Chapter

Planar Antenna Design for Internet of Things Applications

Man Ho Tsoi and Steve W.Y. Mung

Abstract

Planar antenna plays an important role in Internet of Things (IoT) applications because of its small size, low profile and low cost. In IoT wireless module, antenna is typically occupied one-third size of overall circuit; therefore, planar antenna, i.e., integrated on printed circuit board (PCB) is one of attractive design. In this chapter, the fundamental of antenna is firstly discussed. Printed Inverted-F Antenna (PIFA) is taken as an example to explain the design process of simple planar antenna and a size-reduced 2.4 GHz ISM band PIFA is used for experimental explanation for the short-range IoT applications. Finally, a wideband antenna is shown as wideband planar antenna for short-range and long-range IoT applications.

Keywords: bluetooth low energy (BLE), industrial scientific and medical (ISM), printed circuit board (PCB), Internet of Things (IoT), planar antenna, printed inverted-F antenna (PIFA), wideband antenna

1. Introduction

Internet of Things (IoT) aims to connect existing sensors and devices to the internet in real time. Constantly collecting the information from surrounding help users making wiser decision, leading to higher quality in daily life and higher efficiency in industries [1–5]. Short-range and long-range wireless techniques are suitable used in different IoT applications. One of the wireless techniques for short-range IoT applications is bluetooth low energy (BLE) under 2.4 GHz industrial, scientific, and medical (ISM) band because of its low power consumption [6, 7]. On the other hand, cellular communications provide larger coverage in long-range IoT applications but they have high power consumption [8]. In RF/microwave modules, the size reduction and performance enhancement of the antenna are key design parameters, therefore, planar antenna, i.e., integrated on printed circuit board (PCB) is a suitable antenna for IoT applications.

In this chapter, the fundamental of antenna is firstly discussed. Printed Inverted-F Antenna (PIFA) is taken as an example to explain the design process of simple planar antenna and a size-reduced 2.4 GHz ISM band PIFA is used for experimental explanation for the short-range applications. Finally, a wideband antenna is shown as another approach on wideband planar antenna for short-range and long-range IoT applications.

2. Fundamental of antenna

2.1 Introduction of dipole antenna

Dipole antenna is one of the simple antenna that demonstrates the fundamental concept of antenna and it is a foundation of many practical antennas [9]. In **Figure 1**, dipole antenna is configured with two symmetric conductive arms carrying radio frequency current. Its length is required to be half wavelength (0.5λ) for maximum response and a half wavelength corresponds to approximately 6 cm (in air) in the 2.4 GHz ISM band. The current across the dipole generates the electromagnetic wave radiation propagating from the dipole arms.

2.2 Ground plane

A good conductive and reflective ground plane reduces the half wavelength dipole antenna to be quarter wavelength antenna [11]. This ground plane plays the same role of one of the arms and becomes a part of the antenna. This ground plane is considered as a mirror. In an optical mirror, if an object is placed in front of a mirror, a virtual image is generated with the same size and the same distance behind the mirror. In this case, if a signal source is placed above the ground plane, a virtual image of the source is generated with same current flowing direction and same phase shown in **Figure 2**, therefore, a quarter wavelength antenna and a ground plane form a half wavelength antenna. A well-designed ground plane should be very much larger in its dimensions than the half wavelength itself [11]. The active antenna measurement such as the over-the-air (OTA) measurement is a good method to indicate the overall antenna performance in the complete products compared to passive antenna measurement [12]. If the ground plane is significantly small, poor radiation performance is predicted in active antenna measurement.

2.3 Effect on length

An electric field with wavelength λ1 propagates toward to a dipole antenna with length L equals to 0.5λ1. This induces a sinusoidal current distribution shown in

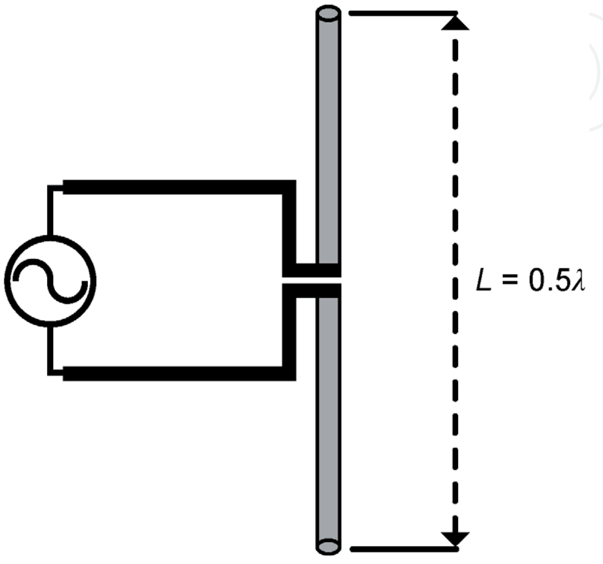

Figure 1.
Configuration of a half wavelength dipole antenna [10].

