# Antenna Representation in Two-Port Network Scattering Parameter

**Teguh Prakoso[1], Razali Ngah[1], Zabih Ghassemlooy[2] and Tharek Abdul Rahman[1]**

[1]Wireless Communication Centre, Faculty of Electrical Engineering Universiti Teknologi Malaysia, Johor Bahru, 81310, Malaysia. Corresponding author: razalin@fke.utm.my

[2]Optical Communications Research Group, NCRLab, School of Computing, Engineering & Information Sciences, University of Northumbria, Newcastle, UK

**Abstract:** This paper proposes a representation of antenna in two-port network s-parameter, by exploiting the analogy between the antenna and a two port network, to produce a suitable method for evaluating antennas in system and circuit simulation. Complicated steps required by previous methods to determine an antenna-specific equivalent-circuit and its corresponding resistor, inductor, and capacitor values are avoided. Simulations results obtained for the circuit and system software confirms the validity of the proposed scheme.

**Keywords**: antenna representation; circuit simulation; s-parameter; system simulation; two-port network

## 1. Introduction

Antenna is vital part in wireless communication systems, to convert guided wave into a free wave, and vice versa, thus making wireless communications possible. It is often desirable for the antenna to be included in system simulation, in order to evaluate its influence to the overall system performance, such as distortion introduced to signal it radiates and receives.

In a system simulation, an antenna should be represented as a 2-port network. The input of the 2-port network of a transmitting antenna is connected to a transmission line followed by an RF amplifier or other components, while its output port is connected to the wireless channel (free space); and vice versa for the receiving antenna.

From antenna simulation and measurements, it is common practice to acquire port parameters (return loss or $S_{11}$), radiation patterns, and the antenna gain at certain frequencies. In existing communication systems simulation software packages (such as Optisystem, VPIphotonics, AWR VSS, Agilent ADS) the frequency dependent parameters of antenna is not given and do not provide a method to represent an antenna in their simulation models. However, commercial systems and circuit simulation software packages commonly provide a two-port network s-parameter (S2P) filter model that can be used to include measured or simulated linear systems.

To the authors' knowledge, only a few methods used to represent an antenna in a two-port network have been reported in the literature [**1, 2, 3, 4**]. In [**1, 3,**

**4**] the value of $S_{12}$ and $S_{22}$ are not determined, and $S_{21}$ is used in the context of antenna efficiency but not the antenna gain. In [**2, 4**] the equivalent circuit model used to represent the antenna and its passive and active components as well as the infinite impulse response (IIR) filter is rather complex and less flexible, since every type of antenna has its own equivalent circuit. In [**1, 2, 3**] the antenna is not modelled in the receiving mode, whereas in [**4**] receiving antenna models are included in system simulation but the S2P values (i.e. $S_{11}$, $S_{21}$, $S_{12}$, and $S_{22}$) are not clearly defined.

In this paper, the S2P values ($S_{11}$, $S_{21}$, $S_{12}$, and $S_{22}$) for the antenna in transmitting and receiving modes are derived. The possibility of using a single S2P block for simultaneous transmitting and receiving (bidirectional mode) is also discussed. Analogy between the IEEE standard antenna definition [**5**] and a two-port network model [**6**] is used for derivation. Furthermore, an example of the circuit and system simulation using derived S2P values is also presented to show the applicability and validity of the method.

## 2. Method

Relationship between antenna parameters is depicted in Figure 1, and the explanation of symbol is tabulated in Table 1 [**5**]. It is noted here that the antenna gain only includes dissipation loss, but not the mismatched and polarization losses. Our proposed method is based on the analogy between antenna and scattering parameter two-port network model (S2P) as described in Figure 2 [**6**].

