A Six-Port as a Wireless Communication Receiver

Six-port devices have originated as an alternative solution for measurements of complex transmission and reflection coefficients in network analyzers. A device has two input and four output ports. When two signals are fed into input ports, the power ratios between the four signals appearing at output ports contain the complete information about the amplitude and phase relationship between the input signals.

The ability of six-port device to resolve amplitude and phase ratios between two signals has recently drawn a lot of attention in the research community as it offers the possibility to simplify modern wireless receivers. A popular architecture for a modern receiver is of homodyne type (also called zero intermediate frequency – zero IF). Classical homodyne architecture utilizes a mixer to down convert the signal at the microwave frequency to the baseband. A frequency of a local oscillator (LO) is selected to be equal to the frequency of a microwave signal. A mixer usually requires high power level from LO to perform non-linear mixing and generates spurious responses that have to be suppressed with additional circuitry. Instead of non-linear mixing, microwave and LO signals can be fed to the inputs of a six-port device. If a detector is connected to each of the output ports, the demodulation of the microwave signal can be accomplished by adequate processing of the four detected signals. The process of down conversion using a six-port device and detectors is additive, requires significantly lower levels from LO than mixing, and does not generate spurious response.

This application note demonstrates the analysis and simulation of a six-port receiver using WIPL-D Microwave design environment.

Six-port Receiver Architecture

The heart of a six-port receiver is a phasing network. It is similar to the phasing network of in-phase/quadrature (I/Q) mixers. The network should provide equal amplitude division of each of the two input signals, with additional requirement that at the outputs signals appear with adequate phase ratio. Such a network comprises four hybrids or equal amplitude power dividers. A topology of the network is not uniquely defined as multiple choices of hybrids and power dividers are acceptable. However, for a reason that will become clear later, a choice of three quadrature hybrids and one in-phase divider has a certain advantage.

The high level schematic of the six-port receiver for the phasing network topology selected as explained is presented in Fig. 1. Ports 1 and 2 are the input ports, while the ports 3-6 are output ports. Received signal from port 1 is fed into one of the quadrature hybrids (Quadrature 1). The other input port of the hybrid is not used and is terminated in 50 Ω resistor. LO signal at port 2 is connected to the input of a Wilkinson power divider (In Phase) providing in-phase signal division.

The outputs of both of the circuits are connected to the input ports of two remaining quadrature hybrids (Quadrature 2 and Quadrature 3). The connections should all be of the same electrical length to equalize the phase delays of all of the paths. When this is the case, the phase ratio between the divided input signals from ports 1 and 2 is as required at all of the output ports - at port 3 signals are in quadrature, i.e. with the phase ratio of 90°; at port 4 signals are also in quadrature, but the phase ratio is 270°; at port 5 signals are out of phase, and they are in phase at port 6. Such phase ratios are adequate to perform demodulation of I/Q signals. The signals at port 5 and 6 can be regarded as a differential I signal, while the signals at port 3 and 4 can be understood as differential Q signal.

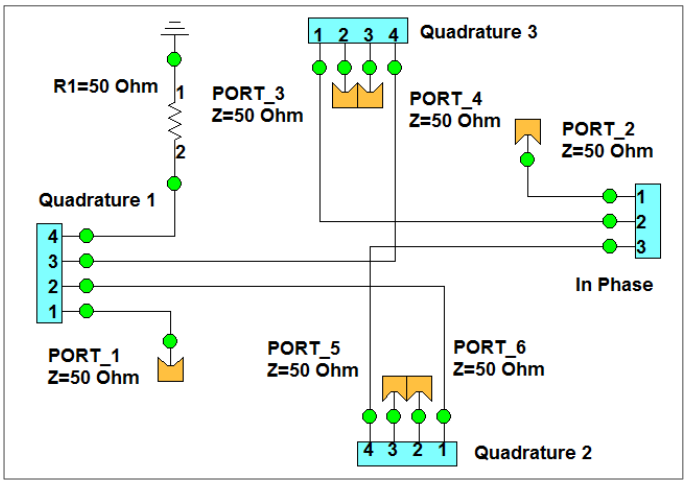

Figure 1. Top level schematic of a six-port.

