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LIMITATIONS OF THE UDA MODEL FOR T-MATCH ANTENNAS

K. R. Demarest and D. D. Deavours

Department of Electrical Engineering and Computer Science
Information and Telecommunications Technology Center
The University of Kansas, Lawrence, Kansas, USA

Abstract—The T-match feed is a useful impedance matching tool for dipole antennas, especially for electrically short dipoles with capacitive loads. The Uda model has been extensively tested for accuracy in the literature for the special case of the folded dipole, but not for the more general T-match dipole, which is often used for RFID antenna design. We investigate the accuracy of the Uda model for this more general case and show that aspects of the model become inaccurate for a number of practical scenarios. Nevertheless, we show that the model can still be used as a guide to T-match dipole designs.

1. INTRODUCTION

The T-match antenna feed has been used successfully in wire and planar dipole antennas since it was originally proposed by Uda in 1954 [1]. The Uda model is simple and elegant, and has been repeated numerous times in texts over the years (e.g., [2, 3]). The analysis shows that the T-match provides two functions: an impedance multiplier of the common-mode impedance, and a shunt reactance.

The folded dipole, where the T-section is the same length as the dipole, is a special case and has been extensively used and studied. Thiel et al. [4] showed that the Uda model is very accurate through the first four resonances for a delta-gap feed. Clark and Fourie [5] extended the Uda model for larger inter-element spacing.

The general T-match, where the T-section is shorter than the dipole, has received renewed attention due to the emergence of RFID antennas. RFID dipoles are frequently both physically and electrically short, and the RF-IC load commonly has a large capacitive reactance.

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Corresponding author: Kenneth R. Demarest (demarest@ku.edu).

The T-match can be used both to scale the dipole impedance and provide a substantial inductive reactance to the antenna in order to achieve an input impedance conjugate to the RF-IC impedance. It is commonly assumed that the Uda model applies equally well to the short T-match sections typically used in RFID antennas [6, 7], but we are unaware of any experimental or numerical validation.

The lack of validation in the literature invokes an interesting and practically useful question: is the Uda model of the T-match generally accurate? If not, what aspects of the model fail, and why? How do various changes in the antenna geometry affect the accuracy of the Uda model? In this paper, we describe a systematic study of the generalized T-match and identify both its strengths and weaknesses, and apply those lessons to the printed dipole for passive UHF RFID antennas.

We begin in Section 2 with a review of the Uda model. In Section 3, we investigate the accuracy of the Uda model for a typical, flat conductor T-match dipole, where we find that the odd-mode impedance can be accurately modeled analytically, but that the impedance multiplier (splitting factor) cannot. We explore this anomalous behavior of the splitting factor in Section 4, where we find that its actual value is a complex function of the antenna geometry. Despite this breakdown in the Uda model, we are still able to use some aspects of it to drive the antenna design process, which we demonstrate in Section 5. Finally, we give our conclusions from this work in Section 6.

2. THE UDA T-MATCH MODEL

The classic Uda model is actually the combination of two concepts: that the one-port, T-match structure can be analyzed as the superposition of an even- and an odd-mode excitation of an associated two-port structure, and that the odd mode can be modeled as a shorted transmission line. In our development, we will deal with these two aspects of the model separately.

2.1. Even-, Odd-mode Analysis

Figure 1 shows a generalized T-match dipole antenna and the even- and odd-modes of the associated two-port model. Here, identical conductors (the "dipole arms") are attached to both ends of a non-uniform rectangular loop. We will refer to the outer perimeter of the rectangular loop segment as the "T-box." Traditionally, because of the practice of constructing antennas from wires or tubes, the dipole

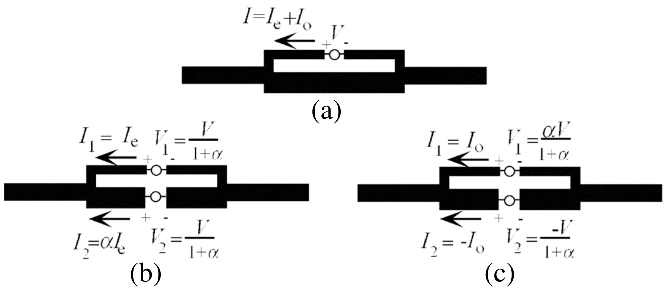

Figure 1. The even-odd mode model of a T-match antenna. (a) Actual one-port antenna. (b) Even mode. (c) Odd mode.

