

Analysis and Design of UHF Bow-Tie RFID Tag Antenna Input Impedance

D. A. Abd El-Aziz¹, T. G. Abouelnaga², E. A. Abdallah², M. El-Said³, Yaser S. E. Abdo¹

¹National Institute for Standards, Giza, Egypt
 ²Electronics Research Institute, Giza, Egypt
 ³Faculty of Engineering, Cairo University, Giza, Egypt
 Email: eng.dina_ali@hotmail.com, taer@eri.sci.eg, moelsaid@hotmail.com, esmataa2@hotmail.com, yaserabdo76@gmail.com

Received 15 May 2016; accepted 19 June 2016; published 22 June 2016

Copyright © 2016 by authors and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY). <u>http://creativecommons.org/licenses/by/4.0/</u>

😨 🛈 Open Access

Abstract

In this paper two proposed methods of input impedance calculation for Bow-Tie antenna are introduced. The proposed methods show input impedance calculation with high accuracy. Also, design curves for input impedance values were developed depending on the geometry of antenna. The proposed design curves are used to design a Bow-Tie type RFID tag antenna. The input impedance of the tag antenna is calculated using proposed methods and compared with that obtained using CST studio suite 2014 and IE3D Zeland version 12.0 software packages. The results are investigated and discussed. The tag antenna is fabricated, measured and the obtained input impedance is compared with the simulation and the proposed methods. Good agreement among measured input impedance and that simulated by CST, IE3D or proposed methods is obtained.

Keywords

Bandwidth, Bow-Tie Antenna, Radio Frequency Identification (RFID), Ultra High Frequency (UHF)

1. Introduction

RFID system consists of reader and tag. The reader interrogates the tags via a wireless link to obtain the data stored on the tags. The tag consists of an antenna and a chip which has an input impedance of complex value. In order to achieve a good performance and low power consumption, chip impedance should be correctly matched to tag antenna. The cheapest RFID tags with the largest commercial potential are passive or semi-passive, where the energy necessary for tag-reader communication is harvested from the reader's signal or the surrounding environment. The most important requirements for tag antenna are extremely low power consumption, small size,

How to cite this paper: Abd El-Aziz, D.A., Abouelnaga, T.G., Abdallah, E.A., El-Said, M. and Abdo, Y.S.E. (2016) Analysis and Design of UHF Bow-Tie RFID Tag Antenna Input Impedance. *Open Journal of Antennas and Propagation*, **4**, 85-107. http://dx.doi.org/10.4236/ojapr.2016.42007 and low cost. Dipole configurations including the Cylindrical [1], Biconical [2] and Bow-Tie [3] have been used as a wide-band antenna for their simple structures and low cost. The Bow-Tie structure was first proposed by George et al. [4]. A hybrid approach involving Bacterial Swarm Optimization (BSO) and Nelder-Mead (NM) algorithm was used to design a Bow-Tie antenna for 2.45 GHz Radio Frequency Identification (RFID) readers. The Bow-Tie antenna was made from a bi-triangular metal sheet with the feed at its vertex. The antenna dimensions: half-height, feeding neck width, and flare angle were optimized to be 21.078 mm, 3.4818 mm, 48.555°, respectively and matched to input impedance of 50 Ω [5]. This antenna gives an excellent reflection coefficient $|S_{11}|$ result equal to -111.96 dB at 2.45 GHz. A T-matched quadrate Bow-Tie antenna (half wavelength dipole antenna) with rounded corners was designed and fabricated with dimensional length 92 mm and width 31.8 mm [6]. This design was used for the matching of the passive antenna terminals to (UCODE G2XM) IC chip impedance $(22 - i191\Omega)$ at resonance frequency of 915 MHz. An ultra-wideband cavity-backed Bow-Tie antenna with the parasitic dipole and parasitic circular ring was designed and fabricated with three layers including the upper substrate layer, the lower substrate layer and the ground plane. Both substrates with permittivity of 2.65, a thickness of 1 mm are supported by the plastic posts, loss tangent of 0.003, a radius of 62 mm [7]. An ultra-wideband impedance characteristic of about 118.2% for VSWR ≤ 2 ranging from 2.75 to 10.7 GHz was achieved. A unidirectional radiation pattern, a stable peak gain of around 7.4 - 10.8 dBi and low cross polarization over the whole operating band were also produced. A wideband directional Bow-Tie antenna with stable radiation patterns fed by a wideband microstrip balun using a coupling triangular structure to induce more balanced current was built on a substrate with thickness of 1 mm and relative permittivity $\varepsilon_{r} = 2.65$ and it's dimensions were 70×40 mm² [8]. The antenna was designed to cover the band from 1.97 GHz to 6.49 GHz and achieved a stable gain of around 9.5 dBi with unidirectional and symmetrical radiation patterns in both E- and H-planes across the whole operating band. A Bow-Tie microstrip antenna was designed to overcome the high path loss and achieve bandwidth requirement in sea water from 2.4 GHz to 5.1 GHz. The antenna was used in WLAN communications and its dimensions was 1.4 cm² [9]. The aforementioned literatures indicate that, in the recent few years, a great effort was made and good results were obtained where the antenna was matched to a 50 Ohm input impedance but the main problem will arise when a complex matching is needed. This problem arises clearly in the design requirements of UHF tag antenna. In this paper, a Bow-Tie tag antenna which is matched to a complex chip input impedance and also to achieve a wide bandwidth is proposed. Also, two proposed methods of input impedance calculation of Bow-Tie antenna are introduced.

The paper is organized as follows: Section 2 gives the Bow-Tie antenna input impedance calculation as in the published literatures, namely quasi-static method, tapered transmission line method and biconical approximation method. It also includes the proposed analytical and graphical methods. The conventional Bow-Tie tag antenna is given in Section 3, while the modified tag antenna design results are given in Section 4. Section 5 gives the experimental results, while Section 6 introduces the conclusions.

2. Bow-Tie Antenna Input Impedance Calculation

The design of Bow-Tie antenna [10] is simple since the antenna structure is completely defined by its angle θ and length L_1 , Figure 1. The Bow-Tie antenna angle determines the antenna impedance and the length determines the operation bandwidth.



Figure 1. Conventional Bow-Tie antenna geometry.

