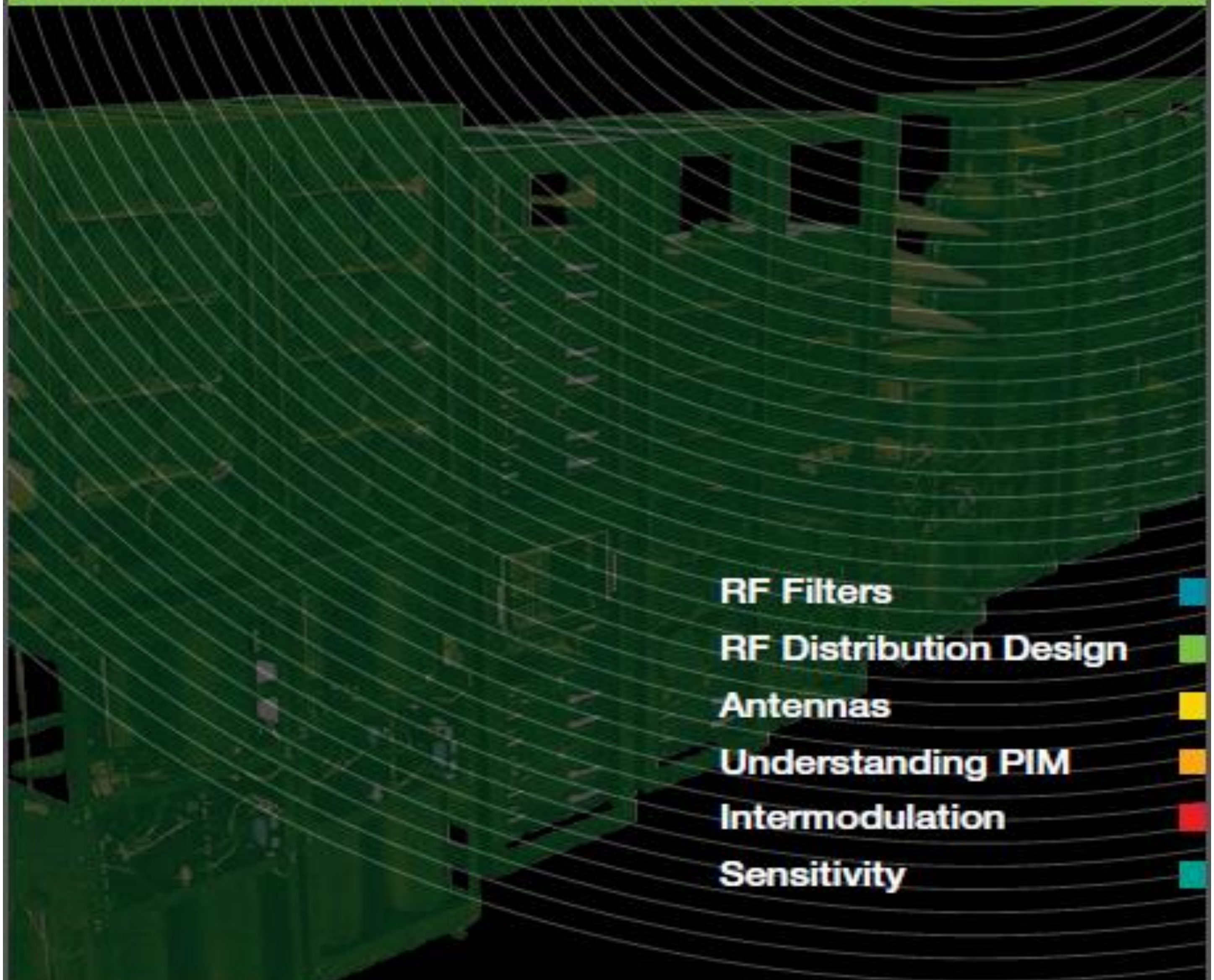
dbSpectra

TECHBOOK

Series

RF DISTRIBUTION DESIGN



- RF Filters
- RF Distribution Design
- Antennas
- Understanding PIM
- Intermodulation
- Sensitivity

What is dbSpectra TECHBOOK series

To ensure a high-quality RF distribution system there are subjects that must be understood. dbSpectra "**TECHBOOK**" series provide simple discussions of important topics and show ways to ensure the highest quality is designed into the delivered system. Understanding these topics and working with our professional RF system engineers, will allow the design requirements to be met in the first design. Each booklet will discuss topics in as low a technical manner as possible. The **TECHBOOK** series is the first step in understanding complex and complicated RF Topics. Detailed training is available from dbSpectra that will provide more in-depth discussions and understanding. Contact dbSpectra for more information and to schedule training.

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Introduction

This booklet examines the design process of creating a system of components that work together to form an RF distribution system. An RF distribution system allows multiple repeaters or base stations to be connected to a minimal number of antennas and properly function together without intra-system interference.