arms were simply continuations of one of the T-box conductors, but the Uda model itself requires no such restriction, and printed antenna technology commonly used for RFID antennas gives us additional design freedom. Thus, we will consider the attachment positions of the dipole arms as a variable. Also, note that the T-match dipole becomes a folded dipole when the dipole arms are absent (i.e., zero-length).

The driven port current I of the T-match antenna in response to a driven voltage V can be considered as the sum of an even mode component I_e and an odd mode component I_o. The even mode (Figure 1(b)) is characterized by equal port voltages, and port currents that have a ratio:

$$\frac{I_{2\,e}}{I_{1\,e}} = \alpha \tag{1}$$

where α is the current splitting factor, given by [8]

$$\alpha = \frac{Z_{11} - Z_{12}}{Z_{22} - Z_{12}}. \tag{2}$$

Similarly, the odd mode (Figure 1(c)) has opposing port currents, and port voltages that have the ratio [1, 8]

$$\frac{V_{1\,o}}{V_{2\,o}} = -\alpha \tag{3}$$

Hence, α is both a current splitting factor for the even mode and voltage splitting factor for the odd mode. Using these definitions, the input impedance Z_{in} can be represented as [1, 8]:

$$Z_{in} = Z_{11} - \frac{Z_{12}^2}{Z_{22}} = \frac{Z_e Z_o}{Z_e + Z_o} = \frac{(1+\alpha)^2 Z_c Z_o}{(1+\alpha)^2 Z_c + Z_o} \tag{4}$$

where Z_o is the odd-mode impedance,

$$Z_o = Z_{11} + Z_{22} - 2Z_{12} \tag{5}$$

and Z_e is the even-mode impedance,

$$Z_e = (1+\alpha)^2 \left[\frac{Z_{11}Z_{22} - Z_{12}^2}{Z_{11} + Z_{22} - 2Z_{12}}\right] = (1+\alpha)^2 Z_c \tag{6}$$

Here, Z_c is the common-mode impedance,

$$Z_c = \frac{Z_{11}Z_{22} - Z_{12}^2}{Z_{11} + Z_{22} - 2Z_{12}}, \tag{7}$$

which is the impedance seen by a single source when connected to both ports in parallel. From these definitions, we obtain the equivalent circuit of the generalized T-matched dipole shown in Figure 2.

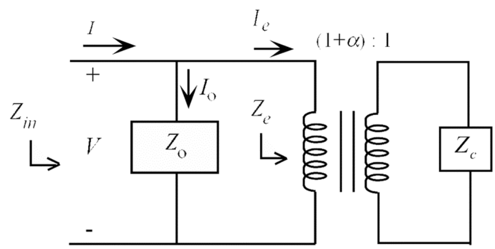

Figure 2. The Uda equivalent circuit of a T-match antenna.

One important and usually neglected issue for the even-odd mode model is the widths of the two ports. Port 1 is a real, driven port, and its width is governed by practical layout or feed structure issues. In modern RFID tags, the RF-IC has a non-zero width and thus does not conform to the delta-gap assumption. The problem is exasperated when considering the RF-IC as part of a larger package. Port 2, on the other hand, is a faux port that must be narrow enough that a conductor bridging the port will constitute a true short circuit, i.e., zero voltage and equal currents at both port edges. Hence, the faux port *must* be a delta-gap in order for the 2-port model to produce the same input impedance as the actual 1-port antenna. In this paper, we will assume that a delta gap is achieved when the propagation delay across the gap is $< 0.01°$.

2.2. The Transmission Line Model

The classic Uda model makes the additional assumption that the odd mode is a pure TEM mode associated with a double-sided, short-circuited, uniform transmission line. This allows the odd-mode impedance Z_o and the splitting factor α to be considered simply as transmission line parameters solely associated with the T-box.

