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An innovative design for a small, broad-band, and radiation-efficient antenna used in a healthcare IoT system

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Abstract:

This paper investigates and develops a novel compact broadband and radiation efficientantenna design for the medical internet of things (M-IoT) healthcare system. The proposed antennacomprisesofanumbrella-shapedmetallicgroundplane(UsMGP)andanimprovedradiator.Ahybrid approach is employed to obtain the optimal results of antenna. The proposed solution isprimarilybasedonthe utilizationof etchingslotsanda loadedstubonthegroundplaneandrectangularpatch.Theantennaconsistsofasimplerectangularpatch,a50Ωmicrostripfeedline,and a portion of the ground plane printed on a relatively inexpensive flame retardant material(FR4)thicksubstratewithanoverallcompactdimensionof22×28×1.5mm^3.Theproposedantennaoffers compact, broadband and radiation efficient features. The antenna is carefully designed byemploying the approximate calculation formulae extracted from the transmission line model. Besides,the parameters study of important variables involved in the antenna design and its influence onimpedancematchingperformanceareanalyzed.Theantennashowshighperformance,includingimpedance bandwidth of 7.76 GHz with a range of 3.65–11.41 GHz results in 103% wider relativebandwidth at 10 dB return loss, 82% optimal radiation efficiency in the operating band, reasonablegain performance, stable monopole-shaped radiation patterns and strong current distribution acrossthe antenna lattice. The suggested antenna is manufactured, and simulation experiments evaluate itsperformance. The findings indicate that the antenna is well suited for medical IoT healthcare systemsapplications.

Keywords:compact;broadband;radiationefficiency;umbrella-shapedmetallicgroundplane(UsMGP);modifiedradiator andmedicalinternet ofthings(M-IoT)healthcaresystems

Introduction

Thegreatprogressofwirelessmedicalhealthcaresystemsneeds compactbroadbandandefficient antennas. The optimal performance of these systems is achieved with the robust antennadesigns. Recently, compact antenna devices have been playing an important role. These devices arepart of the modern healthcare wireless communication system. Therefore, designing a compactantennawiththebestperformanceisstillachallenging taskforactiveantennadesigners.Inaddition,differenttypesof antennaswithdifferentspecificationscoversmodernheterogeneouswireless applications have been reported in the literature [1–4]. The existing antenna designs stillfaces many challenges, such as reasonable antenna behavior, narrow bandwidth (BW), moderateradiationefficiencyandacceptablegainwiththecomparativelylargersize.
Inrecentyears,therehasbeenremarkableresearchandadvancementinthemedicalinternetof things (M-IoT) and healthcare systems and services [5,6].

Antennatechnicaldesignstrategy

In this section, the proposed antenna technical design strategy is briefly described. Before startdesigning the antenna lattice, the type of antenna, selection of the material and its thickness is veryimportant.Basedontherequirement,theplanarmonopole antenna(PMA)hasbeenfocusedduetoits good performance and low-cost FR4 epoxy substrate material is used to curb the fabrication costof the antenna. Afterwards, selection of suitable electromagnetic (EM) software has been decided. The antenna is designed and simulated by using the high frequency structure simulator (HFSS)version 13.0. The step-by-step flow of technical strategical plan of the proposed antenna is brieflyexplained. The proposed antenna is designed by employing the transmission line model equations.Theantenna is designed using the followingtechnical approachillustrated in Figure1.

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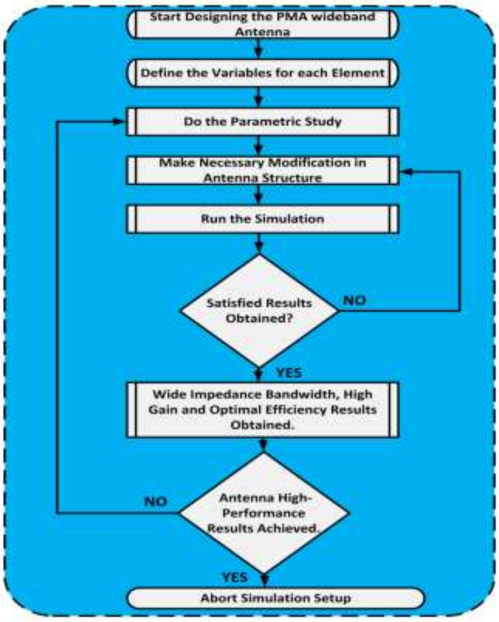

Figure1.Flowchartofdesignedtechnicalstrategy.

