Six-Ports

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The six-port structure is interesting because phase information is obtained by making only amplitude or power measurements. The circuit is composed of passive linear elements. It has six ports (hence the name) and can be used as a modulator, demodulator, network analyzer, or reflectometer. It can be much less expensive than other structures that perform the same roles.

A six-port modulator takes a local oscillator on the transmit frequency, bangs this signal around inside the structure in a particular pattern driven by the values of the baseband digital data, and then sends it out the radio frequency port, ready for transmit. If you're ever in an elevator, and someone asks you how a six-port structure works, that should hold them until the cocktail party.

Here is how this happens. There are six connectors. See Figure 1. The six-port needs baseband digital input data, or else it will have nothing much to say. The baseband digital data, zeroes and ones in a digital format, must be translated into analog signals that the six-port manipulates. The translation is accomplished by switching in and out particular types of terminations.

By convention, G stands for "reflection state." There is one reflection state per data input port. See Figure 2. Our six-port, connected as a modulator, has a local oscillator input (LO), four data input ports that each have an associated reflection state (G1, G2, G3, G4) and one radio frequency output (RF).

The value held by the reflection state is a reflection coefficient. A reflection coefficient describes the amplitude (or intensity) of a reflected wave with respect to an incident wave.

An equation follows. Do not be alarmed.

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G = reflected/incident
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In general, G is either an open or a short. A short at microwave means that G is -1. For reflected/incident to be -1, reflected = -incident. All of the wave is reflected back 180 degrees out of phase. An open at microwave means that G is 1. For reflected/incident to be 1, reflected = incident.

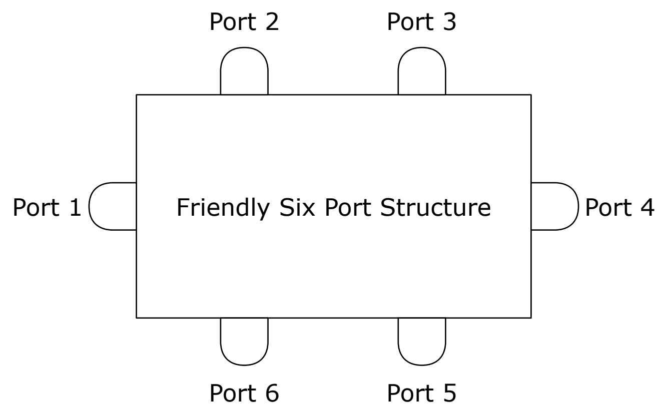


Figure 1: very generic six-port structure

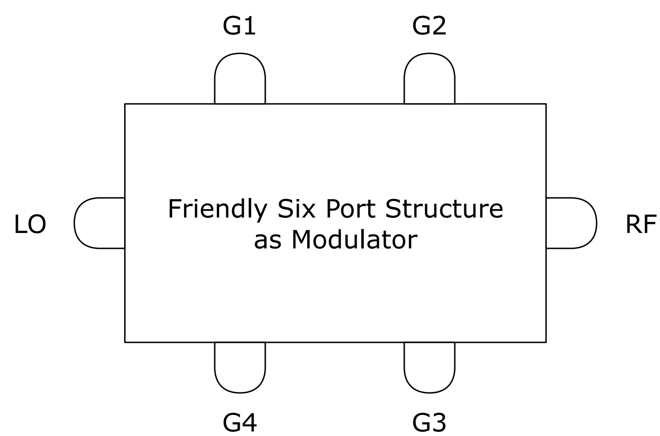


Figure 2: six-port as modulator

All of the wave is reflected back with no phase change.[1]

The zeroes and ones of the input data translate the LO into a modulated waveform (RF) by using the reflection coefficients held by the reflection states

1 As you might expect, G = zero is a perfect match. Food for thought: could we modulate with a spectrum of values between -1 and 1 in order to create something like SSB? We'd have to have a variable reflection coefficient.