Manufacturers have worked hard to develop design best practices used in their products. The focus of these design best practices is important in developing a high-quality RF distribution system that resists interference and provides the best sensitivity and effective radiated power (ERP) possible.

An RF distribution system is defined as all components between the radio unit transmit antenna port or receive antenna port and antenna. Performance is emphasized in this booklet as well as how economics can be applied without jeopardizing performance. Not all designs will require the hardened components or robust filtering needed in a urban environment or on a congested RF site with many collocated radio systems. Options will be discussed when applicable.

Overview of RF Distribution Components

Before the best practice of a design can be discussed, a basic understanding of the components used is required. This overview will outline the components used in the RF distribution design. Other TECHBOOK series cover these components in detail.

Transmitter Cavity Combiner – The transmitter combiner allows multiple transmitters to use a common antenna. Additionally, the most important function of the transmitter combiner is the selectivity that reduces the inherent radio sideband noise thus protects other receivers on site. Without this selectivity, the sideband noise emitted would degrade receivers thereby reducing coverage. Due to close-in carrier selectivity limitations there is a minimum transmitter to transmitter frequency spacing required to use a cavity combiner. As frequency separation decreases, insertion loss increases but with decent separation, a cavity type combiner's loss is low. The transmitter combiner also provide protection from the generation of transmitter IM through the selectivity and the use of ferrite isolators.

Hybrid Transmit Combiner – A hybrid combiner uses various forms of hybrid configurations in conjunction with ferrite isolators to combine multiple transmitters. There is no transmitter to transmitter frequency spacing limitation as with the cavity combiner but the insertion loss can be significantly higher depending on the number of transmitters combined. The theoretical loss is 3 dB for two channels and increases by 3 dB every time the number of channels doubles. The loss of the ferrite isolator on each input plus the connector and cable losses adds to the theoretical losses. Because there is no selectivity in this combiner a transmit filter must be used **ALWAYS** on the output of the hybrid combiner to minimize sideband noise. If a transmit filter is not used the sideband noise emitted by the hybrid combiner will be higher than any of the individual transmitters.

Transmit Window Filter – Adding a transmit window filter on the output of a cavity combiner provides additional transmit sideband noise attenuation to further protect system receivers from degradation. A transmit window filter may also be included in the transmitter combiner design to minimize the number of filters and selectivity required to reduce the transmitter sideband noise. Having a single transmit bandpass window filter after the combiner allows a single cavity network to perform the filtering of multiple cavities per channel. Additionally, the transmit filter minimizes PIM and the PIM requirements of the combiner. In many designs the transmit filter is the most economical component to enhance performance while minimizing the cost and size of the design. The family of milled window filters offered by dbSpectra provide this solution see ***Figure 1*** on next page:

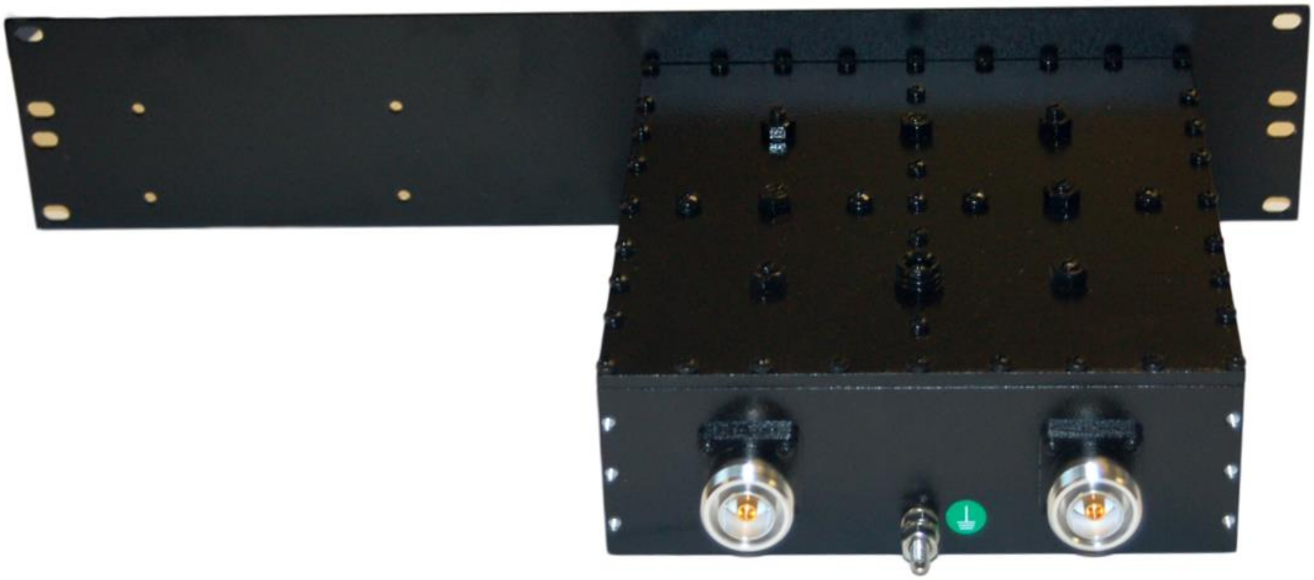

Figure 1: 700/800/900 MHz Transmitter Window Filter design

Receive Filter – The receive filter is extremely important to help achieve the best possible receiver sensitivity. A mistake made in some receive system designs is to minimize the receive filter selectivity and thus risk interference from other radios on site. At the higher frequencies, low noise amplifiers are used to improve system sensitivity over basic receiver sensitivity. This success is achieved only if the receive filter is properly designed. In cases where significant selectivity is required the receive filter may be divided into two sections (Pre-filter and Post-filter). The post filtering will follow the distribution amplifier and will not affect sensitivity.

Antenna – The selection of the antenna is more than a coverage consideration. The selection of the proper antenna for a specific application must not be based solely on gain. Other factors must be considered such as the following: power handling, PIM rating, connector type, size, feed design, and gain are just a few considerations when selecting an antenna.

Connectors – Connectors are more important today than a decade ago. Use of certain types of connectors or reuse of connectors can deteriorate operation. Newer types of connectors, such as 7-16 DIN and mini-DIN, are available that can reduce the risk of interference and preserve operation.

Tower Top Amplifier – One of the most discussed topics is when and why to use a tower top amplifier (TTA). The TTA is important at higher frequencies to overcome the severe cable loss penalty. The TTA can provide the most noticeable improvement of any single component, but requires properly evaluating the application. In most cases use of a TTA is exclusive to higher frequencies above 700 MHz. Advantages below 700 MHz are minimal in most applications.

Other issues that must be considered

Not only are the hardware components important but other considerations must be evaluated and accounted for in the design. A few of these are:

Frequency Plan – The frequency plan is critical at the lower bands (VHF and UHF). At the higher bands (700/800/900 MHz) the frequency plans are organized and the selection of the hardware is not determined by the assigned frequencies which allows the same hardware to be used on all sites. In the VHF and UHF bands frequency allocations and availability of suitable channels by licensing authorities makes the risk of internal interference higher and hardware selection difficult.

A more complex set of frequencies makes the combining and multicoupling more complex and expensive. Attention and careful planning of the frequency plan can allow a properly operating radio system with a lower cost RF distribution system. When possible, design your frequency plan to the hardware not your hardware to the frequency plan.

Intermodulation Risk – Intermodulation occurs when two or more frequencies mix and produce multiple frequency products. Risk exists that one or more of these products may fall on or near a receive frequency. Where the mix takes place varies depending on the equipment and its configuration. Again, due to existing frequency allocations, VHF and UHF present the greatest risk of intermodulation issues. Intermodulation risk can be minimized with careful frequency and hardware selection. More information will be provided on intermodulation in a separate TECHBOOK.

Passive Intermodulation (PIM) – PIM is the largest IM risk at VHF and UHF. The elimination of PIM relies on selecting and configuring the correct hardware. See PIM TECHBOOK for more information.

Design Requirements and Considerations

Filtering Selectivity – The amount of isolation between transmitter and receiver systems is critical to the performance of a communication system. Isolation is obtained with filters and physical separation between transmit and receive antennas. Receive filtering is critical in the elimination of unwanted carriers. In a perfect world, the receive frequency is the only frequency the receiver sees and the transmit carrier is a pure single frequency carrier. This scenario does not exist in the real world. In the real world, dozens or more carriers are present at most sites but a compromise can achieve similar operational results. The first consideration that must be addressed is for what band the equipment is being designed. VHF, UHF, 700/800 MHz, and 900 MHz systems each have their own requirements, hardware, and challenges.

There are three isolation factors to consider when designing an RF distribution system. The isolation provided from transmit to receive frequencies, that provided by transmit to receive antenna physical separation and the isolation provide from receiver to transmitter frequencies by the receive filter. These components all focus on reducing or eliminating any destructive or sensitivity reducing RF levels arriving at the receiver frequencies.

- **Transmitter Combiner and Transmit Filter** Transmit filtering provides the ability to reduce unwanted emissions from being radiated or entering the receiver. This is ideally done in two stages to minimize insertion loss and maximize radiated power. The first stage is the combiner which combines the transmit signals together and provides the first stage of filtering. The transmit filter provides further attenuation of the sideband noise generated by all connected transmitters. *Figure 2* shows the application of the transmit filter and combiner in the transmit network.