Besides, the approximated mathematical formulation based on the transmission line model isalso expressed here.

Antennaevolutionstagesanddesignedlayout

Thesuggestedantennamodel'sdevelopmentandarchitecture aredepictedinFigure2(e)–(f).Thedesigned antenna is etched on a low-cost FR4 epoxy thick substrate material with a relative dielectricpermittivity of $\varepsilon r = 4.4$, a loss tangent value of $\delta = 0.02$, and a copper thickness of 0.035 mm. Thesuggested antenna is 28 mm long, 22 mm wide, and 1.5 mm thick. The intended antenna was createdbymodifyingthemetallicgroundplane(MGP)andcreatingasmallrectangularpatch.Onthetopsideof the laminate, a basic rectangular patch with compact dimensions of (10.5×14.0 mm^2) and a 50 Ωmicrostripfeedstructureareetched,andasmallminiaturepartialgroundplane(PGP)isetchedontheflipsideofthesubstrate, asshowninFigure2(a).

Thechamferedoperationof5.0mmisperformedontheupperleftandrightedgesofthePGPandconstructs the antenna model-2 as shown in Figure 2(b). Further, an 8.0 mm fillet operation isperformedonlowerleftandrightedgeofchamferedPGPtoformanumbrella-shapedmetallicgroundplane(UsMGP),asdepictedinFigure2(c).ThepurposeofmakingthischangeonthePGPistorealizethe high-performance features of the antenna. Then, as illustrated in Figure 2(d), trim the upper-rightedgeofthecompactrectangularpatchusinga3.0mmfillet operationtocreatetheantennamodel-4.Finally, the proposed antenna model is constructed by again applying fillet operation of 3.0 mmonthelower-leftedgeofrectangularpatchandtheloadedcirculardiscstubwiththeminimumsizeof1.5mmontheupper-rightedgeofthecompactimprovedrectangularpatchaselucidatedinFigure2(e).The variables and their optimal values of the proposed antenna design are listed in Table 1. Theelectromagnetic high frequency structure simulator (HFSS) software program develops and simulatestheproposedantenna.Moreover,theproposedantennamodelisalsodesignedonthethree-dimensional(3D)Altiumdesigner(AD)toolwidelyusedinthe industry,asshowninFigure2(f).

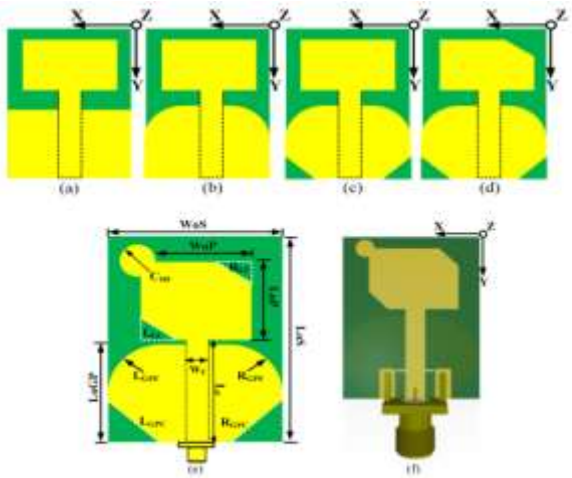

Figure2. Proposedantenna developmentprocess,(a) simplepartial groundplane(PGP),
(b)chamferedPGP,(c)umbrella-shapedmetallicgroundplane(UsMGP),(d)filletradiatorand UsMGP,(e)proposedantennaprototype,(f)3Ddesignedantennamodelwith SMAconnector.

Table1. Proposedantennadesignedvariablesandoptimizedvalues(unit:mm).

Defined variables	Optimized value	Defined Variables	Optimized value
WoS = WoGP	22.0	LoS	28.0
HoS	1.5	LoGP	14.5
$L_{GPC} = R_{GPC}$	8.0	$L_{GPF} = R_{GPF}$	5.0
W_f	3.1	L_f	17.0
LoP	14.0	WoP	10.5
$R_{FC} = L_{FC}$	3.0	C_{SD}1.5	