### 2.1. Transmitting Mode:

In transmitting mode, the equivalent isotropically radiated power (*EIRP*) of the antenna and the power accepted by the antenna $P_0$ are analogous with the power delivered to the load $P_L$ in S2P and the power delivered to network $P_{in}$ in S2P, respectively. *EIRP* is defined as [**5**]:

$$EIRP = P_0 G = P_M M_2 G = P_M (1 - |\Gamma_{in}|^2) G = P_M G_R \tag{1}$$

where *G* is the antenna gain in particular direction and particular polarization which is defined as the operating power gain $G_P$ in S2P [**5, 6**] and is given by:

$$G = G_P = 1/(1 + |\Gamma_{in}|) \cdot |S_{21}|^2 \cdot (1 - |\Gamma_L|^2)/(|1 - S_{22}\Gamma_L|^2) \tag{2}$$

From Figure 2, for a matched network (i.e. $Z_S = Z_L = Z_0$) $\Gamma_S = \Gamma_L = 0$, $\Gamma_{in} = S_{11}$, and $\Gamma_{out} = S_{22}$, the power gain reduces to:

$$G = G_P = P_L/P_{in} = |S_{21}|^2/(1 - |S_{11}|^2) \tag{3}$$

and therefore:

$$|S_{21}| = \text{sqrt}(G(1 - |S_{11}|^2) \tag{4}$$

with sqrt() is square root function.

All the values for S2P file are tabulated in Table 2. The value for $S_{12}$ and $S_{22}$ can be arbitrary chosen, but to ensure unilaterality $S_{12}$ and $S_{22}$ should be equal to zero. The magnitude and phase of $S_{11}$ and *G* are commonly available from electromagnetic simulator or measurement using vector network

analyzer (VNA). Method described in [7] can be used as alternative way to obtain the phase of $S_{21}$.

## 2.2. Receiving Mode

In receiving mode, the power available at the antenna terminal $P_{avn}$ is equal to the product of the antenna's effective aperture $A_e$ and the power flux density of plane wave incidence on the antenna $W_i$ [8]. The ratio of $A_e$ to the isotropic antenna's effective aperture $A_{ei}$ is equal to the gain of the antenna. Therefore, power available from network $P_{avn} = GW_iA_{ei}$, where $W_iA_{ei}$ is the power captured ($P_s$) by an isotropic antenna. Since isotropic antenna has no losses or mismatch, $P_S$ can be seen as the available power from a source $P_{avs}$ that is used in a two-port network representing the behaviour of an antenna in receiving mode, delivered to a load.

$V_S$ in Figure 2 represents the power captured by the isotropic antenna $P_S$. The use of $V_S$ as a single source in this model is acceptable, since it is only dealing with "the treatment of the power transfer to $Z_L$" and not considering scattering problems in the receiving antenna [9].

There should be no reflection in the source ($V_1^- = 0$), so $Z_S = Z_0$. However, the load impedance $Z_L$ (such as filter, LNA, etc.) may not be matched to $Z_0$, therefore $\Gamma_L$ is not always equal to zero. Hence, to ensure that $V_1^- = 0$, it is mandatory that $S_{11} = S_{12} = 0$. Thus, $\Gamma_{out} = S_{22}$ but $S_{22}$ values in S2P file in the receiving mode must be taken from the antenna $S_{11}$ values.

The available power from the antenna $P_0$ is analogous with the power available from network $P_{avn}$ in S2P [6]. Given that $Z_{in} = Z_0 = Z_S$, then the antenna gain (or the available gain $G_A$) is given by:

$$G=G_A=P_{avn}/P_{avs}=|S_{21}|^2/(1-|S_{22}|^2) \tag{5}$$

and therefore resulting in:

$$|S21|=\text{sqrt}(G(1-|S_{22}|^2)) \tag{6}$$

Values of the S2P file for antenna in the receiving mode is tabulated in Table 3.