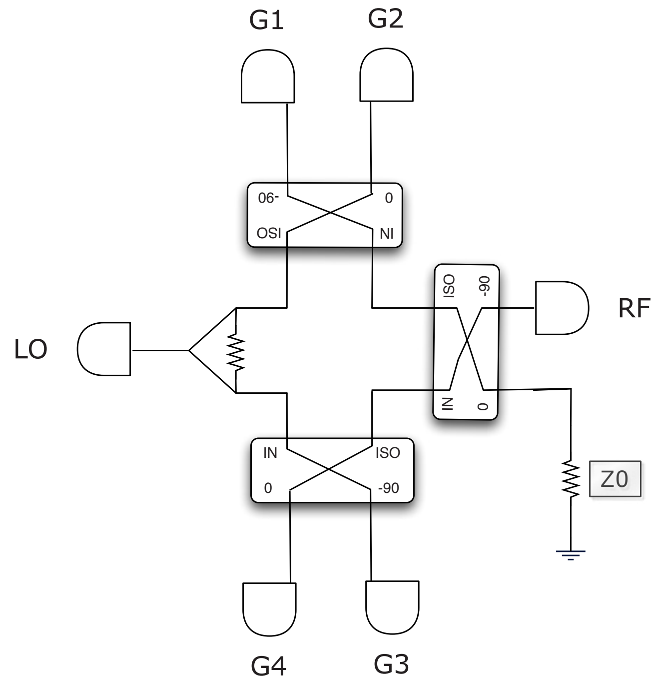


Figure 3: specific six-port structure

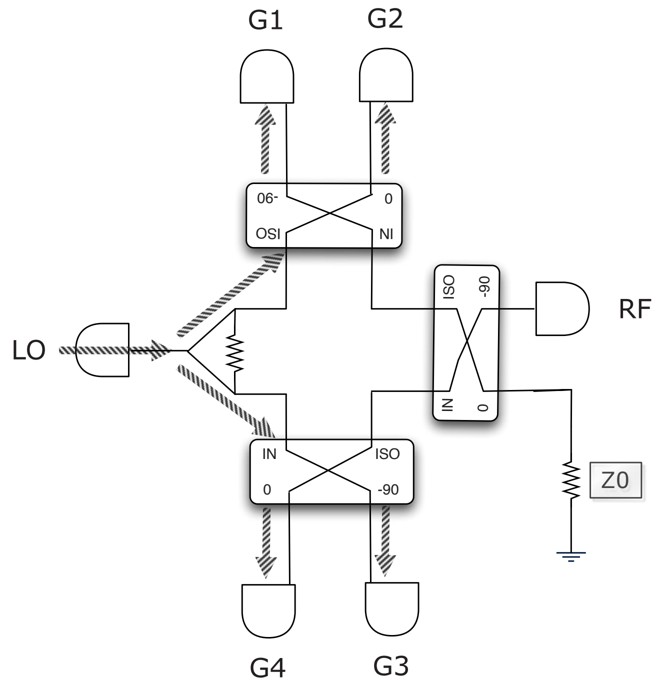


Figure 5: LO reaches ports G1-G4

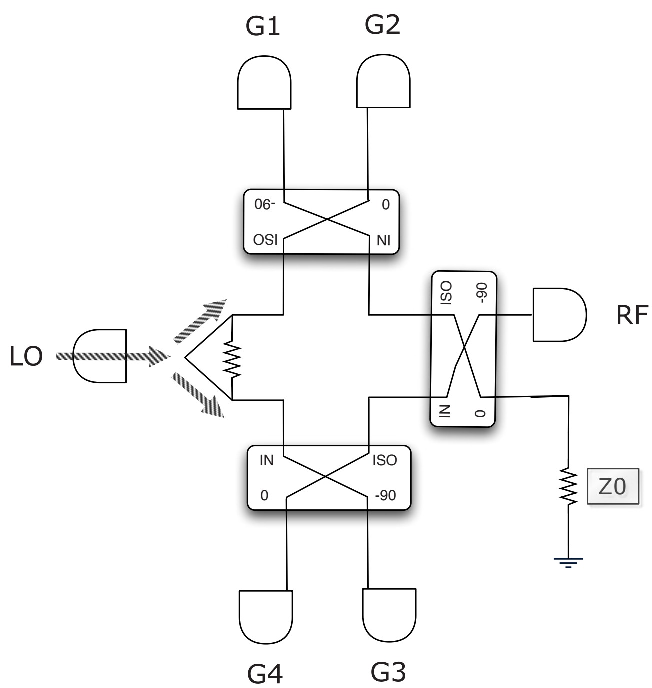


Figure 4: LO after power splitter

of the six-port structure. The reflection coefficients are functions of the input data.