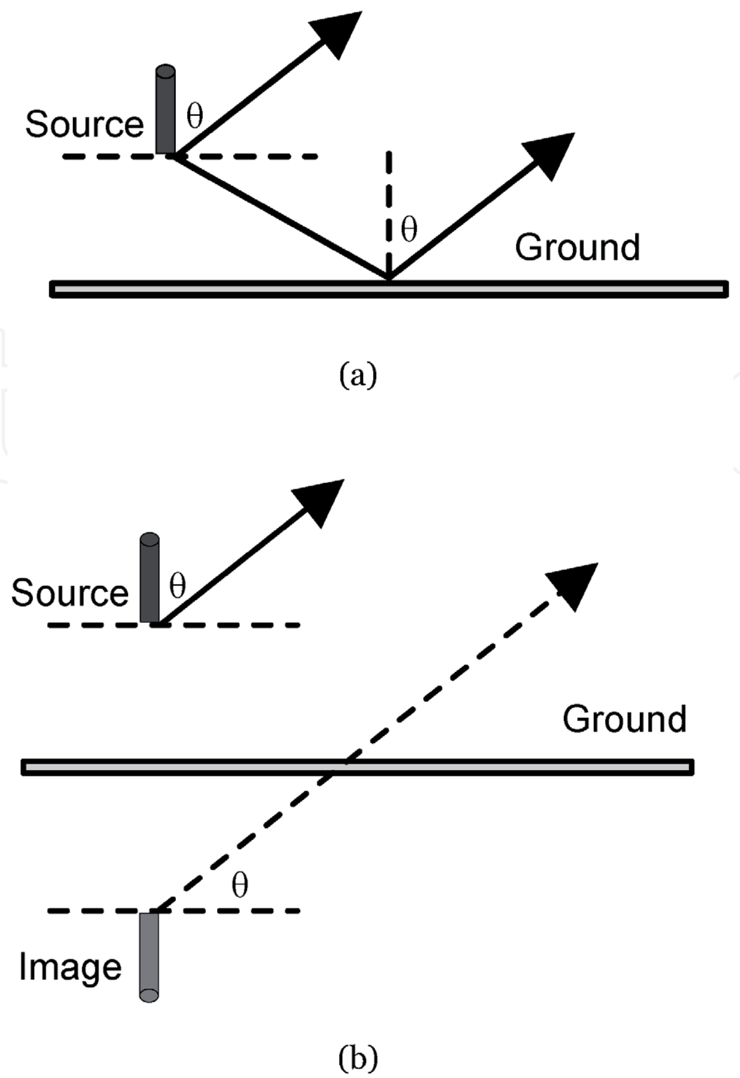

Figure 2.
Signal source and ground plane effect [11]. (a) Actual condition above a ground plane. (b) Equivalent condition with a virtual image under the ground plane.

Figure 3(a), given that the current distribution on the dipole is uniform. If the incident wave has wavelength λ2 which is much longer than the dipole length, for example L = 0.1λ2, current distribution is induced in triangular shape. The maximum current occurs at the center feed point and decreased linearly toward two ends to zero, as shown in **Figure 3(b)**.

For a dipole with uniform current distribution, the radiation resistance R_{rad} in free space is given by the following well-known equation [9, 10]:

$$R_{rad} = 80\,\pi^2 \left(\frac{L}{\lambda}\right)^2 \tag{1}$$

The radiation resistance of **Figure 3(b)** is much smaller than that of **Figure 3(a)** based on Eq. (1). Low radiation resistance is an indication of inefficient radiation. Most of the power is not radiated by the antenna when the length of antenna is not designed based on the wavelength of incident signal. This poor radiating condition occurs when the antenna operates not equal to its resonant frequency. Matching network is usually used to maximize the power transfer from the radio transceiver to the antenna [10]. Matching network sometimes is used to tune the operating frequency back to the desired value if the resonant frequency is little shifted to desired frequency.

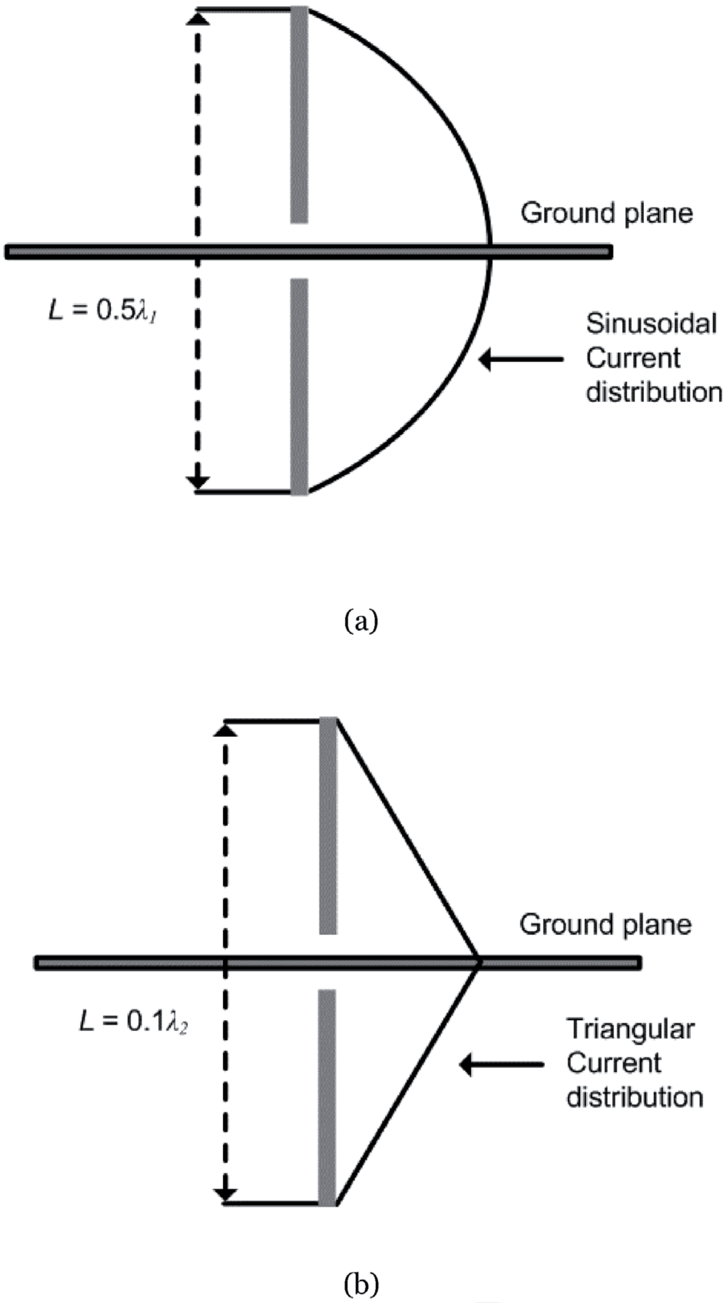

Figure 3.
(a) Sinusoidal current distribution for $L = 0.5\lambda_1$. (b) Triangular current distribution for $L = 0.1\lambda_2$ [9].

3. Design of general printed-F antenna (PIFA)

3.1 Printed inverted-F antenna (PIFA)

The printed inverted-F antenna (PIFA) is one of common planar antennas used in the commercial and medical devices because of its small size, low profile and low cost [13–20]. The typical PIFA structure is shown in **Figure 4**. Its working principle is same as monopole antenna with quarter-wave long along the main resonant line in **Figure 4**, therefore, the size of the ground plane is also an important part of antenna. It has a shorting feed point at the end of the main resonant line. This folded part introduces capacitance to the input impedance of the PIFA which is canceled by the shorting feed point. This foldable part, therefore, reduces the antenna size.