The top level schematic from Fig. 1 has been assembled from previously designed branch hybrid and power divider circuits. Design of subcircuits has been carried out for the operating frequency of 24 GHz. Circuit schematics of microstrip branch line coupler and Wilkinson power divider are shown in Fig. 2 and Fig. 3 respectively. Details on the design of these circuits will not be presented here as they are explained elsewhere, e.g. in the application note "Modeling Wilkinson Combiner/Divider at High Microwave Frequencies" available for download from WIPL-D company web site.

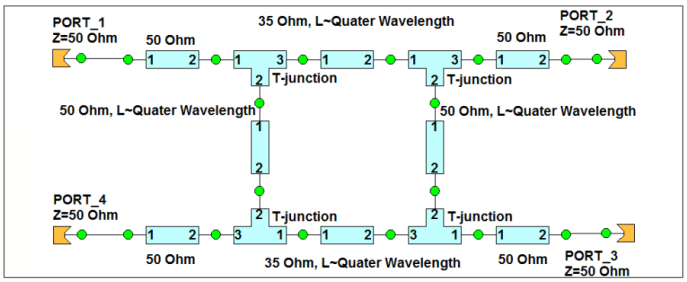

Figure 2. Branch line hybrid.

The complete schematic of the phasing network presented in Fig. 4 provides the information about possible microstrip layout. The figure illustrates that the choice of a branch line hybrid and a Wilkinson divider results in the network that does not require a crossover to make connections between these elements. Besides, the size of the network in considerably smaller comparing to the case where rat race hybrids are used.

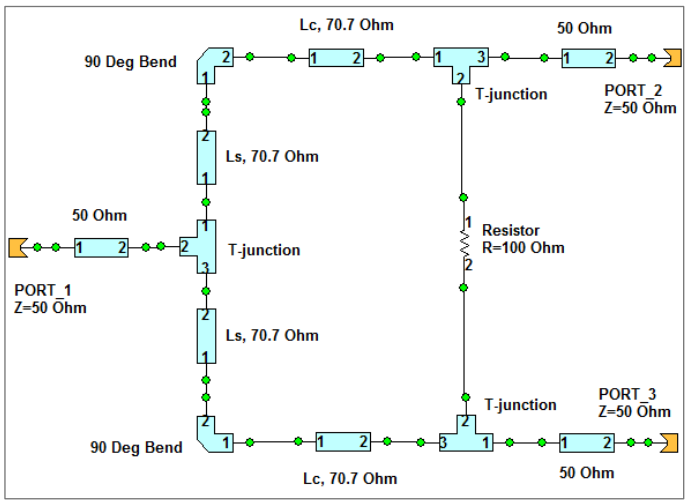

Figure 3. Wilkinson power divider.

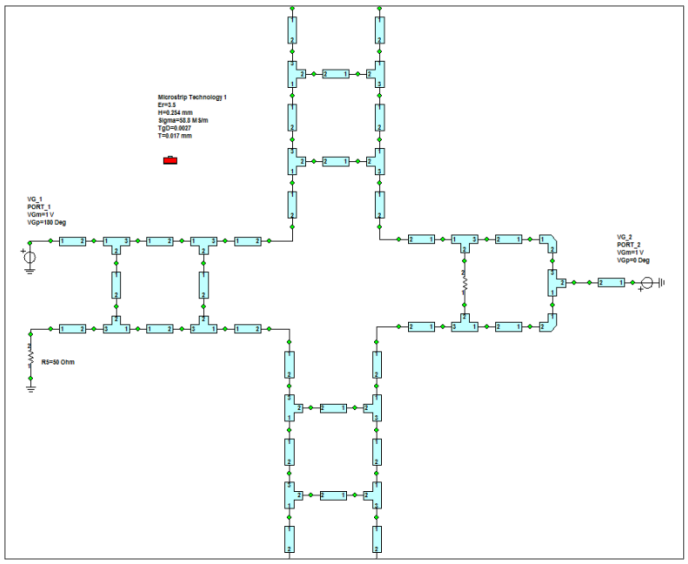

Figure 4. Complete WIPL-D Microwave microstrip schematic of the six-port receiver topology under consideration.

For the fully operational six-port receiver, a diode power detector must be connected at each of the output ports of the phasing network. Detected voltages can then be further processed by a digital signal processing unit (DSPU) to perform the demodulation. Detector diode is usually required to operate in the square low region which makes detected voltage proportional to the power of the signal applied to the detector input. A good matching of the detector is important as the poor match can cause amplitude and phase imbalance in the phasing network leading to errors in the demodulation process. For more details how to design a matched detector please refer to application note "Design of a Power Detector with a Zero-Bias Schottky Diode" available from WIPL-D company web site.