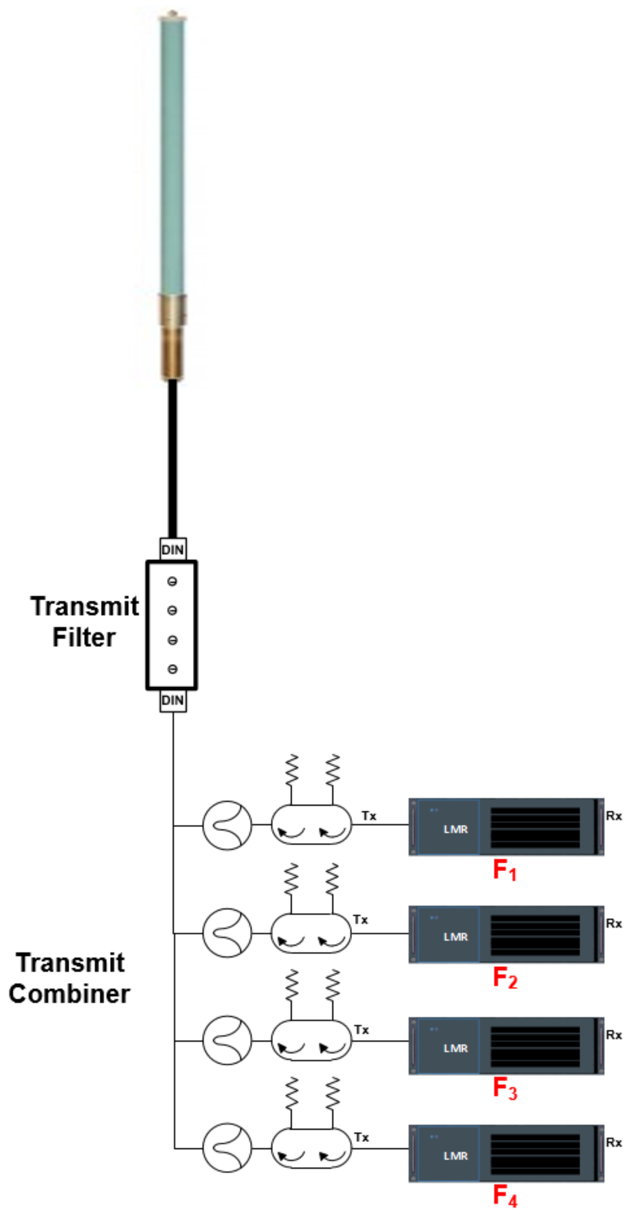

Figure 2: Transmit Combiner and Transmit Filter

- **Antenna Isolation** – Antenna isolation between the transmit antenna and receive antenna reduces both the carrier and sideband noise levels into the receiver. Antenna isolation is the most efficient means of protecting the receiver because it does not affect operation. The amount of antenna isolation delivered also determines the required amount of filter selectivity. ***Figure 3*** demonstrates the isolation provided for two 6 dBd gain VHF antennas mounted with horizontal (tip to tip physical separation). As can be seen in the graph, very little isolation is provided using horizontal separation without great spacing distance.