For the odd mode, the T-box is driven as a loop, so the left and right hand short circuited transmission lines appear in series at the driven port. Thus, $Z_o = 2Z_T$, where Z_T is the input impedance to either of the short-circuited transmission lines. If both ports are delta gaps and the shorts are "good," the odd-mode impedance is estimated by [1]

$$Z_o = 2Z_T = j2Z_{ch} \tan\left(\frac{\beta t}{2}\right), \tag{8}$$

where Z_{ch} and β are the characteristic impedance and phase constant of the transmission line, respectively, and t is the total length the transmission line within the T-box. Formulas for Z_{ch} are available for many transmission line cross sections, e.g., [9], and values can also be obtained readily from a wide variety of numerical codes.

The splitting factor for a transmission line is the ratio of the port voltages required to drive exactly opposite port currents. It is real-valued and independent of the length of the line and the load impedance as long as *only* the TEM mode is present on the line. Analytic formulas exist in the literature for α_{TEM} of both wire [1] and strip [10, 11] transmission lines. One particularly simple case is when the two conductors have identical cross sections, for which $\alpha_{TEM} = 1$.

2.3. Design Using the Uda Model

The Uda model suggests a convenient procedure for T-match antenna design. A typical situation is to design a T-match antenna that provides a conjugate match to a known load. The procedure typically proceeds by (a) determining the values of α and Z_o necessary for a conjugate match, and (b) designing the various geometrical parameters (lengths widths, etc.) to achieve these values.

Consistent with the transmission line assumption, the Uda model assumes that α is real-valued and Z_o is imaginary-valued regardless of the cross-sectional shapes and dimensions of the transmission line conductors. This means that there are unique values of α and Z_o required to obtain a conjugate match to a load, and these can be known solely in terms of the common-mode impedance $Z_c = R_c + jX_c$ and the load admittance $Y_L = \frac{1}{R_{Lp}} + \frac{1}{jX_{Lp}}$, where R_{Lp} and X_{Lp} are parallel (i.e., shunt) resistance and reactance of the load, respectively. Requiring $1/Z_{in}^* = Y_L$, it follows from (4) and (6) that:

$$\alpha_{Uda} = \sqrt{\frac{R_c R_{Lp}}{R_c^2 + X_c^2}} - 1 \tag{9}$$

$$Z_{o-Uda} = -j\left[X_{Lp} + \frac{R_c^2 + X_c^2}{X_c}\left(1 + \alpha_{Uda}\right)^2\right] \quad (10)$$

With α_{Uda} and Z_{o-Uda} known, the designer then proceeds by adjusting the transmission line conductor lengths, widths and spacing to achieve these values.

Of course, this procedure will produce a realizable antenna only if the underlying assumptions are valid. As we will show in the sections that follow, the assumption that α is real is valid for folded dipoles with delta-gap feeds, but is typically invalid for the more general T-match, especially when the feed is not a delta-gap. As a result, the values of α and Z_o required for a conjugate match will be quite different from those predicted by (9) and (10).

3. NUMERICAL SIMULATIONS VS. THE UDA MODEL

To investigate the accuracy of the Uda model for T-matched dipoles, consider the T-match antenna shown in Figure 3. Here, all the conductors are thin (i.e., printed) strips. For our experiment, the outer height h and width w of T-box are 8.6 mm and 25.66 mm, respectively. The T-box void has a height d of 1.5 mm and a width t of 17.5 mm, respectively. The T-box void is exactly centered within the T-box, so $w_1 = w_2$. The dipole arm extensions are $a = 1.1$ mm wide and are attached to the T-box shorting straps at equal and variable vertical alignments with the T-box edges: flush with the top ($s_1 = 0$), centered ($s_1 = s_2$), and flush with the bottom ($s_2 = 0$). These dimensions were chosen so that the common-mode impedance would resonate at approximately 915 MHz, the odd-mode impedance would be inductive (to match with a capacitive RF-IC), and the TEM spitting factor α_{TEM} is unity (since $w_1 = w_2$).