The underlying behavior of the six-port modulator is that of a device that performs linear combinations. A linear combination is a sum where each element of the sum is from a set, and each element is multiplied by a constant. For the six-port structure, the linear combination is formed from combinations of the LO. The reflection coefficients at ports G1, G2, G3, G4 are the constants of the linear combination.

Here's how the signals pass through an example circuit. See Figure 3. This is a specific six-port example. There are many six-port architectures, employing different arrangements of splitters and hybrid couplers. We'll use this one particular example in this discussion. You may notice that there are two resistors in the circuit. These resistors are there to handle the reflections that don't bounce out the RF port. These are extra reflections that we don't need to create our modulated waveform. Let's follow the path of the signals that do end up at the RF output.

A local oscillator signal is input at port LO. The signal is split by a 3dB power divider, which divides the signal into two signals. Each of these two signals is half the power of the original signal. Each of these two signals has the same phase. See Figure 4, where we now have two signals. Each signal is divided again by the two quadrature hybrid couplers, one right before ports G1 and G2, and the other right before ports G3 and G4. Now we have four signals. See Figure 5.

Quadrature hybrid couplers are four-port devices that couple an input signal into two signals that are 90 degrees out of phase. Other phase shifts are available, but 90 degrees is commonly encountered. The couplers work in either