2.1. Quasi-Static Method

This method was used to calculate the characteristic impedance of Bow-Tie antenna [11]. The theoretical quasisi-static impedance Z_{qs} [3] of an infinite Bow-Tie printed on a dielectric half-space, obtained using conformal mapping is given by:

$$Z_{qs} = \eta_o \sqrt{\frac{2}{\varepsilon_r + 1}} \frac{K(k)}{K'(k)} \tag{1}$$

where η_o is the free space wave impedance (=120 $\pi \Omega$), ε_r is the substrate dielectric constant and K(k) represents a complete elliptic integral function with argument k,

$$k = \tan^2 \left(45^\circ - \theta/4 \right) \tag{2}$$

and K'(k): complementary function given by K'(k) = K(k')

$$k' = \sqrt{1 - k^2} \tag{3}$$

Based on Equation (1) a matlab code is built and the results are shown in **Figure 2**. Referring to **Figure 2**, it can be noticed that a good agreement is found with the curves the curve of Z_{qs} that was published in [10], in which it has been calculated as a function of bow-tie angle θ for different values of ε_r .

2.2. Tapered Transmission Line Method

In a multi-section quarter-wave transformer used to match two transmission lines with different characteristic impedances, the change in impedance level is obtained in a number of discrete steps. An alternative is to use a tapered transition which has characteristic impedance that varies continuously in a smooth fashion from the impedance of one line to that of the other line. A transition or matching section, of this type is referred to as a tapered transmission line [12], Figure 3.



Figure 3. Tapered transmission line matching section.

Wide line $\frac{w_1/2}{h} \ge 1$:

$$\varepsilon_{eff1} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\left(1 + 12 \frac{h}{w_1/2} \right)^{-0.5} \right]$$
(4)

$$Z_{1} = \frac{120\pi}{\sqrt{\varepsilon_{eff1}} \left(\frac{w_{1}/2}{h} + 1.393 + 0.667 \ln\left(\frac{w_{1}/2}{h} + 1.444\right)\right)} \times 2$$
(5)

Narrow line $\left(\frac{w_2/2}{h}\right) \le 1$:

$$\varepsilon_{eff\,2} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\left(1 + 12\frac{h}{w_2/2} \right)^{-0.5} + 0.04 \left(1 - \frac{w_2/2}{h} \right)^2 \right] \tag{6}$$

$$Z_{2} = \frac{60}{\sqrt{\varepsilon_{eff\,2}}} \ln\left(\frac{8h}{w_{2}/2} + 0.25\frac{w_{2}/2}{h}\right) \times 2$$
(7)

$$Z(z) = Z_2 \left[1 + \left(\frac{Z_1}{Z_2} - 1\right) \frac{z}{L_1} \right]$$
(8)

Taking the average value of Z(z):

 $Z_{av.} = Z(z) / \text{number of stepsin length}$ (9)

where $w_1/2$ is the half width at impedance $Z_1/2$, $w_2/2$ is the half width at impedance $Z_2/2$ [1] [13], Figure 3, ε_{eff1} , ε_{eff2} are the effective dielectric constants at $w_1/2$ and $w_2/2$, h is the height of dielectric substrate, Z(z) is the characteristic impedance function of distance z along the taper and L_1 is the length of the taper.

2.3. Biconical Approximation Method

The problem of finding the input terminal resistance and also reactance taking into account the effect of conductor thickness is most simply approach by Schelkunoff's treatment of the biconical antenna. This method was used to determine the characteristic impedance of finite biconical antenna [2]. This is analogues to finite or terminated transmission line. A TEM mode wave can exist along the biconical conductor, but in the space beyond the cones transmission can be only in higher order modes. Schelkunoff's has defined the sphere coinciding with the ends of the cones as a boundary sphere and the sphere radius is equal to radius of cone ($r = L_1$). Inside the sphere TEM wave can exist and also higher order modes may be presented, but outside only the higher order modes can exist. At the cones most of the outgoing TEM wave is reflected, but near the equator most of the energy escapes, **Figure 4(a)**. But a step of imagine from the impedance view point, the magnetic shell acting as a load impedance Z_L connected across the open end of the cones. Neglecting the end caps of the cones, the finite biconical antenna can now be treated as a transmission line of characteristic impedance Z_k terminated in the load impedance Z_L , **Figure 4(b**). If the load impedance Z_L can be found, the impedance Z_{in1} at the input terminal of biconical antenna can be calculable.

$$Z_k = 120\ln\cot(\theta_e/2) \tag{10}$$

where Z_k is the characteristic impedance of finite biconical antenna and θ_e is the half angle of the cone.

$$Z_{in1} = Z_k \frac{Z_L + jZ_k \tan(\beta_1 L_1)}{Z_k + jZ_L \tan(\beta_1 L_1)}$$
(11)

$$\beta_1 = \frac{2\pi}{\lambda} = \frac{2\pi}{\lambda_o} \sqrt{\varepsilon_{eff\,1}} \tag{12}$$



Figure 4. (a) Schelkunoff's finite biconical antenna and boundary sphere; (b) Equivalent transmission line.

where β_1 is the phase constant for bow-tie width w_1 , **Figure 1**, λ_o is the free space wavelength, λ is the guide wave length, and ε_{eff1} was derived by substituting w_1 instead of $w_1/2$ in Equation (4).

Schelkunoff's method was used to determine Z_L . This method consists first of calculating Z_m at current maximum on a very thin biconical antenna, a sinusoidal current distribution being assumed, where Z_m is the impedance which appears between the current maximum on one cone and corresponding point on other cone. Since this impedance occurs at $\lambda/4$ from the open end of the antenna, Z_L is then equal to Z_m transformed a line $\lambda/4$, **Figure 5(a)**. Finally, the input impedance Z_{in1} is Z_L transformed over a line of characteristic impedance Z_k and length L_1 , **Figure 5(b)**.

$$Z_{L} = Z_{k} \frac{Z_{m} + jZ_{k} \tan(\beta x)}{Z_{k} + jZ_{m} \tan(\beta x)}$$
(13)

and since $\beta x = \pi/2$, so

$$Z_L = Z_k^2 / Z_m \tag{14}$$

where $\beta = \frac{2\pi}{\lambda}$ is the phase constant, and x is equal to $\lambda/4$.

$$Z_m = R_m + jX_m \tag{15}$$

$$R_{m} = 60Cin(2\beta_{1}L_{1}) + 30(0.577 + \ln(\beta_{1}L_{1}) - 2Ci(2\beta_{1}L_{1}) + Ci(4\beta_{1}L_{1}))\cos(2\beta_{1}L_{1}) + 30(Si(4\beta_{1}L_{1}) - 2Si(2\beta_{1}L_{1}))\sin(2\beta_{1}L_{1})$$
(16)

$$X_{m} = 60Si(2\beta_{1}L_{1}) + 30(Ci(4\beta_{1}L_{1}) - \ln(\beta_{1}L_{1}) - 0.577)sin(2\beta_{1}L_{1}) - 30Si(4\beta_{1}L_{1})cos(2\beta_{1}L_{1})$$
(17)

 R_m is the radiation resistance at a current maximum of a very thin linear antenna, X_m is the radiation reactance, L_1 is the length of one cone [2], Figure 5. Schelkunoff's has extended his analysis for thin biconical antennas as outlined above, to thin antennas of other shapes by considering the characteristic impedance of the antenna. So, on the same manner based on biconical approximation method, substitute in Equation (11) and Equation (13) to get the input impedance of Bow-Tie antenna Z_{in1} and load impedance Z_L using characteristic impedance based on quasi static method Z_{as} Equation (1), tapered transmission line method Z_{av} . Equation (9).

