

Project of antennas for GPS, ISM 2.4 and 5.8 GHz mobile terminals

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Abstract

An intensive study on small multiband antennas was conducted in this work, alongside with their properties and importance within Wireless communications. A subject that is growing larger each day. A multiband small antenna structure is built in university radio-frequency (RF) laboratory. The built prototype consists of a PIFA (planar inverted F antenna) structure with two substrates distanced over a 2.5 mm height approximately. One of the substrates works as a ground plane, and the other supports the top metallic structure, which contains two slots and a meander. The antenna design is made always aiming antennas able to operate in the GPS L1, ISM 2.45 and 5.8 GHz bands for wireless devices. After a careful analysis of these antennas importance, it is assessed the impact of enclosing the designed antenna in a PLA box. So, it is built in a 3D printer a smartphone sized box, and the dissertation antenna prototype is tested inside the box, with lid open and closed. The obtained experimental results in laboratory were compared to the simulated ones and were suitable and satisfactory for the thesis initial purpose. The designed antenna has four resonances, one in the ISM 5.8 GHz band, two in the S band, and one in C band.

Keywords: Multiband Antenna, GPS, ISM bands 2.45 GHz and 5.8 GHz, Small Antenna, Wi-Fi and Bluetooth

1. Introduction

The growing of technology development changes the people's lifestyle by introducing a numerous of different devices and methods for their everyday needs. The number of ways users have to communicate and share data between them is making communication more efficient and portable, nowadays devices like mobile phones, tablets, portable computers are considered almost indispensable.

This progress in wireless communication has required small devices and other equipment to the developing of multiband communication. *What permits to connect all these devices? What is that one design detail essential to this question?* These are fundamental questions in wireless devices design. Antennas are the essential part of the communication system and devices design, responsible for receiving and/or transmitting electromagnetic signal these antennas brings great interest to study and development.

All the evolution attached to the nowadays technology requires reliable portable products in terms of communication and data transfer and this brings big importance to mobile systems [3]. Since in mobile communications small antennas are integrated

into mobile terminals, antenna specifications like small-size, compactness, and light weight are fundamental in the telecommunications market [19] [1].

By now, the importance of wireless antennas is clear but with the extensive demand for modern mobile communications devices with big touchscreens and other components, the left space within the device for an antenna is only a small percentage of the total occupied area. Therefore, multi-band operations are also an important requirement to add to these antennas [17] [11]. Antenna designers have constantly to keep up with communication development and innovation, creating new small and wireless antennas, always considering low prices to compete with the market values [8].

In short, big relevance is given to miniaturization, multiband ability operations and improved the functioning of nowadays antennas [28] [27]. As a result of big mobile communication systems development and evolution, more frequency bands have been used to diverse wireless applications like machine control, tracking devices, medical support, smartphones and others. All wireless communications services and applications conduct to a more crowded usage of the frequency bands. Therefore,

the reason to start using more free bands as an alternative [26]. There is also a tendency to use higher frequency bands as they allow for greater data transfer capacity. Most used IEEE radio bands are S-band, L-band, and C-band and examples of applications are GPS, LTE, GSM, UMTS, WLAN, ISM and Wi-Max. These applications have also their frequency bands allocated but they are within the previously mentioned bands [10].

This work study addresses the multiband antenna solutions to attenuate the problem of the excess of electronic components in mobile terminals. Mobile terminals nowadays have to be considered for many applications in just one device: Camera, Radio, Finger prints, Bluetooth, WI-FI, GPS, Phone Call, Messages and others, are examples of those applications. Action is always needed in these telecommunications technologies and one way to upgrade and smooth this problem impact in designing antennas capable of multiband operations, so only one antenna is used for diverse applications. In this work, an antenna structure of small dimensions is proposed. An antenna that allows minimizing the number the antennas used in mobile terminals and aims to operate at the ISM 2.4, 5.8 GHz and GPS L1 1.5 GHz bands.

2. Multiband antennas for GPS and ISM bands

The emerging of the usage of more frequency bands has driven an increase of multiband antennas operation demand. This section introduces some of the most used frequency bands for mobile terminals applications, namely, GPS 1.5 GHz and the ISM bands 2.4 GHz and 5.8 GHz.

