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System and Circuit Models for Microwave Antennas

Mohamed I. Sobhy, Benito Sanz-Izquierdo and John C. Batchelor

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System and Circuit Models for Microwave Antennas

Mohamed I. Sobhy, Benito Sanz-Izquierdo and John C. Batchelor

Abstract: Computer aided procedures have been developed to derive system and circuit models to match measured responses of the reflection coefficient of microwave antennas. System models are used to study the effect of the antenna on digital signals in digital communication systems. Circuit models are used as an aid to designing the antenna and relating the antenna performance to its physical structure.

I. INTRODUCTION [1]

THE most common design aid for designing microwave antenna is the Electromagnetic simulator where the physical antenna structure is simulated and its response calculated. To complete the design cycle further understanding of the antenna characteristics is required. Since most modern communication systems are digital, a model compatible with digital system simulation would be a valuable design aid. An equivalent circuit model would help the designer relate the antenna response to the physical structure and to study the effects of varying the antenna dimensions on the response.

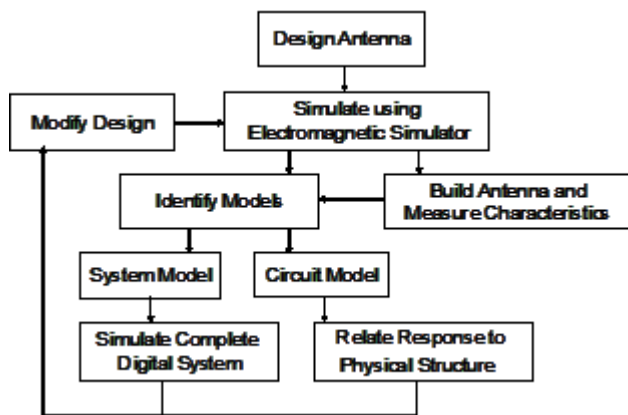


Figure 1. Antenna design procedure including system and circuit modelling.

For these reasons we have integrated CAD procedures in the antenna design cycle in order to identify both system and circuit models from either measurement or from the results of the Electromagnetic simulator. The design procedure is shown in Fig. 1.

The results usually available to antenna designers are the magnitude and phase of the input scattering parameter S_{11} . In this work we shall show how from knowledge of only S_{11} we can achieve the following:

- Derive of an equivalent circuit that accurately represents S_{11} .
- Identify the radiation resistance and determine its value.

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- Calculate of the power radiated from the antenna.
- Derive the voltage transfer function.
- Identify system models to represent S_{11} and the voltage transfer function.
- Derive a system model when the antenna is used as a receiving antenna.
- Include both the transmitting and receiving antenna models in the simulation of a digital communication system and assess the effect of the antennas on the Bit Error Rate (BER).

II. THE SYSTEM MODEL [2]

This model is used to represent the antenna in the simulation of an entire communication system. Since almost all modern communication systems are digital, the model has to be compatible with digital system simulation software such as Simulink. Unlike models based on equivalent electrical networks, this model does not have to obey Kirchhoff's and Ohm's laws. This makes the model more flexible and low order models can be identified for complex responses.

The system identification process assumes that the response of any linear time invariant system can be represented as the ratio of two polynomials

$$F(s) = \frac{a_0 s^n + a_1 s^{n-1} + a_2 s^{n-2} + \dots + a_n}{b_0 s^m + b_1 s^{m-1} + b_2 s^{m-2} \dots + b_m} \quad (1)$$

$$= \frac{a_0 s^{n-m} + a_1 s^{n-m-1} + a_2 s^{n-m-2} \dots + a_n s^{-m}}{b_0 + b_1 s^{-1} + b_2 s^{-2} + \dots + b_m s^{-m}}$$

where n and m are the order of the numerator and denominator polynomials. Without loss of generality, the coefficient b_0 is set to 1 and the response is represented by the IIR filter model in Fig. 2.

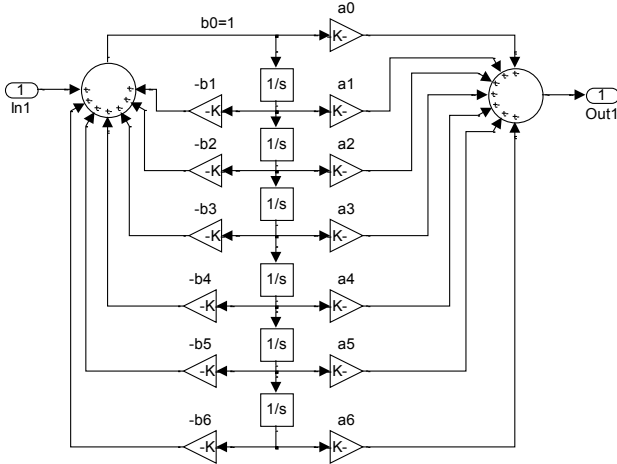


Figure 2. Example of a system model based on IIR filter.

The model can then be incorporated in the simulation of a complete digital communication system as is shown later. The model shown is for $n = m$ and models for n not equal to m are easily derived.

