The Art of Combiner Design

A Customer Primer to Understanding and Influencing the Design Process

While many engineers involved in land mobile radio systems are aware of the benefits of combiner: decreased tower load, fewer antennas and cable runs; few fully understand the combiner design process in its entirety. Some design considerations are customer driven, while others are inherent in the components and combining techniques available to the designer. By better understanding the combiner design process, the customer can weigh the pros and cons of a given combiner solution, and make a more informed decision when purchasing a combiner for their application.

Primary Design Goals of a Cavity Combiner

When designing a cavity based combining solution, there are two major design goals. The first design goal is the actual combination of the multiple channels onto a single antenna line. There are many ways to achieve this: hybrid couplers, cable harnesses, specialized cavities, and other more obscure techniques. For the sake of this discussion, the focus will be on the cavity based approach, specifically the TX-RX Brand of T-Pass combining cavities.

The second design goal of any combining solution is providing adequate isolation between the transmitters and receivers in the system. Transmitters naturally create noise outside of their transmitting frequency. Receivers, likewise, can become desensitized by any transmitters close in frequency to their primary receive frequency. It is thus important in a combining system to minimize the impact of a transmitter's noise on a receiver, and the impact of a receiver's sensitivity to a particular transmitter. This is achieved by providing adequate isolation either through antenna separation/ free space loss or through filtering. These transmitter noise and receiver desense characteristics (TNRD) are a function of the actual radio; differing brands and models may have better or worse TNRD characteristics. Since these characteristics differ from radio to radio, the needed isolation to meet TNRD filtering requirements may vary from system to system.

For the sake of this discussion, the focus will be on the transmit side of a VHF combining system, which means the primary goal will be eliminating the threat of transmitter noise on the receivers in the system. VHF bands will be discussed as there is no FCC coordinated band plan for VHF and thus the chances of TNRD issues are increased. Note that while the discussion will be focused on the transmit side of the system, the receiver side would require similar attention to mitigate a receivers sensitivity to transmitters in the system. This means that if filtering is required for the transmitter side, the receiver side will need it as well.

Customer Requirements

The first stage of any combiner design is soliciting the system requirements from the customer. While many aspects of the combiner system are ultimately dictated by physics, there are still some decisions a customer can make that could result in a smaller, less expensive, and better performing system. The following sections outline the requirements most useful to the combiner designer, and lays out some tips and tricks for the customer for positively influencing the end combiner design.

Antenna Selection and Isolation

One of the most vital choices a customer can make is the selection of the number of antennas for a site and the positions of those antennas on the site. As mentioned previously, adequate transmit and receive isolation can be achieved through a combination of filtering and transmit and receive antenna spacing. Whatever isolation achieved through antenna spacing, it doesn't have to be provided by cavity filters. Sometimes just moving an antenna up the tower a couple feet is enough to shrink a combiner system to half of its original size.

The recommended antenna configuration is one antenna for receive and one or more antennas for transmit. The receive antenna should be vertically aligned directly above or below the transmit antennas with as much tip to bottom separation between the receive antenna and transmit antenna as possible. While transmit and receive antennas can be horizontally separated, like on top of a building or water tower, this configuration results in a much lower isolation. This is due to the antennas lying directly in each other's main lobes; increased antenna gain will further reduce the isolation in a horizontal configuration.

