IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 29, 2019, accepted December 12, 2019, date of publication January 1, 2020, date of current version January 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2963644

Novel Wideband Microstrip Monopole Antenna Designs for WiFi/LTE/WiMax Devices

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ABSTRACT In this paper, two compact and broadband microstrip monopole antennas have been proposed, designed, and presented using two novel sets of design equations. Each monopole antenna design has different dimension and characteristic. The proposed designs have been verified using a commercial electromagnetic simulator (CST-Studio) and implemented prototypes mounted on FR-4 substrate having a thickness of 1.6 mm. In addition, a linear array consists of only two monopole elements has been designed and presented to enhance the gain of the proposed monopole antenna. Simulation results confirmed the validity of the two novel sets of design equations for both monopole and array antennas. Also, the proposed array antenna (38×36 mm^2 size), achieved a moderate gain of (6.0 dBi), a satisfying efficiency of (81%), a VSWR that is less than 1.2 and a 22% fractional bandwidth of about 1200 MHz. Moreover, simulated and measured return losses of the proposed monopole antennas (single and array) accomplish a reasonable agreement. The proposed monopole antennas are simple designs and compact in size, and they can be used for many wireless applications including WiFi, LTE, and WiMax. In addition, a compact array of large monopole number can achieve a higher gain that is up to 18 dBi (four to eight monopole array elements with overall size 38×72 mm^2 to 38×144 mm^2). The novelty of this paper is by introducing the proposed and closed form design equations for a monopole introducing the length of monopole and ground of substrate dimensions as a function of ϵ_r and thickness.

INDEX TERMS Microstrip antenna, broadband monopole antenna, dual band monopole antenna, compact monopole.

I. INTRODUCTION

Over the past few years, software and hardware development of communication systems has been rapidly growth to cover many wireless applications. This includes broadband (BB), wideband (WB), and ultra-wideband (UWB) microwave transceivers. Planar multiband antenna structures (microstrip (MS), coplanar waveguide (CPW), and stripline (SL)) become very popular antennas due to their compact sizes, low cost, less weight, and easy to install with the current microwave wireless devices as compared to the conventional wire antennas (helical, yagi-Uda and spiral) [1]–[4]. In fact, a great deal of attentions has been received for designing an efficient multiband antenna module to achieve the desired characteristic within the effective operating frequency band. Moreover, multiband antennas have a great advantage of using filter circuits to suppress band interferences. Compact printed microstrip monopole antennas are one of the most important and current multiband antenna structures which can be used for many wireless applications including GPS, WLAN, RFID, LTE, WiMax and UWB. In addition, microstrip antenna configuration has superior advantages over the other planar structures (CPW/SL) including easy fabrication and excellent compatibility with the modern microwave circuits. On the other hand, several printed monopole antenna structures were proposed, analyzed, and reported to include many wireless applications [5]–[15]. Some of these antennas are broadband/wideband microstrip monopole structures to cover several applications including WLAN and WiMax [5]–[8]. These monopole antennas cover only a single frequency band to achieve multiband operation, and they are mounted on a

The associate editor coordinating the review of this manuscript and approving it for publication was Lu Guo.

compact substrate of average dimensions 45×74 mm^2. Other group of monopole antennas is dual band microstrip configurations covering GPS, UMTS, IMT200, Bluetooth, WiBRO, 802.11b/g and 802.11a [9]–[11]. These antennas cover a dual broadband with advantage of average compact substrate dimensions of 33×32 mm^2. A planar monopole microstrip antenna loaded with composite right/left-handed transmission line (CRLH-TL) for broadband LTE mobile phone was proposed, analyzed and fabricated [12]. This antenna covers LTE700/2500, GSM850/900/1800/1900, UMTS2100 and WLAN2400 frequency bands, and it is etched on a single substrate of dimensions 16×60 mm^2. The last group of multiband antennas is dual/triple frequency bands covering the standard WLAN and WiMax frequency bands [13]–[15]. There are several issues should be considered in designing an efficient multiband monopole antenna. This includes overall antenna dimensions, effective percentage bandwidth, average dBi gain, average efficiency and desired radiation pattern. Therefore, these parameters should be investigated and optimized to achieve the required application target.

In this paper, a compact and broadband microstrip monopole antenna has been firstly proposed, analyzed, and experimental verified using a fabricated prototype_I and it is referred to as Compact Microstrip Antenna (CMP) antenna. Second, a compact and broadband microstrip monopole linear array antenna has been proposed and experimental verified using a fabricated prototype_II, and it is referred to as MPA antenna. A full-wave electromagnetic simulator (CST-microwave Studio ver. 2012) is used to simulate, investigate, and optimize the proposed monopole antennas. The presented paper is organized as follows. Section 2 presents the detailed description and the design equations of our proposed microstrip monopole (MPA)& CMP antennas. Simulation results of proposed monopole antennas (return loss, gain in dBi, percentage bandwidth, VSWR, and radiation pattern in E and H planes) are presented, investigated and discussed in Section 3. A detailed parametric analysis of the key dimensions of the proposed monopole is also presented, investigated, and optimized in Section 3. In addition, the experimental results of the fabricated hardware antennas (CMP and MPA) are compared to the simulated results, and they are also presented at the end of Section 3. Finally, Section 4 concludes presented paper.