## 2.3. Bidirectional Mode

Since antennas have the same characteristics in transmitting and receiving modes, a bidirectional S2P network model could be adopted for our study. In this model, port 1 of S2P is used as an input and output for antenna in transmitting and receiving modes, respectively. Port 2 is used as the output and input ports for the antenna in transmitting and receiving modes, respectively. With this arrangement, adoption of S2P values for antennas in Tx mode (Table 2) and Rx mode (Table 3) for bidirectional mode is tabulated in Table 4. In S2P file, $S_{11,tx}$ and $S_{22,rx}$ have the same values defined as $S_{11,bd}$ in the bidirectional S2P. In the bidirectional model $S_{21,tx}$ and $S_{21,rx}$ are changed to $S_{21,bd}$ and $S_{12,bd}$, respectively. The problem is in determining the value of $S_{21,bd}$. Since $S_{12,rx}$ should be equal to zero and $S_{12,tx}$ has a non-zero value, then it may not be possible to build a bidirectional S2P network model for the antenna, except when different frequencies are adopted for transmission and reception as outlined in Table 5.

## 3. System and Circuit Simulation
### 3.1. Antenna Evaluation using IEEE 802.11a Signal
Visual System Simulator (VSS) and the Microwave Office (MWO) as part of AWR Design Environment, and Optisystem v8.0 were used to demonstrate the applicability and validity of the proposed technique. To be comparable with previous result, a button antenna presented in circuit model and used in system simulation in [**4**], is represented in S2P  using the method derived in Section II of this letter, and is included in the system simulation. From results presented in [**4**], $S_{11}$ value is captured from Figure 2, gain magnitude is deduced from Figure 5  using (1), and $S_{21}$ phase is acquired from Figure 6. It should be noted here that Figure 5 actually is not presenting gain, but total radiated power. However, the frequency dependency characteristic of it is the same with gain, therefore quite representative to be adopted for $S_{21}$.

An MWO circuit simulation model for the transmit-receive antenna is depicted in Figure 3. S2P representation of the button antenna in the transmit mode (Tx Antenna) is applied to the "modul 1" the output of which is feed to the "modul 2" containing S2P for the receive antenna (Rx Antenna). Magnitudes and phases of $S_{11}$ and $S_{21}$ against the frequency for the button Tx, Rx, and Tx/Rx antennas are displayed in Figure 4 and 5, respectively. The $S_{11}$, the gain ($S_{21}$) magnitudes and the phases of Tx and Rx antennas resemble the antenna given in [**4**], indicating the accuracy of S2P representations of the button antenna. The magnitude and phase responses of the Tx-Rx antenna are twice that of the Tx or Rx antennas as expected. The group delay profiles as a function of the frequency for the Tx, Rx, and Tx-Rx antennas are depicted in Figure 6. The value obtained using the measurement in the AWR software. This parameter is essential for evaluating the system distortion introduced. Distortionless systems require a constant group delay response over the operating bandwidth [**10**].

Since the antenna is intended to be used for WLAN at 2.4 GHz and 5 GHz bands, we have carried out an evaluation of the antenna based on the IEEE 802.11a, using VSS, see Figure 7. S2P files for the Tx and Rx antennas are enclosed in two LIN_S blocks. Error vector magnitude (EVM) values produced by these simulations are tabulated in Table 6. The frequency range used is 1 GHz-to-6 GHz and the EVM is adopted as the figure of merit. The frequency range is chosen to show how the antenna performs well at its intended operating bands and how it distort signal badly at certain band.

When no thermal noise, EVM values are determined solely by the antenna distortion. Since the Tx and Rx antennas use identical button antennas, the distortion experienced by the signal when using a Tx-Rx antenna is twice that of the Tx antenna alone. This is confirmed by observing columns 2 and 3 in Table 6.

Since the distortion level introduced by an antenna is influenced by the differential of antenna's "transfer function" over the frequency range (related to the "group delay"), a flat $S_{21}$ and a low value $S_{11}$ will result in low values of EVM, as can be observed at around 5 GHz band in Figs. 4-6.  The 2.4 GHz band has higher values of EVM, this is because its gain and impedance bandwidth is narrower than the 5 GHz band.

It also can be observed that the EVM values at 1 GHz are lower compared to the 2.5 GHz band due to the lower group delay variation. However, the

transmitted power at 1 GHz is very low, thus resulting in lower signal-to-noise ratio, see Table 6. The worst EVM is observed at around 3 GHz band. This is mainly due to the abrupt group delay changes, a high reflection coefficient and a null $S_{21}$. At this frequency, the IEEE 802.11a signal is highly distorted by the antenna.