The advantages of the system model are:

- It can be used in the simulation of a complete communication system.
- It can handle either digital or analogue signals.
- It can be directly implemented in digital hardware.
- It is easy to increase the order of the model to fit a complicated response.
- The basic structure of the model is the same for any system and only n and m vary, hence the identification process is systematic.

However this approach has also a number of disadvantages. These are:

- The model does not readily relate to the physical structure.
- Increasing the order of the model leads to numerical inaccuracies.
- The model is not guaranteed to be stable.

III. THE CIRCUIT MODEL

The circuit model is the most popular approach in model identification. It consists of deriving an equivalent electrical circuit to realise the measured response.

There are two main steps in developing the circuit model

- Determine a suitable topology: This is usually made by inspecting the electromagnetic structure and identifying the circuit elements. In the proposed research a CAD based procedure will be developed either to modify the initial topology for a better fit or to develop a topology by examining the supplied data.
- Determine the element values: This is achieved by an iterative optimization process to fit the model response to the supplied data.

When developing this model, care should be taken to relate the elements as closely as possible to the physical structure and to identify the radiation resistance and the losses in the antenna.

The circuit model has the following advantages:

- It can relate directly to the physical structure.
- It is a help in the antenna design process.
- Stability is guaranteed if only positive circuit elements are used.

The disadvantages are:

- It cannot be included in the simulation of digital communication systems.
- Each system will require a different model on an *ad hoc* basis.

IV. SYSTEM MODEL DERIVED FROM CIRCUIT MODEL

We shall show in section IX that it is possible to derive a system model from the circuit model. The system model can be used in the simulation of digital communication systems in the same way as the IIR model described above. However since all the circuit elements are easily identifiable in this model, optimisation of the antenna performance is made much easier.

V. THE DOUBLE BUTTON ANTENNA [3-6]

We shall develop models for the Double Button Antenna shown in Fig 3. This antenna was developed as a wearable antenna with two bands at 2.4 GHz and 5 GHz for Bluetooth and WIFI applications. The aim of the modelling procedure is to be able ultimately to include a transmitting and a receiving antenna in a complete digital communication simulation in order to assess the effect of the two antennas on the system performance.

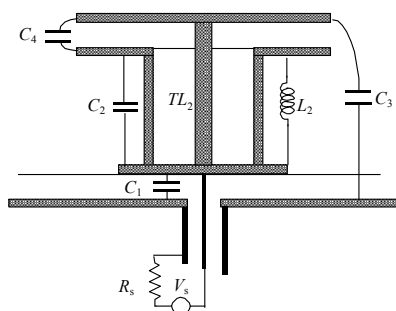


Figure 3. The Double Button Antenna.

The circuit elements representing the electromagnetic structure were identified and the optimisation procedure used to calculate their values in to match the responses from the EM simulator. The results for S_{11} are shown in Fig. 4. It is difficult to distinguish between the results from the EM simulator and the model due to the accuracy of the modelling procedure.

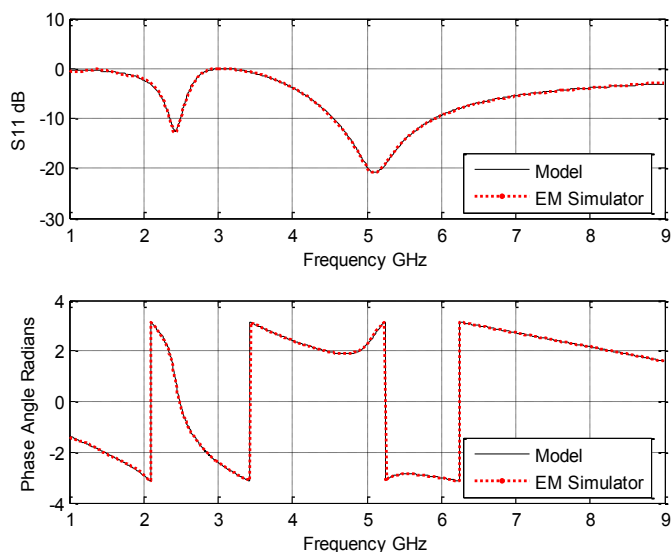


Figure 4. Modelled and measured responses of the Double Button Antenna.

The circuit model is shown in Fig. 5 and the result from the circuit simulator is shown in Fig. 6.

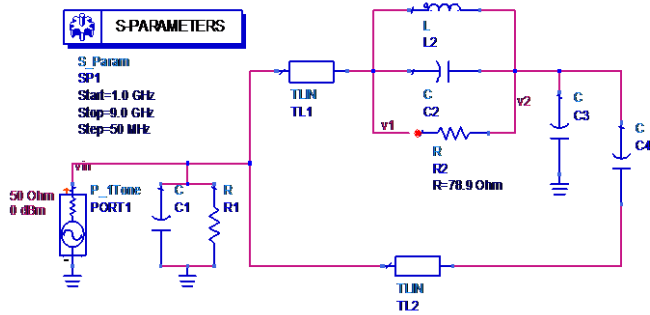


Figure 5. Equivalent circuit of the Double button Antenna.