II. PROPOSED MONOPOLE ANTENNAS: DISCRIPTION AND DESIGN

In this section, two compact and broadband microstrip monopole antennas have been proposed, designed, and presented.These are single compact monopole antenna (CMP) and compact linear array antenna of two monopole elements (MPA). The proposed monopole antennas are mounted on FR-4 substrate (height h of 1.6mm, tangential loss δ of 0.025, dielectric constant ϵ_r of 4.7 and conductor thickness T of 0.035mm), and they are fed by a transmission of width W_1 and length L_1 (50.0Ω line). First: the proposed microstrip monopole antenna (CMP) and its dimension symbols are show in Figure 1. The length of the proposed monopole L_m is given by:

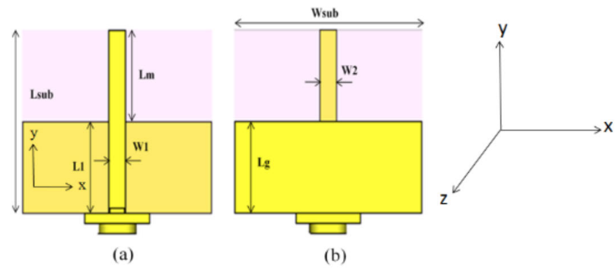

FIGURE 1. Proposed microstrip monopole antenna (CMP) structure in x-y plane: (a) Top view (b) Bottom view.

$$L_e < L_m < L_o \tag{1a}$$

L_o denotes the free-space quarter wavelength

$$\left(L_o = \frac{\lambda_o}{4} = \frac{c}{4f_o}\right)$$

L_{sg} denotes the substrate guided quarter wavelength

$$\left(L_{sg} = \frac{\lambda_{sg}}{4} = \frac{c}{4f_o\sqrt{\epsilon_{sub}}}\right)$$

L_{eg} denotes the effective guided quarter wavelength

$$\left(L_{eg} = \frac{\lambda_{eg}}{4} = \frac{c}{4f_o\sqrt{\epsilon_{eff}}}\right)$$

L_e denotes the average effective quarter wavelength

$$\left(L_e = \frac{\lambda_e}{4} = \frac{L_{sg} + L_{eg}}{2}\right)$$

$$\epsilon_{eff} = 0.5(\epsilon_r + 1) + 0.5(\epsilon_r - 1)\left(1 + 12\left(\frac{h}{W_1}\right)\right)^{-0.5} \tag{1b}$$

where ϵ_{eff} denotes the effective dielectric constant of the conventional microstrip transmission line.

First set of design equations (2a, 2b and 2c) are proposed and verified by simulation and further proof is done by the fabrication and measurement. Dimensions of the compact microstrip monopole antenna including substrate length L_{sub}, substrate width W_{sub}, and partial ground length L_g are calculated based on two novel sets of proposed design equations. These equations sets are referred to as the first design set (Dgn. #1) and the second design set (Dgn. #2) respectively. The first set of the design equations is given by:

$$W_{sub} = 2.5L_m \tag{2a}$$
$$L_{sub} = 2L_m \tag{2b}$$
$$L_g \geq L_m, \tag{2c}$$

and the design equations of the second set are given by:

$$W_{sub} = 2L_m - T_w \tag{3a}$$
$$L_{sub} = L_g + L_m \tag{3b}$$

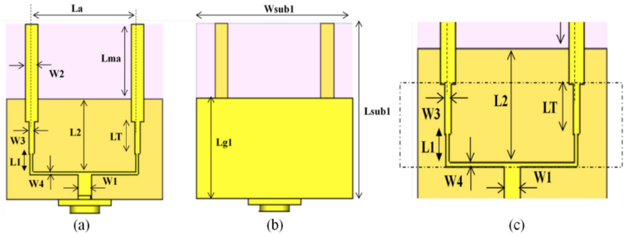

FIGURE 2. Proposed Linear array of monopole antenna (MPA) structure in x-y plane: (a) Top view (b) Bottom view and (c) Zoom view of power divider and matching circuit (PDAMC).