The input impedance of Bow-Tie antenna and load impedance, Figure 1 are given by:

$$Z_{in1} = Z_c \frac{Z_c + jZ_L \tan\left(\beta_1 L_1\right)}{Z_L + jZ_c \tan\left(\beta_1 L_1\right)}$$
(18)

$$Z_{L} = Z_{c} \frac{Z_{m} + jZ_{c} \tan\left(\beta x\right)}{Z_{c} + jZ_{m} \tan\left(\beta x\right)}$$
(19)

where Z_c is the characteristic impedance for different methods quasi static, Equation (1), tapered transmission line, Equation (9) and biconical methods, Equation (10).

A Bow-Tie antenna, **Figure 6** was designed [14]. This antenna is fed with a characteristic impedance of value $Z_o = 300 \Omega$ at f = 900 MHz. The corresponding parameters of this antenna are shown in **Table 1**.

The general input impedance Z_{in} , Figure 1 is given by

$$Z_{in} = Z_o \frac{Z_{in1} + jZ_o \tan(\beta_2 L_2)}{Z_o + jZ_{in1} \tan(\beta_2 L_2)}$$
(20)

$$\beta_2 = \frac{2\pi}{\lambda_o} \sqrt{\frac{\varepsilon_{eff\,2} + 1}{2}} \tag{21}$$

where β_2 is the phase constant for feeding line width w_2 , Figure 1, ε_{eff2} was derived by substituting w_2 instead of $w_2/2$ in Equation (6).



Figure 5. Thin finite biconcial antenna and transmission line equivalent for finding Z_L .



Figure 6. Traditional Bow-Tie antenna.

able1. Traditional Bow-Tie antenna parameters at 900 MHz.								
Substrate material	\mathcal{E}_r	$ an(\delta)$	Substrate thickness	L				
FR4	4.3	0.02	1.6 mm	114.34 mm				
L_1	W_1	L_2	W_2	W				
54.93 mm	56 mm	39.3 mm	1.6 mm	68.65 mm				

The aforementioned methods were used to calculate the Bow-Tie antenna input impedance, **Figure 7** and **Figure 8**. These figures indicate that the aforementioned conventional analytical methods for obtaining the Bow-Tie input impedance gave accurate results as indicated in **Table 2**. Also, proposed methodsare used to form alternative equation for solving the input impedance of Bow-Tie antenna presented in Section 2.4.

2.4. Proposed Methods for Bow-Tie Antenna Input Impedance Calculation

There are two proposed methods to obtain input impedance of Bow-Tie antenna, analytical and graphical.



Figure 7. Bow-Tie antenna input impedance, real part.



Figure 8. Bow-Tie antenna input impedance, imaginary part.

Table 2. Input impedance calculation using Zeland IE3D, quasi-static, biconical approximation and tapered transmission line methods of analysis at resonance frequency 900 MHz.

Method of calculation	Z _{real}	Z _{imag.}
Zeland software simulation	309.41 Ω	-9.92 Ω
Quasi-static method	463 Ω	-9.69 Ω
Biconical approximation method	489 Ω	-10.5 Ω
Tapered transmission line method	362 Ω	-15 Ω

2.4.1. Analytical Method

In this method, the universal UHF RFID frequency band from 860 MHz to 960 MHz is only considered. Parametric studies on Bow-Tie antenna width and length and their effect on the input impedance of the antenna are carried out. Finally, an equation which describes the input impedance as a function of geometry is obtained. IE3D software is used to calculate the input impedance of the Bow-Tie antenna as its length and width were changed from 105 mm to 140 mm and from 1 to 70 mm, respectively. Curve fitting technique is used to obtain the best fit analytical equation; 8^{th} degree sum of sines for the real part of input impedance Z_r .

$$Z_{r} = \sum_{i=1}^{N} a_{i} \sin(b_{i} f + c_{i})$$
(22)

where $i = 1, 2, 3, \dots, N$.

As stated in Equation (22) Z_r depends on Bow-Tie antenna frequency *f* and coefficients $a_1, b_1, c_1, \dots, a_N, b_N, c_N$. These coefficients depend on both length and width of Bow-Tie antenna. The aforementioned coefficients are obtained by using curve fitting technique which gives the best fit equations; 8th Fourier as given below:

$$a_{i}(L) = x_{0} + \sum_{m=1}^{M} \left[x_{m} \cos(m_{aL}L) + X_{m} \sin(m_{aL}L) \right]$$
(23)

where $a_i(L)$ is coefficient a_i which depends on length L, and $m = 1, 2, 3, \dots, M$, coefficients $(x_0, x_1, X_1, \dots, x_M, X_M, m_{aL})$ in Equation (23) are stated in **Table 3**.

Table 3. The value of coefficients $(x_0, x_1, X_1, \dots, x_8, X_8, m_{aL}, m_{aW})$ for $a_i(L)$ and $a_i(W)$.