The matching network in **Figure 4** is used for maximum power transfer and, hence, efficient radiation [10]. Lump elements are normally used in matching network to minimize the size. In this section, PIFA is used as example of planar antenna since PIFA fulfills the requirements of IoT applications.

3.2 Meandered PIFA design

Figure 4 shows a typical PIFA structure on a printed circuit board (PCB) which is indicated with the dotted area at the PCB upper layer. Meandering line is commonly used to increase the total length in antenna design. The meandering line in **Figure 5** is used to replace the main resonant line in PIFA shown by combination of horizontal and vertical lines to form multiple turns.

The requirements of the PIFA are the operation frequency, power transmission efficiency, size and even cost. Simulation, fabrication and measurement are conducted until the antenna fulfills the defined application requirements. In general, a well-designed PIFA has the feature of having resonance at the operation frequency and good return loss, i.e., effective power transmission to antenna and compact in size.

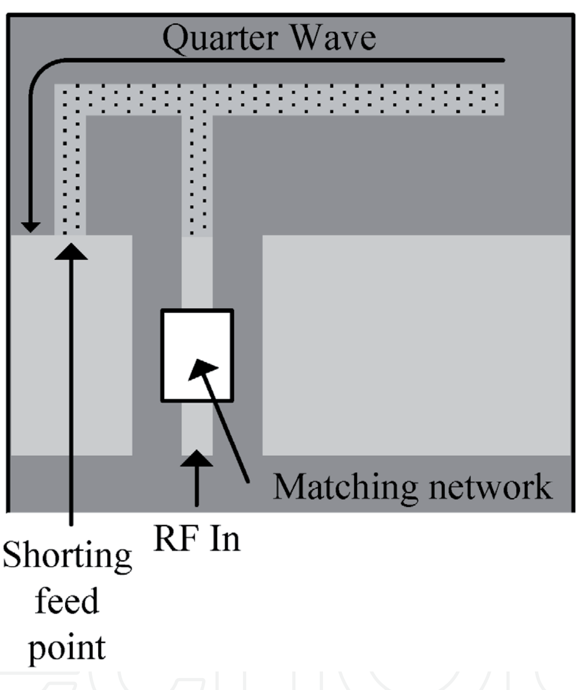

Figure 4.
Typical PIFA structure [13].

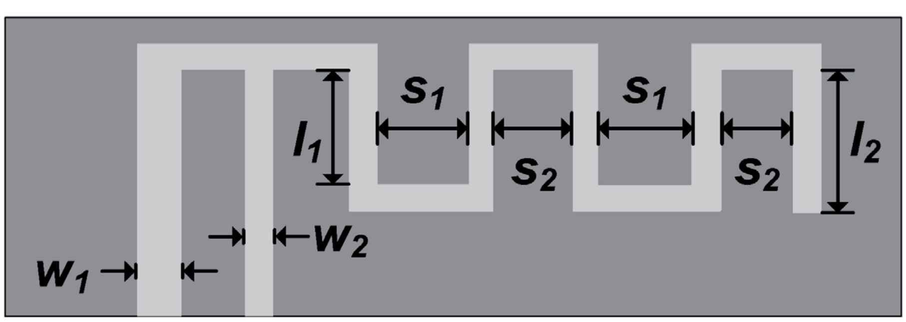

Figure 5.
PIFA with meandering line.

High directivity sometimes is considered in certain situation. However, it will not be discussed here since most of planar antennas are omni-directional transmission and reception instead of unidirectional antennas. The basic design rules and antenna performance characterization methods are addressed by case study in 2.4 GHz ISM band. The operation frequency of the antenna is governed by the basic dispersion relation $c = f\lambda$. The letter c represents the speed of electromagnetic wave in the air, which is a constant if only consider the wave traveling in single medium. In previous section, it shows that a dipole antenna resonates when the physical length of antenna equals to the quarter wavelength of incident signal and a sufficiently large ground plane form the mirror image under the plane. The length of the resonant line occupies a considerable area on the PCB, which is around one third of a wireless module. Proper selection of traces' length and width reduces the occupied area and impedance matching network for maximum power transfer [13].

3.3 Simulation and experimental results

Powerful computer simulation tools are used to drastically reduce the design time. Advanced Design System (from Keysight) is one of the electromagnetic (EM) simulators used to estimate the performance of certain designs in this chapter. Normally, there is small variation between the simulation and measurement results because of the fabrication variation, material variation and connectors mismatch, etc. There is limited effect on frequency below 6 GHz, however, this becomes significant when the frequencies are in millimeter wave. Two antennas are designed based on structure in **Figure 5**. The dimensions of these two examples (called Antenna PCB A and Antenna PCB B) of PIFA shown in **Table 1** and in **Figure 6**.

Antennas in **Figure 6** were simulated on FR4 substrate with a dielectric constant of 4.6 and 0.8 mm thickness. The PCB design mainly contains PIFA, ground plane, transmission line and 3.5 mm SMA connector. The size of PCB, 18.8 mm× 43.2 mm was chosen, which is the normal size of a 2.4 GHz ISM band wireless module. At end of meandering line is 4.2 mm for Antenna PCB A and 2.9 mm for Antenna PCB B. The resonance frequency of Antenna PCB A is expected to be lower due to the longer trace. Antenna PCB C was fabricated to calibrate the transmission line by the port extension measurement. The simulated results of Antenna PCB A and Antenna PCB B are shown in **Figure 7** and the return loss indicates the resonant frequency of the antennas [9]. The input feed point in the simulation is at Port A in **Figure 6(a)** which is without the transmission line and connector but others are the same as in **Figure 6(a)**.

In **Figure 7**, the resonance frequency of Antenna PCB A is lower than that of Antenna PCB B. Antenna PCB A and Antenna PCB B were fabricated with

Parameters	Length (mm)
w_1	0.9
w_2	0.5
s_1	2.0
s_2	1.7
l_1	2.5
l_2 (Antenna PCB A)	4.2
l_3 (Antenna PCB B)	2.9

Table 1.
Parameters used in the PIFA.