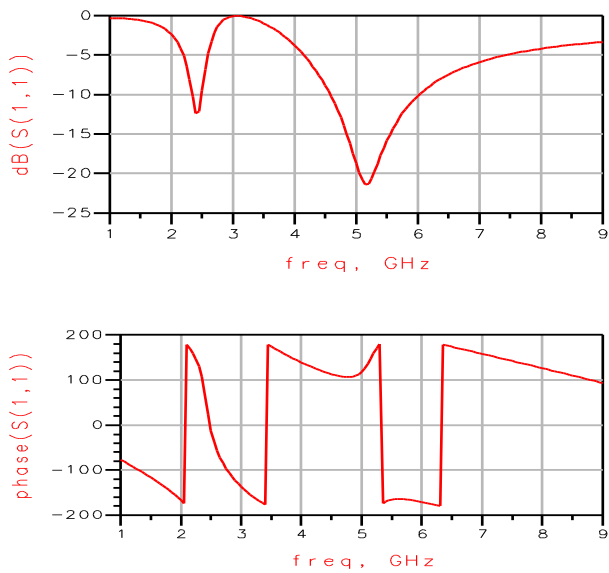


Figure 6. Response of Double Button Antenna from circuit simulator.

A system model of order $m = n = 6$ was then derived. The model is as shown in Fig. 2 and the response to a sweep signal from a system simulator is shown in Fig. 7.

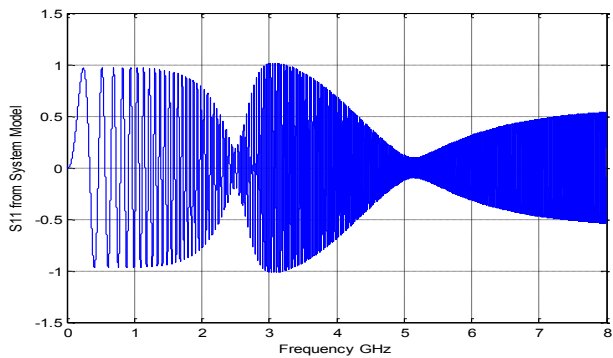


Figure 7. Result from system model.

The above results show that both the circuit and system models match the measured results very well.

Next we wish to identify the radiation resistance and develop a system model for the antenna transfer function. The radiation resistance is readily identified as the $78.9 \Sigma R_2$ in Fig. 5 and the radiated power is shown in Fig. 8 showing clearly the two radiation bands at 2.4 and 5 GHz.

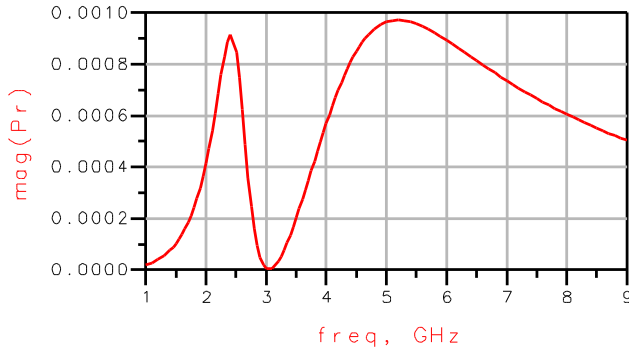


Figure 8. Radiated power from Double Button.

The voltage transfer function V_r/V_s is shown in Fig. 9 and was calculated using the circuit simulator, where V_r is the voltage across the radiation resistance and V_s the source voltage.

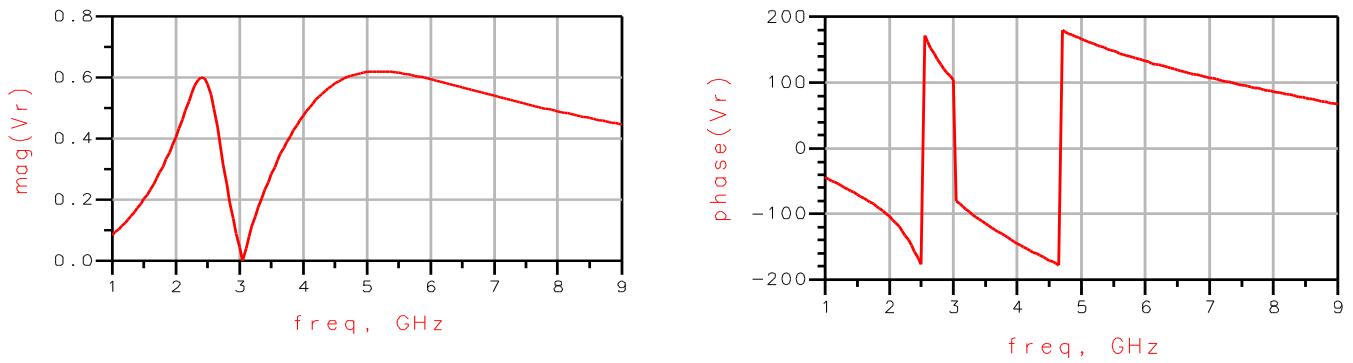


Figure 9. Transfer function of Double Button from circuit simulator.