## 3.2. Bidirectional S2P
To the authors' knowledge, only the OptiSystem has a bidirectional S2P block. Figure 8 depicts a block diagram of a simulation system using OptiSystem. In the S2P block, frequency ranges of 1 – 3 GHz and 3 – 9 GHz are used for the transmitting and receiving modes, respectively. The EVM values shown in Figure 9 are similar with the OptiSystem simulation using the unidirectional S2P, and hence confirming the possibility of using a bidirectional S2P with different frequencies for transmitting and receiving modes.

## 4. Conclusion
Simulation results presented have confirmed the correct operation and applicability of the proposed method. Using a circuit and communication systems software, the effect of a test antenna on the system under investigation can be evaluated and analyzed. It was shown that the proposed is rather simple requiring less complex steps to obtain the equivalent circuit and corresponding RLC values or the filter coefficients.

# References

1. R. H. Johnston and J. G. McRory, An improved small antenna radiation-efficiency measurement method, IEEE Antennas and Propagation Magazine 40 (1998), no. 5, 40-48.
2. S. D. Rogers, J. T. Aberle and D. T. Auckland, Two-port model of an antenna for use in characterizing wireless communications systems, obtained using efficiency measurements, IEEE Antennas and Propagation Magazine 45 (2003), no. 3, 115-118.
3. J. T. Aberle, Two-port representation of an antenna with application to non-foster matching networks, IEEE Transactions on Antennas and Propagation 56 (2008), no. 5, 1218-1222.
4. M. I. Sobhy, B. Sanz-Izquierdo and J. C. Batchelor, System and circuit models for microwave antennas, IEEE Transactions on Microwave Theory and Techniques 55 (2007), no. 4, 729-735.
5. IEEE standard definitions of terms for antennas, IEEE Std 145-1993 (1993).
6. D. M. Pozar, Microwave engineering, John Wiley & Sons, New York, 2004.
7. Y. Duroc, A. Ghiotto, T. P. Vuong and S. Tedjini, On the characterization of uwb antennas, International Journal of RF and Microwave Computer-Aided Engineering 19 (2009), no. 2, 258-269.
8. C. A. Balanis, Antenna theory: Analysis and design, John Wiley & Sons, Inc., Hoboken, New Jersey, 2005.
9. J. B. Andersen and R. G. Vaughan, Transmitting, receiving, and scattering properties of antennas, IEEE Antennas and Propagation Magazine 45 (2003), no. 4, 93-98.
10. W. Sörgel and W. Wiesbeck, Influence of the antennas on the ultra-wideband transmission, EURASIP Journal on Applied Signal Processing 2005 (2005), no. 3, 296-305.

TABLE I
Glossary of Antenna Terms [5]

| Symbol | Quantity |
|---|---|
| $P_M$ | power to matched transmission line from the connected transmitter |
| $P_O$ | power accepted by the antenna |
| $P_R$ | power radiated by the antenna |
| $M_2$ | impedance mismatch factor 2 |
| $\eta$ | radiation efficiency |
| $G_R$ | realized gain |
| $G$ | Gain |
| $D$ | Directivity |

TABLE II
S2P Values for Antenna in Transmitting Mode

| | Magnitude | Phase |
|---|---|---|
| $S_{11,tx}$ | $\lvert S_{11} \rvert$ of the antenna | $\angle S_{11}$ of the antenna |
| $S_{21,tx}$ | $\lvert S_{21} \rvert = \sqrt{G\left(1-\lvert S_{11}\rvert^2\right)}$ | $\angle S_{21}$ of the antenna |
| $S_{12,tx}$ | 0 * | 0 * |
| $S_{22,tx}$ | 0 * | 0 * |

* the values can be arbitrary; however, to ensure unilaterality, the values should be equal to 0.