DOI: http://dx.doi.org/10.5772/intechopen.92456

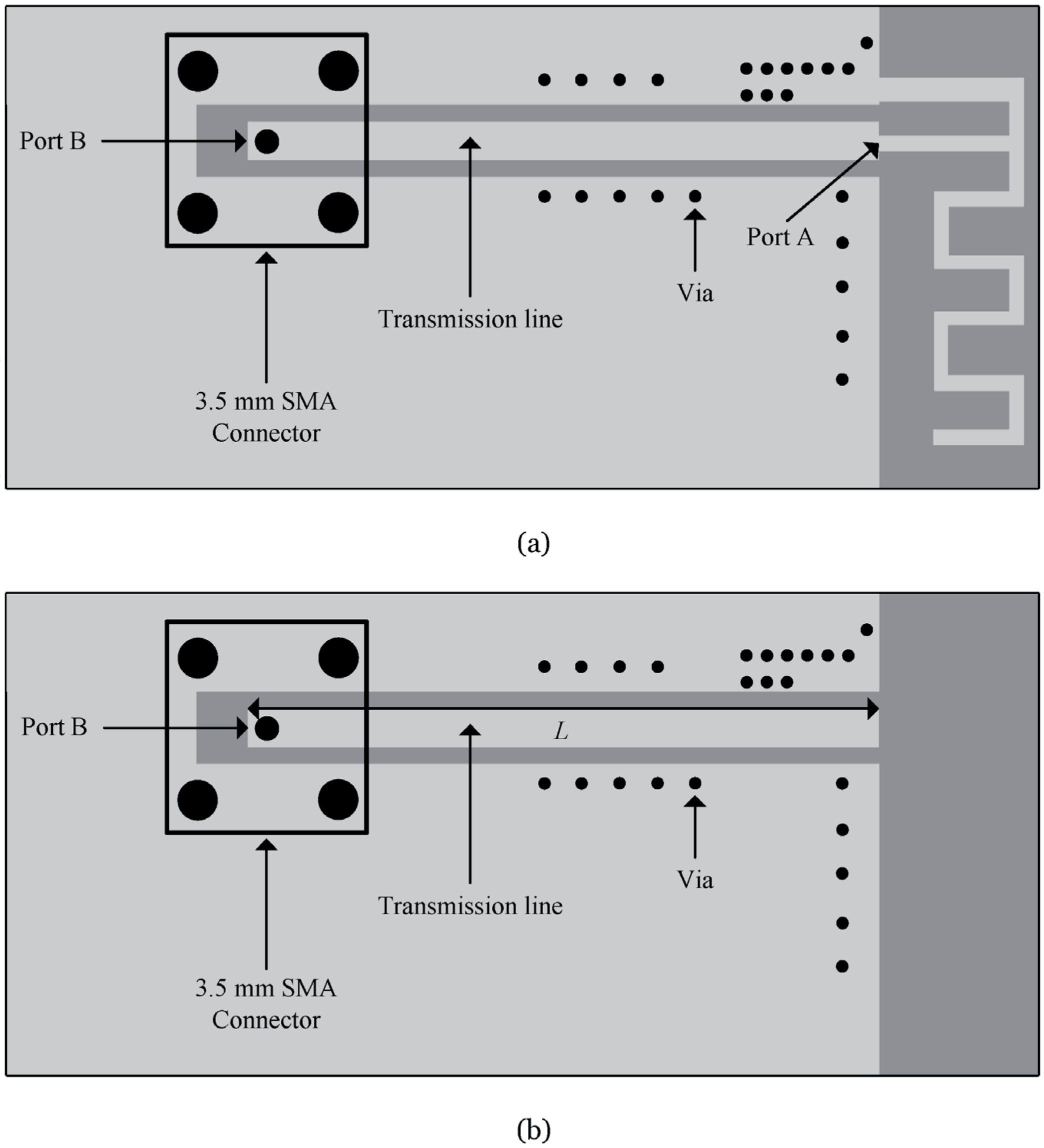

Figure 6.
PIFA: (a) Antenna PCB A (l2 = 4.2 mm) and Antenna PCB B (l3 = 2.9 mm) (b) and Antenna PCB C.

the transmission line and connector in **Figure 6(a)**. The width of the transmission line is 1.5 mm so that the characteristic impedance of the line is equal to 50 Ohm. The return losses of antenna were measured by vector network analyzer (VNA). If the return losses are not significant high enough, matching network is needed for maximum power transfer. Antenna PCB C is used for port extension by VNA so that the measurement reference plane is moved to Port A since the VNA can predict the open circuit at end of the transmission line from the connector in Antenna PCB C by the electrical length *L* of the transmission line. The simulated and measured results of Antenna PCB B are plotted in **Figure 8**. It is also shown that the overall performance of antenna at Port B is close to the same at Port A. The radiation patterns and gain measurement are carried out by passive antenna measurement system. The active antenna measurement sometimes is used to indicate the overall transmission and reception of the complete products. The maximum gain of the PIFA is normally around 3 dBi. Antenna PCB B, therefore, is suitable for 2.4 GHz ISM band applications. **Table 2** shows the comparison table of different antennas, which shows that the dielectric antennas have a little size smaller than the PIFA. However, PIFAs were only fabricated on PCB, which is approximately zero in thickness as well as zero cost of antenna and matching components.