Theperformanceoftheevolvedantennamodels in termsofreturn loss (|S11|)isdepicted inFigure 3; it is discovered that the initially designed antenna model obtained a wide impedancebandwidth (BW) of 4.9 GHz with a range of 3.9–8.8 GHz at a return loss of 10 dB. Additionally, theantenna model-2 has an impedance BW of 5.98 GHz and a frequency range of 3.78–9.76 GHz. TheimpedanceBWisimprovedby22%comparedtotheproposedantennamodel-1.Thepartialgroundplane (PGP) is used to achieve this increase in impedance BW. Likewise, the antenna model-3 isdesigned to have an impedance BW of 6.08 GHz and a frequency range of 3.72–9.8 GHz. Moreover,the suggested antenna type achieves a greater impedance BW of 6.19 GHz over the 3.76–9.95 GHzfrequency range. Finally, the proposed antenna model obtains an impedance BW of 7.76 GHz with a3.65–11.41 GHz frequency range. Also, it can be seen that the proposed antenna model's impedanceBWhasbeenenhancedby58.4%whencomparedto theinitialantennadesignmodel.

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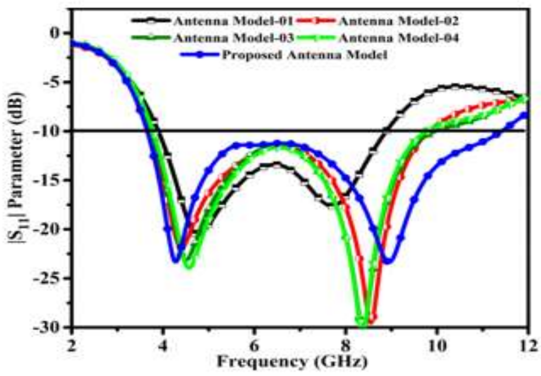

Figure3.|S11|performanceofoverallantennadesignedprototypesacrosstheoperablefrequency.

Simulationresultsanddiscussion

This section explains the parametric analysis of the variables used to develop the proposedantennadesign.Theparametersassociatedwiththeintendedvariablescanbeexaminedbyemployingtheelectromagnetichighfrequencystructuresimulator(HFSS)softwarepackageforrigorousmultipletimes simulation. The main purpose of this study is to obtain proper impedance matching, wideimpedanceBWandbestperformanceresultsfortheproposedantenna.

InfluenceofLoGPandWoP

The size of the length of the ground plane (LoGP) and width of the patch (WoP) influences theproposed antenna impedance matching performance and resonance tuning features. As shown inFigure4(a),theproperimpedancematchingandwiderBWareachievedatamaximum14.5mmvalueof the ground plane. Likewise, the second resonance tunability has been achieved at the maximumvalueofthevariable.Further,thepropermatching,widerimpedanceBWandsecondresonancetuningareachieved at the valueof WoP14.0 mm,asshowninFigure4(b).

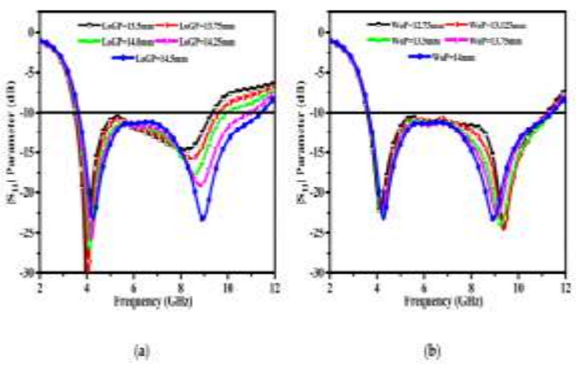

Figure4.Influenceofvariablesovertheentireoperablefrequencyrange,(a)lengthofgroundplaneLoGP,(b)widthofthepatch(WoP).

InfluenceofLoPandHoS

The length of the patch (LoP) and the thickness of the substrate (HoS) strongly influence theimpedance matching, BW and frequency tuning performance of the proposed antenna. It can beanalyzed from Figure 5(a); the antenna matching performance is achieved at the patch value of 10.5mm.Further,substratethicknessstronglyaffectstheimpedancematchingperformanceoftheproposedantenna,asshowninFigure5(b).Itcanbeseenthatatthelowervalueofthethicknessofthesubstrate, the antenna exhibited the dual-band frequency response. The wider impedance BW isachievedattheoptimizedsubstratethicknessvalueof1.5 mm.