From these results a system model was developed to realise the voltage transfer function. The model is as shown in Fig. 2 with the appropriate coefficients and the output voltage response to a swept signal is shown in Fig. 10.

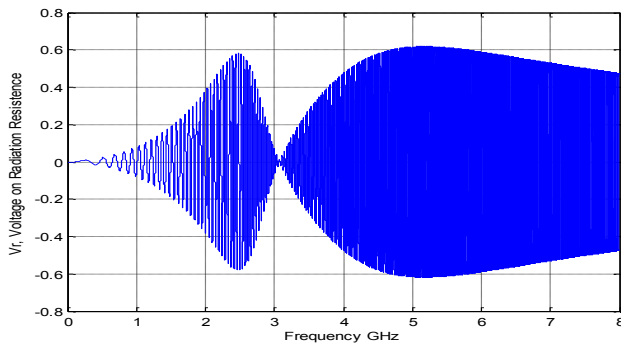


Figure 10. Voltage on radiation resistance from system model.

It is not surprising that we are able to obtain the transfer function with only knowledge of the input scattering parameter S_{11} . For a passive network the scattering matrix is unitary and obeys the relation $\mathbf{S}^* \mathbf{S} = \mathbf{I}$ where \mathbf{I} is the identity matrix. This gives four equations relating the scattering parameters. In classical filter synthesis procedure [7], the input scattering parameter and

the input impedance are derived from knowledge of only the required insertion loss. In our case we have derived the transfer function numerically using the circuit simulator instead of analytically as in the case of filter synthesis. However, it is also possible to derive an analytical expression for the transfer function using equation (1) for S_{11} .

VI. SIMULATION OF A DIGITAL COMMUNICATION SYSTEMS

Once a system model representing the voltage transfer function has been identified, we are ready to include the transmitting antenna in a digital communication system. Fig. 11 shows the transmitting antenna included in a Rectangular Quam system with $M = 64$ which is the standard for WIFI. The parameters of the system are given in Table I.

Modulation Scheme	Rectangular Quam
M-ary number	64
RF Frequency	2.4 GHz
Symbol Time	18 ns
Symbol Rate	55.6 M Symbol/s
Samples per Symbol	2
Resulting BER	0

Table I Parameters of digital communication system.

The results given in this section are for the above parameters. However, the antenna works equally well with other parameters, in particular for the 5 GHz band. Fig. 12 shows the constellation diagram before and after the antenna with no added noise.

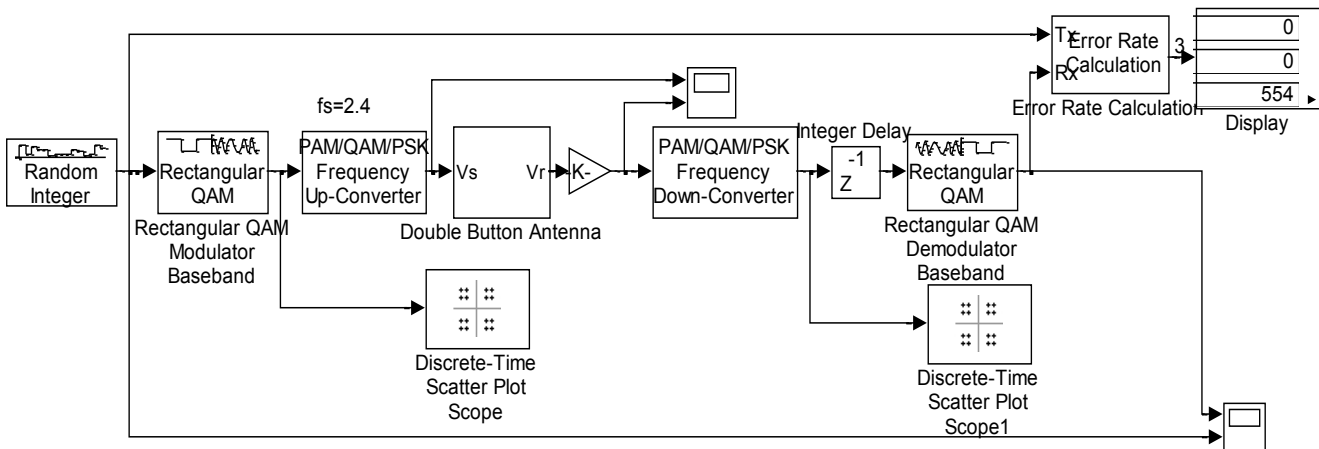


Figure 11. Digital communication system with Double Button antenna.