$$\frac{L_m}{4} \leq T_w < \frac{L_m}{2} \tag{3c}$$
$$\frac{L_m}{4} \leq L_g < L_m \tag{3d}$$

where, the parameter T_w is used to optimize the substrate width, while the parameters L_g and L_m are used to control the antenna resonance frequency as well as the operating bandwidth. Second: the compact and broadband microstrip monopole array (MPA) antenna with indicated dimension symbols is shown in Figure 2. In this case the monopole array length L_{ma} is given by:

$$L_{ma} = L_m + \Delta L_m \tag{4a}$$
$$\frac{L_m}{8} < \Delta L_m < \frac{L_m}{2} \tag{4b}$$

In fact, ΔL_m can be precisely determined using the optimizer of the CST simulator (parametric study). Dimensions of the proposed microstrip monopole array antenna (MPA) including substrate length L_{sub1}, substrate width W_{sub1}, and partial ground length L_{g1} are given by:

$$W_{sub} < W_{sub1} < \left(\frac{W_{sub}}{2} + 2(N-1)L_{ma}\right) \tag{5a}$$
$$L_{sub} = L_{g1} + L_{ma} \tag{5b}$$
$$L_{g1} = 2L_g + L_T + L_1 + W_4 \tag{5c}$$

The equations are derived and then proved using the simulation and the measurement results. So for example equation (1b) that is used to calculate the value of (Eeff) was used after that to show a relation between the (Er) and the length. The simulation and measurement results show that the relation between (Eeff) and the length checks & The proposed designing equations are only for single element. The array designed follows the standard rules, including the spacing and matching circuits. Where, N is the array dimension (number of elements), and W_{sub} is substrate width of a single monopole either Dgn. #1or Dgn. #2 as given by Eq. (2) and Eq. (3) respectively. The partial ground length of the single monopole L_g is extended to accommodate additional space for the power divider and matching circuit (PDAMC, see Figure 2(c)). This circuit has U_shape transmission line with stepped arms of equal lengths designed as $\frac{\lambda_{sg}}{4}$ transformer to match each monopole element. The design parameters of PDAMC are L_T, L_1, W_3, and W_4. The line width W_4 is designed to have about 100Ω independent on its length (line impedance of power divider), while the line width W_3 (quarter wavelength transformer) is designed to provide an optimum matching (minimum reflection) for each the monopole elements. In addition, the line of length L_1 and width W_4 is used to fine adjust the matching. These parameters are first calculated and then they are together optimized through extensive parametric study. The word optimization means the MPA achieve the same CMP characteristic but with enhanced gain.

TABLE 1. Parameters values (in mm) of Eq. (1) for FR-4 substrate.

Quarter Wavelength (in mm)	$F_1 = 3.0$ GHz	$F_2 = 5.0$ GHz
L_o	25.0000	15.0000
L_{sg}	11.5316	6.9190
L_{eg}	13.3062	7.9803
L_e	12.4150	7.4490

TABLE 2. Optimized dimensions (in mm) of the CMP (F1 and F2) based on the proposed design equations (Eq. (2) and Eq. (3)).

	Dgn.#1		Dgn.#2	
	F_1	F_2	F_1	F_2
L_m	18.3	11.65	19.55	12.15
L_g	18.3	11.65	13.0	5.0
T_w	-	-	7.0	5.0
L_{sub}	$2.0L_m$	$2.0L_m$	$L_m + L_g$	$L_m + L_g$
W_{sub}	$2.5L_m$	$2.5L_m$	$2L_m - T_w$	$2L_m - T_w$
W_1	3.0	3.0	3.0	3.0
W_2	3.0	3.0	3.0	3.0
ϵ_r	4.7	4.7	4.7	4.7
ϵ_{eff}	3.53	3.53	3.53	3.53
h	1.6	1.6	1.6	1.6

The presented monopole designs have been verified and optimized for two center frequencies having the required bandwidth of WiFi, LTE and WiMax applications (center frequencies: $F_1 = 3.0$ and $F_2 = 5.0$ GHz). The values of the parameters defined in Eq. (1) in case of FR-4 substrate ($\epsilon_r = 4.7$) are calculated for F_1 and F_2, and they are listed in Table 1 respectively. The parameter values of L_o and L_e in Eq. (1a) represent the upper and lower limits of the designed monopole length respectively. The optimized dimensions of the proposed microstrip monopole antennas (CMP and MPA) are listed in Table 2 and Table 3 respectively.

III. SIMULATION RESULTS AND EXPERIMENTAL VERFICATION

This section presents design, simulation, evaluation, investigation, and experimental verification of two proposed microstrip monopole types. These types are CMP and MPA as presented in Figure 1 and Figure 2 respectively. Two proposed designs of the presented CMP antenna have been simulated and investigated using the microwave simulator (CST-Studio) for the dimensions listed in Table 1. These dimensions have been calculated based on the two proposed sets of design equations (Eq. (1) through Eq. (3)), and they are optimized through a full parametric study. Results of simulation are

TABLE 3. Optimized dimensions (in mm) of the proposed monopole array (MPA: Dgn. #2 at F2) based on the proposed design equations (Eq. (2) through Eq. (5)).

