How Frequency Affects Transmit Combiner Design

Introduction

Many factors are taken into consideration when our Application Engineers design a transmit combiner. One of the most important items taken into consideration is frequency assignments. The frequency plan in use at your site is one of the biggest influences for determining the physical size, cost, and performance of your transmit combiner.

Many frequency bands have standard offsets between transmit and receive frequencies. VHF high band is one of the few frequency bands that do not have a band plan. This lack of band plan can lead to all kinds of different offsets between transmit and receive frequencies at a site. This paper reviews the basic effects that a frequency plan in the VHF high band has on the design of a transmit combiner for your performance requirements and RF environment.

The Effect of Transmit to Receive Frequency Separation

Typically, in Combiner and Receiver Multicoupler designs, we aim to have 90 dB of isolation between the transmitter and receiver. This isolation is achieved through a combination of antenna isolation (created by physically separating transmit and receive antennas) and filtering on transmitters and receivers.

There are many different types of filters that can be used to help us achieve the goal of 90 dB isolation. With TX RX products we typically use cavity filters because of their power handling, ease of reuse, and filtering capabilities. One of these types of filters is a bandpass filter. A bandpass filter is designed to pass a certain frequency bandwidth and attenuate frequencies outside of that bandwidth.

On the next page is a curve for a TX RX 6.625” diameter cavity bandpass filter model number 11-37-01, with a pass frequency of 132 MHz. In this configuration, the filter will pass a bandwidth of approximately 25 kHz that is centered on 132 MHz with minimum insertion loss, and attenuate frequencies outside of that frequency range.
The curve shows the performance of the bandpass cavity at two different insertion losses: 0.5 dB and 2.5 dB. It is interesting to note that as the insertion loss increases, the pass bandwidth decreases, and the attenuation increases.

This particular filter has the same performance when tuned across the VHF high band frequency range. If a T-connector is connected to the bandpass filter on one port, another bandpass filter can be added in parallel to combine two frequencies onto a single antenna. This is how our T-Pass combiners function. We can assume that adding the T-connector will have a minimal impact to the performance of the cavity. Using this curve, let’s look at some examples of transmit and receive frequencies, as well as their effects on the design of the transmit combiner.

A great advantage to bandpass filters is that when they are connected in series, the attenuation of the filters will add together. Combining two bandpass cavities at 0.5 dB insertion loss will provide more attenuation than one bandpass cavity at 1.0 dB insertion loss. While using two cavities increases the cost and physical size of a combiner, it can keep insertion losses lower.

On the next page is a performance curve for 11-37-02, which is two 11-37-01 6.625” cavities together in series.
Example 1:

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>136.0000 MHz</td>
</tr>
<tr>
<td>132.5000 MHz</td>
<td>136.5000 MHz</td>
</tr>
</tbody>
</table>
We want to provide a minimum of 90 dB of isolation between each transmit frequency and each receive frequency. The chart below shows the isolation that is provided by one 11-37-01 band pass filter used on each transmit and receive channel at both 0.5 dB and 2.5 dB insertion loss settings.

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
<th>Isolation provided at 0.5 dB insertion loss</th>
<th>Isolation provided at 2.5 dB insertion loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>136.0000 MHz</td>
<td>26 dB</td>
<td>40 dB</td>
</tr>
<tr>
<td>132.0000 MHz</td>
<td>136.5000 MHz</td>
<td>27 dB</td>
<td>41 dB</td>
</tr>
<tr>
<td>132.5000 MHz</td>
<td>136.0000 MHz</td>
<td>25 dB</td>
<td>39 dB</td>
</tr>
<tr>
<td>132.5000 MHz</td>
<td>136.5000 MHz</td>
<td>26 dB</td>
<td>40 dB</td>
</tr>
</tbody>
</table>

If we have 30 dB of antenna isolation between our transmit and receive antennas and only have bandpass/T-Pass filters available, we would need several of these cavity filters for each transmit frequency. By cascading two bandpass/T-Pass cavities with a combination of these insertion loss settings, we can create a transmit combiner that has approximately 3.0 dB insertion loss per channel.

In real world applications the insertion loss would be higher than this. We would add an isolator on each channel which would increase insertion loss. There is also bridging loss that occurs which increases insertion loss.

Bridging loss is resulted from bridging an impedance across a transmission system. When using transmission line to connect two or more transmitters together, this additional bridging loss is introduced to the system. In T-Pass combiners, the bridging loss can be precisely measured and predicted.
Example 2:

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>132.5000 MHz</td>
</tr>
<tr>
<td>134.0000 MHz</td>
<td>134.5000 MHz</td>
</tr>
</tbody>
</table>
In this example, each transmit frequency is only 500 kHz away from the paired receive frequency. We will continue assuming an antenna separation of 30 dB which means we need 60 dB of isolation between each transmit frequency and each receive frequency from our transmit combiner. The chart below shows the isolation that is provided by one 11-37-01 band pass filter used on each transmit and receive channel at both 0.5 dB and 2.5 dB insertion loss settings.