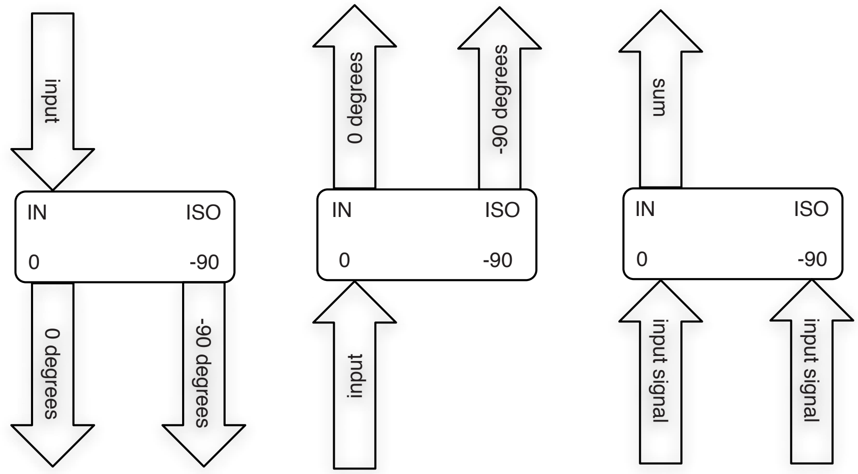


Figure 6: hybrid couplers

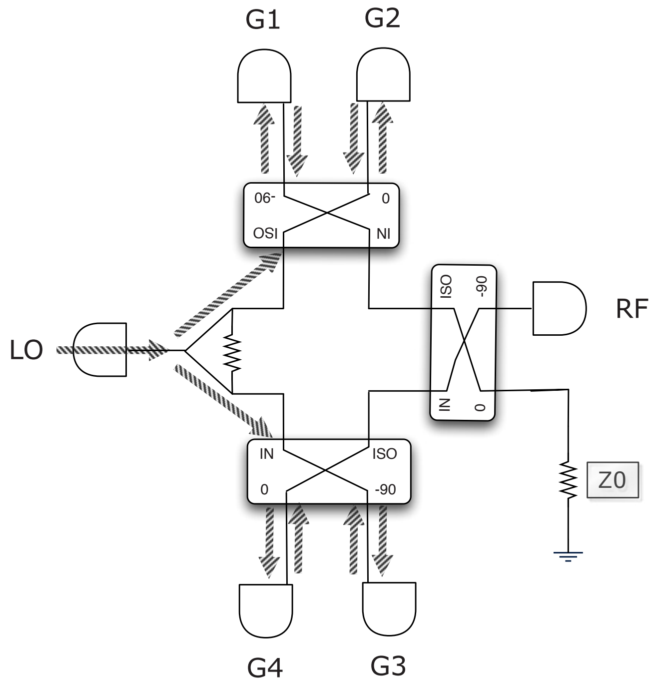


Figure 7: LO bounces off terminations

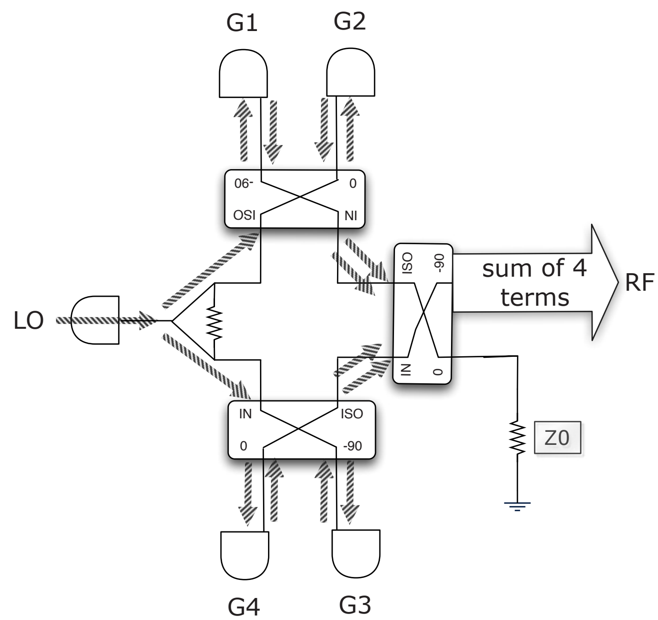


Figure 8: linear combination at RF

direction. Figure 6 is a diagram of a coupler with the input applied to the same coupler, first in one direction and then the other to demonstrate how the input signal is split. When two signals are applied to the coupler, they are phase shifted and summed. These couplers are made entirely of traces on a circuit board.

Next, our four signals reflect off of terminations that implement the reflection coefficients represented by the reflection states at ports G1 through G4 (reflection coefficients RC_{G1}, RC_{G2}, RC_{G3}, RC_{G4}). See Figure 7. The role of the terminations at ports G1 through G4 is to get the baseband digital data translated into linear combinations of the LO signal. See Figure 8.

The signals that appear at the RF output port are summed by the third quadrature hybrid coupler of the circuit. The result is the RF output. An equation follows that represents what we've drawn. At this point, it's all right to begin to be alarmed.

aRF = sum over i equals 3 to N (Si1*S2i*G_i selected from alphabet*aLO)

See footnote[2]

The following four waveforms are generated.
Port G1 waveform = $S_{G1,LO}*S_{RF,G1}*RC_{G1}*LO$
Port G2 waveform = $S_{G2,LO}*S_{RF,G2}*RC_{G2}*LO$
Port G3 waveform = $S_{G3,LO}*S_{RF,G3}*RC_{G3}*LO$
Port G4 waveform = $S_{G4,LO}*S_{RF,G4}*RC_{G4}*LO$
where
RC_{G1} through RC_{G4} = reflection coefficient at subscripted port. It is generally 1 or -1.

and where
$S_{i,LO} = |S_{i,LO}|e^{j\theta i,LO}$ $S_{RF,i} = |S_{RF,i}|e^{j\theta RF,i}$

S stands for scattering parameter (s-parameter). A scattering parameter is a complex value that represents the change in amplitude and phase to a signal when it goes across a connection or component or some other sort of disruption. A way to remember how to interpret the notation of s-parameters is to read a parameter such as $S_{1,2}$ as "The response at port 1 due to the signal at port 2."

Here is how the s-parameters affect the signals. The input data controls the value of the reflection coefficients at the four data input ports (G1 through G4). Each of the four waveforms that we sum to create RF are modified by three s-parameters. There are two s-parameters from the two hybrid couplers, and then there is a reflection coefficient from the termination. A reflection coefficient is just a special case s-parameter. The s-parameters represent the amplitude and phase effects that the quadrature hybrid junctions and the termination have upon the waveforms that travel the path from input to output.