TABLE III
S2P Values for Antenna in Receiving Mode

| | Magnitude | Phase |
|---|---|---|
| $S_{11,rx}$ | 0 | 0 |
| $S_{21,rx}$ | $\lvert S_{21} \rvert = \sqrt{G\left(1-\lvert S_{22}\rvert^2\right)}$ | $\angle S_{21}$ of the antenna |
| $S_{12,rx}$ | 0 | 0 |
| $S_{22,rx}$ | $\lvert S_{11} \rvert$ of the antenna | $\angle S_{11}$ of the antenna |

TABLE IV
S2P Values for Antenna in Bidirectional Mode

| | S2P Tx Mode | S2P Rx Mode |
|---|---|---|
| $S_{11,bd}$ | $S_{11,tx}$ | $S_{22,rx}$ |
| $S_{21,bd}$ | $S_{21,tx}$ | 0 |
| $S_{12,bd}$ | arbitrary | $S_{21,rx}$ |
| $S_{22,bd}$ | 0 | 0 |

TABLE V
S2P Values for Antenna in Pseudo-bidirectional Mode

| | $f_1$ [a] | $f_2$ [b] |
|---|---|---|
| $S_{11,bd}$ | $S_{11,tx}$ | $S_{22,rx}$ |
| $S_{21,bd}$ | $S_{21,tx}$ | 0 |
| $S_{12,bd}$ | 0 | $S_{21,rx}$ |
| $S_{22,bd}$ | 0 | 0 |

[a] $f_1$ is used for Tx mode (from port 1 to port 2)

TABLE VI
EVM Comparison of Transmit and Transmit-Receive Antennas (in percentage)

| Frequency (MHz) | Without AWGN | | With AWGN * | |
|---|---|---|---|---|
| | Tx Antenna | Tx-Rx Antenna | Tx Antenna | Tx-Rx Antenna |
| 1000 | 0.366 | 0.733 | 31.760 | 113.470 |
| 1500 | 1.040 | 2.077 | 13.533 | 41.000 |
| 2000 | 0.700 | 1.399 | 6.516 | 9.925 |
| 2400 | 0.306 | 0.613 | 4.442 | 4.684 |
| 2500 | 1.043 | 2.085 | 4.683 | 5.509 |
| 3000 | 9.945 | 19.493 | 51.798 | 136.220 |
| 3500 | 0.962 | 1.923 | 9.477 | 20.748 |
| 4000 | 0.244 | 0.489 | 5.538 | 7.269 |
| 4500 | 0.109 | 0.218 | 4.562 | 4.954 |
| 5000 | 0.020 | 0.054 | 4.282 | 4.364 |
| 5200 | 0.001 | 0.003 | 4.268 | 4.333 |
| 5500 | 0.020 | 0.039 | 4.307 | 4.411 |
| 5800 | 0.029 | 0.059 | 4.379 | 4.559 |
| 6000 | 0.041 | 0.082 | 4.440 | 4.687 |

* Single sideband power spectral density (PSD) of -100dBm/Hz

Figure captions:
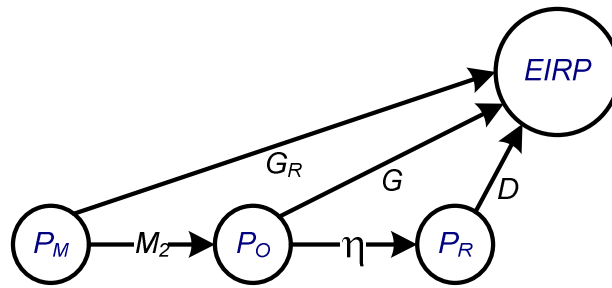


Figure 1. Gain and directivity flowchart [5].
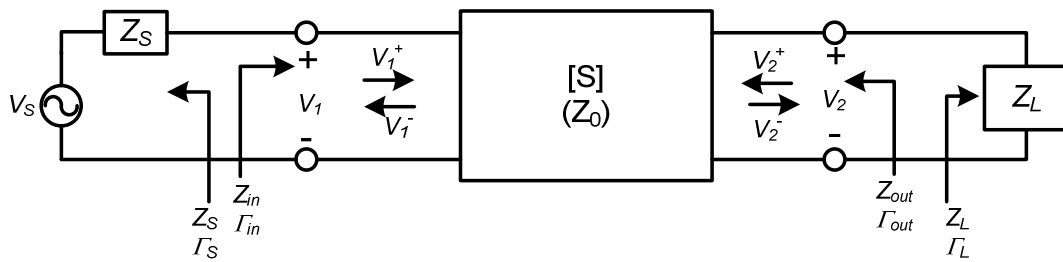