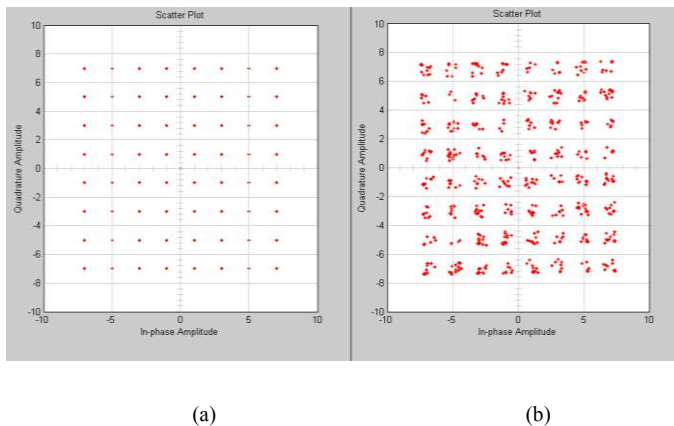


Figure 12. Constellation diagrams (a) Transmitted signal. (b) Received signal.

It is clear from the constellation diagram that the antenna generates scatter in the transmitted signal. This is typical when an analogue sub-system with limited bandwidth is included in a digital system. This can also be seen when comparing the input

and output signals in the time domain as shown in Fig 13. The antenna generates spikes and distortions at the phase and amplitude transitions between symbols.

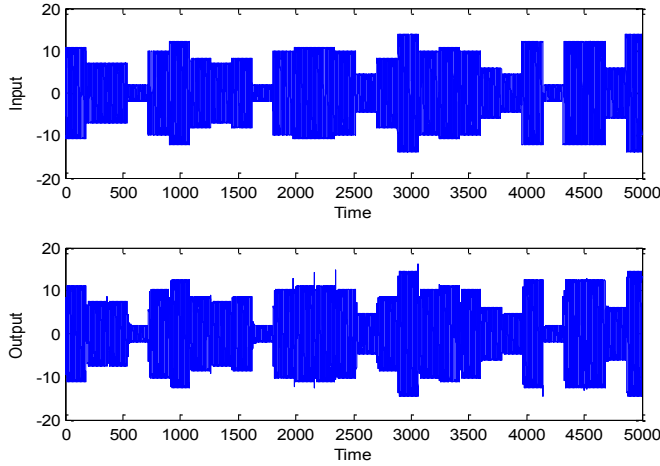


Figure 13. Time domain signal before and after antenna.

VII. THE RECEIVING ANTENNA

The transfer function for the antenna when used as a receiving antenna can be derived from the transfer function of the transmitting antenna.

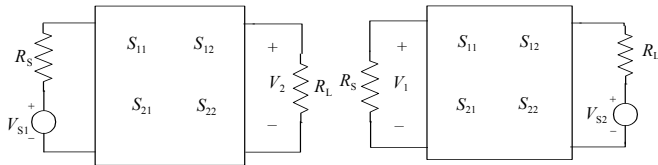


Figure 14. Reciprocal network representation.

For a reciprocal network the scattering parameters S_{12} and S_{21} are the same. When we exchange the source and the load in a two-port we can relate the voltage transfer functions V_2/V_{S1} and V_1/V_{S2} shown in Fig. 14.

The scattering parameters S_{21} and S_{12} are given by

$$S_{21} = \frac{2V_2}{V_{S1}} \sqrt{\frac{R_S}{R_L}} = S_{12} = \frac{2V_1}{V_{S2}} \sqrt{\frac{R_L}{R_S}}. \quad (2)$$

From which
$$\frac{V_1}{V_{S2}} = \frac{V_2}{V_{S1}} \frac{R_S}{R_L}. \quad (3)$$

Thus the voltage transfer function for the receiving antenna is the same as that of a transmitting antenna except for a multiplication factor. In a practical communication system the multiplication factor does not make any difference as the system will include amplifiers and Automatic Gain Control (AGC) to compensate for any variation in signal power. For simulation purposes we can use the same model for the transmitting and receiving antennas to study the effect on the digital transmission.

VIII. COMPLETE DIGITAL SYSTEM SIMULATION

A digital communication system using the Button Antenna is shown in Fig 15. The system includes two channels, one transmitting at 2.4 GHz and the other at 5 GHz, both feeding the same antenna. The RF frequencies correspond to the two antenna bands and the system includes a transmitting and a receiving antenna. The two channels have slightly different parameters which are given in Table II.

	Channel I	Channel II
M-ary number	64	64
RF Frequency	2.4 GHz	5 GHz
Symbol Time	18 ns	20 ns
Symbol Rate M S/s	55.6	50 M
Samples per Symbol	2	2
Resulting BER	0	0

Table II Parameters of the two channels of the digital communication system.