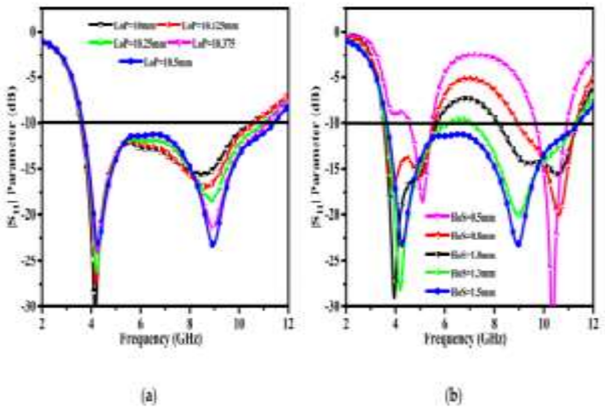

Figure5.Influenceofparameters,(a)lengthofthepatch(LoP)and(b)substratethickness(HoS)acrosstheoperablefrequencyspan.

Surface current distribution (JSURF)

The recommended antenna model's simulated result analysis of the current density at tworesonances is presented in Figure 6(a)–(b). When the proposed antenna resonates at 4.82 GHz, itexhibits a significant distribution current across the entire patch, feeding line, and umbrella-shapedground plane (UsMGP). Additionally, at 8.96 GHz, a slight shift in current is evaluated at the patch'supperedgeandtheUsMGP'slowerleftandrightedges. Asaresultofthedatastatedpreviously,itcanbeinferredthatthesuggestedantennamaneuversadmirablythroughouttheoperablefrequencyrange.

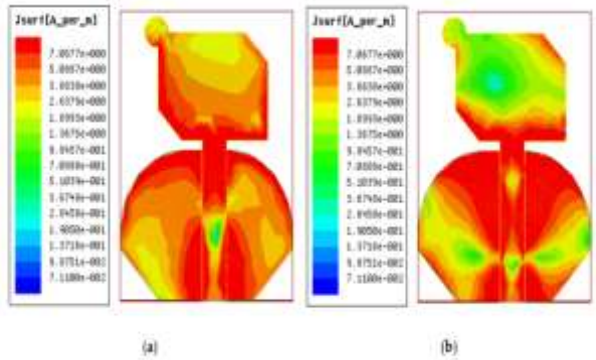

Figure6.Surfacecurrentdistributionoftheproposedantennaatdifferentfrequencies,(a)4.28GHz,(b)8.96GHz.

Experimentalverifiedresults

This section discusses the proposed antenna model's experimentally validated outcomes. Themeasuredandsimulatedvaluesforcriticalantennacharact

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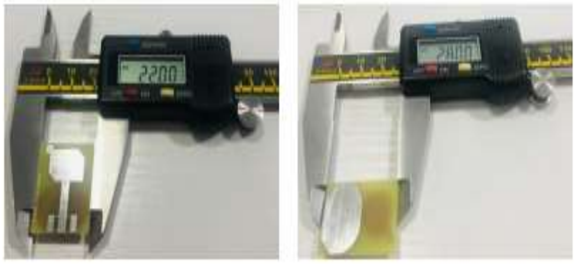
eristicssuchas|S11|(dB),peakrealizedgain(dBi), radiation efficiency (%), and radiation patterns throughout the standard plane are compared,investigated,andanalyzed.

Returnloss|S11|parameter

The manufactured antenna prototype is depicted in Figure 7(a)–(b). Before evaluating the returnloss of the manufactured antenna sample, the vector network analyzer (VNA) is calibrated properly.The antenna model is linked to the VNA's single port. Figure 8 illustrates the simulation andmeasurement results for the proposed and manufactured antenna. The manufactured antenna sample'sreturn loss (|S11|) parameter performance is determined using the Agilent PNA 5230C VNA. AsillustratedinFigure8,theantenna'ssimulationmodelhasabroaderimpedancebandwidth(BW)of7.76GHz,withalowerfrequencyof3.65GHzandahigherfrequencyof11.41GHz.Similarly,at4.28GHz and 8.96 GHz, two resonances are recorded. Additionally, the antenna's constructed modelexhibitstworesonancesidenticaltothesimulationmodel.Ascanbeseen,thelowerresonancehasbeen somewhat pushed away from 3.9 GHz compared to the simulation results. Due to the SMAconnector's faulty welding and the lossy substrate material, discrepancies in the results have beennoted.



(a) (b)

Figure7.Fabricatedantennamodel,(a)frontview,(b)backview.