For example, the local oscillator signal LO enters the circuit. If we are standing at port G4, then we

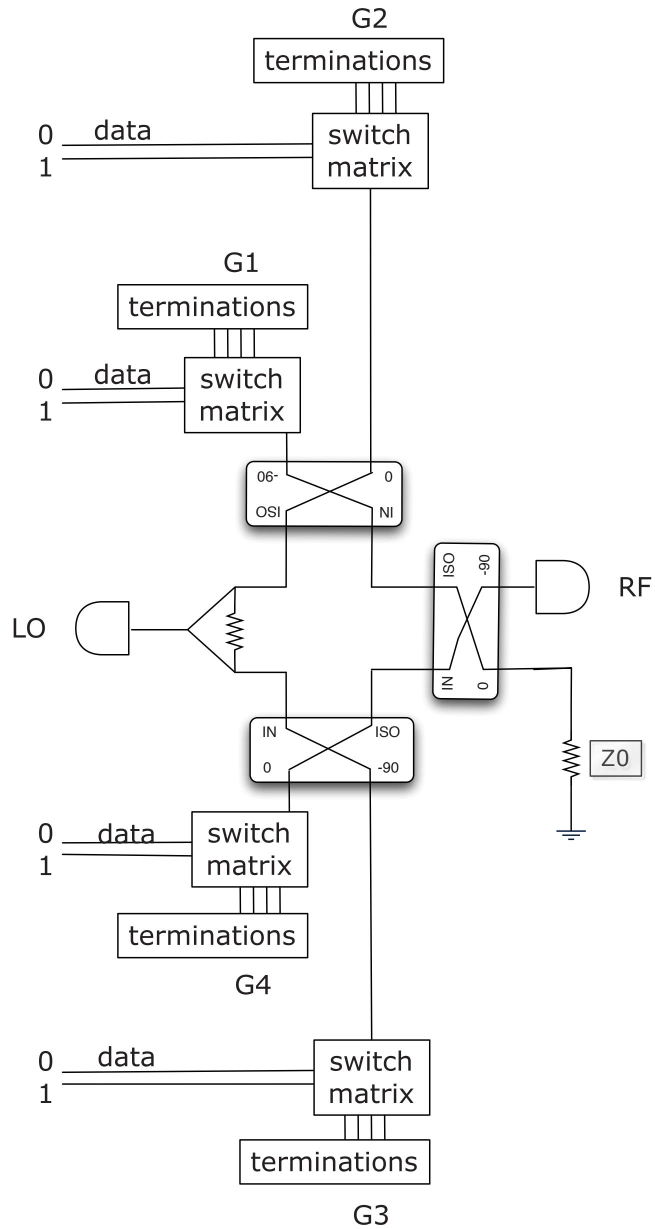


Figure 9: a reflection implementation

see that the LO (after the divider) crosses from the LO port to port G4 (and is modified by $S_{G4,LO}$) and then it is modified by the reflection coefficient RC_{G4} (which might be 1 or -1) and then from port G4 to port RF (and is modified by $S_{RF,G4}$). If you look at the Port G4 waveform equation above, you'll see all three of these terms in there.

There is a subtlety here. It's useful to think of these s-parameters as end-to-end values for a particular port-to-port path. For example, when going from G4 to RF, two different couplers are

2 Fadhel M. Ghannouchi and Abbas Mohammadi, *The Six-Port Technique with Microwave and Wireless Applications* (Boston: Artech House, 2009), 162.