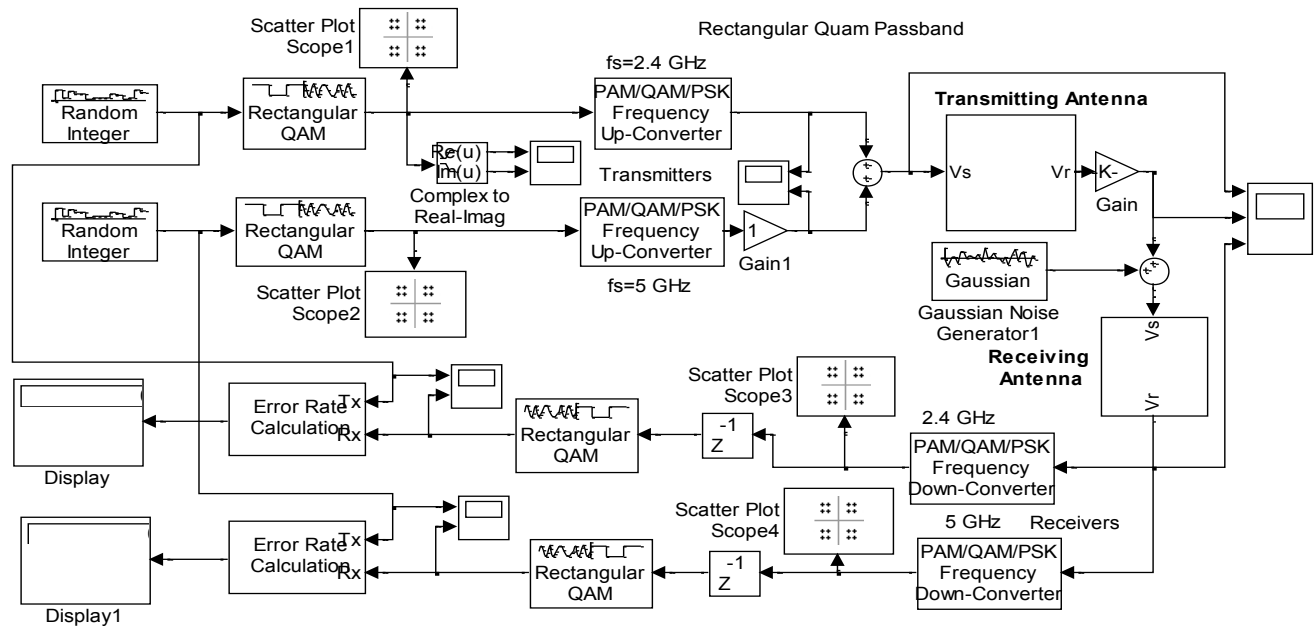


Figure 15. Digital communication system with transmitting and receiving antennas.

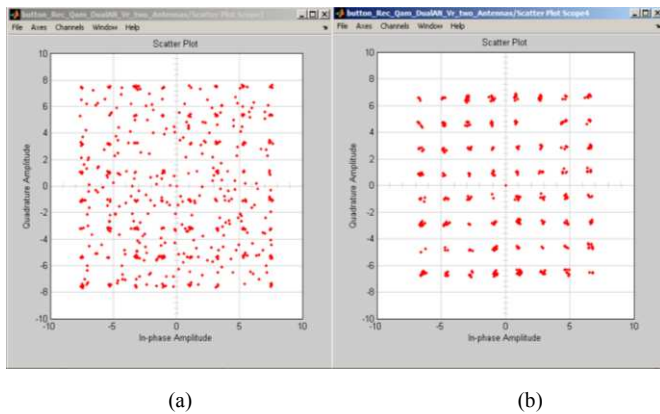


Figure 16. Constellation diagram of the received signals for (a) 2.4 GHz channel. (b) 5 GHz channel.

The constellation diagrams, for both channels, of the received signal are shown in Fig 16. We notice that the scatter for the 2.4 GHz channel is worse than for the 5 GHz channel. This is because the transfer function of the antenna, shown in Fig 9, shows that the 5 GHz channel has a wider bandwidth. We also compare the scatter diagram of Fig 16a with that of Fig 12b. Fig 16a

shows more scatter due to the inclusion of the receiving antenna. Even with the high degree of scatter shown in Fig 16a the demodulator was able to recover the received signal without errors. The above results show a high degree of consistency which gives confidence in the modelling procedure.

IX. SYSTEM MODELS DERIVED FROM CIRCUIT MODELS [8]

When an antenna designer wishes to optimise the antenna performance, it is a great help if the model elements relate as closely as possible to the physical structure. Although the circuit models achieve this aim, the system models based on an IIR digital filter structure do not. We shall describe a method of deriving a system model that has a one to one relation with the equivalent circuit.

The procedure for deriving this model is systematic and follows the following steps:

1. From the circuit model a graph is constructed, containing only nodes and edges, which describes the network interconnections. We use the Button Antenna circuit model shown in Fig. 5. The corresponding network graph is shown in Fig 17.