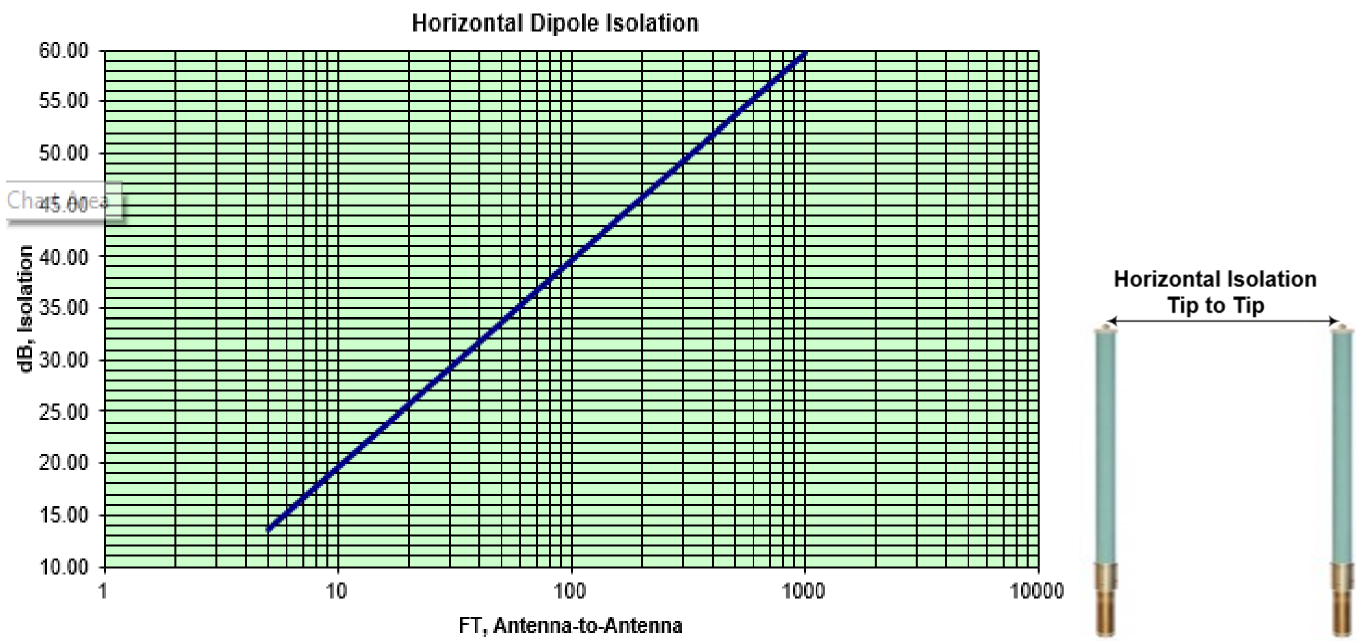

***Figure 3**: VHF Horizontal Isolation*

Figure 4 shows the amount of isolation obtainable with vertical physical separation. As can be seen in the graph, the vertical isolation is significantly more than horizontal. Note that gain antennas provide this degree of isolation. If unity (0 dBd) gain antennas are used isolation is reduced by 20 dB and the vertical isolation advantage is lost. Please see the Antenna TECHBOOK for more information on this subject.

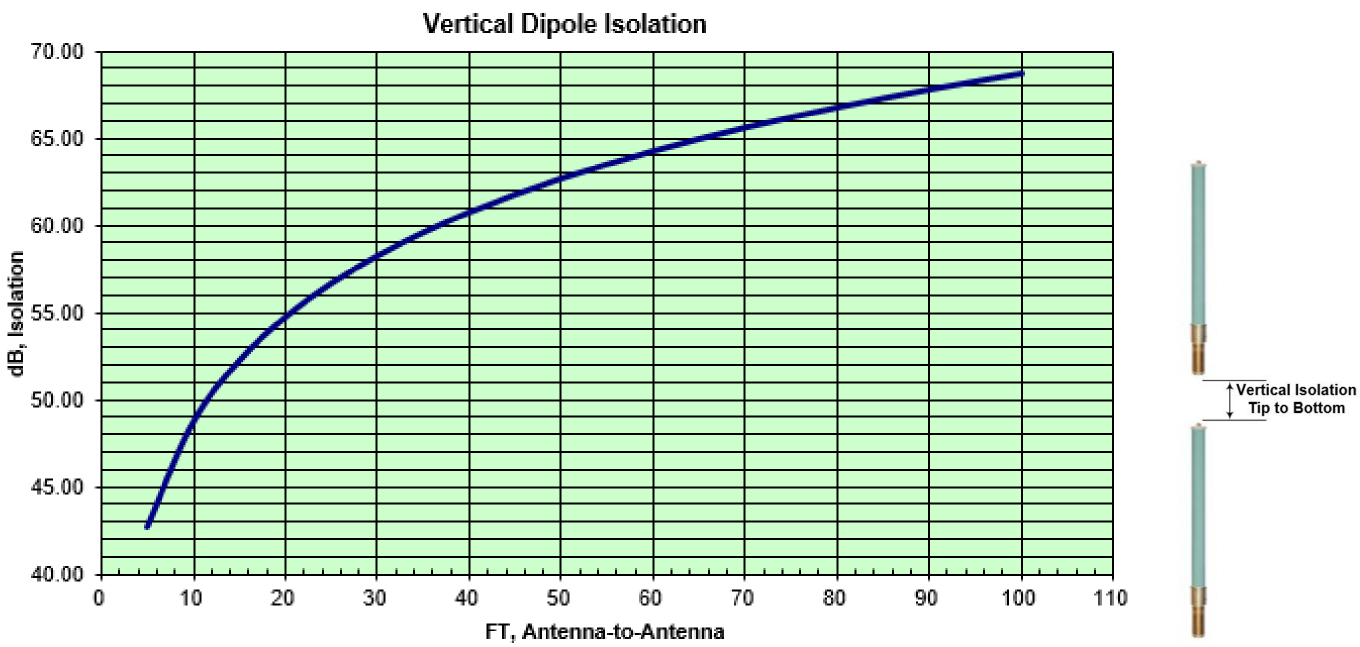

***Figure 4**: VHF Vertical Isolation*

- **Receive Filter** – Receive filtering, also called the preselector or receive window filter protects the sensitive amplifiers in the receive network. There **Must Always** be filtering between the antenna and the first amplifier. The amplifiers will be overdriven and operation degraded by high-level carriers if this filtering is not provided or is inadequate. ***Figure 5A*** shows the configuration of the receive filter in a TTA and NON-TTA application.