Simulation of a Six-port Receiver

In WIPL-D Microwave program, the operation of the six-port receiver can be studied by a simple modification of the schematic presented in Fig. 1. Therefore, the design environment is suitable not only to carry out a design of the individual circuits comprising the receiver system, but also for analysis and simulation of the characteristics of the system itself. An example how to study the impact of hybrid imbalance to receiver performance is presented next.

For receiver simulations, input ports from Fig. 1 should be replaced with voltage generators and output ports should be terminated into 50 Ω resistor with meters (V, I, P) connected as presented in Fig. 5.

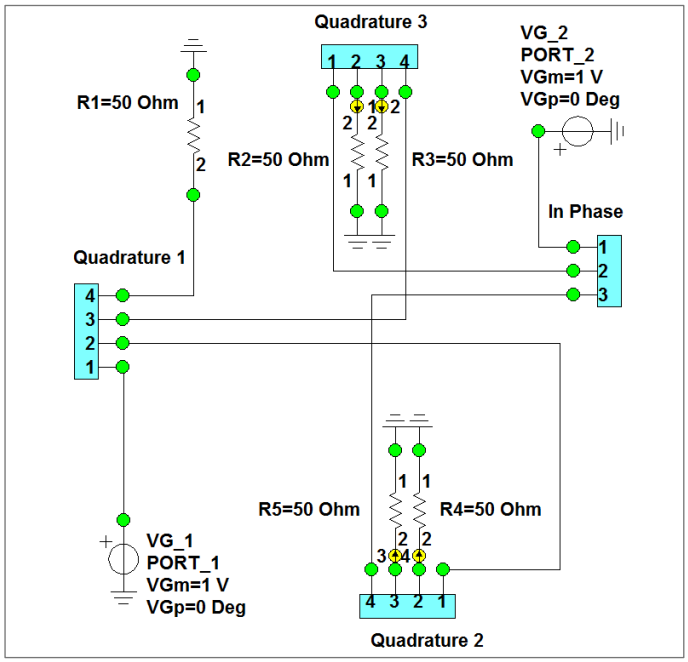

Figure 5. Modified top level WIPL-D Microwave schematic from Fig. 1 for the receiver simulations.

The schematic from Fig. 5 can be used to analyze demodulation process in a six-port receiver. Voltages at ports 3-6 can be graphed and values at 24 GHz read out by positioning a marker on each trace, as presented in Fig. 6. Alternatively, a voltage value can be read directly from the output list. A group of four graphs from the figure illustrates the change in voltage magnitudes as the phase of the generator applied at port 1 is varied with 90° increment. This corresponds to the four states of the Quadrature Phase Shift Keying (QPSK) modulation of the microwave signal. Voltage magnitude values provide the basis for the calculations required to perform demodulation.

Calculations can be completed using the powerful feature of symbolic expressions available in WIPL-D Microwave. In the current version, program does not automatically transfer marker readouts to the symbol list, thus manual input is required.

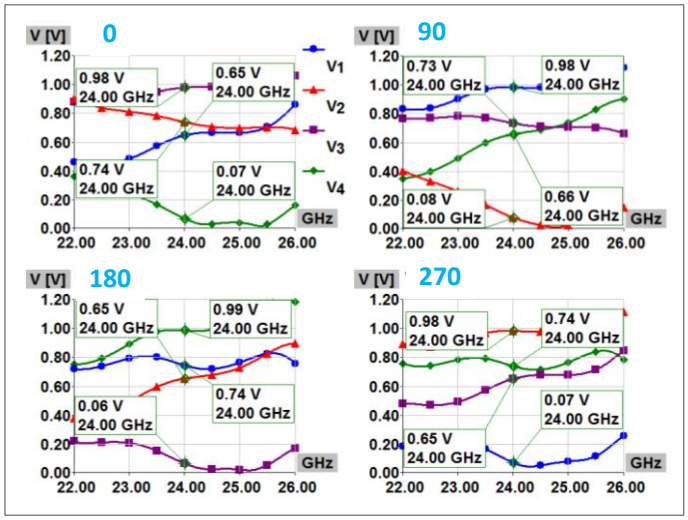

Figure 6. Voltages at the output ports of schematic from Fig. 4 for QPSK received signal.