Choosing the type of structure for the desired antenna, it depends on the wanted characteristics for the antenna. The main objective is to achieve the highest possible efficiency, and at the same time enough bandwidth to cover the required bands [8]. The existing possible structures and combinations are diverse, but this section is focused on studying antennas structures for mobile terminals specifications. For this, it is required to consider what structures can be applied to achieve multiband operations, and where miniaturization techniques can be applied. The most well-known and used antenna's structures, considering their versatility, are based on monopoles, ILA (Inverted -L Antenna), PIFA (Planar Inverted F Antenna), CIFA (coplanar inverted-F), and combinations between them. Patch antennas and microstrip antennas (MSA) are common as well especially for GNSS reception. PIFA, MSA and patch antenna are represented in Figure 1.

The antenna designer has some guidelines when projecting the antenna so that it can achieve a good performance. For impedance match, it is usually

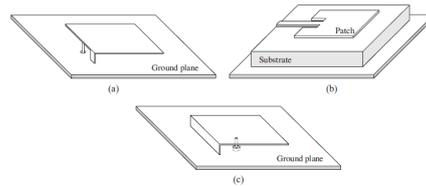


Figure 1: Typical planar antennas; (a) PIFA (Planar Inverted-F Antenna), (b) patch antenna, and (c) MSA (Microstrip Antenna).

established that the voltage standing wave ratio is $VSWR < 3$ and the return loss is $S_{11} < -10$ dB. For the mean effective gain a low value is required, being $0dB_i$ the ideal, since it provides a low directivity pattern to minimize signal variations as handset position is varied. For radiation efficiency, it is required that the minimum value should be about 50% and the bandwidth should be about 8 to 12% of the central frequency (depending on the operating band).

There are also guidelines regarding the antenna dimensions. In a handset device the typical maximum antenna volume is around 5 cm^3 , corresponding to typical dimensions of $35 \times 35 \times 4\text{ mm}^3$, whereas the printed circuit board size of a bar shape phone is $100 \times 40\text{ mm}^2$. But due to the development of smartphones and their applications, this dimensions are often larger [24].

3. Miniaturization and multiband strategies

There are some design strategies to obtain miniaturization and multiband operations, such as the modification of the main radiator or the modification of the ground plane. This technique of altering the main radiator might be done by implementing multiple branches in the structure, which allows the excitation of multiple resonant frequencies, at their fundamental mode. An example is a two branches antenna separated by a feeding strip. The two branches have different sizes, the shorter one generates a higher resonant mode and the longer one a lower resonant mode [1].

Another technique to achieve additional resonances frequencies is to implement multi-stacking or multi-layering due to the creation of new currents paths. Modifications can also be done to the antenna structure geometry by introducing slots. These addition creates new resonant frequencies and band coverage by separating current paths [22] and sustains the antenna miniaturization for multiband wireless devices.

To obtain a more compact design using only one radiator without splitting to branches, and conceiving multiband operations at the same time, it is required the use of other techniques. Examples of

those techniques are meandering, bending, spiraling and folding into a 3-D geometry. Hereupon, it is possible to elongate a single radiator without decreasing the compactness of the antenna's structure. The most used technique is the meandered geometry that minimizes the overall size, and preserves the original length of the radiating element [22].

These techniques are not necessarily used independently. To achieve multiband operations without jeopardizing the antenna's performance, many antenna designers use the combination of multiple techniques in the same antenna structure. An example of multiple techniques combination is an antenna based on a meandered IFA structure with resonance in 915 MHz that with a folded IFA strip was achieved the 1.2 GHz resonance and with an a slot insertion in the IFA strip was achieved an additional resonance, as seen in [19]. The occupied area of this antenna is $25 \times 40 \times 10 \text{ mm}^2$, and achieves to cover L1, L2 and GPS standard bands. The final structure of this antenna is illustrated in Figure 2.