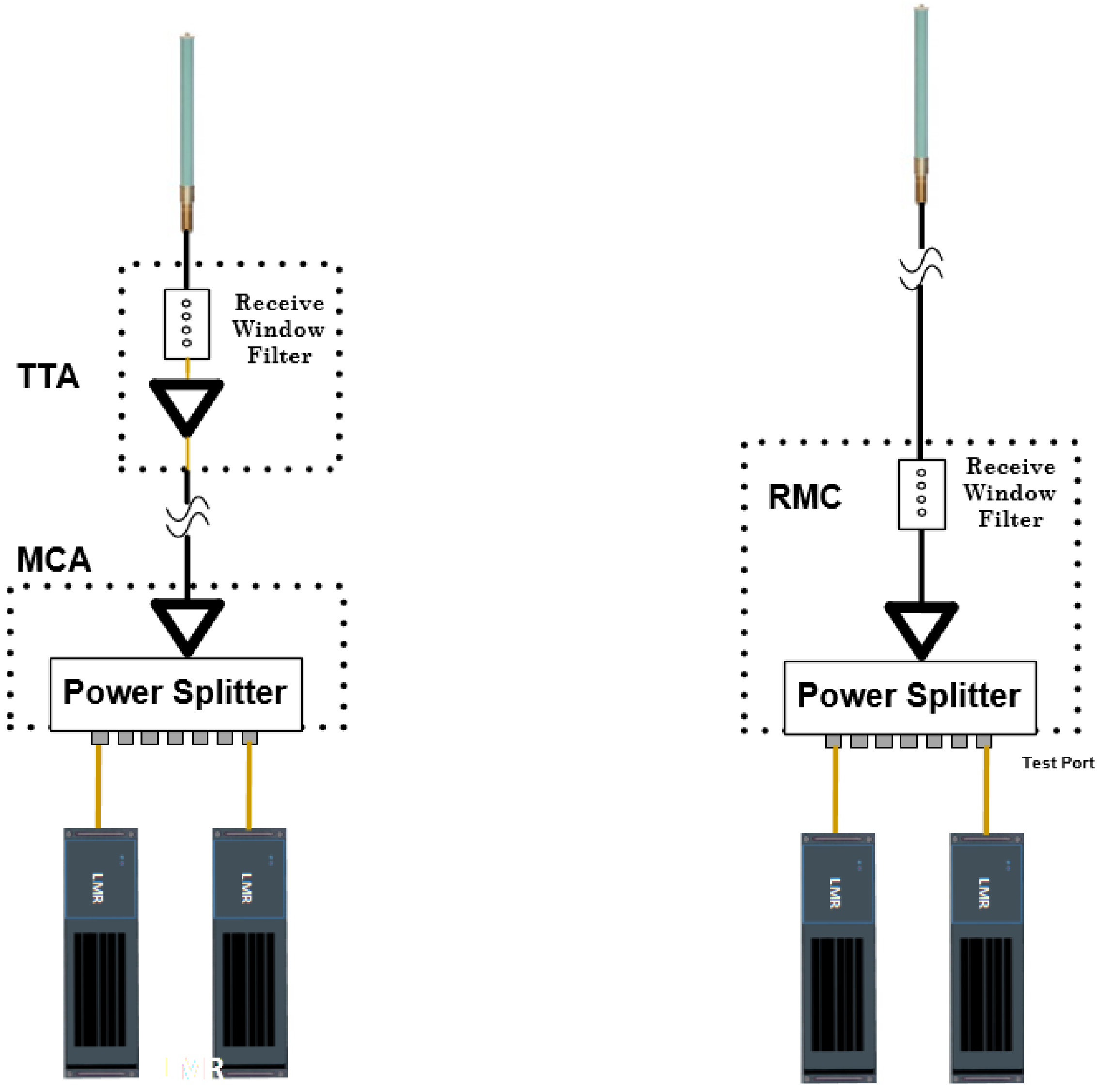

***Figure 5A**: Receive Filter application*

Band Plan

The band plan, as determined by the FCC or other country's controlling entities for each of the frequency bands determines the filtering required. The major question "How much selectivity is enough?" There have been many formulas and charts (such as transmitter noise/receiver desense, TNRD charts) used for determining the amount of selectivity or isolation required. An educated guideline developed over years of experience when designing the transmit RF network is to have a combination of transmit filtering and antenna isolation greater than 90 dB. Less may be possible, depending on the number of transmitters on site and the degree of protection desired by the end user. This degree of transmit isolation will reduce the sideband noise and protect the receivers from collocated transmitters.

The receive network should have between 90 dB and 110 dB of isolation at the closest transmit and receive frequency. This range of receive isolation reduces the high-level carrier of the transmitter to a level that will not affect operation. The higher isolation goal (110 dB) helps ensure the best possible receive sensitivity. ***Figure 5B*** demonstrates results that will be seen at the receiver if the receive filter and antenna isolation are properly designed. Receivers should not be exposed to carriers within the receive band above -35 dBm and system transmit carriers should be reduced below -55 dBm to provide optimum receiver operation.