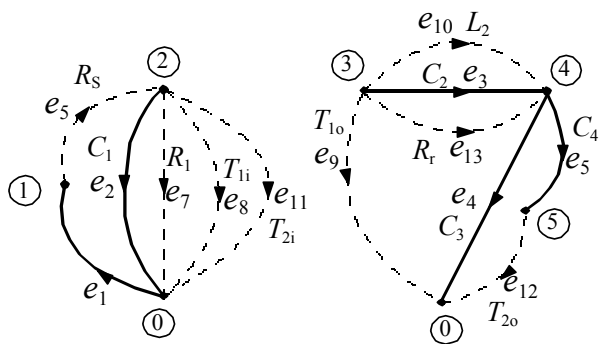


Figure 17. Network graph showing tree and co-tree.

2. A tree is determined for the network graph. A tree is a sub-graph that contains all the nodes but no loops (tie-sets). The remainder of the graph is referred to as the co-tree. In Fig 17. e_1 to e_5 form the tree and e_6 to e_{13} the co-tree.

3. Next the dynamical transformation matrix \mathbf{D} [9-11] is derived. This is done by assigning the columns to the tree edges and the rows to the co-tree edges. Each row is a set of edges that make a loop containing one co-tree edge and as many tree edges as necessary. For the graph shown in Fig. 17 the \mathbf{D} matrix is given by

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & -1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & 0 & 0 & -1 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \quad (4)$$

4. The voltages and currents in the circuit are related by [9]

$$\begin{bmatrix} i_t \\ v_c \end{bmatrix} = \begin{bmatrix} 0 & D \\ -D^T & 0 \end{bmatrix} \begin{bmatrix} v_t \\ i_c \end{bmatrix}. \quad (5)$$

5. Equation (4) gives a description of the network interconnections in terms of a combination of Kirchhoff's first and second laws. We need to add the relations between the currents and the voltages as determined by the type of elements used. These are given by

$$v_t = f_1(i_t) \quad \text{and} \quad i_c = f_2(v_c). \quad (6)$$

6. When the matrix D and the functions f_1 and f_2 are known, a system model representing the circuit can be constructed as shown in Fig 19.

It is important to notice that the functions f_1 and f_2 could take any form and could be functions of any variable in the circuit and not restricted to the variables indicated in equation (6). This gives the possibility of representing non-linear as well as distributed elements such as transmission lines. In the simplest case the functions represent Ohm's law for the circuit elements. Although we are applying this procedure here to antennas, it is a more general procedure that can be applied to develop a digital system model for any analogue network or subsystem.

It is clear from Fig. 19 that the elements of this system model have a one to one correspondence with the circuit model in Fig 5. This enables the designer to relate the model to the electromagnetic structure when trying to optimise the antenna performance. The response of the new model is compared to the IIR filter model as shown in Fig. 18.

When used in digital system simulation, this model gives identical results to those obtained with the IIR filter model.