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
<th>Isolation provided at 0.5 dB insertion loss</th>
<th>Isolation provided at 2.5 dB insertion loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>132.5000 MHz</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>132.0000 MHz</td>
<td>134.5000 MHz</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>134.0000 MHz</td>
<td>132.5000 MHz</td>
<td>17</td>
<td>31</td>
</tr>
<tr>
<td>134.0000 MHz</td>
<td>134.5000 MHz</td>
<td>9</td>
<td>22</td>
</tr>
</tbody>
</table>

In this example, if we only had bandpass/T-pass cavities to build a transmit combiner we would need to use either three or four cavities for each transmit frequency to reach the 60 dB isolation goal.
The three cavity option will cost less and be physically smaller because it uses less cavity filters. To offset the savings of cost and space, the three cavity per transmit frequency option has a higher insertion loss than the four cavities per channel option.

By comparing examples 1 and 2 we can see that as the transmit and receive frequencies get closer to each other, the amount of isolation that we can achieve using a single bandpass cavity decreases. In general, this means we will need to use more cavities to achieve our isolation goals. This leads to systems that are physically large and more expensive. These combiners also tend to have higher insertion losses than combiners for band plans with larger transmit to receive frequency separations.
Luckily, we have more than the bandpass cavity filter in our toolbox. Another cavity filter that we commonly use is called the Vari-Notch filter. Vari-Notch is our brand name for a bandpass, band reject filter. This filter is designed to pass a particular frequency with a low insertion loss and reject a particular frequency with a greater amount of attenuation than a bandpass filter.

Below is a curve for a TX RX 4" diameter cavity Vari-Notch filter model number 15-37-09. This filter has a 0.6 dB insertion loss and can be used to notch frequencies at several different separations from the pass frequency. The bigger the separation between the pass and the notch, the more attenuation we get in the notch. We are able to receive about 48 dB of attenuation at the notch frequency at a separation of 2 MHz or more.
Example 3:

Let’s add the 15-37-09 Vari-Notch filter to our toolbox and rebuild the combiner that we made in example 2.

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
<th>Isolation Provided When Notch is Tuned At Closest RX Frequency (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>132.5000 MHz</td>
<td>28</td>
</tr>
<tr>
<td>132.0000 MHz</td>
<td>134.5000 MHz</td>
<td>6</td>
</tr>
<tr>
<td>134.0000 MHz</td>
<td>132.5000 MHz</td>
<td>4</td>
</tr>
<tr>
<td>134.0000 MHz</td>
<td>134.5000 MHz</td>
<td>28</td>
</tr>
</tbody>
</table>
Now that we have both bandpass/T-Pass cavities and Vari-Notch cavities, and 30 dB antenna isolation, we can build a transmit combiner with three cavities per transmit frequency. This configuration has significantly less insertion loss than the configurations in Example 2.

Vari-notch filters can provide low insertion loss attenuation at notch frequencies as close as 200 kHz. If transmit and receive frequencies are closer than 200 kHz we can use a notch filter. A notch filter is a filter that provides almost no attenuation at every frequency except the notched frequency. At the notched frequency, the notch provides a substantial amount of attenuation. TX RX has several types of notch filters, but the notch filter used most often in our transmit combiners is called a Series Notch filter. Our Series Notch filters use 6.625” or 10” diameter cavities with a specialized notch loop. Below is a table that summarizes the attenuation we are able to achieve with a model 20-37-01 Series Notch cavity which is 6.625” in diameter.
<table>
<thead>
<tr>
<th>Separation Between Pass and Notch Frequency (kHz)</th>
<th>Attenuation at Notch Frequency (Low Pass Configuration)(dB)</th>
<th>Insertion Loss at Pass Frequency (Low Pass Configuration)(dB)</th>
<th>Attenuation at Notch Frequency (High Pass Configuration)(dB)</th>
<th>Insertion Loss at Pass Frequency (High Pass Configuration)(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>10</td>
<td>1.00</td>
<td>10</td>
<td>1.00</td>
</tr>
<tr>
<td>100</td>
<td>15</td>
<td>0.65</td>
<td>15</td>
<td>0.90</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
<td>0.35</td>
<td>15</td>
<td>0.45</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
<td>0.70</td>
<td>20</td>
<td>0.70</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>0.40</td>
<td>200</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Example 4:

<table>
<thead>
<tr>
<th>Transmit Frequency</th>
<th>Receive Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.0000 MHz</td>
<td>132.1000 MHz</td>
</tr>
<tr>
<td>138.0000 MHz</td>
<td>138.1000 MHz</td>
</tr>
</tbody>
</table>
In this example, we can use bandpass/T-Pass cavities and Series Notch cavities to help us reach our isolation goal. We will have 30 dB antenna isolation and we need to use filtering to obtain 60 dB of isolation between each transmit frequency and each receive frequency. We will need two bandpass/T-Pass cavities and four Series Notch cavities for each transmit frequency. Transmit combiners for systems with small transmit to receive guard bands can quickly get physically large and expensive.

Example 4

**The Effect of Transmit-to-Transmit Frequency Separation**

It is not only the frequency separation between transmit and receive frequencies that can affect the design, size, and cost of a transmit combiner. The frequency separation between transmit frequencies also has a major effect.