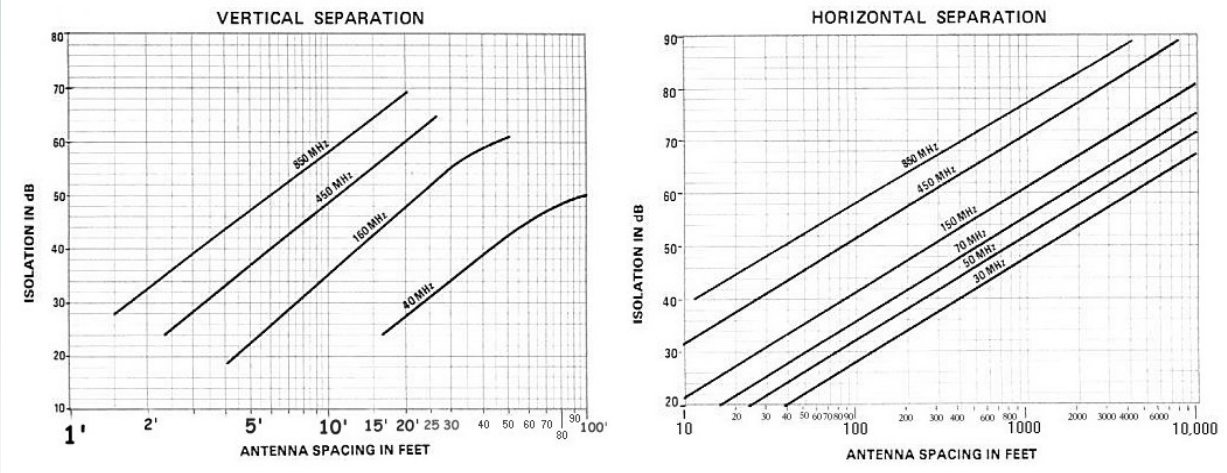


Figure 1: Antenna Separation Curves

Finally, while it is tempting to try and minimize tower load by using only a single antenna for both transmit and receive frequencies, this configuration should be avoided whenever possible. Not only will all of the isolation have to be provided via filtering, resulting in a much larger and higher loss system, but such a configuration is also more susceptible to other sources of interference like intermodulation.

Frequency Selection

The second area where a customer can positively affect the final design of a system is through the selection of frequencies. There are two goals that a customer should have in selecting their frequencies for a new radio system: maintaining adequate transmitter to transmitter frequency spacing, and maximizing transmitter to receiver frequency spacing. Intelligent frequency selection is especially important in the VHF band where there is not an organized band plan that provides adequate transmit to receive frequency spacing by default.

When designing a combiner, one of the important considerations is keeping the insertion loss of the various channels as low as possible. This means that a designer wants to use lower loss combining methods like T-Pass cavities, rather than higher loss methods like hybrid couplers or splitters. Since T-Pass cavities have a minimum transmit to transmit frequency separation that they can support, it is vital to maintain this separation if T-Pass cavities are to be used. Additionally, as the transmit frequencies space out, the T-Pass cavity insertion losses and bridging losses decrease as well. Better transmit to transmit frequency spacing directly translates to lower loss combiners.

Transmit to receive frequency spacing is probably the most important of the customer frequency considerations. As mentioned previously, the TNRD performance is tied directly to the radio type. Generally the off-band transmitter noise and receiver sensitivity of a given radio can be visualized as a bell curve around the primary frequency. As specific transmitters and receivers move closer in frequency, the transmitter noise and receiver desensitizing become more pronounced. This means that more filtering will be needed on both transmit and receive sides of the radio to combat the issue as frequencies move closer. Unfortunately, cavity filters also become less effective at providing isolation at closer spacing as well, so not only does the target isolation increase at closer spacing, but the number of cavities needed to provide a given amount of isolation also increases. This means that more and more cavities are needed to mitigate TNRD issues when transmit and receive frequencies are very close together. It is a good idea to maximize receiver to transmitter frequency spacing whenever possible; the result will be a smaller, less expensive, and lower loss combining system.