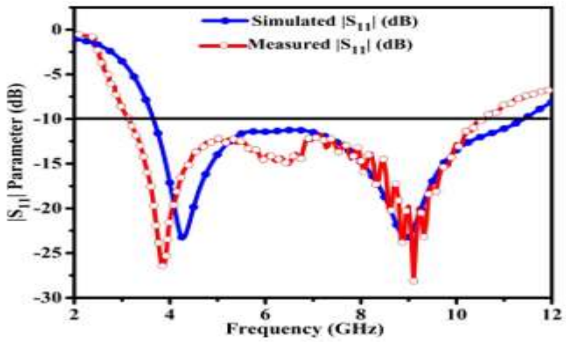


Figure8.Simulationandmeasuredresultsof|S11|entireoperablefrequency span.

PeakrealizedgainandRadiationefficiency

Figure 9(a) illustrates the simulation and measurement findings for the proposed antenna's peakrealized gain. At 10.5 GHz, the planned antenna model's simulation result (streaked blue line)demonstrates a maximum gain of 4.58 dBi. Similarly, a respectable gain is noticed, for example, 4.13dBiat4.28GHzand4.42dBiat8.96GHzresonances.

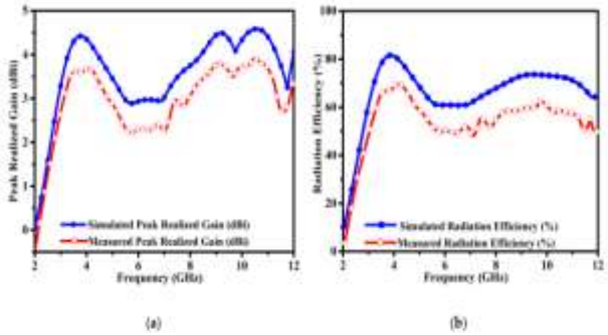


Figure9:Simulationandmeasurementresultsintheentireoperatingfrequencyrange,(a)peakrealizedgain,(b)radiationefficiency.

Additionally, the Friis transmission equation is used to determine the measurement gain of thefabricated antenna. As illustrated in Figure 9(a), the manufactured sample of the antenna reaches apeak realized gain of 4.0 dBi at 10.5 GHz. Similarly, gain values of 3.7 dBi and 3.9 dBi areachievableat4.28GHzand8.96GHzresonances.Duetothe lossofsamplesoftheindoorantennain the anechoic chamber during the measurement process, a difference of 0.58 dBi in the peakrealizedgainbetweenthesimulationandmeasurementdataisseen.

Figure 9(b) depicts the proposed antenna's simulated and measured radiation efficiency. As canbe seen, the antenna's maximum efficiency at 3.9 GHz is 82%. Similarly, the proposed antennaachieved a 78% and 70% radiation efficiency for 4.28 GHz and 8.96 GHz resonances. As can be seen,thesuggestedantennaradiatesefficientlywithinthespecifiedfrequencyrange.Moreover,anefficient gain/directivity approach extracted the proposed fabricated antenna radiation efficiency. Asillustrated in Figure 9(b) (streaked red line), the suggested antenna's fabricated sample reached amaximum efficiency of 72% at 4.5 GHz. Similarly, for resonant frequencies of 4.28 GHz and 8.96GHz, the manufactured antenna sample approaches 70% and 60% radiation efficiency, respectively.Further, the difference observed in the simulation and measurement result of radiation efficiency islessthan20%,whichvalidatestheeffectivenessoftheappliedgaindirectivityapproach.

Radiationpatternperformance

The manufactured antenna sample is put in an anechoic chamber to evaluate and validate thesuggested antenna model's radiation pattern performance. The produced sample and ridge gap hornantenna are positioned in the line of sight (LoS), as seen in Figure 10(a)–(b). The fabricated antennasample(theantennaundertest)ismountedontheturntableandspun360º.

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Figure10.Testenvironmentofanechoicchamberroom,(a)placementofridgehornantennas,(b)placementofantennaundertest(AUT).

The radiation pattern performance of the designed and fabricated model of an antenna on thestandard planes (E-plane at Φ = 0º) and (H-plane at Φ = 90º) is shown in Figure 11(a)–(b). Theproposedantennamodelhasexcellentperformanceandpresentsthemonopole-likeradiationpattern on standardplanesat the resonantfrequencyof4.28GHz, aselucidated inFigure 11(a).The simulation and measurement results are found to be consistent. Similarly, in the H-plane, nullsnear90ºareformed. Additionally,Figure11(b)illustratesthesuggestedantenna'sradiationpatternperformanceacrossstandardplanesatthereson antfrequencyof8.96GHz.Thesuggestedantennaproducesmonopole-likeradiationpatternsalongstandardplanes.Further,azeropointisestablishedabout300ºintheproposedantenna's H-plane. As a result of the preceding discussion, it can be concluded that the simulationresultsagreewellwiththemeasurementdata.Similarly,fortheresonantfrequenciesof4.28GHzand 8.96 GHz, the suggested antenna exhibits stable monopole-like radiation patterns along thestandardplanes.