Parameter	Value
W_{sub1}	36
W_1	3
W_2	3
W_3	1.2
W_4	0.6
L_{sub1}	38
L_m	12.15
ΔL_m	4.15
L_a	24.4
L_1	4.6
L_2	15.8
L_T	6.8
L_{g1}	21.7
T_w	6.4

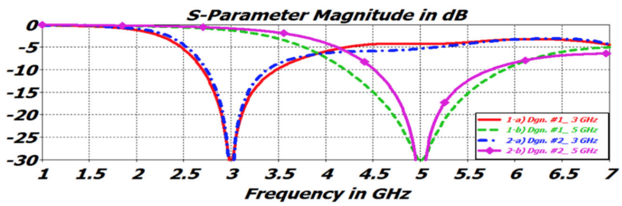

FIGURE 3. $|S_{11}|$ in dB of the proposed CMP antenna with dimension listed in Table 2 for the proposed designs given by Eq. (1) through Eq. (3).

presented in Figure 3. As it is clear from this figure that the proposed monopole antennas (CMP Dgn. #1 and CMP Dgn. #2) resonate at the desired frequencies F_1 and F_2 with broad bandwidth. In addition, CMP Dgn. #1 provides a slight larger bandwidth than CMP Dgn. #2 at F_1. As the center frequency increases the difference in bandwidth also increases; however, the second design is more compact in size (Dgn. #1: $W_{\text{sub}} = 29.13$mm & $L_{\text{sub}} = 23.24$mm and Dgn. #2: $W_{\text{sub}} = 19.3$mm & $L_{\text{sub}} = 17.15$mm at F_2). Therefore, a compromise should be considered to select the required design. The radiation pattern of the proposed monopole is computed in E- and H plane (E-plane (y-z): $\Phi = 90°$ & H-plane (x-z): $\Phi = 0°$), and it is presented in Figure 4. An excellent Omni-directional pattern is achieved over the entire frequency band in case of the two proposed designs; however, a little pattern distortion and asymmetry of Dgn. #1 and Dgn #2 at F_2 is obtained (Figure 4(b) and (d)) due to the finite ground plane. Also, the proposed CMP achieved low VSWR and excellent efficiency; however, the maximum gain is quite low (2.5 to 3.0 dBi). A performance summary of the two monopole designs is presented in Table 4.

As it is previously shown, the maximum gain achieved by CMP is quite low. Therefore, a linear array of two monopole elements has been proposed, designed, simulated, and presented. A U-shape power divider and matching circuit (PDAMC) is designed with parameters L_T, L_1, W_3, and W_4. Each element is fed with transmission line of quarter wavelength ($\frac{\lambda_{sg}}{4}$) L_T and a width W_3 to step down from

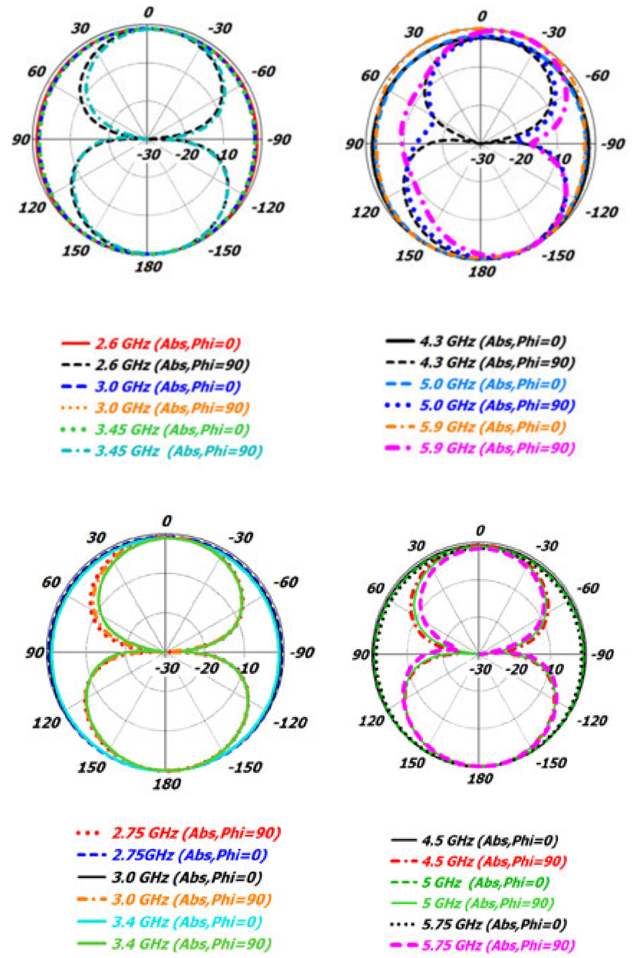

FIGURE 4. Radiation pattern in E-and H planes (y-z and x-z planes) of the proposed CMP antenna with dimensions listed in Table 2: (a) and (b) Dgn. #1 at F_1 and F_2 respectively; (c) and (d) Dgn. #2 at F_1 and F_2 respectively.