When combining transmit channels, the combiner needs to provide an adequate amount of channel-to-channel isolation in order protect the transmitters and minimize the risk of intermodulation. The channel-to-channel isolation measured from one channel primary input/output port to another is the sum of cavity insertion loss, adjacent cavity selectivity and thruline cable mismatch loss.

Adjacent cavity selectivity and channel-to-channel isolation for 10” T-pass cavities at 1.5 dB insertion loss is illustrated on the next page.
The above figure shows that using two 10” T-Pass cavities at 1.5 dB insertion loss to combine 160 MHz and 161 MHz provides a total of 31 dB channel-to-channel isolation. Approximately 24 dB of isolation is provided by adjacent cavity selectivity, approximately 1.5 dB of isolation is provided by cavity insertion loss, and approximately 6 dB of isolation is provided by thruline cable mismatch loss.

Because most of the channel-to-channel isolation comes from adjacent cavity selectivity, the frequency separation between transmitters plays a large role in what types of cavities can be used and how much insertion loss is needed. The table below shows the insertion loss setting needed to combine frequencies with varying TX-TX frequency separations using 10” T-Pass cavities (73-38-05) and 6.625” T-Pass cavities (73-38-01) between 132-174 MHz:

<table>
<thead>
<tr>
<th>Tx-Tx Separation</th>
<th>Cavity Loss</th>
<th>Maximum Power</th>
<th>Loss (dB) vs. number of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1 MHz</td>
<td>-1.5 dB</td>
<td>150 W</td>
<td>-2.6</td>
</tr>
<tr>
<td>250 kHz</td>
<td>-1.5 dB</td>
<td>150 W</td>
<td>-2.9</td>
</tr>
<tr>
<td>100 kHz</td>
<td>-1.5 dB</td>
<td>150 W</td>
<td>-3</td>
</tr>
<tr>
<td>75 kHz</td>
<td>-2.0 dB</td>
<td>150 W</td>
<td>-3.5</td>
</tr>
<tr>
<td>50 kHz</td>
<td>-2.5 dB</td>
<td>130 W</td>
<td>-4.1</td>
</tr>
</tbody>
</table>
In this example we have a very good guardband but the transmit channels are only 250 kHz apart. If we assume that we have 30 dB of antenna isolation, we could get 60 dB of isolation between each transmit and each receive frequency by using one 6.625” T-Pass cavity and one 6.625” bandpass
cavity at the 0.5 dB Insertion loss setting. This would give us a low insertion loss of about 1.0 dB, but would not provide us with enough transmit channel isolation. The chart for cavity loss settings for 6.625” T-Pass cavities on the previous page says that we need to use a 1.5 dB insertion loss setting at 250 kHz separation in order to achieve the required transmit channel isolation.

Example 5

The tables on previous pages show that as the transmit-to-transmit frequency separation decreases, the insertion loss of the transmit combiner increases. Once the frequency separation gets too small (less than 50 kHz) it is no longer possible to achieve the needed channel-to-channel isolation with the T-Pass cavity combining solution alone, and other combining methods need to be considered.

One option is to separate the frequencies that are too closely spaced onto separate antennas. This will usually allow us to keep insertion losses low but may add costs to the overall project by requiring additional antennas.

A second option is to use hybrid couplers to combine frequencies together. A hybrid combiner has higher insertion losses than other types of combiners but can combine closely spaced frequencies. A hybrid coupler can be used to combine frequencies without regard to transmit-to-transmit frequency spacing because the channel isolation of a hybrid combiner comes from the port-to-port isolation of the hybrid coupler itself, rather than from filtering.

Below is a diagram of a hybrid coupler that is being used to combine two frequencies.
Frequency 1 is input at port 1, and frequency 2 is input at port 4. This hybrid coupler has a port-to-port isolation of 25 dB. This is a 3.0 dB coupler, which means that both the coupling loss and the thru line loss are 3.0 dB. When you input frequency 1 at port 1, half of the power of frequency 1 carries through to port 2 and half of the power is dumped into the load at port 3. When you input frequency 2 at port 4, half of the power of frequency 1 carries through to port 2 and half of the power is dumped into the load at port 3. Frequency 1 and frequency 2 have been combined, but have experienced a 3 dB loss without gaining any isolation to protect the receive frequencies on site.

In order to make a hybrid combiner that provides isolation to protect the receive frequencies, you also have to use some kind of filtering which will further increase the insertion loss of the transmit frequencies. Below are two examples of hybrid combiners.
Conclusion

A good frequency plan with well-spaced transmit frequencies and a large guard band is the key to being able to use less expensive and low loss transmit combiners. Unfortunately, frequency plans can often get messy in the VHF band. It is important to understand when making preliminary project budgets that as transmit-transmit or transmit-to-receive frequency separations decrease, the cost, insertion loss, and physical size of a transmit combiner is likely to increase.

TX RX Systems has been providing combiner solutions for the LMR market for more than 40 years. Our Applications Engineers would be glad to assist you with choosing the right combiner for your frequency plan or putting together a custom-configured system for your particular needs.