A New Modeling and Simulation Methodology of a Patch Antenna by Bond Graph Approach

Sabri Jmal, Hichem Taghouti, and Abdelkader Mami

Abstract—In order to develop a new tool for modeling and simulation, more effective for multi-triangular patch antenna, we thought, in this paper, to use the Bond-Graph approach jointly with the Scattering formalism. Indeed, what we seek is a simple, effective, fast tool, allowing integrating our antenna with other components. This new technique is based on a physical interpretation of patch antennas that will lead to a conventional Bond-Graph model. The analytical procedure operating Scattering parameters, developed in our previous research, will be applied on the Bond-Graph model of patch antenna to validate the results.

Index Terms—Bond-Graph Approach, Patch Antenna, Scattering formalism, Scattering Parameters, Bow Tie antenna, Modeling, Simulation.

I. INTRODUCTION

Several techniques for studying the patch antennas [1, 2] have evolved according to the requirements of modern applications. These techniques can be classified according to their principles some are based on purely numerical methods and other analytical approximations [6]. On the other hand, the characterization of patch antenna by the distribution of incident and reflected waves at different system access is a technique known and used since the beginning of the century under the name scattering formalism [15]. This formalism is transcribed by a matrix called scattering matrix noted S. In addition, the Bond-Graph is a graphical tool multidisciplinary applicable to any physical field (mechanical, electrical, hydraulic, pneumatic, etc.). Represents the transfer of energy in the system [7], it is based on the principle of conservation of power, hence the idea of using it in conjunction with the Scattering formalism to develop a new technique for modeling and simulation of patch antenna [16, 18].

In this paper we present a new methodology for modeling and simulation of patch antenna by the Bond-Graph approach. At the beginning we will start by introducing the principle of this new technique. This technique will, thereafter, apply to a patch antenna structure Bow Tie modified [3, 4]. Finally we validate the results found by a simple comparison with other techniques and our technique is based on the analytical procedure operating Scattering parameters [8, 9, 10].

II. PRINCIPLE OF THE NEW TECHNIQUE

The principle of the new technique of modeling and simulation [13] of patch antenna by Bond-Graph approach and Scattering formalism [7, 15], is to monitor the steps as follows:
- Perform interpretation and analysis physical of the antenna studied.
- Develop the conventional Bond-Graph model of the antenna.
- Apply the analytical procedure operating parameters scattering on Bond-Graph model.
- Simulation of scattering parameters found.

Fig.1 illustrates the principle of the new technique for modeling and simulation of patch antenna.

A. Physical interpretation and translation in Bond-Graph of the antenna

Our physical interpretation is based on works where researchers have considered that any patch antenna is a resonant element [5] which can be translated as, generally, Bond-Graph by three basic elements namely: resistive element (R), inductive element (I) and capacitive element (C) connected with the junction 0 [11]. The determination of these parameters values must include the geometrical parameters of
antenna and his environment: substrate, losses, radiation ... [17, 19].

![Fig.2 Bond-Graph model of triangular patch antenna](image)

Losses of the planar antenna in its environment will be translated into Bond-Graph by a resistive element (R). This is calculated by the following equation:

$$
R = \frac{Q_f h}{\pi f_r \varepsilon_{dy} \varepsilon_0 WL \cos^2 \left( \frac{\pi x_0}{L} \right)}
$$  \hspace{1cm} (1)

Where: \( f_r \): is the resonant frequency, \( Q_f \): is the quality factor, \( \varepsilon_{dy} \): is the permittivity dynamic, is the distance between the excitation point and the side of the patch, \( L \) and \( W \) are the dimensions of the patch, and \( h \) is the height of the substrate.

All the losses must be inserting calculate the quality factor. This factor is calculated by the expression (2).

$$
Q_f = \left( \frac{1}{Q_a} + \frac{1}{Q_c} + \frac{1}{Q_D} \right)^{-1}
$$  \hspace{1cm} (2)

- \( Q_a = \frac{e_0 \varepsilon_{dy}}{4 f_r H} \): Losses by radiation.
- \( Q_b = \frac{1}{T g \delta} \): Losses in the dielectric.
- \( Q_c = \frac{0.786 f Z_{dy}(W) H}{P_a} \): Loss metal.

In the expression of \( Q_c \), the term \( Z_y(W) \) refers to the characteristic impedance of a microstrip line laid on the air. It is given by the following relation.

$$
Z_y (W) = \frac{60 \pi}{\varepsilon_r} \sqrt{\varepsilon_r} \left( \varepsilon_r + 1 \right) \left( 1.451 + \ln \left( \frac{W}{2H} + 0.94 \right) \right)
$$  \hspace{1cm} (3)

With: \( W/H > 2 \).