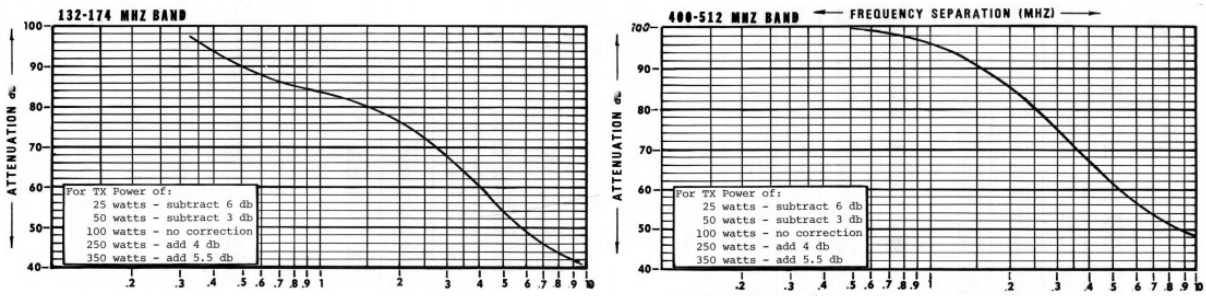


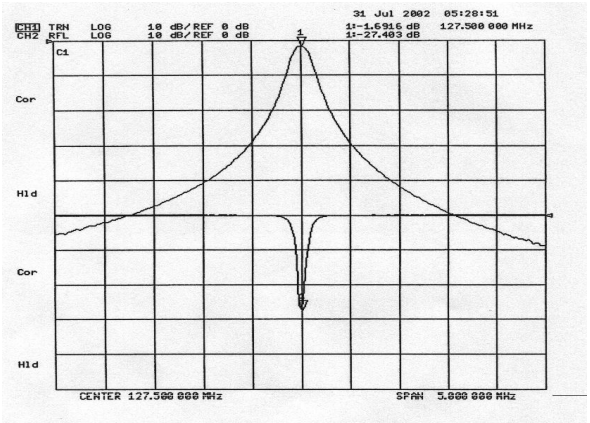
Figure 2: Typical TNRD Curves

Designing a Combiner

Once the antenna placement and frequencies have been established, the design of the combiner can begin. The actual combining is the easiest part of the design process. Assuming that the minimum TX to TX frequency spacing was met, the T-Pass cavities take care of bringing all of the channels together onto a single line using a frequency sensitive cable daisy chain.

The more difficult task in the design process is selecting the filtering required to provide adequate isolation for the radios. The isolation required in filtering is calculated as the specific TNRD curve requirement for the given spacing, that is the spacing between the frequency for which filtering is being provided and the target frequencies being filtered against, minus the isolation gained through antenna isolation. The combiner designer will look at the separations between the frequency to be passed and the frequencies to be rejected, as well as the isolation needed to fully reject the frequencies. Using this information, the designer will select an appropriate set of cavity filters for each channel in the combiner, either T-Pass, Band pass, Vari-notch, or Series notch, to provide the target isolation needed for all rejected frequencies. The following paragraphs detail the types of rejection responses and outline the filter selection process generally employed by the designer.

T-Pass Cavity Stage



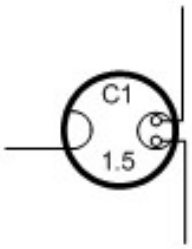


Figure 1: T-Pass Curve and Symbol

The T-Pass cavity is usually the first cavity used when providing filtering for a channel. Assuming that the customer selected a spacing that was adequate to combine using T-Pass cavities, this is the cavity that would actually combine multiple channels onto a single line. The details of how this is accomplished are discussed in detail in other documentation.

In addition to combining, the T-Pass cavity also provides a fairly standard bandpass cavity response. Bandpass responses look like a symmetrical bell curve, with the top of the bell where loss is the lowest being the frequency one wants to pass, and all the other frequencies are to be rejected. The sharpness of the rejection is defined by the set insertion loss of the cavity. That is, the more loss there is for the passed frequency, the better the cavity is at rejecting other frequencies around it.

Once a T-Pass cavity has been selected to do the actual combining, its band pass response is compared to the target isolation values to see if it provides adequate isolation against all of the receivers. If it does, then no other additional cavities are needed, and the designer moves on to providing filtering for the next transmitter. If not, then the designer will add additional cavities to provide the remaining isolation needed for the remaining receive frequencies.

Bandpass Cavity Stage

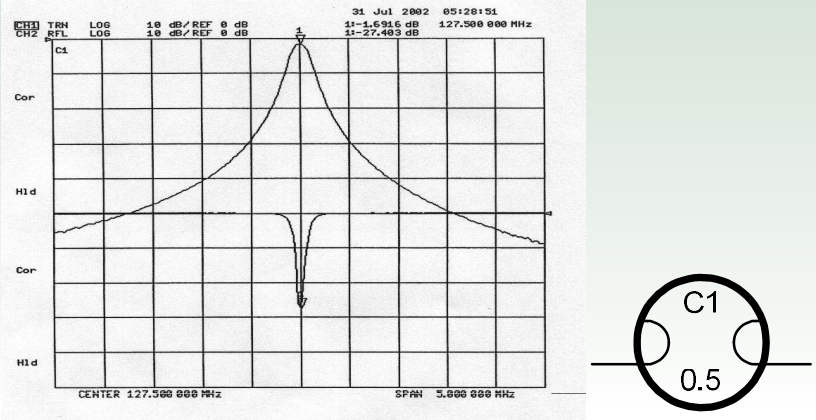


Figure 1: Bandpass Curve and Symbol

If additional isolation is needed on the transmit side against the remaining receivers, then an bandpass cavity is the next option for the designer to look at. A bandpass cavity is similar in response to the T-Pass cavity, but does not have the special loop for combining.