We computed the input impedance using a MoM solver (Ansoft Designer) for all three dipole-arm alignments using two different methods. First, we computed the "exact" Z_{in} using only the two-

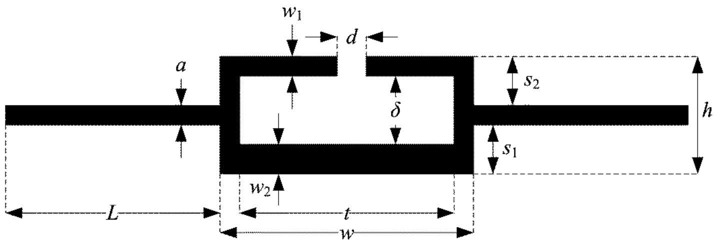

Figure 3. A generalized T-match dipole antenna.

port Z parameters in (4). Second, we computed Z_{in} again using (4), but with the Uda assumptions for α and Z_o. In this case, Z_c was calculated exactly from the 2-port Z parameters using (7), α was set to unity as predicted by the TEM assumption, and Z_o was calculated from (8) using $Z_{ch} = 219\,\Omega$ (found numerically using the MoM tool). The results are plotted in Figure 4. The three "exact" solutions are plotted independently, but all three calculations using the Uda model were within 5% of each other, so they are represented by a common curve with error bars showing the variation. It is clear from this figure that both the real and imaginary parts of Z_{in} as predicted by the Uda analysis are only weakly dependant on the dipole arm placement, whereas the exact values are strong functions of the dipole arm placement and are very different from the Uda-predicted values. Clearly, something about the Uda model is failing for this antenna.

Finding the cause of breakdown of the Uda model for this example is relatively simple, since the Uda equivalent circuit involves only three parameters: Z_c, Z_o, and α. Using (5) and (7), respectively, we found that neither Z_o nor Z_c are appreciably affected by the dipole arm placement in this example. Also, Z_o is predicted to within 5% by the by the transmission line model (8), and nearly exact when the characteristic impedance Z_{ch} is adjusted slightly (to 208 Ω in this case) to compensate for edge effects at the port gaps [12]. Hence, neither Z_c nor Z_o are responsible for the significant errors of the Uda model seen in Figure 4.

The splitting factor α, on the other hand, is very affected by the feed gap size, as well as the dipole-arm lengths and alignments. As

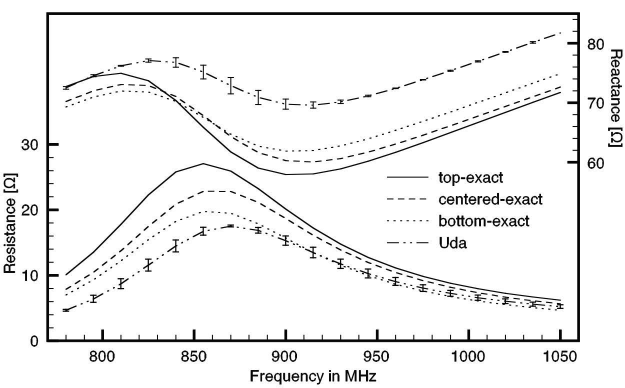

Figure 4. Exact vs. Uda model values of Z_{in} vs. frequency for top, centered, and bottom placed dipole arms for a 2 mm feed gap. Lower cluster: resistance. Upper cluster: reactance.