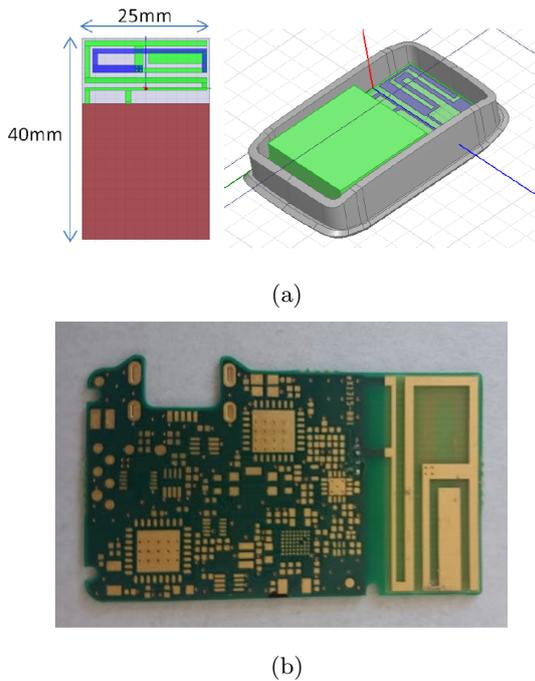


Figure 2: Multiband antenna structure as presented in [19] (a) Structure representation; green for top metallization and blue for bottom metallization, and a 3D view of the PCB inside the plastic casing (b) Picture of the fabricated antenna.

An alternative solution to obtain and determining the resonant frequency, is a better employment of the structure ground plane. The relevance in the radiation process of the ground plane is sometimes underestimated, since implementing parasitic elements such as slots, conductive strip to lengthen

the ground plane or even using traps to electrically can reduce the ground plane and thus obtain better antenna performance. As an example, we have coplanar elements used as a parasitic element and since these elements lie on the same plane as the ground plane, a better usage of the ground plane was obtained [2].

The parasitic elements are employed to widen the original bandwidth, and the driven element continues mostly to act as the main radiator. A triple band can be achieved, for example, by an employment of a cross slot in the ground plane [6].

Inserting a slot into a ground plane causes the primary radiator's electric current to reroute its path along the conducting surface of the ground. This also leads to an increase of the electrical length of the ground. There are some cases that with an extended length, the parasitic elements can act as the second/main radiator. Another example is given in [16], where the purposed antenna, with an occupied area of $18 \times 37 \text{ mm}^2$ and only two metallic strip elements, has employed a parasitic stub as the main radiator, a driven stub as a choker and a incorporated virtual slot structure. With this structure, it was achieved three separate resonance modes covering six standard bands.

There are different techniques used to achieve many frequency bands and compactness characteristics. In another exemplar antenna four techniques were used in the same structure [28]. It was used a meandering strip, an antenna slot, parasitic branches and a stub on the ground plane.

In terms of designing and manufacturing a small multiband antenna, it is also needed to pay attention to the design parameters, described in the previous section, as well as the feeding and loading structures like the matching network, inductive loads, capacitive loading, feed/ground connection loading, parasitic elements and others [23]. Others structures alongside with performance strategies are presented in the literature such as, an antenna with an occupied volume of $27 \times 25 \times 0.8 \text{ mm}^3$, where it was used a monopole with a meander line [25], an antenna with an occupied area of $34 \times 15 \text{ mm}^2$, in this one, it was used a compact slotted antenna composed by an S-shaped slot and an inverted-L slot on the ground plane [14] and an impressive small occupied area of $9 \times 7 \text{ mm}^2$ that covers of WLAN 2.4 GHz and 5.2/5.8 GHz bands was presented in [15].

4. Antenna Performance effects

This section addresses some relevant issues in antenna design in terms of antenna's surrounding effects, such as casing and human proximity effect.

Figure 4a is illustrated the three different positions used. In Figure 4b the influences of the hand position in the antenna's total efficiency are presented, and is noted that the two desired frequency in the referred study, are a little detuned and widened for different gripping positions due to the power absorbed by the user's hand. The antenna's performance also varies, depending the hand's touch on the metal rim.