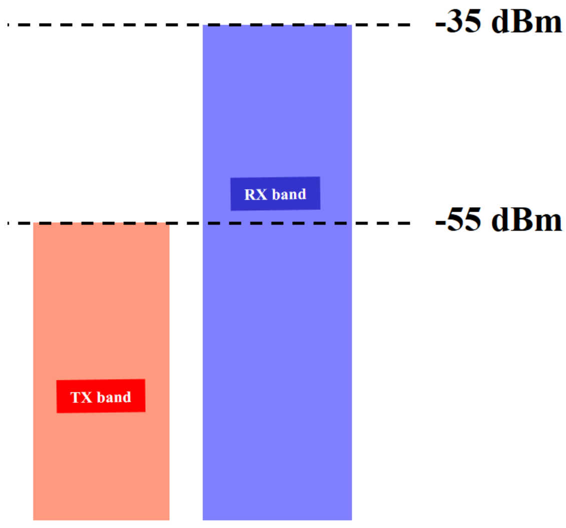

***Figure 5B*: Maximum carrier level at receiver**

RF Distribution System Design

Designing filtering for a band plan requires not only understanding the relationship between the transmitter frequencies and receive frequencies, but also the relationship between each other. The relationship involves understanding the bandwidth and guard band of the frequency plan, the transmitter spacing, and multiple band relationship. One of the most important issues that must be considered is frequency separation. To properly identify and understand frequency separation we must consider all frequency separations within our design, see ***Figure 6***. Understanding the frequencies used in the bandplan can be complicated but optimum operation depends on designing to the frequency plan.

An ideal band plan would use the customer frequencies only. This is risky since other carriers on site could cause interference and may need to be included in the filter design. Finding and identifying the frequencies that can cause interference may require physical monitoring of the spectrum before the design. Collecting spectrum information on site allows the site characteristics to be included in the design. In most cases the transmit frequencies of other radios on or near the site is all that is required because to protect every receiver on site within a design can be very costly and require extensive filtering.

The first step in defining the frequency plan is to understand and define the guard band and bandwidth. These determine the filter application as well as difficulty in designing the hardware.

Guard Band (G) – The guard band is the frequency separation between the lowest transmit frequency and the highest Rx frequency. This separation applies to the closest separation between the transmit and receive frequency bands. The guard band is the frequency spacing the filters use to develop the selectivity required. If a bandplan has a small guard band the filters must provide higher selectivity at a closer separation and likely be larger in size. Understanding the guard band allows the correct filtering to be used. Depending on the frequency band there may be multiple guard bands to consider. 450 MHz utilizes three bands (450 MHz, 460 MHz, and 470 MHz). These bands can interact and require multiple filters and complex filtering to operate together.

Bandwidth (B) or Frequency Spread – Bandwidth/Frequency spread is the difference between the highest and lowest transmit frequency. This identifies the spectrum that requires no selectivity and minimum insertion loss. The bandwidth is important to ensure all the system frequencies will fit within the design. Additionally, if other transmitters on site are considered, the receive filter may require special selectivity to prevent these transmitters from interfering with the receivers.

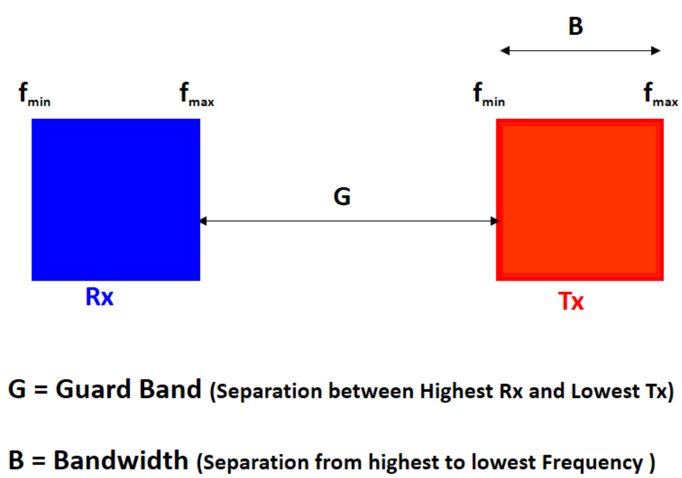

***Figure 6*: Guard band/ Bandwidth definition**

Graphical examination of frequency plan

Looking at the frequencies as raw numbers provides little insight into design problems or other issues in creating a RF distribution design. ***Figure 7*** shows an example frequency plan for UHF.

Transmit	Receive
453.24375 MHz	458.24375 MHz
453.53750 MHz	458.53750 MHz
460.03750 MHz	465.03750 MHz
460.13750 MHz	465.13750 MHz
460.58750 MHz	465.58750 MHz
463.27500 MHz	468.27500 MHz

Figure 7: Raw table of customer frequencies

Laying out the frequencies graphically allows the spectral relationship of the frequencies to be considered and the complexity of the filters to be fully understood. ***Figure 8*** shows one example of graphically laying out the frequency plan shown in Figure 7. For easy identification, the transmitter frequencies are red, and the receive frequencies are blue. In this example, there is a significant amount of information available to the design engineer.