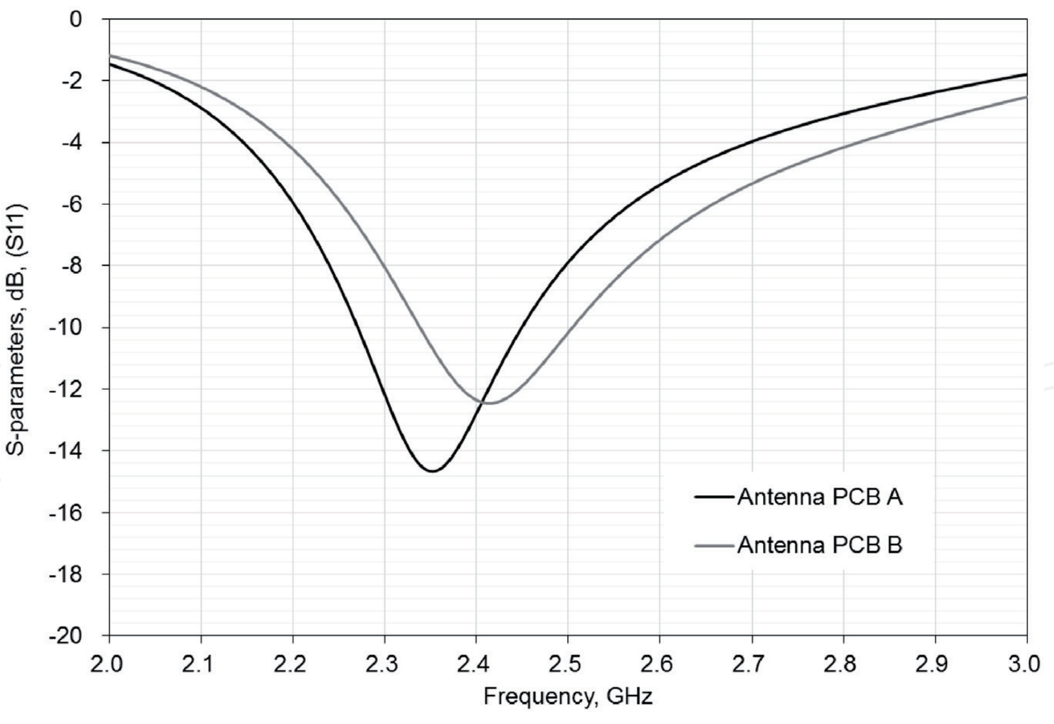

Figure 7.
Simulated S-parameter, S11 of Antenna PCB A and Antenna PCB B at Port A.

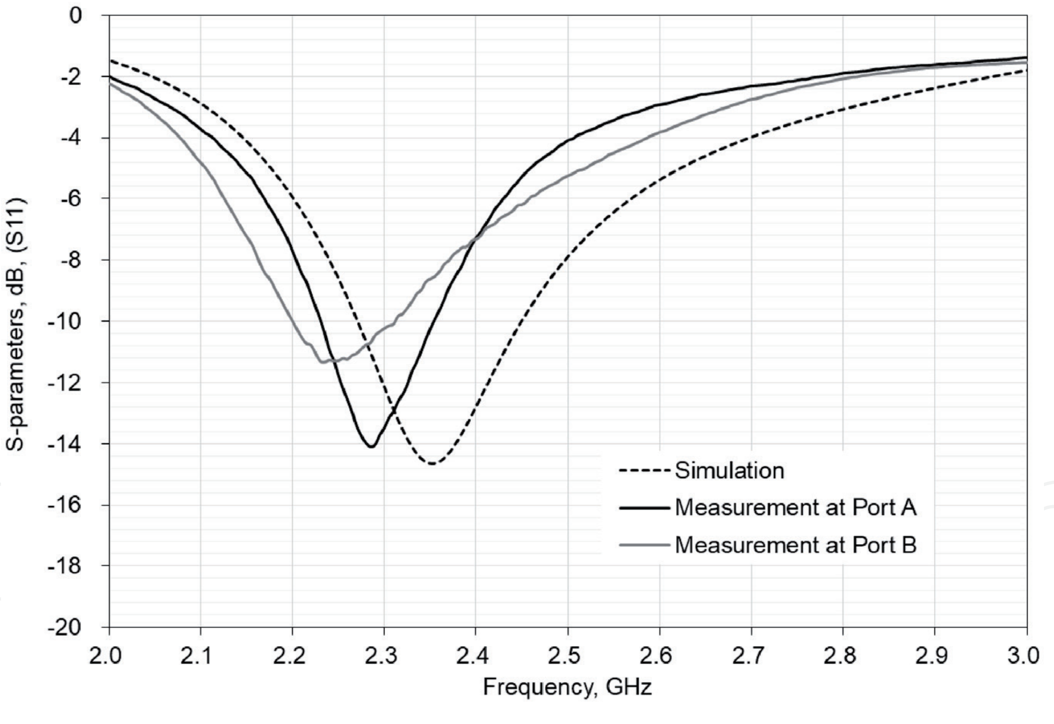

Figure 8.
Antenna PCB B: Simulated (at Port A) and measured (at Port A and B) S-*parameter,* S11.

4. Wideband planar antenna: foldable and non-foldable

4.1 Wideband planar antenna for IoT applications

Various IoT applications use different solutions to connect devices and sensors. Low power technologies such as Bluetooth and Zigbee are preferred for short-range applications because of their low power usage. Cellular communication technologies sometimes are required used for large coverage and high data rate applications

Antenna	Plane	Total average (dBi)	Area (mm^2)
PIFA (Antenna PCB B)	Y-Z	1.60	16 × 7.0
	X-Z	3.30	
	X-Y	1.10	
Miniaturized PIFA [13]	Y-Z	−0.70	15 × 6.0
	X-Z	−1.98	
	X-Y	−1.26	
Capacitive-loaded antenna	Y-Z	—	12 × 5.0
	X-Z	−1.76	
	X-Y	−3.32	
Dielectric antenna (3 mm length)	Y-Z	0.89	12 × 5.0
	X-Z	−1.85	
	X-Y	−2.56	
Dielectric antenna (5 mm length)	Y-Z	−3.22	18 × 11
	X-Z	−3.24	
	X-Y	−3.12	

Table 2.
Gain between dielectric and PCB antennas [10] (includes the area of matching network, but not the ground plane).

despite its large power consumption. Multiple narrowband antennas are needed when different technologies are used in IoT applications. One wideband antenna, therefore, is an attractive approach to replace multiple narrowband antennas. Different wideband structures were proposed to combine different frequency bands into one individual wideband antenna to serve different technologies in order to reduce the size and simplicity [21–23]. The wideband antenna is still large to be used in portable devices, therefore, foldable design [21] provides flexibility of IoT products as well as further size reduction.