Adding a bandpass cavity to the transmit channel is the next logical choice if two conditions are met. Firstly, if there are remaining receiver frequencies to be filtered that are fairly far away, like roughly 700 kHz in a VHF system, then the remaining receiver frequencies can be filtered effectively with a bandpass cavity. Secondly, if the receiver frequencies are somewhat far apart from each other, like on either side of the pass frequency, then a bandpass cavity's symmetrical response would eliminate multiple receivers with just one cavity, as opposed to needing multiple notch style cavities.

Once a bandpass cavity has been selected, the designer then looks at the remaining isolation needed for the remaining receiver frequencies. If any receiver frequencies look like they are close to being fully filtered, then the insertion loss on the bandpass cavity should be increased until they are completely eliminated. If any RX frequencies are left not fully filtered, but still meet the previously mentioned spacing criteria, the designer should then look at adding another bandpass cavity. Generally, if more than two bandpass cavities are needed, then the designer should be looking at using a notch style cavity instead.

Vari-notch Cavity Stage

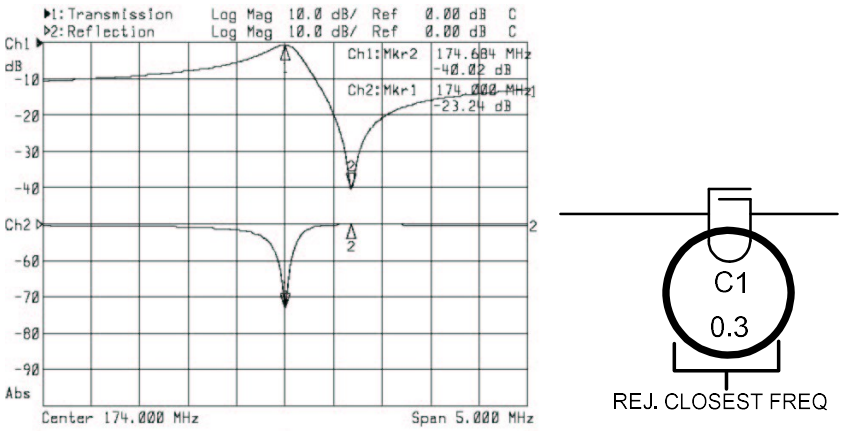


Figure 2: Vari-notch Cavity Curve and Symbol

Once all remaining receive frequencies to be rejected are within 700 kHz of the pass frequency, then the designer begins to use notch style cavities to eliminate them one by one. There are two types of notch cavities that can be utilized in a combiner design.

A vari-notch cavity is usually the next filter type to be considered, and is characterized by a pseudo-bandpass response with a fairly wide and deep notch. This type of cavity is usually selected to eliminate target frequencies roughly 250 kHz and further away from the pass band. The designer will add one of these cavities with the notch set on the closest target frequency until there is adequate isolation. Because the notch tends to be rather wide, it is possible to eliminate other frequencies that fall close to the notched frequency. The process of adding vari-notch cavities is then repeated to eliminate the remaining target frequencies.