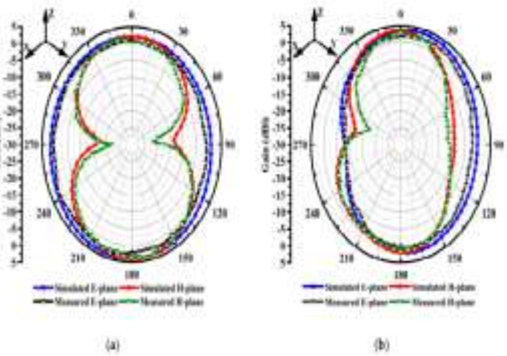

Figure11.Theproposedantenna'ssimulationandmeasurementradiationpatternsperformance,(a)@4.28GHz,(b) @8.96GHz,onstandardplanes.

Performance comparison analysis

This section summarizes the suggested antenna's performance study regarding total occupiedspace,impedancebandwidth(BW),peakrealizedgainandradiationefficiencycomparedtopreviously published literature. As shown in Table 2, the proposed antenna achieved high gain valuesof2.08dBi,1.08dBi,and0.58dBiincomparisontotherefences[10,20,32].Theproposedantenna exhibits the higher impedance BW of 2.74 GHz, 4.54 GHz, 3.96 GHz and 4.16 GHz incomparisontotheresultsreportedin[10,13,19,32,53]. Further,theproposedantennasizeisreducedby34.18%,70.8%,86.96%,90.98%,74.26%,90.94%,41.3%,70.83%,85.4% and99.69%ascomparedtoinvestigatedantennasin[18–21,27,28,39,40,61,62].Furthermore,itisnotedthattheantennaradiationefficiencyresultsin[19,21,27,28,61,62] are not reported. As shown in Table 2 and the above explained analysis, theproposed antenna is small in size and achieves a high performance compared to most recentlyexaminedantennasdescribedintheliterature.

Table2. Performancecomparisonanalysisoftheproposedantennawithrecentlyreportedworks.

Ref. / Year	Occupied space (mm^2)	Bandwidth (GHz)	Peak gain (dBi)	Efficiency (%)
This work / 2022	616	7.76	4.58	82
[27] / 2021	936	5.02	9.3	Not reported (NR)
[28] / 2020	2116	8.3	2.5	NR
[18] / 2019	4725	3.22	3.5	90
[19] / 2019	6832	8.01	6.5	NR
[20] / 2019	2393.6	8.9	7.0	90
[21] / 2018	6804	3.8	7.35	NR
[39] / 2018	1050	10	5.0	84
[40] / 2016	2112	3.6	4.0	95
[61] / 2016	4224	7.03	11.8	NR
[62] / 2015	202500	9.8	10	NR

Conclusions

In this article a novel compact broadband and radiation efficient antenna for medical IoThealthcare system has been proposed. The antenna design comprises of a compact improved radiator,umbrella-shaped metal ground plane (UsMGP) and 50 Ω microstrip feed line. In this research, a newhybrid technique is proposed to acquire the ideal antenna findings. The proposed approach is mainlybased on etched slots and short load stubs employed on a partial ground plane (PGP) and rectangularpatch. The suggested antenna is imprinted on a thick substrate made of a low-cost flame retardantmaterial (FR4). The antenna has a compact dimension of 22 × 28 × 1.5 mm^3. The proposed antennawas carefully designed by using mathematical formulations extratcetd from the transmission linemodel. The parameters study of important variables involved in antenna design and its influence onimpedance matching performance are analyzed. The designed antenna shows high performance,including103%widerelativebandwidth,82%bestradiationefficiency,reasonablepeakrealizedgain performance of 4.58 dBi, stable monopole-like radiation pattern and strong current distributionacross the operable frequency span. The proposed antenna has been fabricated, and the experimentalresults have been validtated through simulation experiments. The designed antenna is suitable forM-IoThealthcaresystemsandcoversheterogeneouswirelesscommunicationapplications(HWCA).

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