Figure 2. A two port network with general source and load impedance.
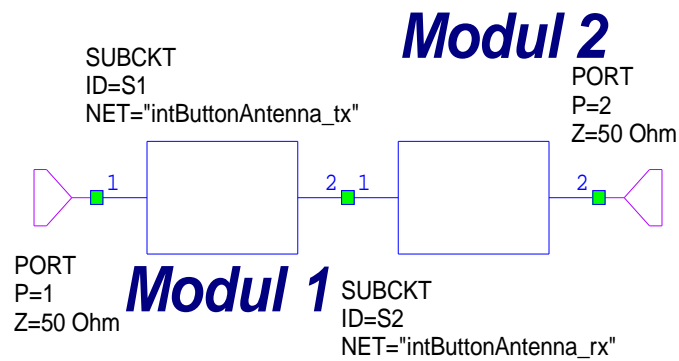


Figure3. MWO circuit simulation of example antenna in transmit-receive mode.
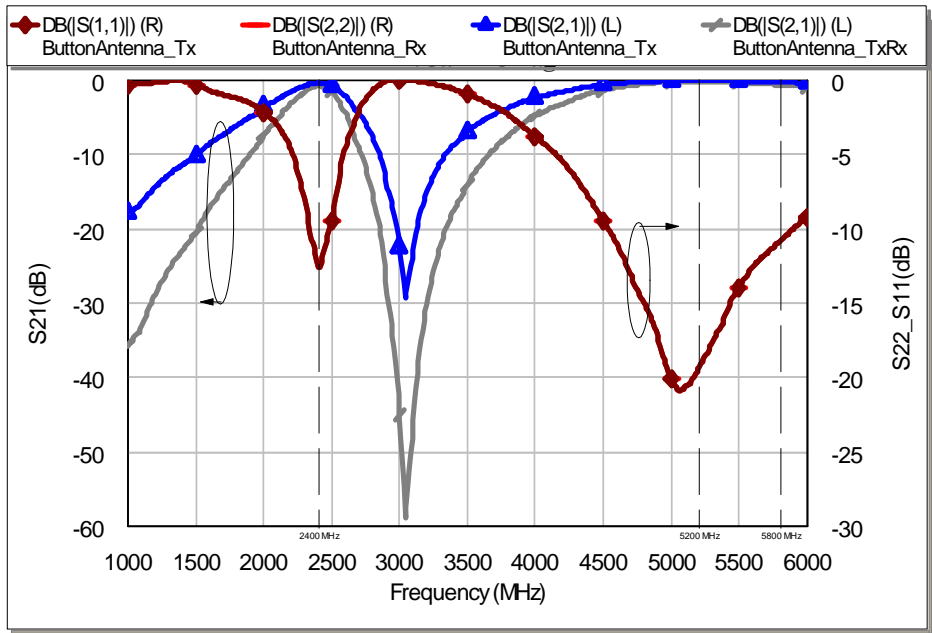
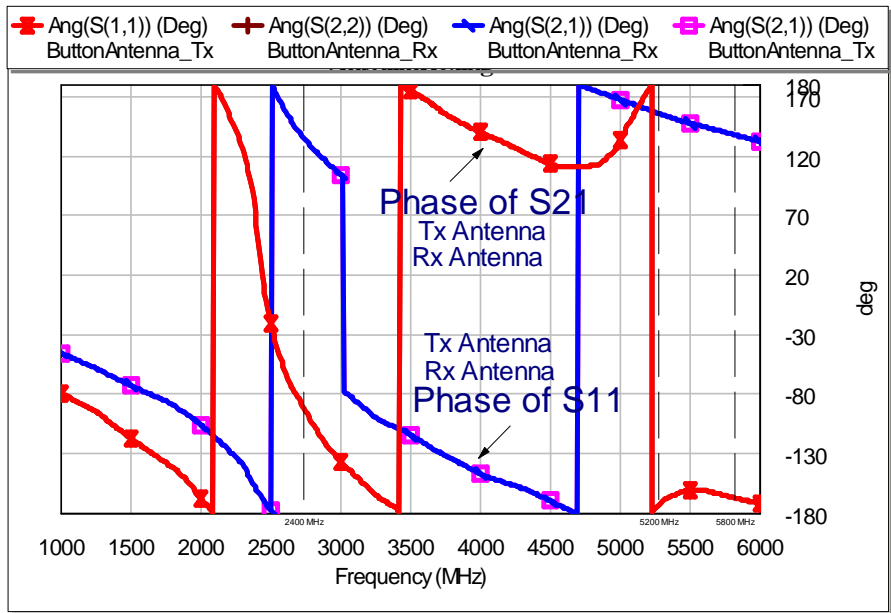Figure 4. Magnitudes of S11 and S21 for the transmit, receive, and transmit-receive antennas.