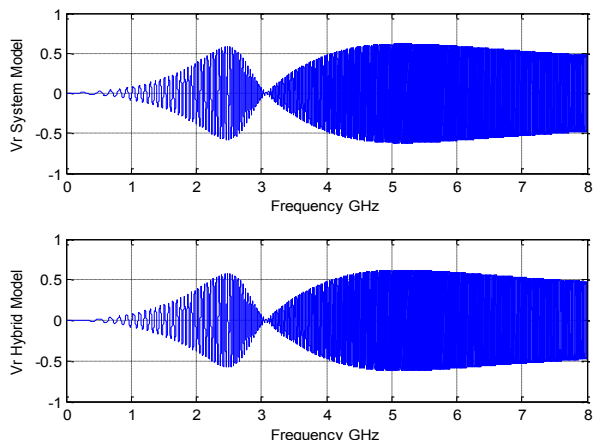


Figure 18. Response of Hybrid model compared to the IIR model

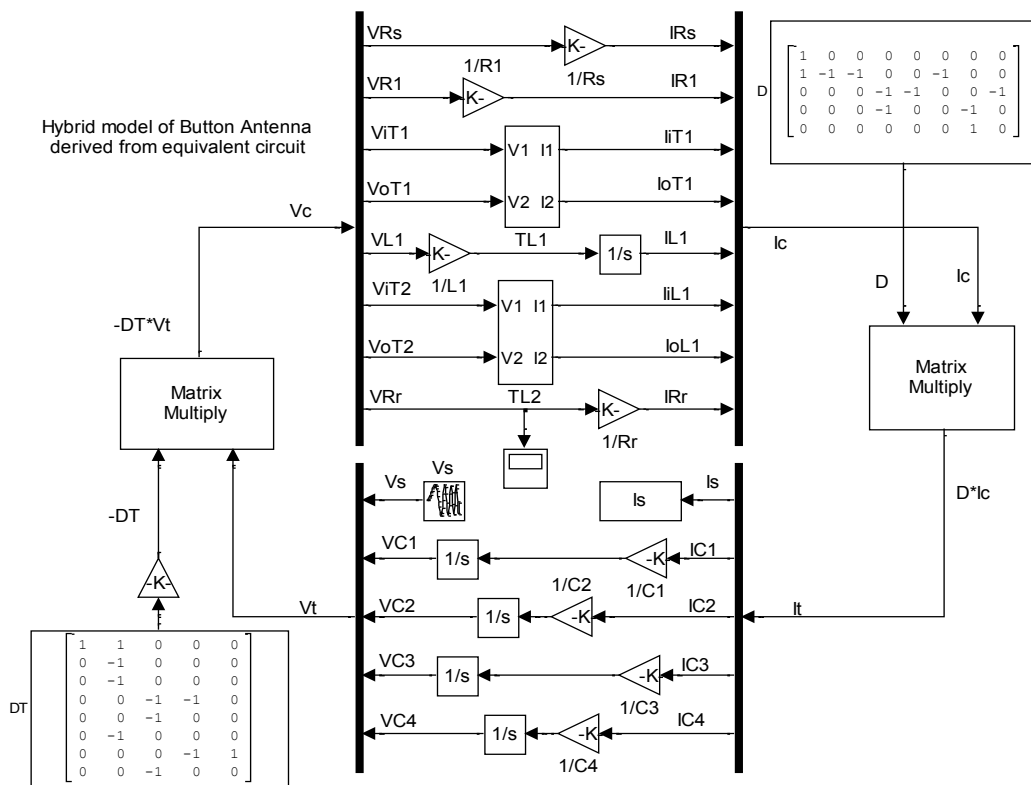


Figure 19. Hybrid model of Button Antenna.

X. THE MULTI-BAND ANTENNA [12-14]

The above results concentrated on the Button Antenna but the procedure could be applied to antennas with more complicated responses. We present results for a multi-band antenna. This antenna was designed to cover the European bands for GSM, DCS-1800, DECT, UMTS, Bluetooth and HiperLAN2. This obviously made the identification process more difficult and a high order model is required. Fig. 10 shows the antenna, which is a planar structure, the measured response and the response from the identified system model. The order of the identified model was $n = 26$ and $m = 25$. Higher orders will of course give a better fit to the measured response but will increase the complexity of the model and lead to inaccuracies.

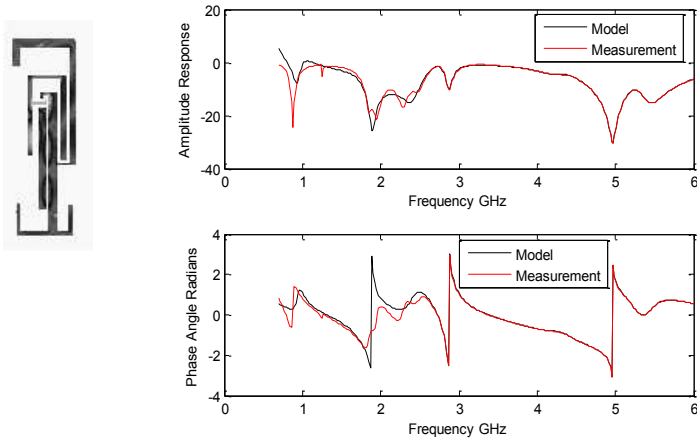


Figure 20. The Multi-band antenna , its measured and model responses.

XI. THE ULTRA-WIDE-BAND ANTENNA [15,16]

A similar procedure was followed to identify a model for an antenna for UWB applications. Fig.21 shows the antenna and a comparison between the measured response, the mathematical model and the system model. The results of the system model were obtained using Simulink. The order of the system model was $n = 18$ and $m = 18$ with excellent results as shown.

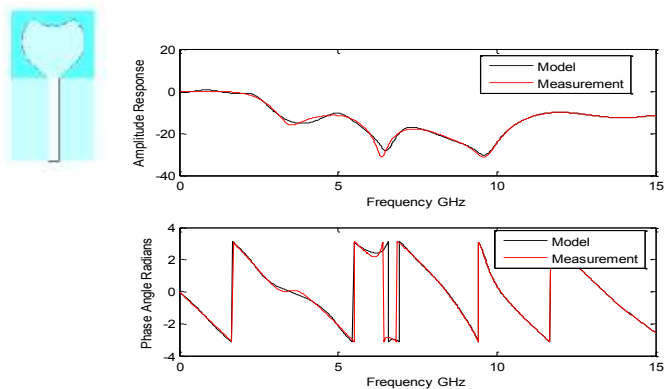


Figure 21. The UWB antenna and its measured and system model responses.

Fuller results for the Multi-band and the UWB antennas will be reported in a later publication.

XII. CONCLUSION

A full modelling procedure has been presented for the derivation of antenna models that could be used in the simulation of digital systems. This enables the system designer to assess the degradation in system performance due to the antenna and to optimise the antenna design for best digital performance. The method starts with knowledge of only the input scattering parameter of the antenna which can be easily obtained from measurements or electromagnetic simulations. The procedure enables the derivation of a circuit and a system model for the input scattering parameter, the identification of the radiation resistance and the derivation of a system model for the transfer function of the antenna when used either in either the transmitting or receiving modes.

Although the presented results concentrated on antennas, the basic procedures can be applied to derive digital models for any analogue subsystem containing lumped, distributed and nonlinear elements.

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