Figure 10: output corresponding to input data symbol 00

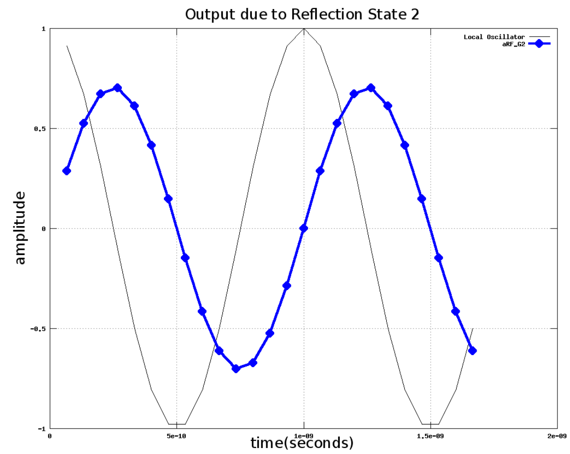


Figure 11: output corresponding to input data symbol 01

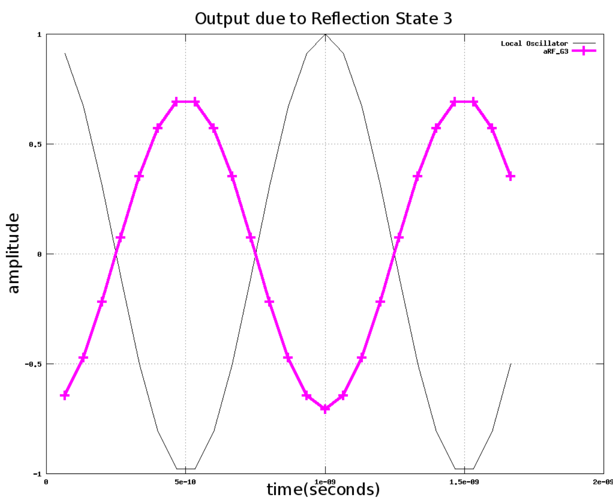


Figure 12: output corresponding to input data symbol 10

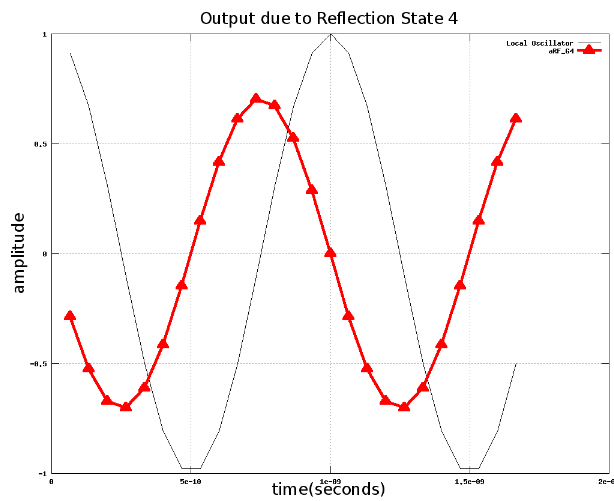


Figure 13: output corresponding to input data symbol 11

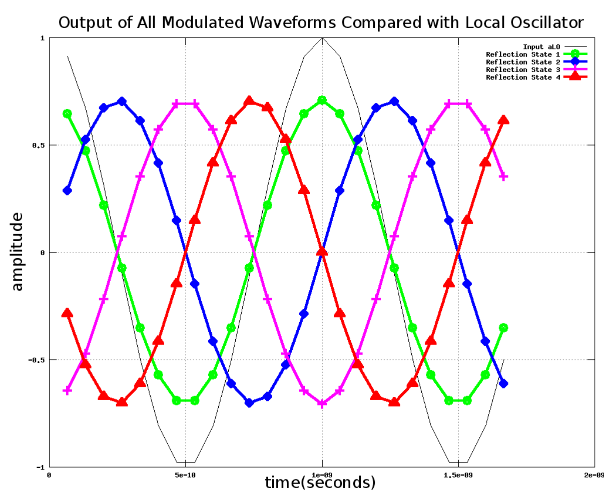


Figure 14: all four modulated output waveforms compared against the LO.

traversed. It might be tempting to write down two s-parameters, one for each interface. However, we can combine the amplitude and phase information for the path into one s-parameter. This lets us use simpler equations.

Reflection coefficients can be implemented with a switch matrix and terminations. See Figure 9. The switch matrix is set depending on the value of the baseband data.

The number of reflection coefficients needed per port depends on the type of modulation. In Figure 9, we have four choices of terminations. How did we obtain this number? To determine the number of reflection coefficients needed, there is a happy little equation.

N = number of reflection coefficients.
M = number of bits per modulation symbol

$$N = 2^M$$

For binary phase shift keying (BPSK), there are two values, 0 and 1. We only need one bit to hold these two values. That bit is called a symbol when it is large enough to hold all the values we need to communicate.

Using the equation above, $2^1 = 2$, therefore there are two reflection coefficients per port, one for each value of the symbol. There are four ports, so there is a total of eight reflection coefficients that work together to produce two RF output waveforms.

For quadrature phase shift keying (QPSK), there are four values, 00, 01, 10, and 11. This requires two bits to represent. The symbol is therefore two bits wide.

$2^2 = 4$, therefore there are four reflection coefficients per port, one for each value of the symbol. There are four ports, so there are a total of sixteen reflection coefficients. For QPSK, all the reflection coefficients can be represented as a four-by-four matrix of complex values. Four output waveforms are produced, one for each of the four input symbols.