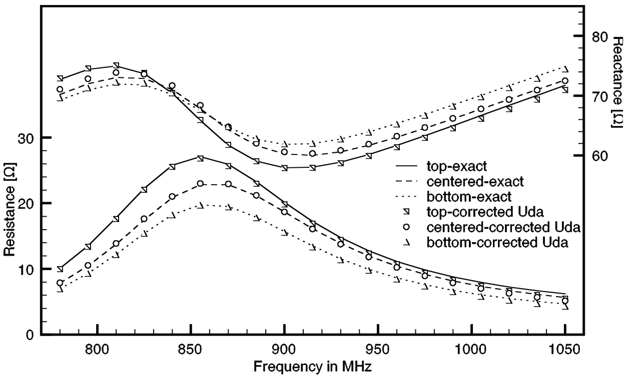

Figure 5. Comparison of exact and corrected-Uda values of Z_{in} for top, centered, and bottom placed dipole arms for a 2 mm feed gap. Lower cluster: resistance. Upper cluster: reactance.

evidence of this, Figure 5 compares the "exact" and "numerically-corrected Uda model" values of Z_{in} for the same T-match antenna geometry used for Figure 4. For the numerically-corrected Uda model, Z_{in} is found using (4) as before, but α is found numerically using (2) and Z_o is computed using (8), where the adjusted $Z_{ch} = 208\,\Omega$ is used.

As can be seen, the common "Uda" resistance and reactance curves of Figure 4 split into three separate curves in Figure 5, which lie almost exactly on the exact curves. This remarkable agreement clearly shows that the problem with the Uda model is the assumption that the α for the T-match antenna can be predicted solely in terms of the cross-sectional dimensions of the transmission line. In the section that follows, we will investigate this anomalous behavior of the splitting factor more fully.

4. THE ANOMALOUS CHARACTERISTICS OF THE SPLITTING FACTOR

In this section, we demonstrate how α is affected by the length and alignment of the dipole arms and the feed-gap width. To keep the discussion as simple as possible, we will use the same T-match antenna considered in the previous section (Figure 3, where $w_1 = w_2$) that has $\alpha_{TEM} = 1$.

Figure 6 shows the actual value of α (i.e., as found from (2)) as a function of electrical dipole-arm length L/λ at 915 MHz for delta-gap feed. Values are shown for all three dipole-arm attachment alignments: top, centered, and bottom. Here, it is seen that $\alpha = 1$ when the

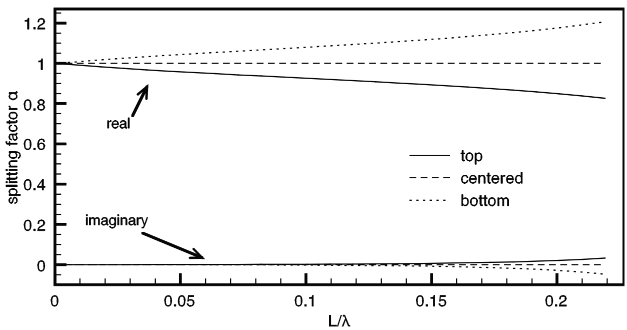

Figure 6. Alpha vs. dipole arm attachment length for delta feed gap at 915 MHz for top, centered, and bottom dipole arm alignments.

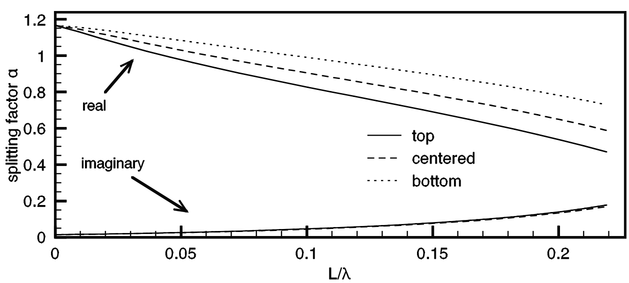

Figure 7. Alpha vs. dipole arm attachment length for 2 mm feed gap at 915 MHz for top, centered, and bottom dipole arm alignments.

dipole arms are centered on the T-box, but deviates increasingly from this value as L/λ increases for the top- and bottom-aligned cases. The dipole-arm alignments affect the magnitude of α, but α is predominantly real-valued for a delta-gap feed.

The added affect of a finite-width $d = 2.0$ mm feed port on α is shown in Figure 7. Here, we see an even larger deviation from the expected α_{TEM}=1 for all thee dipole arm alignments, and these values do not converge to unity as $L/\lambda \rightarrow 0$. In addition, the imaginary part of α is significant in all three cases as L/λ increases, but unlike the real part, has nearly the same value for all three dipole arm alignments.