Series Notch Cavity Stage

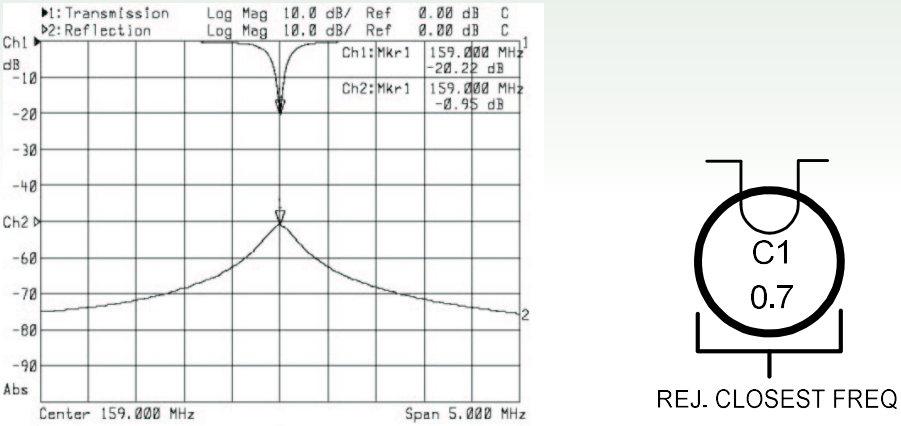


Figure 1: Series Notch Cavity Curve and Symbol

Finally, the designer will look at any remaining frequencies that have not been eliminated by the T-Pass, bandpass, and vari-notch cavities. The remaining frequencies will usually be ones that are very close to the pass frequency. At this point, the final cavity to consider is the series notch cavity. The series notch cavity response has a fairly wide pass band, but a single sharp notch for eliminating single frequencies. This notch can tune in closer to the pass frequency than the notch in a vari-notch cavity, so it is generally used to notch from around 100 kHz to 250 kHz away from the pass band.

While series notch cavities technically can notch as close in as 50 kHz, the notch becomes more shallow at closer frequencies, and can become prohibitive in the number of cavities needed and the incurred insertion loss. Often, a muting schedule is used at these closer separations instead of notch cavities to keep costs and losses down. Much like the vari-notch cavity, series notch cavities are applied to each remaining target frequency until all receivers have been adequately filtered.

Continuing the Process

Upon providing adequate isolation against all receivers for a transmitter, the process of filter selection is repeated for the next transmitter. This process is repeated until the entire transmit combiner is constructed, providing adequate isolation for all transmitters against all receivers. Usually, the same process is then followed for the receive side, in providing filtering for the receivers to protect against the transmitters.

Once all of the transmitters have adequate filtering applied then the design process for the transmit combiner is mostly complete. Transmit combiners will usually have isolators included to provide additional transmit to transmit isolation. Receive combiners may include amplifiers to mitigate cavity loss. In the end, most VHF combiners will end up with a combination of T-Pass, bandpass, Vari-notch and series notch cavities to provide adequate isolation.

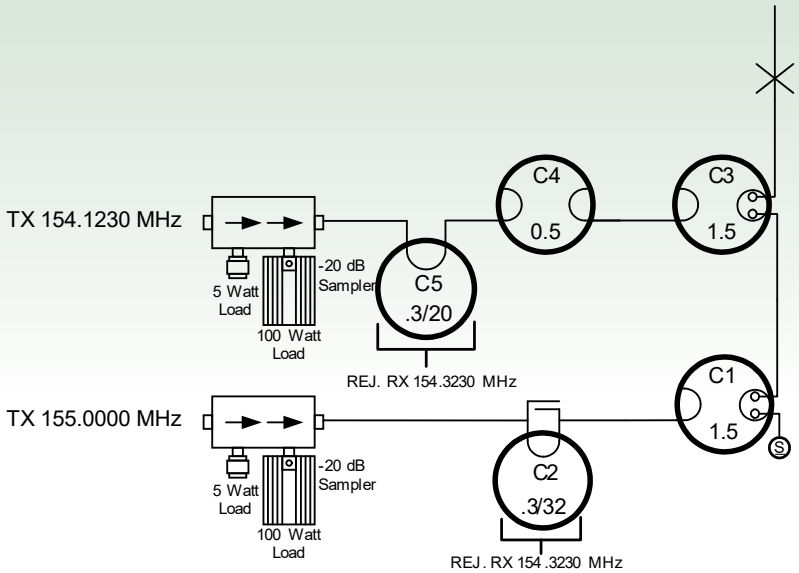


Figure 1: Example TX Combiner

Conclusion

The end design of a combiner is ultimately defined by two primary sources: customer defined parameters, and the types of filters available to the designer. The designer usually has an array of various filter types that are used for various situations. Proper selection of these combiner components can lead to a more efficient, better-performing system. However, the transmit noise and receiver desense performance of the individual radio, the number of antennas and their positions on the site, and the transmit and receive frequency selections are customer-driven parameters that often have a greater effect on the overall system design than the types of filters that are ultimately selected by the designer. By choosing their parameters wisely, and understanding the consequences of these choices, a customer can drive the end design of a combiner toward a smaller, cost-efficient, and lower loss design.

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