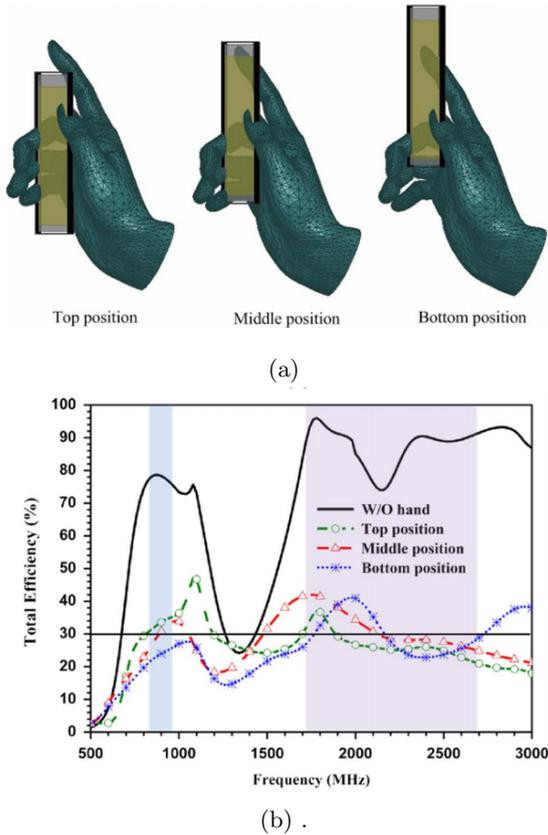


Figure 4: Hand effect study on antenna performance, [4] . (a) Configuration of hand grip smartphone at different positions (the metal rim is directly touched by the hand in each simulated mode). (b) Simulated results of hand grip at different positions: total efficiency (mismatching loss included).

Attached to human body effects, there is also a second issue to analyze. The interaction between user and handset device not only affects the handset performance but also user's health standards, since the antenna radiates EM waves, and it can penetrate the human body tissue and, consequently, contribute to serious health risks [25]. For studying the interaction between handset device EM radiation and its absorption on human tissue, the requirement of specific absorption rate (SAR) is introduced. The SAR value represents the quantity of RF power is absorbed by the surrounding including

the user. This ratio can be expressed as

$$SAR = \frac{\sigma}{2\rho} |E|^2 \quad (1)$$

where ρ stands for the material density in kg/m^3 , σ stands for electric conductivity in S/m , and E is the electric field in V/m introduced by the radiated energy. The SAR value is expressed usually in SI units W/kg and refers to averages over cells weighing 1g or 10g.

5. Proposed antenna design

Throughout the antenna project, study and simulations, a small antenna structure was developed, capable of multiband operations. The proposed antenna of this dissertation is a slotted antenna with a meandered part, and it is made with a double substrate that has a total dimension of $40mm \times 40mm$, and is represented in Figure 5. For the antenna metallic part, copper and a gold-plated sheet for the shorting plate was used. To keep the distance between substrates it is used plastics screws M2.5. The two substrates are made of Rogers RO3035, and the 3D printed box is made with PLA, that has a permittivity of 1.3. It was used the EZ34 coaxial cable, terminated by a 50Ω SMA connector.

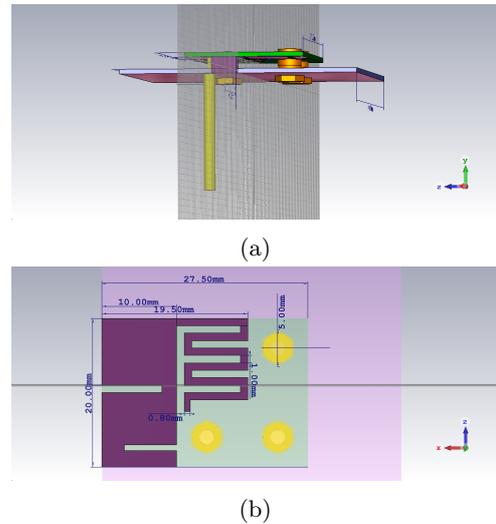
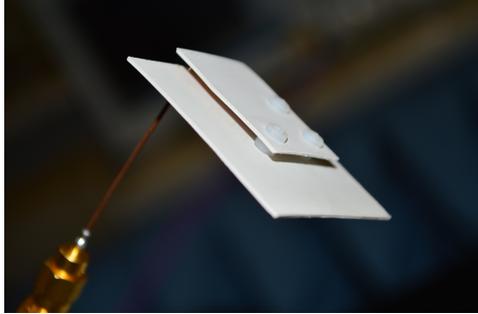


Figure 5: Final antenna design model. (a) Final structure from the side point of view. (b) Final structure from the side point of view.

