X., Shi, X.W., Hu, W., Fei, P., Yu, J.F., 2013. Compact Triband ACS–fed Monopole Antenna Employing Open–ended Slots for Wireless Communication, IEEE Antennas Wireless Propag Lett., 12, 388–391.
19. Jin, N.B., Rahmat–Samii, Y., 2005. Parallel Particle Swarm Optimization and Finite Difference Time Domain Algorithm for Multiband and Wideband Patch Antenna Designs, IEEE Trans Antennas Propag, 53, 3459–3468.
20. Yilmaz, A.E., Kuzuoglu, M., 2007. Calculation of Optimized Parameters of Rectangular Microstrip Patch Antenna Using Particle Swarm Optimization, Microwave Opt Technol Lett., 49, 2905–2907.
21. Namkung, J., Hines, E.L., Green, R.J., Leeson, M.S., 2007. Probe–feed Microstip Antenna Feed Point Optimization using a Genetic Algorithm and the Method of Moments, Microwave Opt Technol Lett., 49, 325–329.
22. Zhang, L., Cui, Z., Jiao, Y.C., Zhang, F.S., 2009. Broadband Patch Antenna Design using Differential Evolution Algorithm, Microwave Opt Technol Lett., 51, 1692–1695.
23. Toktas, A., Bicer, M.B., Kayabasi, A., Ustun, D., Akdagli, A., Kurt, K., 2015. A Novel and Simple Expression to Accurately Calculate the Resonant Frequency of Annular–ring Microstrip Antennas, International Journal of Microwave and Wireless Technologies, 7, no. 6, 727–733.
24. Toktas, A., Akdagli, A., 2012. Computation of Resonant Frequency of E–Shaped Compact Microstrip Antennas, Journal of the Faculty of

Engineering and Architecture of Gazi University, 27, 847–854.

25. Toktas, A., Bicer, M.B., Akdagli, A., Kayabasi, A., 2011. A Simple Formulas for Calculating Resonant Frequencies of C and H Shaped Compact Microstrip Antennas Obtained by Using Artificial Bee Colony Algorithm, Journal of Electromagnetic Waves and Applications, 25, 1718–1729.

26. Toktas, A., Akdagli, A., 2010. A Novel Expression in Calculating Resonant Frequency of H–Shaped Compact Microstrip Antennas Obtained by using Artificial Bee Colony Algorithm, Journal of Electromagnetic Waves and Applications, 24, 2049–2061.

27. Karaboga, D., 2010. Artificial Bee Colony Algorithm, Scholarpedia 5 (3) 6915 from www.scholarpedia.org/article/Artificial.bee.colony.algorithm.

28. Karaboga, D., 2005. An Idea Based on Honey Bee Swarm for Numerical Optimization, Technical Report–TR06, Erciyes University, Engineering Faculty, Computer Engineering Department.

29. Karaboga, D., Gorkemli, B., Ozturk C., Karaboga, N., 2012. A Comprehensive Survey: Artificial Bee Colony (ABC) Algorithm and Applications, Artif.Intell. Rev. (ex. 15.05.2016) from http://dx.doi.org/10.1007/s10462-012-9328-0.

30. Storn, R., Price, K., 1997. Differential Evolution–a Simple and Efficient Heuristic for Global Optimization Over Continuous Spaces, J Global Optim., 1, 1341–359.

31. HyperLynx® 3D EM. Version 15. Mentor Graphics Corporation, Wilsonville (OR).

32. Harrington, R.F., 1993. Field Computation by Moment Methods, Piscataway (NJ): IEEE Press.