TABLE 4. Optimized characteristic and substrate dimensions (mm) of proposed monopole antennas (CMP Dgn. #1 and CMP Dgn. #2).

		Dgn. #1	Dgn. #2
CMP at F_1	BW (MHz)	850	650
	Tot. ϵ_{eff}%	95	94
	Tot. G_o dBi	3.0	2.8
	L_{sub}%	36.6	32.1
	W_{sub}%	45.75	32.55
CMP at F_2	BW (MHz)	1600	1200
	Tot. ϵ_{eff}%	90.0	93.0
	Tot. G_o dBi	2.9	2.5
	L_{sub}%	23.24	17.15
	W_{sub}%	29.13	19.30

78.11Ω to 50Ω. The PMAMC is fed with a line of width W4 to step up from 50Ω to 100.3Ω, and then with a line of length L1 and width W4 to step down from 100.3Ω to 78.11Ω. The spacing between elements La is assumed to be within quarter to half wavelength (λ_o) and it is optimized. In addition, the length of the monopole antenna in array configuration L_{ma} is quite increased by smaller

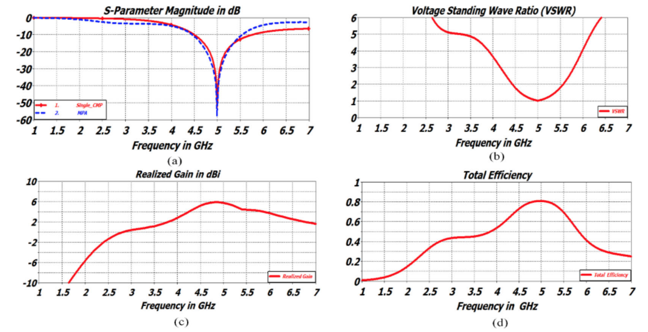

FIGURE 5. Simulated characteristic of proposed monopole array antenna MPA of dimension listed in Table 3: (a) $|S_{11}|$ in dB (b) VSWR (c) Maximum Realized 3-D gain in dBi and (d) Total Efficiency in percentage.

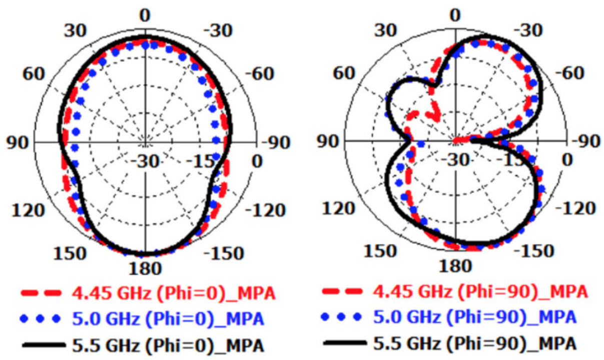

FIGURE 6. Radiation pattern in H-and E planes (x-z and y-z planes) of proposed monopole array (MPA) with dimensions listed in Table 3 respectively: (a) H-plane (a) E-plane.

value (ΔL_{ma}) to maintain the same resonance frequency as the single monopole (Eq. (4)). Therefore, these parameters (L_a, L_T, L_{ma}, L_1, W_3, and W_4) are calculated and optimized, and they are listed in Table 3. Results of simulation are shown in Figure 5(a) through Figure 5(d). It is clear from Figure 5(a) the designed array antenna (MPA) achieved the same resonance frequency as well as the operating frequency band as the proposed CMP antenna. Moreover, low VSWR (Less than 1.2), moderate high gain (6.0 dBi), and good efficiency (81%) have been achieved as shown in Figure 5(b) through Figure 5(d). On the other hand, the radiation pattern is approximately directional pattern (asymmetric pattern of eight figure in E-plane and elliptical pattern in H-plane) as shown in Figure 6. The pattern discrepancies are mainly due to effects of mutual coupling and mismatch (reflections due to PDAMC).

A detailed parametric study has been conducted to verify the validation of our proposed sets of design equations given by Eq. (2) and Eq. (3) along with condition defined in Eq. (1). This study includes the most important design parameters (key parameters). In fact, substrate type (SuBTyPE) is one of the most important parameter needs to be investigated to check the validation of the proposed design equations. Table 5(a) summarizes the key design parameters (KDP) for each proposed microstrip monopole antenna designs.

TABLE 5. Key design parameters and optimized CMP dimensions: (a) Key design parameters (b) CMP designed dimensions for SuBTyPE Dgn. #1 and (c) CMP designed dimensions for SuBTyPE Dgn. #2.