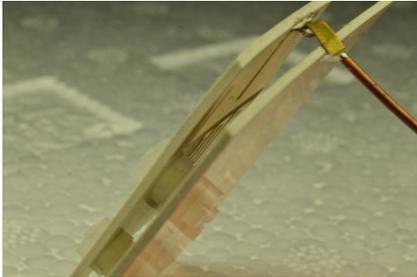
Prototype assembling:

The following step was to construct the antenna's final prototype. The prototype is composed of two Rogers RO3035 substrates. Each substrate has a metalized copper part, one of the substrates is dedicated to the ground plane (base substrate), and the other one (top substrate) to support the top slotted patch and meander. The coaxial cable constituted by external and internal conductors, for the

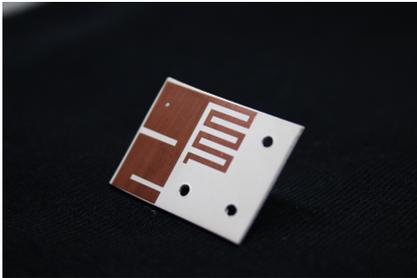
antenna's feeding must pass through the base substrate, and the internal conductor goes up till the metallization of the top substrate. This is a meticulous work, due to the reduced dimensions of the inner conductor, the slots and the meander of the antenna. The assembled antenna structure can be seen in Figure 6a.



(a)



(b)



(c)

Figure 6: The prototype antenna with the coaxial cable ready to test. (a) Antenna prototype from the front point of view. (b) Antenna prototype from the side point of view- special notice to the meander and shorting plate. (c) The metalized part, in the top substrate.

To better understand the antenna behavior in a closed environment, as described before a 3-D-sized printer box was printed. As if this box were a flip case cover of a smartphone as an example. The 3D sized box was designed in *CST*TM software. The printed 3-D-sized box is shown in Figure 7b. The material used for the 3D printer was PLA- polylactic acid in color blue. The polymer PLA have a dielectric dissipation factor \tan of 0.01, a permit-

tivity of 3.1 and a resistivity of 4.3×10^{17} [20].



(a)



(b)

Figure 7: The 3D box model - *.stl* file and the 3D box model printed with blue PLA. (a) The 3D sized box closed *.stl* file. (b) The 3D sized printed box semi-opened.

6. Experimental results

After accomplishing the final antenna design, and, once the prototype is made, the antenna was tested in laboratory environment. In this section is presented the antenna behavior, tested in the university radio-frequency laboratory, that compares the S_{11} reflection coefficient between the experimental and simulation results. The antenna prototype was also tested inside the box, both with the lid closed and with the lid open.

The measurement was done with a Vector Network Analyzer (VNA) E5071C, of Agilent Technologies, Figure 8. The S_{11} coefficient was measured after one VNA port was calibrated to the used coaxial cable. This calibration process is essential to have correct S-parameter measurements, because it helps to mitigate the loss effects produced by the coaxial cable. Radiation patterns were not analyzed experimentally, but they were simulated and studied in *CST*TM software.

Three tests were performed, one in free space environment, and the other two inside the box (lid open or close). A frequency sweep from 0.6 to 7 GHz to the prototype was conducted.

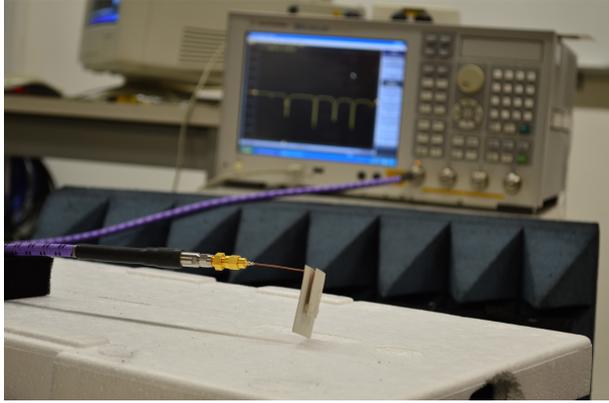


Figure 8: S_{11} measurement with the VNA E5071.

6.1. Antenna measurement in free space

The results presented in Figure 10 are obtained from the free space measurement in the RF laboratory and the free space simulation in *CST*TM software. It is possible to notice the consistency between the experimental resonances in red, and the simulation resonances in green. Only the first resonance shows some discrepancy between the two results. Although this first resonance is not credible to work on, there is still some evidence of reflection on that frequency, which shows that with more detailed work on the structure, it can be possible to bring the S parameter to a lower value. Figure 11 represents the antenna prototype configuration, and the points saw Figure 10 are the following pairs (GHz, dB):

Experimental (1.46, -3.64); (2.32, -23.1); (3.835, -30.5); (4.875, -23.3); (5.815, -31.525)

Simulations (1.52, -10.1); (2.468, -26.4); (4.004, -20.2); (5.048, -17); (5.87, -34,1)

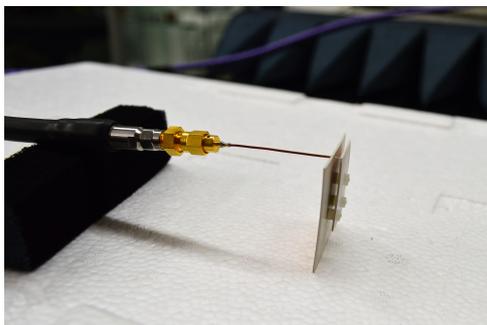


Figure 9: S_{11} measurement with the VNA E5071-free space environment.