	Symbol	
1	0.65	V1=0.65
2	0.74	V2=0.74
3	0.98	V3=0.98
4	0.07	V4=0.07
5	0.4225	P1=V1^2
6	0.5476	P2=V2^2
7	0.9604	P3=V3^2
8	0.0049	P4=V4^2
9	-0.9555	I=P4-P3
10	0.1251	Q=P2-P1

Figure 7. Computation of detected I/Q signals.

Example of the calculations is presented in Fig. 7. As detector diode operates in a square region, the voltage readouts must be squared to obtain normalized detected power levels. The difference of power detected at ports 5 and 6 (voltage meters 3-4) is proportional to I, while the difference of powers at ports 3 and 4 (voltage meters 1-2) is proportional to Q. Calculated values of I and Q can be arranged in a dummy data block of S parameters to graphically represent I/Q constellation diagram using a polar plot. The arbitrary frequencies of four data points in the file can be "coded" to represent a phase setting for generator VG_1 (0°, 90°, 180°, 270°). Example of a simulation setup and a resulting constellation diagram for the case one transmitted and two received QPSK signals is presented in Fig. 8.

The first point on each trace corresponds to the state where phase of generator VG_1 is equal to 0°. The other states are ordered following anticlockwise direction. A phase shift between the transmitted and received signals can be clearly observed. The shift is mainly due to phase delay of the lines connecting four circuits comprising the phasing network and can be calibrated out. However, even if angular shift was calibrated, demodulated states would not completely coincide with the transmitted ones. The reason for the differences is due to the imperfections of the circuits comprising the phasing network. Due to the high frequency of operation the design of the circuits is challenging and even in the simulations some amount of amplitude and phase imbalance is inevitable. For the branch line hybrid with imbalance value of 0.1 dB, the amplitude errors are not significant as four states are distributed along an almost perfect circle. In the extreme case where the imbalance is 1 dB, distortion from the circle shape is clearly seen. For both cases the phase imbalance of the branch hybrid was approximately 1°.

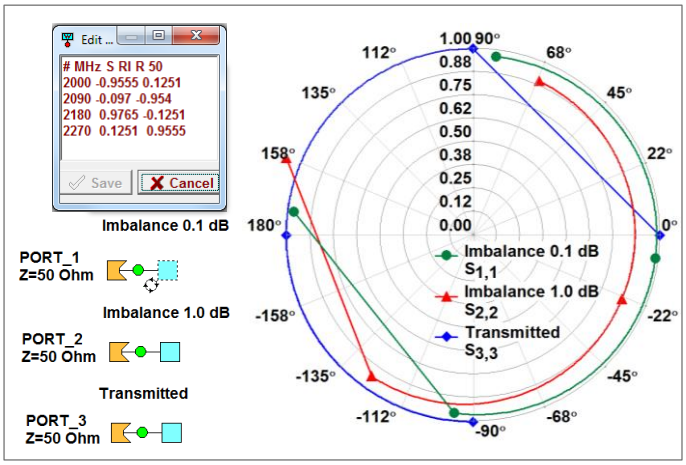

Figure 8. Constellation diagram using a polar plot in WIPL-D Microwave and corresponding simulation setup.

Conclusion

The analysis and simulation of a six-port receiver for 24 GHz QPSK signal usign WIPL-D Microwave design environment has been demonstrated. The set of simulation tools available within the program allows not only for the accurate and reliable design of the individual components comprising a receiver system, but for detailed analysis of the system itself. Example of studying an impact of imperfections of branch-line hybrids to receiver performance has been presented.

Additional simulations of the receiver system are possible. The simulations should address impact of phase imbalance larger then considered 1° to receiver performance. Furthermore, voltages at ports 1 and 2, both been set to 1 V for the demonstration, can be set to more realistic values. Measured voltages can be multiplied by a coefficient to take into account real conversion characteristic of the detector. Knowing sensitivity threshold of DSPU, minimum received signal level can then be determined. Finally, simulation blocks of branch line and Wilkinson combiner circuits can be replaced with the blocks of S parameters measured on fabricated samples to explore signal constellations with real-world circuits. All these simulations can be carried out using WIPL-D Microwave.