4.2 Wideband planar antenna design

Dipole antenna in **Figure 1** could be extended to be a wideband antenna. Two conductive arms are replaced by thicker wire or even a plane to extend the bandwidth. One of example for wideband planar foldable and non-foldable antennas is shown in **Figure 9**.

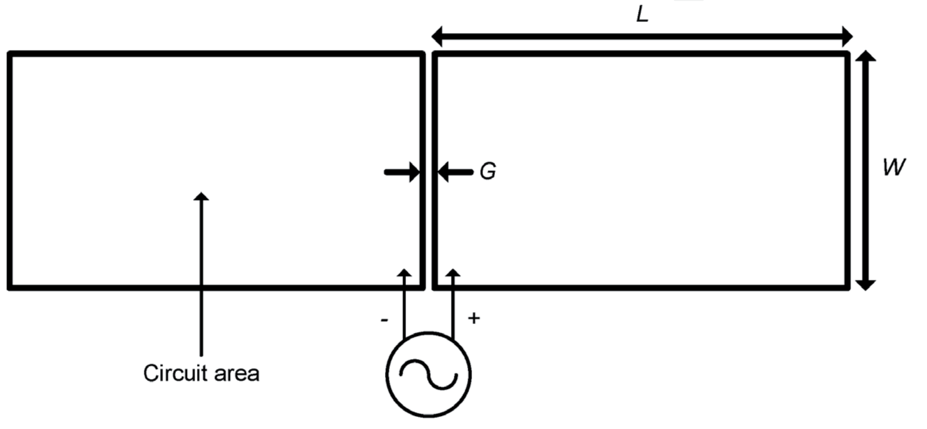

Figure 9.
Wideband planar foldable and non-foldable antennas [21].

Parameters	Length (mm)
G	0.9
W (foldable design)	29
W (non-foldable design)	25

Table 3.
Parameters used in the wideband planar foldable and non-foldable antennas.

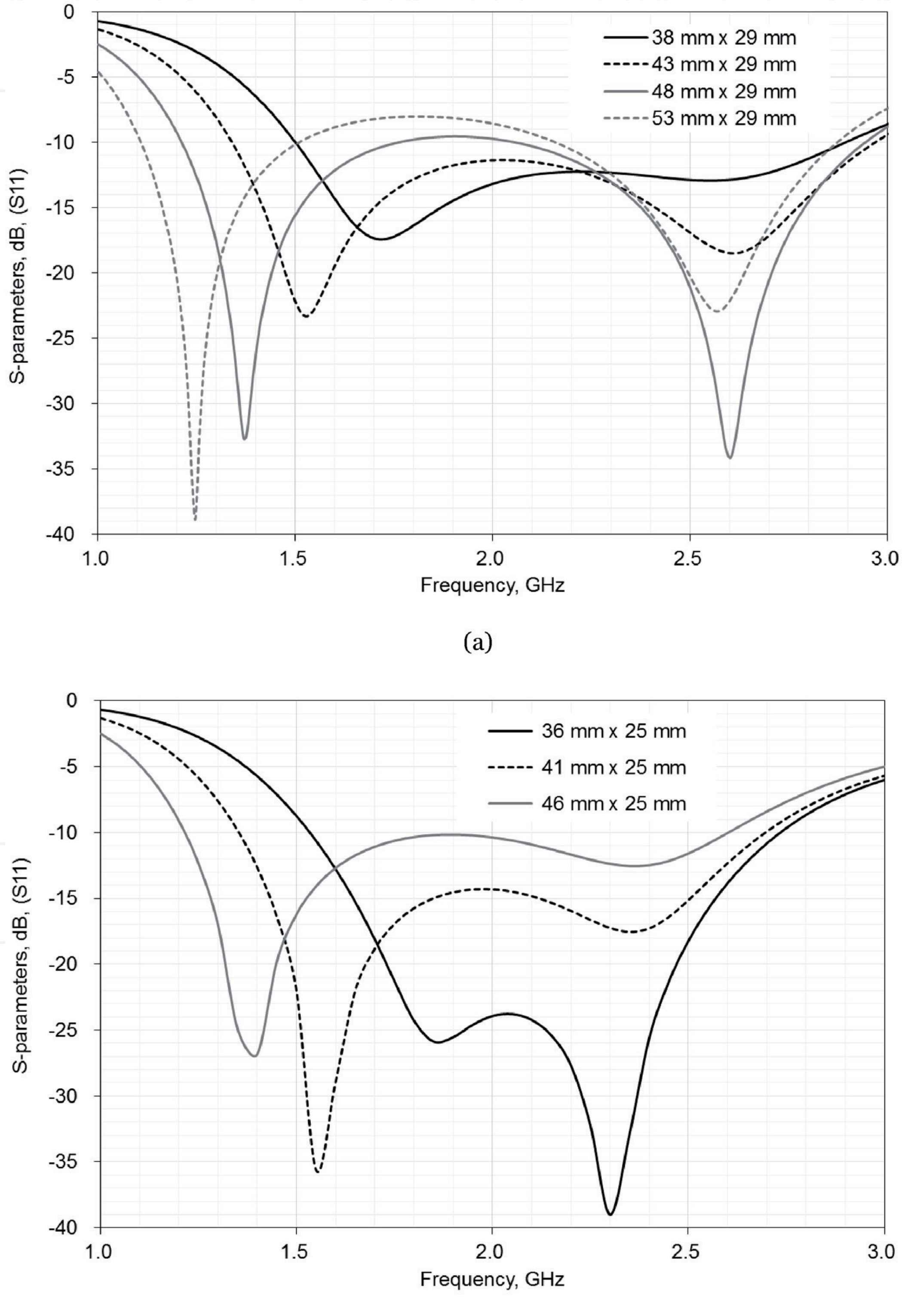

Figure 10.
Simulated results of wideband planar antennas [21]: (a) foldable and (b) non-foldable.