6.2. Antenna measurement within an open box

The results presented in Figure 12 are obtained from the antenna prototype, inside the 3D-printed

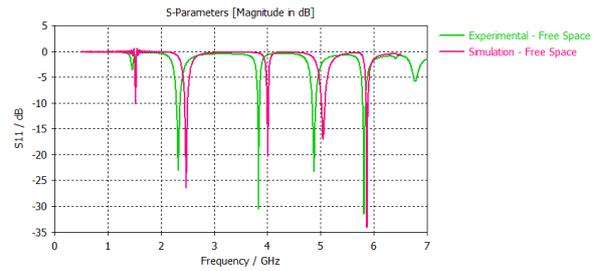


Figure 10: S_{11} comparison between experimental results and simulated results for free space environment.

box configuration, measured in the RF laboratory and the simulation in *CST*TM software.

As the previous measurement, it is observed that the curves have the same S_{11} behavior, except for a frequency shift towards lower frequencies. Figure 11 represents the antenna prototype inside the 3D-printed box configuration, and the points seen in Figure 12 are the following pairs (GHz, dB):

Experimental (1.46, -3.9); (2.33, -24.6); (3.84, -35.3); (4.875, -27.9); (5.815, -26.9)

Simulations (1.502, -9.9); (2.462, -28.9); (3.968, -18); (5.036, -19.3); (5.816, -23.9)



Figure 11: S_{11} measurement with the VNA E5071-open box environment.

6.3. Antenna measurement within a closed box

The results presented in Figure 14 are obtained from the antenna prototype inside the 3D-printed box configuration with the lid closed, measured in the RF laboratory and the simulation in *CST*TM software. The S_{11} experimental and simulation behavior is again similar, like in the previous measurements (experimental resonances in red and the simulation resonances in green). As in the previous case with the 3D printed box open, the results shows a shift towards lower frequencies, but with bigger differences in the S_{11} minimal values. Figure 13 represents the antenna prototype inside the

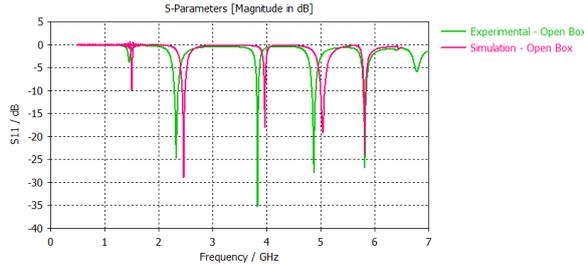


Figure 12: S_{11} comparison between experimental results and simulated results for open box environment.

3D-printed box configuration with the lid closed, and the points seen in Figure 14 are the following pairs (GHz, dB):

Experimental (1.44, -4.2); (2.285, -32.2); (3.8, -21.838); (4.835, -23.4); (5.785, -15.3)

Simulations (1.4842, -9.5) ; (2.4204, -18.6) ; (3.926, -9.6) ; (5, -15.516) ; (5.792, -9.636)

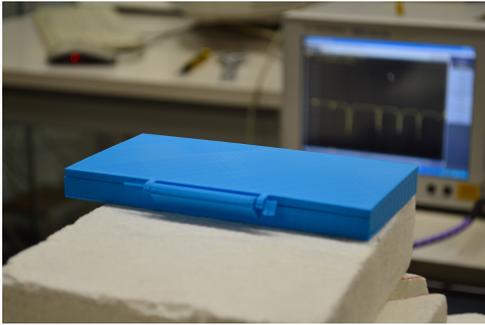


Figure 13: S_{11} measurement with the VNA E5071- open box environment.