	$a_1(L)$	<i>a</i> ₁ (<i>W</i>)	$a_2(L)$	$a_2(W)$	<i>a</i> ₃ (<i>L</i>)	<i>a</i> ₃ (<i>W</i>)	$a_4(L)$	$a_4(W)$	$a_5(L)$	a ₅ (W)	$a_6(L)$	$a_6(W)$	<i>a</i> ₇ (<i>L</i>)	a7 (W)	$a_8(L)$	$a_8(W)$
<i>x</i> ₀	487.1	142.4	82.22	82.86	32.84	106.7	48.53	43.93	63.41	35.6	19.34	20.83	9.67	11.24	5.62	4.172
x_1	-564.3	9.131	8.121	-24.29	-28.61	-4.21	37.72	-33.54	22.27	4.75	-0.9018	-0.406	-1.52	0.378	2.22	-9.504
X_1	172.3	-2.447	-33.41	- 5.241	23.54	116.4	57.26	3.844	5.68	0.646	-1.437	0.66	0.575	0.194	1.94	-6.313
<i>x</i> ₂	192.5	3.991	16.5	-1.163	35.98	-83.38	-13.63	-0.959	25.62	-5.833	-1.348	-0.057	0.784	-0.027	0.323	15.42
X_{2}	-150.7	3.416	-9.285	-15.87	21.58	-15.4	51.19	-12.27	-31.54	-4.235	-0.5421	-0.108	0.307	-0.112	3.286	-7.714
<i>x</i> ₃	0	-5.273	-45.45	-10.21	0.097	-15.65	-62.55	-6.174	0	-3.99	-0.1917	-0.45	0.082	0.309	-1.88	-1.167
X_3	0	0.8525	3.45	-0.336	-21.62	67.04	-46.88	-1.275	0	1.946	-2.378	0.801	-0.44	0.183	1.659	16.19
X_4	0	2.676	-101.7	5.383	0	32.86	0	-15.37	0	-0.384	-0.4302	-0.578	-0.38	-0.283	-1.41	-9.009
$X_{_4}$	0	1.287	15.64	-16.19	0	-3.74	0	-5.266	0	0.797	-1.755	-0.108	0.36	-0.301	0.032	-6.137
<i>x</i> ₅	0	0	0	-5.76	0	0	0	4.428	0	1.875	0	-0.375	0	-0.035	-0.35	4.591
X_{5}	0	0	0	-0.186	0	0	0	-11.14	0	-3.134	0	0.282	0	-0.067	-0.59	-2.167
x_6	0	0	0	16.16	0	0	0	-5.972	0	1.041	0	-5.97	0	0	0	-0.013
$X_{_{6}}$	0	0	0	-8.828	0	0	0	-13.56	0	-2.985	0	-13.56	0	0	0	1.253
<i>x</i> ₇	0	0	0	16.01	0	0	0	3.747	0	0	0	3.747	0	0	0	0
X_{γ}	0	0	0	-2.268	0	0	0	-10.73	0	0	0	-10.73	0	0	0	0
x_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$X_{_8}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
m _{aL}	0.107	0	0.333	0	0.2635	0	0.6642	0	0.2333	0	0.6642	0	0.44	0	0.199	0
$m_{_{aW}}$	0	0.3156	0	0.3868	0	0.2635	0	0.3825	0	0.377	0	0.571	0	0.438	0	0.2146

$$a_{i}(W) = x_{0} + \sum_{j=1}^{J} \left[x_{j} \cos(m_{aW}L) + X_{j} \sin(m_{aW}L) \right]$$
(24)

where $a_i(W)$ is coefficient a_i depends on width W, and $j = 1, 2, 3, \dots, J$, coefficients $(x_0, x_1, X_1, \dots, x_J, X_J, m_{aW})$ in Equation (24) are stated in **Table 3**.

Taking the average value of $a_i(L)$ and $a_i(W)$ to form total coefficient a_i

$$a_{i} = (a_{i}(L) + a_{i}(W))/2$$
(25)

$$b_{i}(L) = y_{0} + \sum_{m=1}^{M} \left[y_{m} \cos(m_{bL}L) + Y_{m} \sin(m_{bL}L) \right]$$
(26)

where $b_i(L)$ is coefficient b_i depends on length L, and $m = 1, 2, 3, \dots, M$, coefficients $(y_0, y_1, Y_1, \dots, y_M, Y_M, m_{bL})$ in Equation (26) are stated in Table 4.

$$b_{i}(W) = y_{0} + \sum_{j=1}^{J} \left[y_{j} \cos(m_{bW}L) + Y_{J} \sin(m_{bW}L) \right]$$
(27)

where $b_i(W)$ is coefficient b_i depends on width W, and $j = 1, 2, 3, \dots, J$, coefficients $(y_0, y_1, Y_1, \dots, y_J, Y_J, m_W)$ in Equation (27) are stated in **Table 4**.

Taking the average value of $b_i(L)$ and $b_i(W)$ to form total coefficient b_i

$$b_i = (b_i(L) + b_i(W))/2$$
 (28)

Table 4. The value of coefficients $(y_0, y_1, Y_1, \dots, y_8, Y_8, m_L, m_W)$ for $b_n(L)$ and $b_n(W)$.

	$b_1(L)$	$b_1(W)$	$b_2(L)$	$b_2(W)$	$b_3(L)$	$b_3(W)$	$b_4(L)$	$b_4(W)$	$b_5(L)$	$b_5(W)$	$b_6(L)$	$b_6(W)$	$b_7(L)$	$b_7(W)$	$b_8(L)$	$b_8(W)$
<i>Y</i> ₀	2.224	2.727	10.07	10.35	14.33	16.53	5.232	14.85	9.804	6.05	23.86	22.73	30.73	29.22	35.2	34.78
y_1	0.2206	-0.015	-0.365	0.1314	-2.374	-0.329	-11.29	4.126	4.819	0.016	-0.090	-0.233	1.341	0.1363	-2.03	0.0775
$Y_{_1}$	0.2649	0.04	-0.168	-0.099	-4.024	-0.264	-6.381	-3.28	-6.843	-0.074	1.02	- 0.269	0.679	0.215	0.5	0.0458
<i>y</i> ₂	-0.035	0.017	-0.485	-0.050	2.651	0.036	-4.621	1.298	0.273	-0.525	0.548	-0.023	0.213	0.087	-1.2	-0.048
Y_2	0.3481	0.022	-0.385	-0.205	-2.496	-0.012	-8.753	-2.908	-4.645	0.0091	-0.138	0.1081	-0.36	0.1257	2.21	0.2046
<i>Y</i> ₃	0.0987	-0.004	0	3.092	1.474	-0.114	1.788	-0.328	-0.103	1.202	0.247	0.1593	0.43	0	-0.3	-0.168
Y_{3}	-0.350	0.237	0	0	1.101	-0.208	-6.513	-3.69	-1.034	0.0215	0.342	-0.153	0.009	0	3.38	-0.18
y_4	0	-0.27	0	0	0	0.076	4.761	-1.97	1.299	0.2916	-0.255	-0.236	-0.50	0	2.53	0
Y_4	0	-0.059	0	0	0	0.314	-2.185	-1.499	-1.783	-0.197	-0.170	-0.004	0	0	2.96	0
<i>Y</i> ₅	0	-0.031	0	0	0	-0.187	5.06	0	-1.284	-0.091	-1.284	0.033	0	0	0	0
Y_5	0	-0.271	0	0	0	0.037	0.04	0	-1.693	-0.176	-1.693	-0.121	0	0	0	0
y_6	0	0	0	0	0	0.14	2.704	0	0	0.505	0	-0.089	0	0	0	0
$Y_{_6}$	0	0	0	0	0	0.22	1.186	0	0	0.2595	0	-0.145	0	0	0	0
y_7	0	0	0	0	0	0	0	0	0	-0.212	0	0	0	0	0	0
Y_7	0	0	0	0	0	0	0	0	0	0.277	0	0	0	0	0	0
y_8	0	0	0	0	0	0	0	0	0	-0.338	0	0	0	0	0	0
$Y_{_8}$	0	0	0	0	0	0	0	0	0	-0.163	0	0	0	0	0	0
$m_{_{bL}}$	0.2843	0	0.307	0	0.2673	0	0.2588	0	0.2488	0	0.2638	0	0.266	0	0.79	0
$m_{_{bW}}$	0	0.7785	0	3.092	0	0.442	0	0.2805	0	0.339	0	0.45	0	3.129	0	0.7993