Dynamic permittivity \( \varepsilon_{dy} \) is calculated according to the total capacitance of the antenna in the presence and absence of the substrate.

$$
\varepsilon_{dy} = \frac{C_{dyn}(\varepsilon)}{C_{dy}(\varepsilon_0)}
$$  \hspace{1cm} (5)

Thus, to determine the value of \( \varepsilon_{dy} \), we first calculated the value of the total dynamic capacity which can be calculated by the following equation:

$$
C_{dyn} = C_p + 2C_{f_1} + 2C_{f_2}
$$  \hspace{1cm} (6)

With:

- \( C_p = \frac{e_0 \varepsilon WL}{H \gamma_n} \): Capacity flat patch without considering the capacity of edge.
- \( h \): height of the substrate and \( \gamma_n = \begin{cases} 1, j=0 \\ 2, j \neq 0 \end{cases} \)
- \( C_{f_1} = \frac{1}{L} \int_0^L \left( Z(W, H, \varepsilon_r = 1) - \frac{e_0 \varepsilon WL}{H} \right) L \): Is the dynamic capacity of side length \( L \).
- \( C_{f_2} = \int_0^W c_{dy} \varepsilon^2 (\varepsilon) \cos^2 \left( \frac{m \pi y}{W} \right) dy = \frac{1}{\gamma_n} c_{dy} \varepsilon \) : Is the static capacitance of the side of length \( L \).

And \( C_{f_i} \) is calculated by the following equation:

$$
C_{f_i} = \frac{1}{2} L \int_0^L \left( Z(W, H, \varepsilon_r = 1) - \frac{e_0 \varepsilon WL}{H} \right) L \]
$$  \hspace{1cm} (7)

$$
C_{f_i} = \int_0^W c_{dy} \varepsilon^2 (\varepsilon) \cos^2 \left( \frac{m \pi y}{W} \right) dy = \frac{1}{\gamma_n} c_{dy} \varepsilon \] (8)

With:

$$
c_{dy} = \frac{1}{2} \left( \frac{Z(L, H, \varepsilon_r = 1) - e_0 \varepsilon L}{H} \right) W
$$

and

$$
c_{dy} = \frac{1}{2} \left( \frac{Z(L, H, \varepsilon_r = 1) - e_0 \varepsilon L}{H} \right) W
$$

The final expression of the dynamic capacity can be simplified by replacing \( Z(W, L, \varepsilon_r) \) and \( Z(W, H, \varepsilon_r) \) by their expressions. Finally, the dynamic capacity is calculated then:

$$
C_{dy} = \frac{e_0 \varepsilon WL}{H \gamma_n} + \frac{1}{2} \left( c_{dy} \varepsilon_r (H, W) - e_0 \varepsilon WL \right)
$$  \hspace{1cm} (9)

With: \( \gamma_n = \begin{cases} 1, j=0 \\ 2, j \neq 0 \end{cases} \)

After determining the dynamic capacity \( C_{dy} \), we can deduce the dynamic permittivity \( \varepsilon_{dy} \).

The inductive element (L) can be calculated by verifying the flowing relationship of resonance written as follows:

$$
\omega_{res} = \frac{1}{\sqrt{LC_{dy}}}
$$  \hspace{1cm} (10)

Whence:

$$
L = \frac{1}{\omega_{res}^2 C_{dy}}
$$  \hspace{1cm} (11)
Note:
The geometrical parameters of antennas and its environment substrate, losses, radiation ... [6] that lead us to determine the resistive inductive and capacitive elements of Bond-Graph model will be integrated into a program in Maple or MatLab software. This program will be the basis for a new modeling and simulation software of patch antennas by Bond-Graph approach [14].

B. Analytical procedure operating scattering parameters

To exploit graphically the Scattering parameter from a Bond-Graph model we must transform the conventional Bond-Graph of the system studied in causal reduced Bond-Graph model. And establish input-output analytical relationships from the reduced causal Bond-Graph on the basis of the notions of causal path and causal loop. Finally we express the terms of reduced effort and flow variable (ε and ϕ) depending on the variable wavelength (wi and wr) of the same port [12].

The following table shows the operating procedure of S-parameters from a Bond-Graph model.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SCATTERING MATRICES ASSOCIATED WITH SEVERAL CASES OF ASSIGNMENT OF CAUSALITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Causality flow-flow</td>
<td>$S = \frac{1}{D} \begin{vmatrix} -1 + H_{ij} + H_{ji} - \Delta H &amp; -2H_{ij} \ 2H_{ji} &amp; -1 - H_{ij} - H_{ji} - \Delta H \end{vmatrix}$</td>
</tr>
<tr>
<td>Case 2: Causality effort-effort</td>
<td>$S = \frac{1}{D} \begin{vmatrix} 1 - H_{ij} - H_{ji} + \Delta H &amp; -2H_{ij} \ 2H_{ji} &amp; 1 + H_{ij} + H_{ji} + \Delta H \end{vmatrix}$</td>
</tr>
<tr>
<td>Case 3: Causality flow-effort</td>
<td>$S = \frac{1}{D} \begin{vmatrix} -1 + H_{ij} + H_{ji} - \Delta H &amp; 2H_{ij} \ 2H_{ji} &amp; 1 + H_{ij} + H_{ji} + \Delta H \end{vmatrix}$</td>
</tr>
<tr>
<td>Case 4: Causality effort-flow</td>
<td>$S = \frac{1}{D} \begin{vmatrix} -1 + H_{ij} + H_{ji} - \Delta H &amp; 2H_{ij} \ 2H_{ji} &amp; -1 - H_{ij} - H_{ji} - \Delta H \end{vmatrix}$</td>
</tr>
</tbody>
</table>

We can write the integro-differential operator $H$ associated with causal paths linking the port $P_i$ to the port $P_j$ [12, 14] as:

$$H(s) = \sum_{t} L_{ij}(s) \Delta_{ij}(t)$$

Where: $\Delta$ : is the determinant of Bond-Graph model defined by: $\Delta = 1 - \sum B_i + \sum B_i B_j - \sum B_i B_j B_k$ (13)

$\sum B_i$ : the sum of individual loop gains.