KDP	Dgn. #1	Dgn. #2
L_m	✓	✓
L_g	✓	✓
T_w	-	✓
W_{sub}	✓	-
SuBTyPE	✓	✓

(a)

Freq.	L_m	L_g	T_w	$W_1 = W_2$	ϵ_r	ϵ_{eff}	h
F_1	20.3	L_m	-	4.875	2.2	1.87	1.55
	19.4	L_m	-	2	3.5	2.74	0.9
	19.2	L_m	-	1.53	4.3	3.26	0.8
F_2	13.35	L_m	-	4.875	2.2	1.87	1.55
	12.9	L_m	-	2	3.5	2.74	0.9
	11.7	L_m	-	1.53	4.3	3.26	0.8

(b)

Freq.	L_m	L_g	T_w	$W_1 = W_2$	ϵ_r	ϵ_{eff}	h
F_1	21.8	15	7	4.875	2.2	1.87	1.55
	20.3	16	6.5	2	3.5	2.74	0.9
	19.8	15	7	1.53	4.3	3.26	0.8
F_2	13.4	6.7	3.35	4.875	2.2	1.87	1.55
	13.2	8.25	4.6	2	3.5	2.74	0.9
	12.15	9	5.8	1.53	4.3	3.26	0.8

(c)

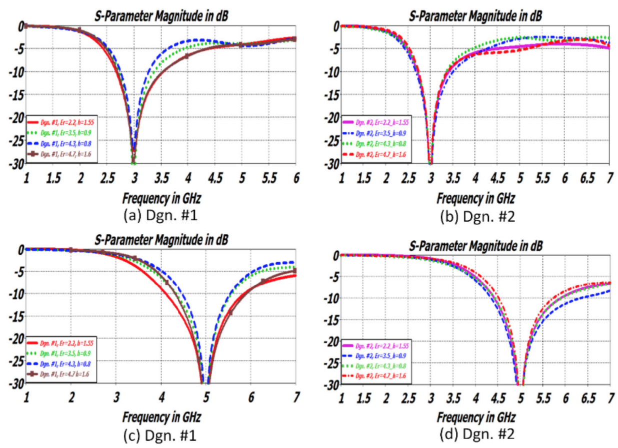

FIGURE 7. $|S_{11}|$ in dB of the proposed CMP for different SuBTyPE at F_1 and F_2: (a) and (c) Dgn. #1 (b) and (d) Dgn. #2.

Table 5(b) and Table 5(c), illustrate two optimized monopole designs for different substrate types (SuBTyPE). The first group of results is shown in Figure 7(a) through Figure 7(d). It is clear from these figures that our proposed design equations are valid for any substrate types (designed resonances are achieved). In addition, the monopole bandwidth is relatively dependent on the substrate types.

The second group of results is presented in Figure 8 and Figure 9. Effect of varying the monopole length L_m on the resonance frequency of CMP Dgn. #1 is illustrates in Figure 8. The results presented in Figure 8(a) and Figure 8(b) validated

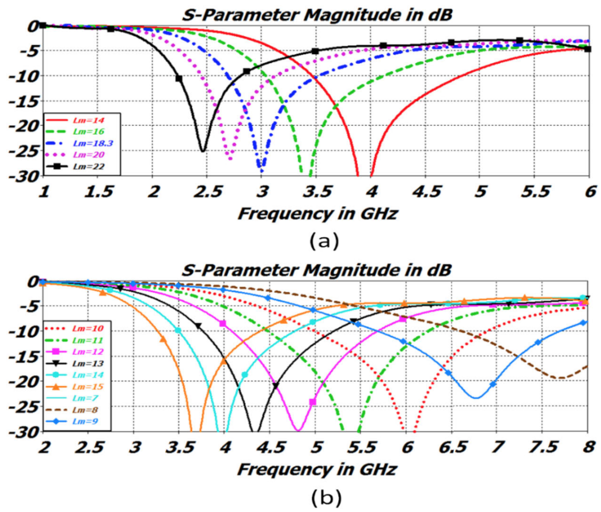

FIGURE 8. $|S_{11}|$ **in dB of the proposed CMP Dgn. #1 for different monopole length** L_m ($W_{sub} = 2.5L_m$, $L_g = L_m$ **and** $L_{sub} = L_g + L_m$): **(a)** F_1 **(b)** F_2.