7. Conclusions

A small multiband antenna design was achieved in this work. The built antenna prototype has

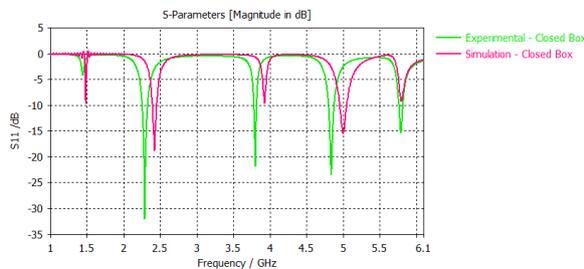


Figure 14: S_{11} comparison between experimental results and simulated results for closed box environment.

two substrates Rogers RO3035 of small dimensions, which one of the substrates have a dimension of $40 \times 40 \text{ mm}^2$, and the other a dimension of $20 \times 27.5 \text{ mm}^2$. Each substrate has a metalized copper part, one of the substrates is dedicated to the ground plane (base substrate), and the other one (top substrate) to support the top slotted patch and meander. The obtained resonances in the free space experimental tests, that meets the criterium of $S_{11} \leq -10 \text{ dB}$ are 2.32GHz, 3.84 GHz, 4.87GHz, and 5.82GHz. The same number of resonances, as in simulated results, has been observed with exception of the 1.5 GHz resonance that doesn't fulfill the matching criterium of $S_{11} \leq -10 \text{ dB}$. Final antenna results presented a resonance shift when compared to the simulation results. This can be associated to the deviations present in the built prototype, that occurred during the antenna assembling. Any lack precision or minor mistakes can and will change the behavior of the antenna, and cause the resonance shifts observed. Despite the deviations seen, this antenna is very promising, and with some assemble adjustment, or even measurements simulation manipulation, can reach the predicted values. This antenna prototype resonances are workable on the 5.8 GHz ISM band, on the S band and on the C band, and for these bands are expected applications within wireless network, WiMAX, Bluetooth and other satellite communications applications. The design of a slotted antenna is very subtle and the laboratory work is very careful, when working with small antennas. This revealed the importance and meticulousness of antenna design and multiband strategies. Special attention is needed to all dimensions and parameters variations, because small variations may cause frequency shifts of the desired resonances.

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References

- [1] Inverted-f antenna-based on-frame gps/wlan antenna for the metal-casing tablet computer. In *2016 10th European Conference on Antennas and Propagation (EuCAP)*, pages 1–4, April 2016.
- [2] J. Anguera, A. Andújar, and C. García. Multiband and small coplanar antenna system for wireless handheld devices. *IEEE Transactions*