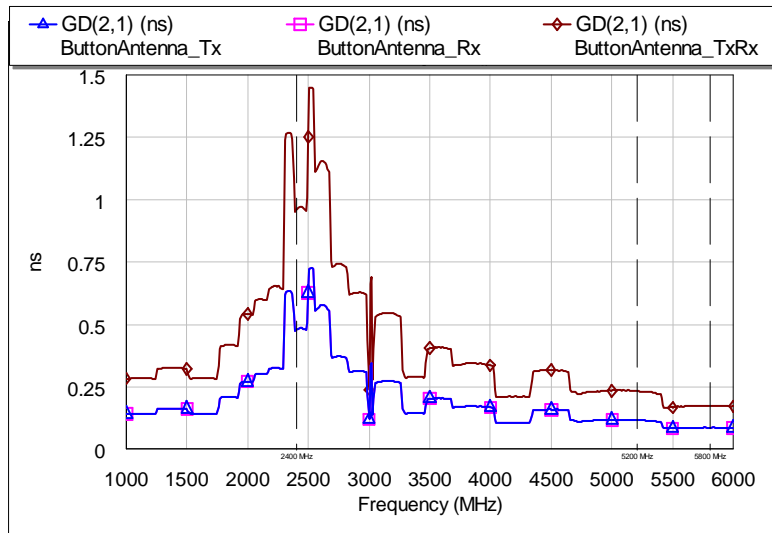Figure 5. Magnitudes of S11 and S21 for the transmit, receive, and transmit-receive antennas.
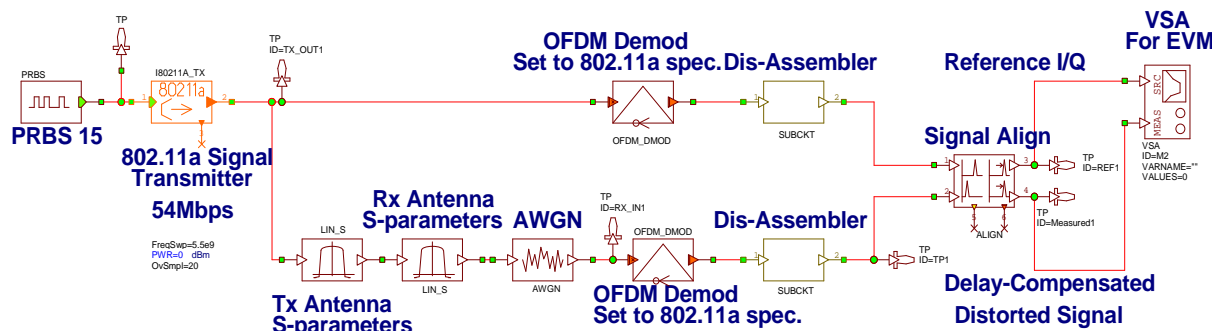
Figure 6. Group delay of Tx, Rx, and Tx-Rx antennas.