These results show that α is not well predicted by the TEM assumption when the dipole arms are electrically long and the feed is not a delta-gap. This deviation is caused by the combined affects of nonzero currents on the dipole arms and unequal gap capacitances (when the driven port is not a delta-gap), both of which affect the balance of the odd-mode port currents. Comparing Figures 6 and 7, it is seen that the deviation of α from its TEM value is greatly amplified when both factors are present.

5. RAMIFICATIONS FOR T-MATCH DESIGN

The results in the previous section show that the splitting factor α is typically complex-valued and is not determined solely by the cross-sectional geometry of the T-box transmission line as predicted by the transmission line (TEM) assumption. Both the magnitude and phase of α are complex functions of almost all the parameters of the antenna and, to the authors' knowledge, cannot be predicted a priori by any known analysis or formulas. In addition, whereas the magnitude of α can be varied in practice by varying the widths and spacing of the transmission line conductors, the phase of α appears to be largely out of the control of the designer. Hence, the common Uda design procedure of determining a target, real-valued α_{Uda} using (10) cannot be used in T-match antenna design with any expectation of accuracy, since real-valued α values do not occur in practice, except for a few special cases.

Fortunately, this anomalous behavior of α is the only part of the Uda model that is invalid for general T-match dipole antennas. In particular, the Uda equivalent circuit (Figure 2) is still valid, as well as the expectation that the odd-mode impedance will follow the TEM model. This suggests that the Uda equivalent circuit can still be used as a guide for designing T-match dipoles. The key is to design in terms of values of the parallel resistance and reactance of the antenna, rather than target values of α and Z_o.

Figure 8 shows the equivalent circuit at the input terminals of a T-match antenna and a load (possibly a RF-IC), where all the components are shown as shunt elements. On the RF-IC side, R_{Lp} and X_{Lp} are the parallel resistance and reactance (usually a capacitance)

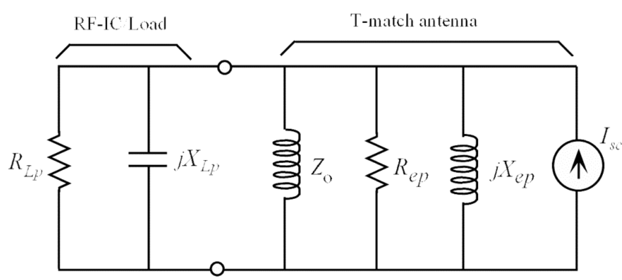

Figure 8. Equivalent circuit at the input terminals of a T-matched antenna.

of the load, respectively. On the T-match antenna side, I_{sc} is the short-circuit current, Z_o is the odd-mode impedance given by (5), and R_{ep} and X_{ep} are the parallel even-mode resistance and reactance, respectively, given by

$$R_{ep} = \left[\mathrm{Re}\left(\frac{1}{(1+\alpha)^2 Z_c}\right)\right]^{-1} \tag{11}$$

$$X_{ep} = \left[\mathrm{Im}\left(\frac{-1}{(1+\alpha)^2 Z_c}\right)\right]^{-1} \tag{12}$$

Z_o is nearly purely imaginary, so a conjugate match at a design frequency requires $R_{Lp} = R_{ep}$ and $\frac{1}{X_{Lp}} = -\frac{1}{X_{ep}} - \frac{1}{\mathrm{Im}[Z_o]}$. These conditions do not yield unique solutions for α and Z_o when α is complex, but for every α that satisfies the resistive requirement, a corresponding value of Z_o can be found that satisfies the reactive requirement.

Even though the α values encountered in T-match antennas tend to be complex-valued and do not follow the TEM formulas (e.g., [1, 10, 11]), our experience with this kind of T-match structure (i.e., Figure 3) has shown that $|\alpha|$ still tends to follow the general trends of these formulas, i.e., that larger values of w_1/w_2 yield smaller values of $|\alpha|$. This observation suggests that the desired impedances can be quickly found with an EM modeling code by adjusting the w_1/w_2 ratio of the T-box to make the source and load shunt resistances equal, and then adjusting the transmission line length t to adjust Z_o to satisfy the reactive requirement for a conjugate match. Since α will no doubt change when t changes, this sequence should be repeated until the values converge. Figure 9 compares this new design procedure with the classic Uda procedure.