The reflection coefficients are grouped into

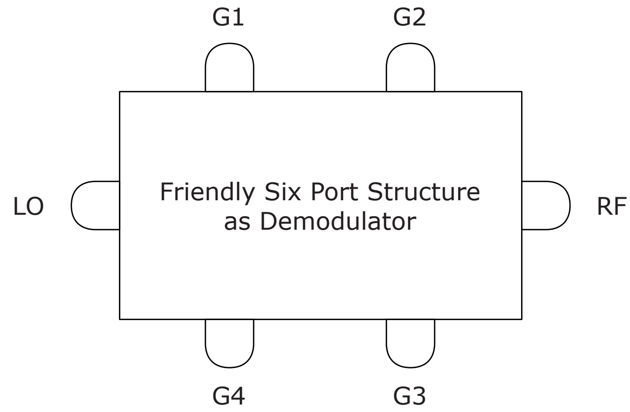


Figure 15: six-port as demodulator

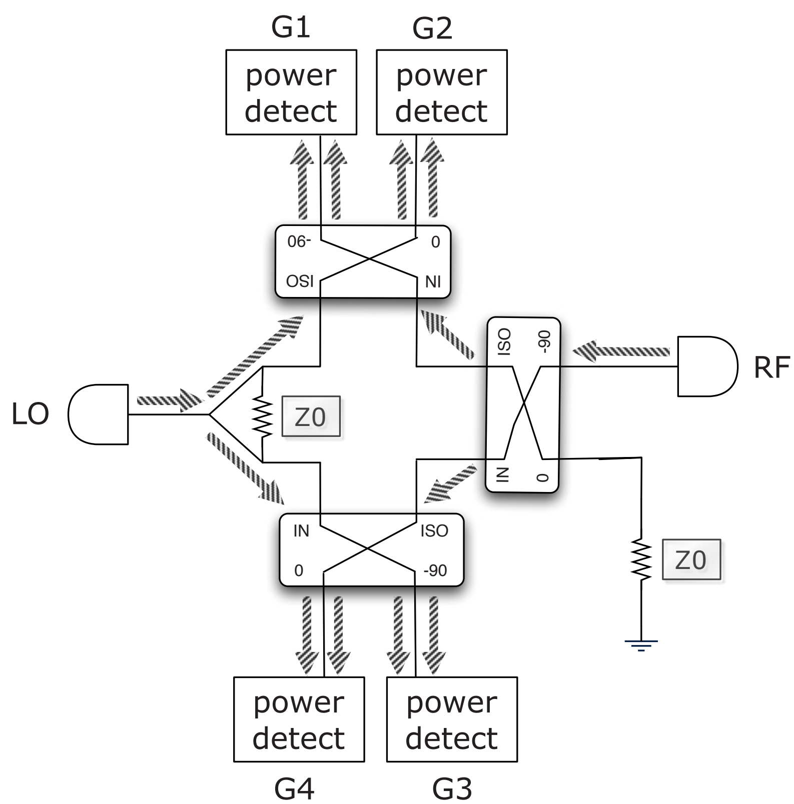


Figure 16: “The Music Goes Round and Round”

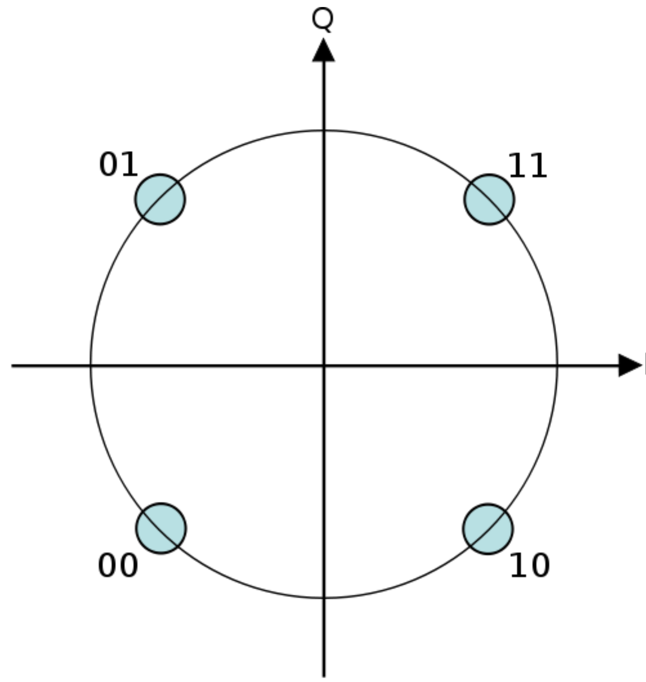
sets. Each of the data input ports needs to "see" the right member of the right set of reflection coefficients in order to help produce that particular waveform. This is why thinking of the reflection coefficients in the form of a matrix is so powerful. For QPSK, a 4 by 4 matrix is formed of all the reflection coefficients. The rows of the matrix are formed of four reflection coefficients. Each row forms a team. Each team has one particular data symbol. Each member of this team is "posted" at the corresponding data input port when that row's symbol comes up in the data stream. When they are all "seen" at once by the various phase-shifted versions of the LO, then the output has a particular and predictable phase shift with respect to the LO. This phase shift corresponds to the input data symbol, and when it's transmitted, it can be received and demodulated by a QPSK receiver.