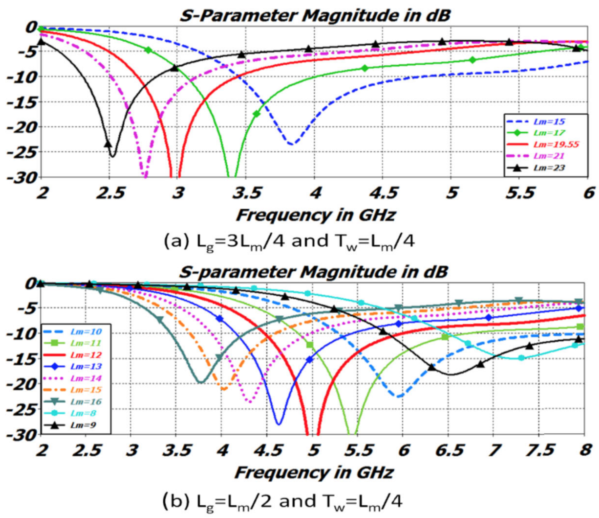

FIGURE 9. $|S_{11}|$ **in dB of the proposed CMP Dgn. #2 for different monopole length** L_m ($W_{sub} = 2L_m - T_w$, **and** $L_{sub} = L_g + L_m$): **(a)** F_1 **(b)** F_2.

the calculated value of L_m (18.3 mm or 11.65 mm) from Eq. (1) and it used in Eq. (2) to design CMP with specific resonance either at F_1 or F_2 (W_{sub}, L_{sub} and L_g). As it is clear from Figure 9, the same results are obtained for the second CMP design which confirmed the designs equations (Eq. (1) and Eq. (3)).

The third parameter is the partial ground length L_g. Simulation results of this parameter are illustrated in Figure 10(a) through Figure 10(d). As it is clear from Figure 10(a) and Figure 10(b), the partial ground L_g satisfied the proposed Eq. (2c) of Dgn. #1 for the two assumed frequencies. Similar results presented in Figure 10(c) and Figure 10(d) confirmed the calculated L_g by proposed equations of Dgn. #2 (Eq. (3d)) for the selected frequencies. Finally, results of the last paramedic

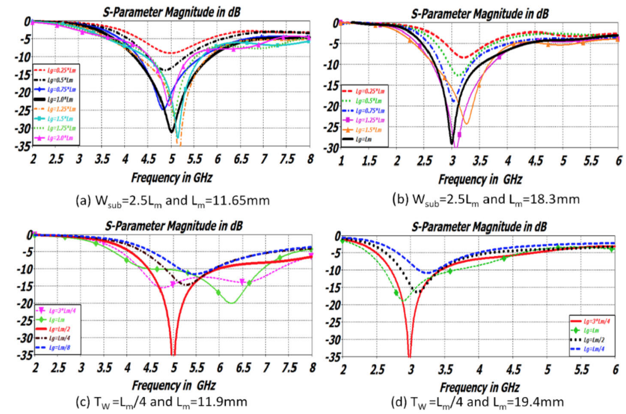

FIGURE 10. $|S_{11}|$ **in dB of the proposed CMP for different monopole ground length** L_g**:: (a) and (b) Dgn. #1 (c) and (d) Dgn. #2.**

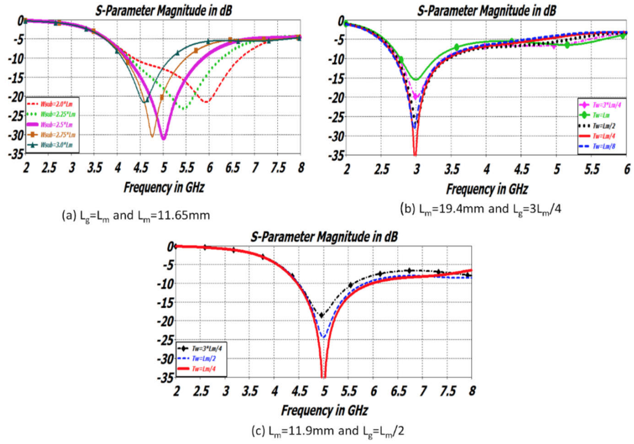

FIGURE 11. $|S_{11}|$ **in dB of the proposed CMP for different substrate (**W_{sub} **and** T_w**): (a) Dgn. #1 (b) and (c) Dgn. #2.**

study of the substrate width (W_{sub} and T_w) are presented in Figure 11(a) through Figure 11(c). The parametric results shown in Figure 11(a) confirm the proposed design equation (Eq. (2a)) for CMP Dgn. #1. On the other hand, Eq. (3-c) of CMP Dgn. #2 is confirmed by the obtained parametric results presented in Figure 11(b) and Figure 11(c).

In summary, the proposed equations can be used to design a single compact microstrip monopole antenna at any specific frequency mounted on the desired substrate. The last verification of our proposed monopole antennas is carried out using three FR-4 fabricated prototypes antennas. The optimized dimensions of these prototypes are listed in Table 2 (single monopole at F_2 = 5.0 GHz) and Table 3 (monopole array at F_2 = 5.0 GHz). The scattering parameters of these prototypes are measured and compared to the simulated results. Reasonable agreement is achieved between measured and simulated return loses as shown in Figure 12.