$$c_{i}(L) = z_{0} + \sum_{m=1}^{M} \left[z_{m} \cos(m_{cL}L) + Z_{m} \sin(m_{cL}L) \right]$$
(29)

where $c_i(L)$ is coefficient c_i depends on length *L*, and $m = 1, 2, 3, \dots, M$, coefficients $(z_0, z_1, Z_1, \dots, z_M, Z_M, m_{cL})$ in Equation (29) are stated in **Table 5**.

$$c_{i}(W) = z_{0} + \sum_{j=1}^{J} \left[z_{m} \cos(m_{cW}L) + Z_{m} \sin(m_{cW}L) \right]$$
(30)

where $c_i(W)$ is coefficient c_i depends on width W, and $j = 1, 2, 3, \dots, J$, coefficients $(z_0, z_1, Z_1, \dots, z_M, Z_M, m_{cW})$ in Equation (30) are stated in **Table 5**.

Taking the average value of $c_i(L)$ and $c_i(W)$ to form total coefficient c_i

$$c_i = \left(c_i\left(L\right) + c_i\left(W\right)\right)/2 \tag{31}$$

The same procedure is performed to obtain an analytical equation for the imaginary part of input impedance $Z_{imag.}$

$$Z_{imag.} = \sum_{k=1}^{K} p_k \sin\left(t_k f + s_k\right)$$
(32)

where $k = 1, 2, 3, \dots, K$.

```
Table 5. The value of coefficients (z_0, z_1, Z_1, \dots, z_8, Z_8, m_{cL}, m_{cW}) for c_n(L) and c_n(W).
```

	$c_1(L)$	$c_1(W)$	$c_2(L)$	$c_2(W)$	$c_{3}\left(L\right)$	$c_3(W)$	$c_4(L)$	$c_4(W)$	$c_{5}\left(L ight)$	$c_5(W)$	$c_{6}\left(L ight)$	$c_6(W)$	$c_7(L)$	$c_7(W)$	$c_{8}\left(L\right)$	$c_8(W)$
Z_0	-0.327	-0.951	-4.13	-11.42	4.222	2.203	0.5044	-8.567	-10.41	47.87	-0.867	0.093	-0.66	1.043	-0.23	3.933
Z_1	-0.417	-0.034	5.23	19.44	-3.501	-2.937	-0.642	10.73	7.469	-41.5	-1.179	-0.298	-0.37	0.6224	0.186	-2.506
Z_1	0.045	-0.052	2.923	1.246	-0.409	-1.76	1.296	10.73	19.69	-77.16	-0.109	0.239	1.04	0.123	-1.00	-3.066
Z_2	0.279	0.075	-4.913	-15.09	1.109	0.199	0.7859	5.143	11.87	-40.15	-1.198	-0.038	-0.41	0.0075	-1.73	-1.012
Z_{2}	0.407	0.0025	0.339	-1.612	-4.04	0.922	1.017	-12.01	-6.195	61.34	-0.025	-0.027	1.25	0.512	0.04	4.079
Z_3	0	-0.09	5.503	10.22	0.197	-0.467	0.907	-9.222	-4.506	53.73	0	-0.085	0.84	-0.246	0.438	3.169
Z_3	0	-0.041	-1.627	1.663	2.086	1.054	-1.117	1.646	-4.108	3.738	0	0.062	0.23	0.299	-0.27	-2.038
Z_4	0	-0.023	-2.795	-5.582	-1.462	0.375	-0.123	3.006	-0.531	-15.5	0	0.004	0.08	-0.404	-0.38	-2.793
$Z_{_4}$	0	0.0428	-0.199	-0.858	1.161	-0.225	-1.458	2.409	1.454	-30.97	0	0.196	-0.58	0.0716	1.131	-0.149
Z_5	0	0	0	2.274	0	0.643	0.2968	0	0	-10.21	0	0.085	0	-0.1213	0	1.292
Z_5	0	0	0	0.2532	0	-0.139	-1.51	0	0	14.69	0	0.137	0	-0.185	0	1.067
Z_6	0	0	0	-0.826	0	-0.399	0	0	0	7.441	0	-0.060	0	0.0232	0	-0.252
Z_6	0	0	0	0.0873	0	-0.467	0	0	0	0.006	0	-0.045	0	-0.1472	0	-0.634
Z_7	0	0	0	0	0	0	0	0	0	-1.216	0	0.078	0	0.1293	0	0
Z_{γ}	0	0	0	0	0	0	0	0	0	-1.557	0	-0.056	0	-0.0517	0	0
Z_8	0	0	0	0	0	0	0	0	0	0	0	0.109	0	0	0	0
Z_8	0	0	0	0	0	0	0	0	0	0	0	-0.039	0	0	0	0
m _{cL}	0.269	0	0.668	0	0.2769	0	0.2527	0	0.1801	0	0.1818	0	0.231	0	0.267	0
$m_{_{cW}}$	0	0.3394	0	0.2353	0	0.3374	0	0.2511	0	0.255	0	0.255	0	0.3056	0	0.2436

A MATLAB program was carried out to calculate these coefficients. It is found that good accuracy is obtained when N = M = J = K = 8.

2.4.2. Graphical Method

In this method both length and width are changed at the same time at resonance frequency of 900 MHz which is within the frequency band from 860 MHz to 960 MHz. The input impedance at resonance is calculated using IE3D software and then data is imported to matlab to plot charts as shown in **Figure 9** and **Figure 10**. **Figure 9** indicates that bow-tie antenna matched with characteristic impedance 300 Ω , it's input impedance can be varied from 276 Ω to 336 Ω depending on antenna length and width variation at fixed resonance frequency 900 MHz. Same procedure is used for the input impedance calculation but at resonance of 2.45 GHz, which also indicates antenna impedance variation from 274 Ω to 432 Ω , **Figure 10**. It can be noticed that resonant input impedance can be easily identified using both aforementioned figures just by knowing length and width.