$\sum B_i B_j$ : the sum of the products of pairs of loops gains not touching.

$\Delta_{ij}$ : is the determinant reduces extracted from $\Delta$ by removing the loops touching the causal input-output path.

$L_{ij}$ : is the transmittance of the path from j to i.

III. APPLICATION OF THE NEW METHODOLOGY ON A PATCH ANTENNA

The antenna implemented having a bow tie modified structure, connected by a single microstrip line of length L, width W and excited by a coaxial cable to the end of the line [3, 6]. Fig.3 shows the structure of antenna used.

The values of parameters of the antenna structure used are: $a = 3$ mm, $L = 7$ mm, $W = 0.15$ mm.

A. Realization procedure of Bond-Graph model for the antenna

The realization of the Bond-Graph model for the studied antenna through the following steps [10, 16, 18] :

- The sections of the multi-triangular antenna are identical; they are transformed into Bond-Graph approach in three elements: resistive element (R), inductive element (I) and capacitive element (C) connected with the 0 junction.
- The microstrip line is modeled in Bond-Graph like the method used for modeling the sections of the antenna.
- The excitation that represents the source of energy to the antenna, will be modeled in Bond-Graph approach a source of effort noted $S_e$. The coaxial cable, which has a resistivity that can store energy, modeling in Bond-Graph by a resistive element (R) and an inductive element (I). These elements are interconnected by a junction 1.
- The interconnection between two sections of the antenna is effected by means of a junction 0.
- The interconnection of the microstrip line and the four sections of the antenna will translate in Bond-Graph by junction 1.

Fig.4 shows the acausal Bond-Graph model of the multi-triangular antenna where we gathered its various sections and their interconnections with the microstrip line and the excitation source.
B. Application of the analytical procedure operating scattering parameters

Bond-Graph model of Fig.4 is not in the right form, we simplify it by reducing the 0 junctions (Fig 5.a) and make it in the causal and reduced form (Fig 5.b) [11].

![Fig. 5.a: more compressed Bond-Graph model of the antenna.](image)

![Fig. 5.b: reduced and causal Bond-Graph model of the antenna.](image)

With:

\[
\begin{align*}
R_{eq} &= \frac{R_1 R_2}{R_1 + R_2} \\
L_{eq} &= \frac{L_1 L_2}{L_1 + L_2} \\
C_{eq} &= C_1 + C_2
\end{align*}
\]

\[
\begin{align*}
R_{eq} &= \frac{R_1 R_2}{R_1 + R_2} \\
L_{eq} &= \frac{L_1 L_2}{L_1 + L_2} \\
C_{eq} &= C_1 + C_2
\end{align*}
\]

\[
\begin{align*}
y_1 &= \frac{1}{\tau_{eq} + \tau_{eq1} + \tau_{eq2}} \\
y_2 &= \frac{1}{\tau_{eq1} + \tau_{eq2}} \\
y_2 &= \frac{1}{\tau_{eq1}} + \frac{1}{\tau_{eq2}} \\
\end{align*}
\]

\[
\begin{align*}
z &= 1 + z + z
\end{align*}
\]

and

\[
\begin{align*}
F &= \frac{R}{R_0} \\
\tau &= \frac{1}{\tau_0 + \tau_0} \\
\tau &= \frac{1}{\tau_0 + \tau_0} \\
\tau &= \frac{1}{\tau_0 + \tau_0} \\
\tau &= \frac{1}{\tau_0 + \tau_0}
\end{align*}
\]

The application of the operating procedure of scattering parameters on the Bond-Graph model [14] of Fig.5.b translates into Fig.6 below.

![Fig. 6. Operating the S matrix.](image)

C. Simulation scattering parameters of the antenna

We apply our new methodology [4, 8, 14] and we find the simulation results found in Fig.7.

![Fig. 7. Simulation of the scattering parameter of the antenna with the new methodology](image)
D. Simulation of the antenna by the HP-ADS

We have conducted a simulation of scattering parameters for the antenna with the HP-ADS. Fig. 8 illustrates the simulation found.

![Simulation of the scattering parameters of antenna with HP-ADS.](image)

Order to validate our new methodology, we note the resonance frequency and bandwidth for each simulation performed and we see that the two simulations are identical.

IV. CONCLUSION

To find the best tool for modeling and simulation, we have developed a new methodology for the study at different structure of patch antenna such as multi-triangular structures. This methodology is based on a physical interpretation for the determination of Bond-Graph model of the studied antenna structure.

REFERENCES


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