To illustrate, we used this iterative procedure to design two simple T-match dipoles that achieve conjugate matches with commercially available RF-IC chips at 915 MHz. Both antennas are of the basic form shown in Figure 3, but differ mainly according to their tip-to-tip lengths. The "short" and "long" antennas have total lengths of 130 mm (0.4λ) and 169.5 mm (0.52λ), respectively. In both cases, the T-box widths (w), heights (h), and void heights (d) were chosen so that the required splitting factor and odd-mode impedances could be obtained iteratively by varying just two parameters: the transmission line length t and w_1/w_2 ratio. Since d was held constant, the characteristic impedance Z_{ch} of the transmission line was relatively unaffected by changes in either dimension, so Z_o was mostly affected by the void length t. On the other hand, $|\alpha|$ was determined largely by the w_1/w_2 ratio of the transmission line.

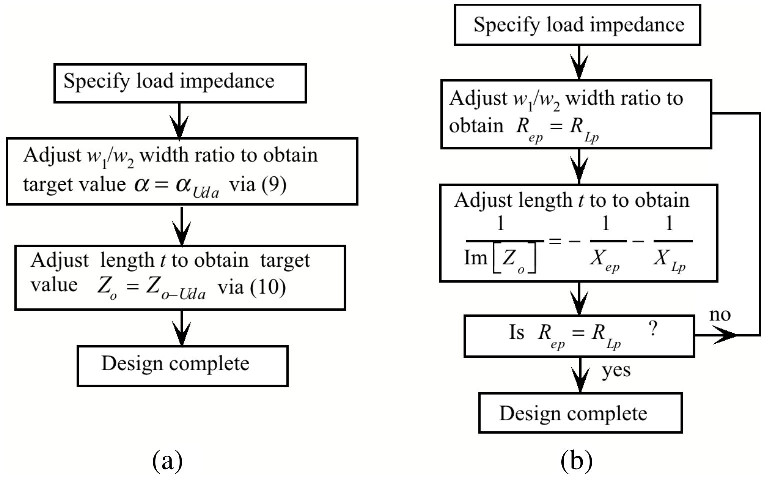

Figure 9. Comparison of the (a) classic Uda design procedure and (b) the proposed design procedure.

The short antenna was designed to match to an Alien Higgs 2 chip [13], which has shunt resistance and reactance of $1.5\,\mathrm{k}\Omega$ and $-135\,\Omega$, respectively, with an input impedance of $12 - j134\,\Omega$. The T-box height h and width w were 8 mm and 25 mm, respectively, $d = 3$ mm, $a = 2$ mm, and $d = 2$ mm. The final design parameters for three dipole arm alignments (top, centered, and bottom) of the short T-match dipole design are summarized in Table 1. In each case, a nearly perfect conjugate match into the chip was accomplished in two or three iterations of t and w_1/w_2. The odd-mode impedance Z_o and α that achieve a conjugate match were quite similar for all dipole arm alignments, since Z_c varied only slightly with the dipole arm location, but the w_1/w_2 ratios needed to attain this α were quite different for varying alignments. In none of these cases was the actual value of α reasonably close to α_{TEM}.

Also shown in Table 1 are the target values of α_{Uda} and Z_{o_Uda} predicted by the classic Uda model from Z_c alone that follow from (9) and (10), respectively. As can be seen, these values differ significantly from the true values of α and Z_o for all three dipole arm alignments. These differences are further evidence of the breakdown of the transmission line assumption in the Uda model for T-match dipoles.

Using a similar design process, the long antenna was designed to match into a Texas Instruments chip [14], which has shunt resistance and reactance of $254\,\Omega$ and $-59\,\Omega$, respectively, with an

Table 1. Design parameters for the short T-match dipole.