2.5. Comparison between Input Impedance Calculated by Different Methods

In this section the real and imaginary parts of the input impedance of the Bow-Tie antenna are calculated using IE3D simulator, CST simulator, and the adopted analytical and graphical methods for the same geometric dimensions stated before, Figure 11 and Figure 12.







Figure 10. Bow-Tie antenna input impedance at 2.45 GHz.



Figure 11. Bow-Tie antenna real part input impedance versus frequency using analytical, graphical, IE3D and CST methods.



Figure 12. Bow-Tie antenna imaginary part input impedance versus frequency using analytical, graphical, IE3D and CST methods.

Referring to **Figure 11** and **Figure 12**, it can be noticed that the proposed analytical input impedance calculation gives good result, while the proposed graphical method gives more accurate result exactly similar to Zeland IE3D, **Table 6**, because in this method we depend on Zeland software package in obtaining the graphical input impedance results. Also, only the frequency bandwidth from 700 MHz to 1000 MHz is considered that is why the Bow-Tie antenna real part input impedance is quite similar with that using graphical method except at the low frequency (0.5 - 0.7GHz) and at the high frequency (over 1 GHz).

3. Conventional Bow-Tie Tag Antenna Design and Results

A Bow-Tie Tag antenna shown in **Figure 13** is designed on FR4 substrate ($\varepsilon_r = 4.3$, thickness h = 1.6 mm, and $\tan(\delta) = 0.02$). Its dimensions, length L = 56.77 mm and width w = 40 mm are determined using gometrical method design curve shown in **Figure 14** as discussed in Section 2.4.2. The antenna is designed to achieve a conjugate matching to chip input impedance model Monza 5 $Z_{chip} = 15.05 - j163.91\Omega$ at 900 MHz within operating frequency extends from 860 MHz to 960 MHz. **Figure 14** indicates that antenna impedance chart curve

graphical proposed methods.								
Method of calculations	Z _{real}	Z _{imag.}						
Zeland software simulation	309.41 Ω	-9.92 Ω						
CST simulator	228.24 Ω	-16.02 Ω						
Analytically proposed method	312.89 Ω	-14.2 Ω						
Graphically proposed method	309.2 Ω	-9.378 Ω						

Table 6. Input impedance calculation at resonance frequency 900 MHz using Zeland IE3D, CST, analytical and graphical proposed methods.



Figure 13. Bow-Tie Tag antenna geometry using Zeland IE3D.





varies from 10 Ω to 32 Ω according to antenna dimensions which can cover the chip input impedance variation from 16.47 – *j*171.4 Ω at 860 MHz to 13.24 – *j*153.8 Ω at 960 MHz, respectively, **Figure 15**. The real and imaginary parts of input impedance of the antenna are then computed using analytical method Equation (22) and Equation (32), **Figure 16**. The structure is simulated using Zeland IE3D.

The Bow-Tie antenna reflection coefficient $|S_{11}|$ as shown in Figure 17 is -23.161 dB at 899 MHz. The antenna bandwidth extends from 889 MHz to 912 MHz for $|S_{11}| = -10$ dB, which is considered as a narrow band













98

as compared to the universal bandwidth. The simulated input impedance $Z_{antenna}$ using IE3D method as shown in **Figure 16** is $17.22 + j163.44 \Omega$, which indicates that the tag antenna achieves a good conjugate matching with the chip at this frequency.

The bow-tie antenna input impedance as shown in **Figure 16** is $17.31 + j163.62 \Omega$ at 900 MHz. For more accurate perfectly matching to chip input impedance result and to minimize the feeding line length, we intended to use T-matched circuit. Referring to **Figure 18**, the input impedance of a planar dipole of length *l* can be changed by introducing a centered short-circuited stub. The antenna source is connected to a second dipole of length *a*, placed at a close distance *b* from the first and larger one. The electric current distributes along the two main radiators depends on the size of their transverse sections. It can be proved, that the impedance at the source point is given by [15]:

$$Z_{in} = \frac{2Z_t (1+\alpha)^2 Z_A}{2Z_t + (1+\alpha)^2 Z_A}$$
(33)

$$Z_t = jZ_o \tan\left(\frac{ka}{2}\right) \tag{34}$$

where Z_t is the input impedance of the short-circuit stub formed by the T-match conductors and part of the dipole.

$$Z_o = \frac{\eta}{\pi} \cosh^{-1} \left(\frac{b/2}{\sqrt{r_e r'_e}} \right)$$
(35)

$$r_e = 0.25(2w) \tag{36}$$

$$r'_{e} = 0.25(2w') \tag{37}$$

where Z_o is the characteristic impedance of the two-conductor transmission line with spacing b, Z_A is the dipole impedance taken at its center in the absence of the T-match connection, and r_e, r'_e are the equivalent radii of the dipole and of the matching stub, supposed to be planar traces.

$$\alpha = \frac{\cosh^{-1}\left(\frac{v^2 - u^2 + 1}{2v}\right)}{\cosh^{-1}\left(\frac{v^2 + u^2 - 1}{2uv}\right)}$$
(38)



Figure 18. T-matched configuration for planar dipoles and equivalent circuit where the impedance step-up ratio $(1 + \alpha)$ is related to the conductors' cross-sections [15].

$$u = \frac{w}{w'} \tag{39}$$

$$v = \frac{b}{0.25(2w')}$$
(40)

where α is the current division factor between the two conductors. The geometrical parameters, *a*, *b*, and the trace's width, *w*', can be adjusted to match the complex chip impedance, Z_{chip} . For simplicity, we define two new aspect ratio terms, a/l as second dipole length to first dipole length and b/2w as distance between first and second dipole to total strip width, respectively.

4. Modified Bow-Tie Antenna Design and Results:

The proposed modified shape Bow-Tie antenna is shown in **Figure 19**, As stated in section 3 that bandwidth of conventional bow-tie antenna is so narrow to covers RFID band, we decided to insert slots on bow-tie antenna so as to increase it's bandwidth. Also, a T-matched circuit, [15] is used for matching enhancement purpose. The T-matched circuit is designed by applying Equation (33) on the bow-tie antenna, **Figure 13** with input impedance of $17.31 + j163.62 \Omega$ at 900 MHz and u = w/w' = 2, an impedance chart for the T-matched circuit as shown in **Figure 20** can be plotted. As a starting point b/2w = 3 and a/l = 0.2 are chosen which from **Figure 20** gives total input impedance of approximately $11.5 + j163.8 \Omega$. Then using the IE3D simulator both b/2w and a/l are optimized to be 2.4 and 0.17, respectively.