Finally by comparing our designs lasted 5 papers, getting this table

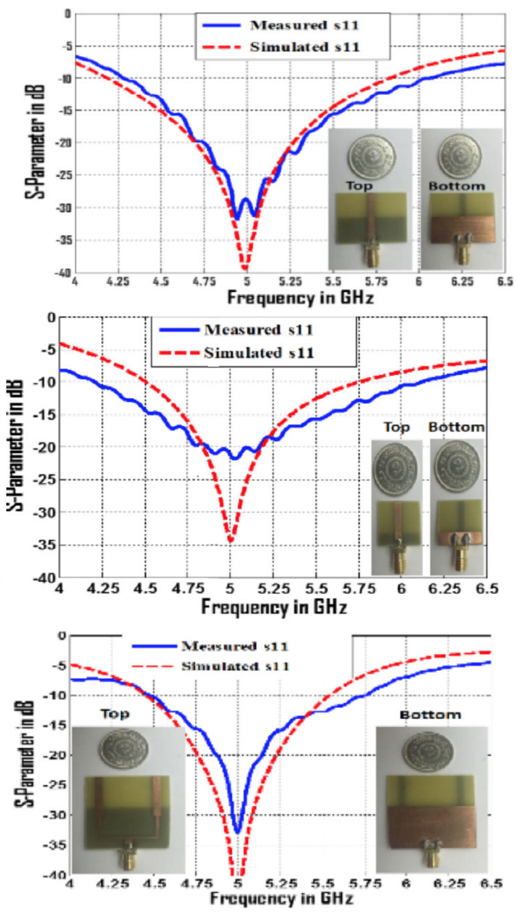

FIGURE 12. Simulated and measured $|S_{11}|$ in dB of the proposed monopole CMP and MPA antennas at $F_2 = 5.0$ GHz: (a) CMP Dgn. #1 Table 2 (b) CMP Dgn. #2 Table 2 and (c) MPA Dgn. #2 Table 3.

TABLE 6. Optimized characteristic and substrate dimensions (mm) of proposed monopole antennas (CMP Dgn. #1 and CMP Dgn. #2).

Reference	Dimensions(in mm) h=1.6mm/Normalize λ	Substrate	Freq. BW	Gain (dBi) [max. achieved]
[16]	140×120 mm^2 approximate=$2.5\lambda \times 2\lambda$	FR-4	(1.8 - 2.9 GHz)	10
[17]	13.4×5.2mm^2 approximate= $0.16\lambda \times 0.06\ \lambda$	Rogers RT/Duroid5880	(0.4 - 4.7 GHz)	2
[18]	60.4 x 71.4 mm^2 approximate= $0.2\lambda \times 0.25\lambda$	FR4	(0.165 - 0.875 GHz)	1.2
[19]	22×22 mm^2 approximate= $0.5\lambda \times 0.5\lambda$	FR-4	(3.12 - 3.82 GHz) (5.15 - 5.83 GHz)	3.44
[20]	26×15 mm^2 approximate= $0.4\lambda \times 0.23\lambda$	FR-4	(2.24 - 2.40 GHz) (3.38 - 3.83 GHz) (5.0 - 6.25 GHz)	3.3
[21]	53×25.25 mm^2 approximate= $\lambda \times 0.5\lambda$	Rogers RT/Duroid5880	(3.24 to 4.35 GHz)	4-6.8
[22]	27×8 mm^2 approximate= $0.36\lambda \times 0.1\lambda$	Rogers RO4350B	(700-960 MHz) (1710-2690 MHz)	7
This work (CMP)	17.15×19.3 mm^2 approximate= $0.36\lambda \times 0.1\lambda$	FR-4	(4.25 - 6.25 GHz)	2.9
This work (MPA)	36×38 mm^2 approximate= $0.6\lambda \times 0.7\lambda$	FR-4	(4.5 - 5.75 GHz)	6

IV. CONCLUSION

A broadband microstrip monopole antenna has been proposed, designed, fabricated, and presented. The monopole antenna designs are based on two sets of proposed equations, and they are simulated using the CST-simulator. These design equations have been verified through a detailed parametric study, and the monopole antenna performance has been investigated and optimized. Excellent Omni-directive pattern, low VSWR, adequate maximum gain, and broad bandwidth have been achieved. Moreover, a linear array of two monopole elements has been designed, optimized, and fabricated to enhance the maximum gain. The proposed array has been achieved good efficiency (81%), about 22% fractional bandwidth, directive pattern with moderate high gain (6.0 dBi), and low VSWR. Reasonable agreement has been achieved between measured and simulated results. The presented microstrip monopole antennas are compact in size, and they can be used for WiFi, LTE and WiMax devices. In addition, a compact array of large monopole number can be achieved a higher gain up to 18 dBi (four to eight monopole array elements with overall size 38×7 mm^2 to 38×144 mm^2).

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