This planar antenna consists of two rectangular metal planes. The important parameters could be tuned in this design are width W, length L and gap G. The length is used for tuning in this example as it has significant impact on the performance of antenna. All parameters are fixed in **Table 3** except the length L which is the parameter chosen to be tuned for foldable and non-foldable antennas. The foldable design was fabricated in the metal sheet and the non-foldable design was fabricated on the FR4 substrate with a dielectric constant of 4.6 and thickness of 0.8 mm. The simulated results of return loss are shown in **Figure 10** with different lengths of sheet L. In **Figure 10**, the frequency range is shifted to the lower side with a longer length L because the length L is closer to the quarter-wavelength of a lower frequency.

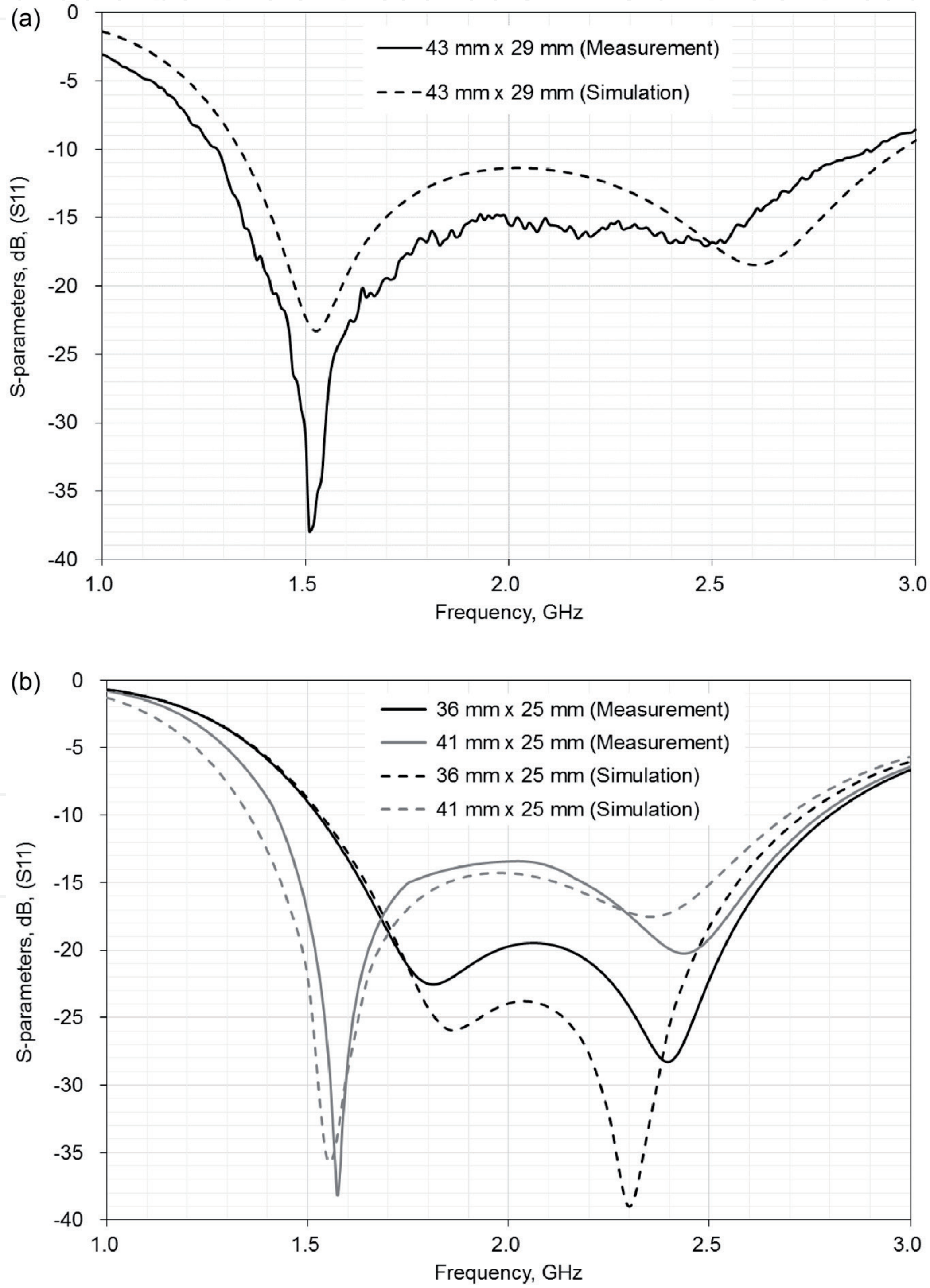

Figure 11.
Comparison between simulated and measured results of wideband planar antennas [21]: (a) foldable and (b) non-foldable.

Figure 11 shows the comparison between simulated and measured results of wideband planar foldable and non-foldable antennas. **Figure 11(a)** shows the simulated and measured results of the fabricated foldable antenna which shows that the simulated and measured results are close to each other with the bandwidth of 76% from 1.3 to 2.9 GHz. This range covers the applications in GPS, the 2.4 GHz ISM band, and the general 3GPP WCDMA bands and LTE bands. **Figure 11(b)** shows the simulated and measured results with L equal to 36 and 41 mm (same width of W = 25 mm). Simulated and measured results show that they are close to each other with the bandwidth of 76% from 1.35 to 2.75 GHz, which is little worse than the foldable design in **Figure 11(a)**. The maximum gain of the non-foldable is between 2.5 and 3.5 dBi.

5. Conclusion

The architecture of the PIFA on PCB with meandering line was shown. The measurement results of return loss and gain performances shown that it has better performances compared to the dielectric antennas as well as without any extra matching components. When only single communication technology is used in IoT product, PIFA is recommended. Using meandering line can reduce the antenna size as well as keeping the performance. PIFA design, therefore, is suitable for ISM band and other IoT applications. In the product utilizing numbers of communication technologies at same times, one wideband antenna integrated in the product is more suitable. Both foldable and non-foldable wideband structures, therefore, were proposed and fabricated for their different uses in IoT applications. Both measurement results of two structures show more than 65% in bandwidth. Their operating frequency covers IoT applications in GPS, the 2.4 GHz ISM band, and the common 3GPP WCDMA and LTE bands. And the foldable structure has advantage of wearable applications.

During the design process, the type of antenna is firstly confirmed and then the key parameters such as frequency and size need to be determined. Simulation software and measurement equipment are important tools to verify its performance and further design iterations may be required for fine-tuning the performance.