Figure 20. T-matched circuit chart for conventional bow-tie antenna with $17.31 + j163.62 \Omega$ input impedance, u = w/w' = 2 at f = 900 MHz.

4.1. T-Matched Circuit Parameters Effect on Antenna Bandwidth and Matching

Table 7. Modified Bow-Tie antenna with T-matched and slots dimensions.

The dimensions of the modified bow-tie antenna are given in **Table 7**. The T-matched height y-parameter is varied starting from 6 mm to 8 mm, other dimension, **Table 7** are kept at the same values, and the simulations were carried out, **Figure 21(a)**. It is quite clear at y = 7 mm the antenna can achieve acceptable matching and

D T:-	L	W	G							
Dow-Tie	71.42 mm	45 mm	1 mm							
T motobod	W_T	<i>a</i> /2	b	у	z					
1-matcheu	1 mm	6.12 mm	18.54 mm	7 mm	10.68 mm					
S1-4-	L_{S1}	L_{S2}	L_{S3}	L_{S4}	L_{S5}	L_{S6}	L_{S7}	Wslot	$W_{slot(gap)}$	X
Slots	40.85 mm	32.24 mm	25.29 mm	19 mm	12.5 mm	8 mm	5.05 mm	0.6 mm	1.6 mm	17.1 mm



Figure 21. Modified Bow-Tie antenna reflection coefficient versus frequency at different values for both T-matched circuit and slot dimensions.

bandwidth, below and above this value both matching and bandwidth are degraded. On the same manner W_T -parameter is varied starting from 0.6 mm to 1.2 mm. It can be noticed from Figure 21(b) that as W_T value increases, both antenna matching and bandwidth are enhanced increase until W_T reaches 1 mm after that both matching and bandwidth are degraded. Also, for b-parameter which is varied from 17.54 mm to 19.54 mm, Figure 21(c), good results occurs at b = 18.54 mm.

4.2. Slot Dimensions Effect on Antenna Bandwidth and Matching

By changing the value of slot width W_{slot} from 0.6 mm to 0.8 mm, Figure 21(d). It can be noticed that slot width is inversely proportional with antenna matching performance and bandwidth, as it decreases they increase, so good result achieved at $W_{slot} = 0.6$ mm. The results are compared with conventional one, Table 8. The obtained bandwidth is extended from 859 MHz to 1.02 GHz, which indicates that the antenna achieves a wide bandwidth that covers the chip operating frequency, Figure 22. The antenna input impedance $Z_{antenna}$ is 15.38 + *j*163.7 Ω which has a good matching to chip impedance $Z_{chip} = 15.05 - j163.91 \Omega$ at frequency 900 MHz.

Results	Conventional Bowtie antenna	Modified Bowtie antenna with T-matched and slots
Resonant frequency	899 MHz	901 MHz
S_{11}	-23.161 dB	-35.28 dB
Z_{chip}	15.0	$5 - j163.91 \Omega$ at $f = 900 \text{ MHz}$
$Z_{antenna}$	$17.22 + j163.44 \ \Omega$	$15.38 + j163.7 \ \Omega$
Standard bandwidth		860 MHz - 960 MHz
f_{\min} at $S_{11} = -10 \text{ dB}$	889 MHz	859 MHz
$f_{\rm max}$ at $S_{11} = -10 {\rm dB}$	912 MHz	1.02 GHz
Fractional bandwidth = $\frac{f_{\text{max}} - f_{\text{min}}}{f} \times 100\%$	2.55%	18%
Reading range (m)	6 m	5.9 m
Directivity	2.134 dBi	2.81 dBi
Gain	-8.99 dBi	-9.7 dBi
Radiation efficiency	69.86%	56.12%
Conjugate match efficiency	34.9%	28.06%





Figure 22. Reflection coefficient versus frequency for both conventional and modified Bow-Tie antenna.

It can be noticed from Figure 22 that due to the presence of the slot, a second resonant frequency of 995 MHz can be properly excited close to the fundamental mode. The ratio of the frequency of the two modes is made low enough to realize a wideband operation thus able to cover the entire UHF band [16]. The reading range of conventional and modified Bow-Tie tag antennas [17] with readers able to transmit at maximum power $P_{EIRP} = 4$ watt for most of that bandwidth, $P_{chip} = -20$ dBm [18], Z_{chip} and Z_A is shown in Figure 23.

The maximum directivity for modified Bow-Tie antenna increased to 3.3 dBi, as the electrical path has been increased. It can be indicated from **Figure 19** that the existence of slots in the modified Bow-Tie antenna increases the bandwidth. For RFID applications, the antenna efficiency and antenna gain defined by IE3D may not be useful as stated in **Table 8** because RFID devices behave more like constant voltage sources. For constant voltage sources, it is required to achieve conjugate matching for best efficiency [15] [19]. The current distribution for both conventional and modified bow-tie antennas are shown in **Figure 24**. The arrows in **Figure 24**(a) and **Figure 24**(b) indicates the average current density path through the antennas where their lengths indicate the amplitude which is of same magnitude for both antenna sides but with 180° out of phase, as well known for the dipoles shapes.

The simulated coplanar and cross polarization radiation pattern of both conventional and modified bow-tie antennas are shown in Figure 25(a) and Figure 25(b). In this figure, the E_{theta} -field is the co-polar component,



Figure 23. Reading range versus frequency for both conventional and modified Bow-Tie antenna.



Figure 24. Current distribution for both conventional and modified Bow-Tie antenna. (a) Conventional Bow-Tie antenna. (b) Modified Bow-Tie antenna.

and the E_{phi} -field is the cross-polar component. These patterns show that the designed antenna provides linear polarization with a cross polarization level about -30.3 dBi lower than the co-polarization level -8.9 dBi for conventional bow-tie antenna and about -27.4 dBi lower than the co-polarization level -10.29 dBi for modified bow-tie antenna.

Figure 26 shows the radiation pattern of both conventional and modified bow-tie antennas which is almost omnidirectional at the H-plane and figure of eight at the E-plane that is suitable for the RFID surveillance application







Figure 26. Radiation pattern of conventional and modified Bow-Tie antenna at 900 MHz. (a) Conventional Bow-Tie antenna; (b) Modified Bow-Tie antenna.