Alignment	Final values from iterative procedure						Uda-predicted values	
	t (mm)	w_1/w_2	Z_c (Ω)	Z_o (Ω)	α	α_{TEM}	α_{Uda}	$Z_{o\text{–}Uda}$ (Ω)
top	19.5	0.62	$29.8-j133$	$j105$	$0.85+j.08$	1.29	0.55	$j338$
center	19	1.06	$30.1-j136$	$j104$	$0.77+j.06$	0.96	0.53	$j334$
bottom	18.8	1.44	$30.6-j134$	$j104$	$0.77+j.06$	0.81	0.56	$j343$

Table 2. Design parameters for the long T-match dipole.

Alignment	Final values from iterative procedure						Uda-predicted values	
	t (mm)	w_1/w_2	Z_c (Ω)	Z_o (Ω)	α	α_{TEM}	α_{Uda}	Z_{o-Uda} (Ω)
top	12	0.62	$96.1-j24.1$	$j68$	$0.54+j0.18$	1.3	0.57	$j915.3$
center	12	1.07	$94.5-j22.6$	$j66$	$0.53+j0.16$	0.95	0.59	$j1063$
bottom	11.5	2.29	$95.6-j28.4$	$j66$	$0.52+j0.16$	0.61	0.56	$j855$

input impedance of $13-j56\,\Omega$. The T-box height h and width w were 8.6 mm and 20 mm, respectively. Also, $d = 3$ mm, $d = 2$ mm, and $a = 1.1$ mm. The final design parameters for the three variations of the long T-match dipole design are summarized in Table 2.

These results are similar to those of the short dipole, but the affects of the breakdown of the TEM assumption are even more evident, due to the increased electrical lengths of the dipole arm extensions. Here, the range of w_1/w_2 needed to achieve the required α values for the three dipole alignments is larger. Even more noticeable are the differences between the actual and Uda-predicted Z_{o_Uda} required for a match. This is a result of the increased angles of the splitting factors — roughly 17° — which increases the phase of the common-mode impedance as seen from the input terminals, which in turn changes the shunt reactance needed for a match.

These two examples show that the failure of the transmission line assumption of the Uda model greatly impacts the necessary and attainable physical design parameters for T-match dipole antennas, to the point where the Uda-predicted target values of α and Z_o are of little practical worth. On the other hand, the Uda equivalent circuit is still valid and can still be used as a guide in the design process.

6. SUMMARY AND CONCLUSIONS

In this paper, we examined the Uda model of the T-match dipole for the case in which the T-box was shorter than $\lambda/4$, which has recently become popular from its widespread use for RFID antenna design. We showed that the transmission line assumption of the Uda model is moderately accurate for computing the odd-mode impedance, but inaccurate for estimating the splitting factor α, and that these changes in α can cause large deviations from the intended input impedance.

Specifically, the Uda model assumes that α is real-valued, but the experimental data shows that α is actually complex, except for a few special cases. In some cases, we observed that α has a phase angle of about 45 degrees and deviates from the classic model with an error of nearly 75%. We found that the dipole arm location, length, and feed gap width all affect α, none of which is predicted by the Uda model and thus is a serious limitation of the model. Since it does not appear that the angle of the splitting factor can be predicted analytically a priori, this means that design parameters must be found numerically. In addition, this process generally needs to be iterative, since it does not appear that the angle of the splitting factor can be easily controlled or anticipated.

Despite these, many aspects of the Uda model are still useful. For example, the use of the two-port Z-parameters to determine the Uda model parameters is valid and can be used to both obtain model characteristics and assist in the design process. We know, for example, that the shunt resistance of the antenna is controlled by α, and that the shunt reactance is controlled primarily by Z_o, and that this insight can guide an iterative design process. Using that process, we were able to design a number of RFID tag antennas using the Uda equivalent circuit in a small number of iterations.

Finally, we believe that these results call for new research in developing more accurate models of the practical T-match so that we can have better insight into the behavior of the antenna. Perhaps a combination of new and more accurate models, and new geometries, can ultimately yield an accurate analytical model and rigorous design process.

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