This process can be thought of as a symphony orchestra. The data symbol is the conductor. Each port plays a particular instrument. Each port needs to play the right note, at the right time, in order to stay in time and produce the right output. The sheet music is which reflection coefficients correspond to the data symbol the conductor is going on about.

Wideband, small, and cheap digital transceivers are in great demand. The six-port structure provides wide bandwidth, very low power consumption, and extremely simple construction as a modulator[3].

It's also compelling as a demodulator. The LO and received RF are now inputs, and the four data ports (G1 through G4) are outputs. See Figure 15.

The received RF is summed with an LO under various phase angles. For our six-port demodulator, there is a power detector at each of the four data output ports. See Figure 16.
We want a QPSK output. There are two components to a QPSK signal. They're called I (in phase) and Q (quadrature). We need them in order to figure out which modulation symbol (from the set of 00, 01, 10, 11) was sent to us. The received symbols can be shown in a drawing



called a constellation diagram. Here is what QPSK looks like:
Here are some equations! Watch out!

I = sum over k equals 1 to 4 of ($\boldsymbol{a}_k$*$Pout_k$)
Q = sum over k equals 1 to 4 of ($\boldsymbol{b}_k$ * $Pout_k$)

I and Q are the components of the modulated signal. k is which data output port we're currently gathering. ***a*** and ***b*** are the demodulation coefficients. And here is where the cheese gets binding, because the determination of ***a*** and ***b*** can be hard.

The performance and simplicity of construction come at a cost. There are two areas of complexity in six-port devices. The first is that they must be carefully calibrated. The second area of complexity is that the mathematical procedures

3 Lay out your own wilkinson divider and quadrature hybrid divider or combiner by using the information from Paul Wade in "Combining Microwave Amplifiers." QST October 2010: Page 96.

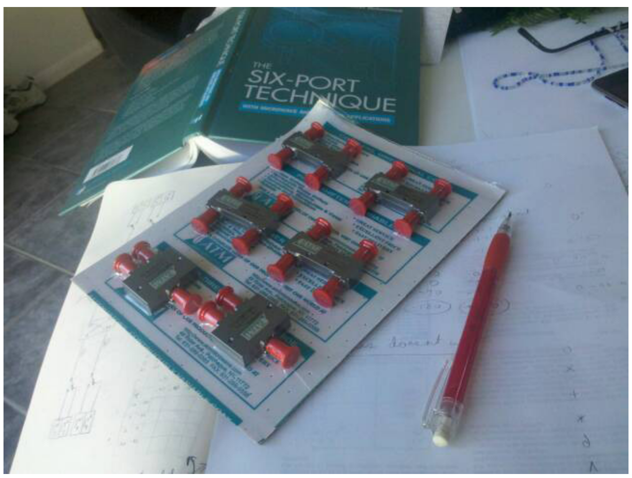
to calculate the complex reflection coefficients from the four amplitudes at the demodulator output ports can be complicated.

Despite these complexities (or perhaps because of them!) I believe these characteristics of six-port devices are a good fit for a wideband digital communications system for amateur microwave.

Write me about six-ports! w5nyv@yahoo.com

Our amateur microwave project page, with an emphasis on six-port development:

http://www.delmarnorth.com/microwave/



Above, four off-the-shelf hybrid couplers and two power dividers from Advanced Technical Materials await their fate as a 1.2GHz amateur microwave six-port. The book in the background is The Six-Port Technique, by Ghannouchi and Mohammadi. It’s one of very few books on six-ports. There are a variety of papers covering six-port structures, calibration, and performance. While many of these papers are behind an ieeexplore paywall, there are papers available for free from other sources.