- on *Antennas and Propagation*, 61(7):3782–3789, July 2013.
- [3] J. Anguera, A. Andújar, M.-C. Huynh, C. Orlenius, C. Picher, and C. Puente. Advances in antenna technology for wireless handheld devices. *International Journal of Antennas and Propagation*, 2013, 2013. doi:10.1155/2013/838364.
- [4] Y.-L. Ban, Y.-F. Qiang, Z. Chen, K. Kang, and J.-H. Guo. A dual-loop antenna design for hepta-band wwan/lte metal-rimmed smartphone applications. *IEEE Transactions on Antennas and Propagation*, 63(1):48–58, 2015.
- [5] Y.-L. Ban, S. Yang, Z. Chen, K. Kang, and J. L.-W. Li. Decoupled planar wwan antennas with t-shaped protruded ground for smartphone applications. *IEEE Antennas and Wireless Propagation Letters*, 13:483–486, 2014.
- [6] X. Bao and M. Ammann. Compact concentric annular-ring patch antenna for triple-frequency operation. *Electronics Letters*, 42(20):1129–1130, 2006.
- [7] H. Chen and A. Zhao. Lte antenna design for mobile phone with metal frame. *IEEE Antennas and Wireless Propagation Letters*, 15:1462–1465, 2016.
- [8] Z. Chen. *Antennas for Portable Devices*. Wiley, 2007.
- [9] J.-H. Chou, J.-F. Chang, D.-B. Lin, H.-J. Li, and T.-L. Wu. A compact loop-slot mode combination antenna for ultra-thin tablet computer with metallic bottom cover. *IEEE Antennas and Wireless Propagation Letters*, 13:746–749, 2014.
- [10] C. C. for input. 3.8 ghz to 4.2 ghz band: Opportunities for innovation. 2016.
- [11] K. Fujimoto and H. Morishita. *Modern Small Antennas*. Cambridge University Press, 1st edition, 2013. ISBN:978-0-521-87786-2.
- [12] B. Gowrish and A. Basu. Casing and hand effect on pcb antenna in 2.4 ghz wireless mouse: A measurement based characterization. In *Antennas and Propagation (APCAP), 2014 3rd Asia-Pacific Conference on*, pages 853–856, July 2014.
- [13] N. S. Jeong and F. Carobolante. Enabling wireless power transfer through a metal encased handheld device. In *Wireless Power Transfer Conference (WPTC), 2016 IEEE*, pages 1–3. IEEE, 2016.
- [14] Y.-C. Lee and J.-S. Sun. Compact multiband slotted antenna for wireless communication applications. *Microwave and Optical Technology Letters*, 51(2):502–503, 2009.
- [15] S.-J. Liao, K.-L. Wong, and L.-C. Chou. Small-size uniplanar coupled-fed pifa for 2.4/5.2/5.8 ghz wlan operation in the laptop computer. *Microwave and optical technology letters*, 51(4):1023–1028, 2009.
- [16] K.-C. Lin, C.-H. Lin, and Y.-C. Lin. Simple printed multiband antenna with novel parasitic-element design for multistandard mobile phone applications. *IEEE Transactions on Antennas and Propagation*, 61(1):488–491, 2013.
- [17] G. Liu, Y. Liu, and S. Gong. A coupled-fed loop antenna for metal-rimmed mobile phone applications. *Microwave and Optical Technology Letters*, 59(2):371–377, 2017.
- [18] M. K. Mandal and M. Kahar. A multiband robust planar antenna for wireless handheld devices. In *Microwave Conference (APMC), 2016 Asia-Pacific*, pages 1–4. IEEE, 2016.
- [19] P. Monin, F. FERRERO, L. Lizzi, C. Danchesi, N. Sornin, and S. Boudaud. Enabling Miniature Position Tracker Using LoRa and GPS Technology. In *European Conference on Antennas and Propagation (EuCAP), Proc. European Conference on Antennas and Propagation (EuCAP)*, pages CS09.1: Antenna for IoT applications (2905–2908), Davos, Switzerland, Apr. 2016.
- [20] T. Nakatsuka. Poly(lactic acid)-coated cable. 2011.
- [21] M. Pelosi, O. Franek, M. B. Knudsen, G. F. Pedersen, and J. B. Andersen. Antenna proximity effects for talk and data modes in mobile phones. *IEEE Antennas and Propagation Magazine*, 52(3):15–27, 2010.
- [22] A. R. Razali, A. M. Abbosh, and M. A. Antoniadis. *Compact Planar Multiband Antennas for Mobile Applications*, chapter 4 in *Advancement in Microstrip Antennas with Recent Applications*, pages 75–97. InTech, 2013.
- [23] C. Rowll and E. Y. Lam. Mobile-phone antenna design. *IEEE Antennas and Propagation Magazine*, 54:14–34, 2012. ISBN: 1045-9243.
- [24] W. L. Stutzman and G. A. Thiele. *Antenna theory and design*. John Wiley & Sons, 2012.

- [25] K. Sultan, H. Abdullah, E. Abdallah, and E. Hashish. Low-sar, miniaturized printed antenna for mobile, ism, and wlan services. *IEEE antennas and wireless propagation letters*, 12:1106–1109, 2013.
- [26] Tallinn. specific uwb applications in the bands 3.4 - 4.8 ghz and 6 - 8.5 ghz location tracking applications for emergency services (laes), location tracking applications type 2 (lt2) and location tracking and sensor applications for automotive and transportation environments (lta). *Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT)*.
- [27] Z. Wu, H. Wang, P. Chen, W. Shen, and G. Yang. A compact gps/wlan antenna design for mobile terminal with full metal housing. *Progress in Electromagnetics Research C*, 64:169–177, 2016.
- [28] Y. Yao, W. Chen, X. Chen, and J. Yu. Analysis and design of a novel multiband antenna for mobile terminals. *International Journal of Antennas and Propagation*, 2015, 2015. doi:10.1155/2015/591269.
- [29] J. Zhong, K.-K. Chen, and X. Sun. A novel multi-band antenna for mobile phone with metal frame. In *Wireless Communications, Networking and Mobile Computing (WiCOM), 2012 8th International Conference on*, pages 1–4. IEEE, 2012.