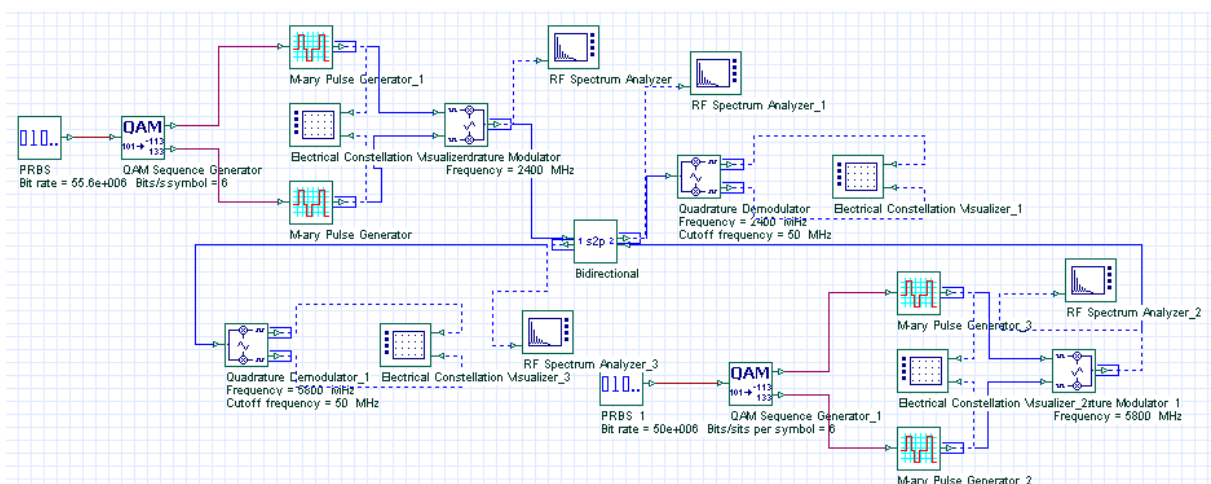Figure 7. VSS simulation using IEEE 802.11a signal to evaluate an example antenna.
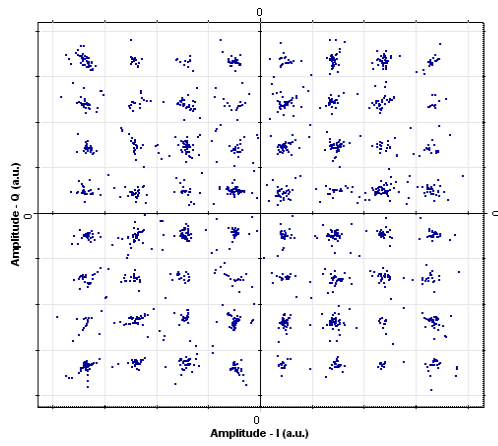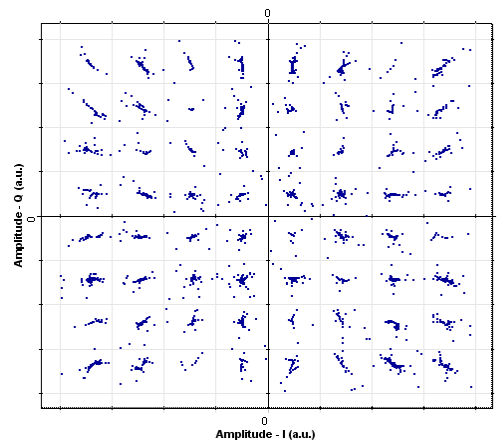


Figure 8. OptiSystem v8.0 simulation using bidirectional S2P.

Bidirectional-S2P EVM: 6.74%

Unidirectional-S2P EVM: 6.77%

(a)

Bidirectional-S2P EVM: 5.92%

Unidirectional-S2P EVM: 6.07%

(b)

Figure 9. Constellation diagram of bidirectional communication system (a) transmitting mode at 2.4 GHz (b) receiving mode at 5.8 GHz.