[15]. The design procedure is given by the flow chart, **Figure 27**, where the proposed graphical method is used to find the initial geometry of the Bow-Tie antenna. Analytical method is used to calculate the antenna input impedance. IE3D simulator is used to confirm the result. If the required antenna bandwidth and required antenna matching to chip impedance are achieved, the antenna design is finished else a modification is needed and the result again has to be confirmed with IE3D simulator.

5. Fabrication and Measurements

The proposed conventional and modified bow-tie antennas were fabricated on FR4 substrate ($\varepsilon_r = 4.3$, thickness h = 1.6 mm, $\tan(\delta) = 0.02$) as shown in **Figure 28** and **Figure 29**. Input impedance of both conventional and modified proposed antennas were measured using the vector network analyzer (VNA HP8719ES) by measuring the half of the structure over ground plane and multiply the resultant input impedance by two, also $|S_{11}|$ dB were calculated for both antennas [15] as shown in **Figure 30** and **Figure 31**. As indicated, there is big difference between the simulated and the measured results. This difference is due to the air layer which was presented



Figure 27. Flow chart of the design procedure of Bow-Tie antenna



Figure 28. Fabricated conventional bow-tie antenna on FR4 substrate.





between ground plane and the half of the antenna structure. So, in the simulation a 1mm air gap was inserted between ground plane and the half of the antenna. Now, it can be noticed that the simulated results with air gap

obtained agrees well with the measured one, Figure 30 and Figure 31.

6. Conclusion

A new proposed method for calculating the input impedance of Bow-Tie antenna had been demonstrated. It had been shown that high-accuracy calculation was obtained. Also design curves for input impedance values were developed depending on the geometry of antenna. The proposed design curves were used to design a Bow-Tie type RFID tag antenna. Good matching with the Monza 5 chip reactance is guaranteed for the conventional Bow-Tie antenna but with narrow operating frequency band, which is not suitable for the Europe and North America UHF RFID band range. A modified bow-tie antenna was designed so as to achieve a better conjugate matching to complex chip impedance and also to increase the bandwidth than conventional one. The antenna results demonstrate that it has maximum reading range which extends to 6 m.

References

- [1] Balanis, C.A. (2005) Advanced Engineering Electromagnetics. 3rd Edition, John Wiley & Sons Inc., Hoboken.
- [2] (1989) McGraw-Hill Electrical and Electronics Engineering Series. 5th Edition, Chapter 8, McGraw-Hill, New York, Toronto, London.
- [3] Abraham, M. and Becker, R. (1985) Electricity and Magnetism. G. E. Stechert & Company, New York.
- [4] George, J., Deepukumar, M., Aanandan, C.K., Mohanan, P. and Nair, K.G. (1996) New Compact Microstrip Antenna. *Electronics Letters*, 32, 508-509. <u>http://dx.doi.org/10.1049/el:19960357</u>
- [5] Mahmoud, K.R. (2010) Design Optimization of a Bow-Tie Antenna for 2.45 Ghz RFID Readers Using a Hybrid BSO-NM Algorithm. *Progress in Electromagnetics Research*, **100**, 105-117. <u>http://dx.doi.org/10.2528/PIER09102903</u>
- [6] Amin, Y., Chen, Q., Tenhunen, H. and Zheng, L.R. (2012) Performance-Optimized Quadrate Bowtie RFID Antennas for Cost-Effective and Eco-Friendly Industrial Applications. *Progress in Electromagnetics Research*, **126**, 49-64. http://dx.doi.org/10.2528/PIER12020805
- [7] Zhang, Z., Zuo, S., Zhang, X. and Fu, G. (2013) Ultra-Wideband Cavity-Backed Bowtie Antenna for Pattern Improvement. *Progress in Electromagnetics Research Letters*, 37, 37-46. <u>http://dx.doi.org/10.2528/PIERL12110909</u>
- [8] Zhao, J.Y., Zhang, Z.Y., Liu, N.W., Fu, G. and Gong, S.X. (2014) Wideband Unidirectional Bowtie Antenna with Pattern Improvement. *Progress in Electromagnetics Research Letters*, 44, 119-124. <u>http://dx.doi.org/10.2528/PIERL13122007</u>
- Karagianni, E.A. (2015) Electromagnetic Waves under Sea: Bow-Tie Antennas Design for Wi-Fi Underwater Communications. Progress in Electromagnetics Research M, 41, 189-198. <u>http://dx.doi.org/10.2528/PIERM15012106</u>
- [10] Khodier, M.M. (1997) Analysis and Design of Broadband Antennas for the Double Quantum Well Terahertz Detector. M.Sc Thesis, Electrical Engineering, Jordan University of Science & Technology, Jordon, 29-32.
- [11] Compton, R.C. (1987) Bow-Tie Antennas on a Dielectric Half-Space: Theory and Experiment. *IEEE Transactions on Antennas and Propagation*, **35**, 622-631. <u>http://dx.doi.org/10.1109/TAP.1987.1144162</u>
- [12] Collin, R.E. (1992) Foundations for Microwave Engineering. 2nd Edition, Tata McGraw-Hill, New York.
- [13] Pozar, D. (2012) Microwave Engineering. 4th Edition, John Wiley & Sons Inc., Hoboken.
- [14] Sayidmari, K.H. and Fadhel, Y.A. (2013) A Planar Self-Complementary Bow-Tie Antenna for UWB Applications. Progress in Electromagnetics Research C, 35, 253-267. <u>http://dx.doi.org/10.2528/PIERC12103109</u>
- [15] Abouelnaga, T.G. (2012) Design and Implementation of Radio Frequency Identification (RFID) Antennas. Ph.D. Thesis, Ain Shams University, Cairo.
- [16] Bashri, M.S.R., Ibrahimy, M.I. and Motakabber, S.M.A. (2015) A Compact Wideband Patch Antenna for Ultra High Frequency RFID Tag. Automatika—Journal for Control, Measurement, Electronics, Computing and Communications, 56, 76-83. <u>http://dx.doi.org/10.7305/automatika.2015.04.598</u>
- [17] Gao, Y.H., Zhang, Z.H., Lu, H.L. and Wang, H.W. (2012) Calculation of Read Distance in Passive Backscatter RFID Systems and Application. *Journal of System and Management Sciences*, 2, 40-49.
- [18] Impinj Support Portal (2015) Monza 5 Tag Chip Datasheet. https://support.impinj.com/hc/en-us/articles/202756948-Monza-5-Tag-Chip-Datasheet
- [19] Zhang, J., Babar, A., Ukkonen, L., Sydanheimo, L., Elsherbeni, A. and Yang, F. (2008) Performance of RFID Bowtie Tag Antenna with Different Impedance Matching. 2008 Asia-Pacific Microwave Conference, Macau, 16-20 December 2008, 1-4.