Abbreviations

IoT	Internet of Things
ISM	industrial, scientific, and medical
BLE	bluetooth low energy
PIFA	printed inverted-F antenna
PCB	printed circuit board
OTA	over-the-air
EM	electromagnetic
VNA	vector network analyzer
GPS	global positioning system
WCDMA	wideband code division multiple access
LTE	long-term evolution
3GPP	3rd generation partnership project

Author details

Man Ho Tsoi and Steve W.Y. Mung*
The Hong Kong Polytechnic University, Hong Kong

*Address all correspondence to: mungwaiyin@hotmail.com

References

[1] Ahlgren B, Hidell M, Ngai EC-H. Internet of things for smart cities: Interoperability and open data. IEEE Internet Computing. 2016;**20**:52-56. DOI: 10.1109/MIC.2016.124

[2] Sun Y, Song H, Jara AJ, Bie R. Internet of things and big data analytics for smart and connected communities. IEEE Access. 2016;**4**:766-773. DOI: 10.1109/ACCESS.2016.2529723

[3] He W, Yan G, Da Xu L. Developing vehicular data cloud services in the IoT environment. IEEE Transactions on Industrial Informatics. 2014;**10**(2):1587-1595. DOI: 10.1109/TII.2014.2299233

[4] Zanella A, Bui N, Castellani A, Vangelista L, Zorzi M. Internet of things for smart cities. IEEE Internet of Things Journal. 2014;**1**(1):22-32. DOI: 10.1109/JIOT.2014.2306328

[5] Satija U, Ramkumar B, Sabarimalai MM. Real-time signal quality-aware ECG telemetry system for IoT-based health care monitoring. IEEE Internet of Things Journal. 2017;**4**(3):815-823. DOI: 10.1109/JIOT.2017.2670022

[6] The Bluetooth Special Interest Group (Bluetooth SIG). Bluetooth Core Specification [Internet]. 2019. Available from: https://www.bluetooth.com/specifications/bluetooth-core-specification [Accessed: 25 February 2020]

[7] Tabish R, Ben Mnaouer A, Touati F, Ghaleb AM. A comparative analysis of BLE and 6LoWPAN for U-HealthCare applications. In: 2013 7th IEEE GCC Conference and Exhibition (GCC). 7-20 November, 2013; Doha. New York: IEEE; 2013. pp. 286-291

[8] The 3rd Generation Partnership Project (3GPP). Specifications. Available from: https://www.3gpp.org/specifications/specifications [Accessed: 25 February 2020]

[9] Kraus JD, Marhefka RJ. Antennas: For all Applications. 3rd ed. New York: McGraw Hill; 2003

[10] Mung SWY, Wu KM, Yuen JSM. Design trade-offs and challenges on miniaturized antenna for bluetooth in internet of things applications. Engineering Technology Open Access Journal. 2019;**3**(1):555602. DOI: 10.19080/ETOAJ.2019.03.555602

[11] Holzman E. Essentials of RF and Microwave Grounding. 1st ed. Boston: Artech House; 2006

[12] Huang Y, Loh TH, Foged LJ, Lu Y, Boyes S. Broadband antenna measurement comparisons. In: Proceedings of the Fourth European Conference on Antennas and Propagation. 12-16 April, 2010; Barcelona. New York: IEEE; 2010. pp. 1-5

[13] Cheung CY, Yuen JSM, Mung SWY. Miniaturized printed inverted-F antenna for internet of things: A design on PCB with a meandering line and shorting strip. International Journal of Antennas and Propagation. 2018;**2018**. DOI: 10.1155/2018/5172960

[14] Hristov HD, Carrasco H, Feick R. Bent inverted-F antenna for WLAN units. Microwave and Optical Technology Letters. 2008;**50**(6):1505-1510. DOI: 10.1002/mop.23405

[15] Ammann MJ, Doyle LE. A loaded inverted-f antenna for mobile handsets. Microwave and Optical Technology Letters. 2001;**28**(4):226-228. DOI: 10.1002/1098-2760(20010220)28:4<226::AID-MOP1002>3.0.CO;2-T

[16] Palukuru VK, Pekonen A, Pynttäri V, Mäkinen R, Hagberg J,

Jantunen H. An inkjet-printed inverted-F antenna for 2.4-Ghz wrist applications. Microwave and Optical Technology Letters. 2009;**51**(12):2936-2938. DOI: 10.1002/mop.24777

[17] Su SW. Linearly-polarized patch PIFA for GPS/GLONASS operation for tablet-computer applications. Microwave and Optical Technology Letters. 2015;**57**(1):149-153. DOI: 10.1002/mop.28800

[18] Soras C, Karaboikis M, Tsachtsiris G, Makios V. Analysis and design of an inverted-F antenna printed on a PCMCIA card for the 2.4 GHz ISM band. IEEE Antennas and Propagation Magazine. 2002;**44**(1):37-44. DOI: 10.1109/74.997891

[19] Yang HYD. Printed straight F antennas for WLAN and Bluetooth. In: IEEE Antennas and Propagation Society International Symposium, Vol. 2. 22-27 June, 2003; Columbus, OH, USA. New York: IEEE; 2003. pp. 918-921

[20] Ali M, Hayes GJ. Small printed integrated inverted-F antenna for Bluetooth application. Microwave and Optical Technology Letters. 2002;**33**(5):347-349. DOI: 10.1002/mop.10317

[21] Mung SWY, Cheung CY, Wu KM, Yuen JSM. Wideband rectangular foldable and non-foldable antenna for internet of things applications. International Journal of Antennas and Propagation. 2019;**2019**. DOI: 10.1155/2019/2125713

[22] Chen JH, Ho CJ, Wu CH, Chen SY, Hsu P. Dual band planar monopole antenna for multiband mobile systems. IEEE Antennas and Wireless Propagation Letters. 2008;**7**:769-772. DOI: 10.1109/LAWP.2008.2008110

[23] Li RL, Pan B, Laskar J, Tentzeris MM. A compact broadband planar antenna for GPS, DCS-1800, IMT-2000, and WLAN applications. IEEE Antennas and Wireless Propagation Letters. 2007;**6**:25-27. DOI: 10.1109/LAWP.2006.890754