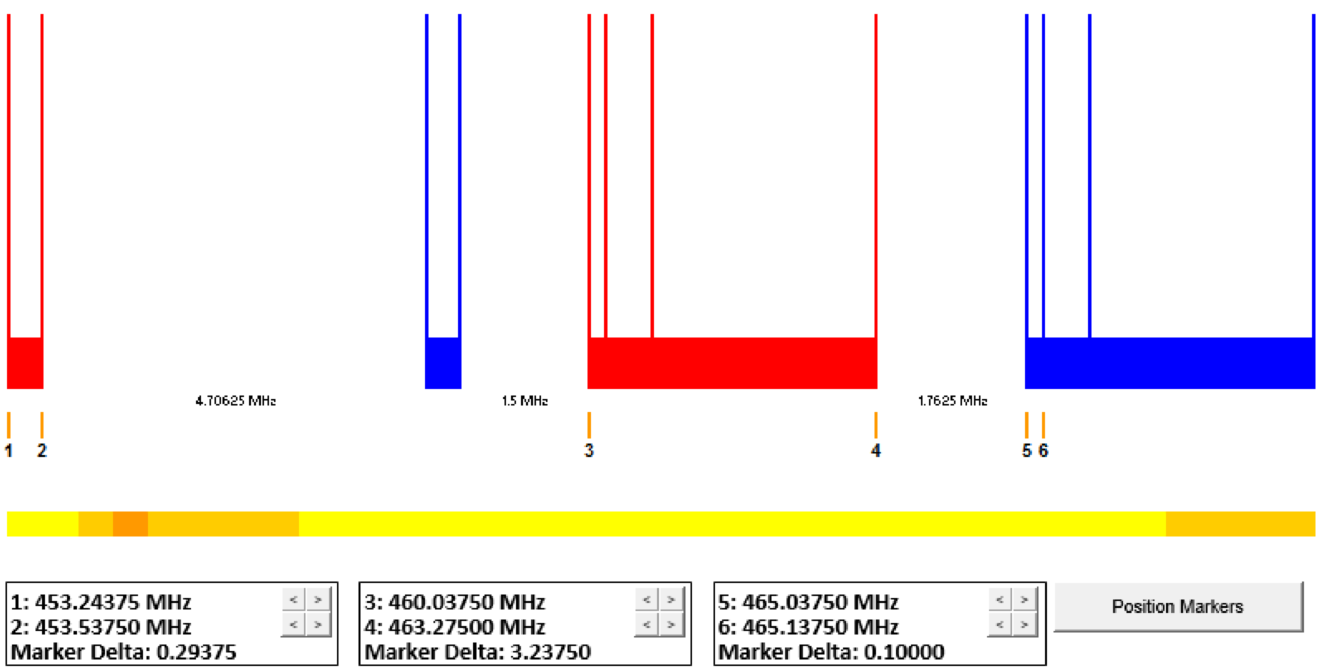

Figure 8: Graphical layout of frequency plan

Bandwidth – The bandwidth/frequency spread of the transmit and receive band is important because it identifies the bandpass required for the transmit filter and the receiver receive filter. In this example the frequency plan will require two bandpass filters for both the transmit filter and the receive filter. Looking at markers 1 and 2 and markers 3 and 4 shows the two bandpass filters will need to be at least 294 kHz wide and 3.3 MHz wide respectively.

- **Guard band** – The Guard band of this frequency plan is 4.7 MHz between the 450 MHz receive and transmit band, 1.5 MHz between the 450 MHz transmit band and 460 MHz receive band, and 1.7 MHz between the 460 MHz receive and transmit band.
- **Tx – Tx spacing** – Markers 5 and 6 show the closest spacing of the transmitters which is 100 kHz.

The information obtained from examining the frequency plan graphically allows the hardware requirements to be selected. For this design the hardware selected must comply with the following requirements:

- 450 MHz receive filter passband must be greater than 300 kHz
- 460 MHz receive filter passband must be greater than 3.3 MHz
- 450 MHz transmit filter passband must be greater than 300 kHz
- 460 MHz transmit filter passband must be greater than 3.3 kHz
- 450 MHz receive filter must provide selectivity within 4 MHz on the low side and 1.5 MHz on the high side
- 460 MHz transmit filter must provide selectivity within 1.7 MHz on the low side
- Transmit cavity combiner must accommodate 100 kHz or use two combiners

Identification of the bandplan characteristics allows the engineer to select the hardware to use. The dual band receive filters can use standard receive filters that allow 3.5 MHz bandpass and 1.5 MHz guard band (The filter provides 45 db of isolation at 1.5 MHz. Within the limits of the filter design, the 460 MHz receive filter can be narrowed down if desired.

Example Design of frequency plan in Figure 7

- **Electrical Design** - ***Figure 9*** shows the transmit combiner and receive filter design requirement for the frequency plan in Figure 7. This design requires two window filters for both the transmitter combiner and receive window filter. ***Figure 10*** shows the design rules of the transmit network. ***Figure 11*** shows the receive system and the dual receive filter required.

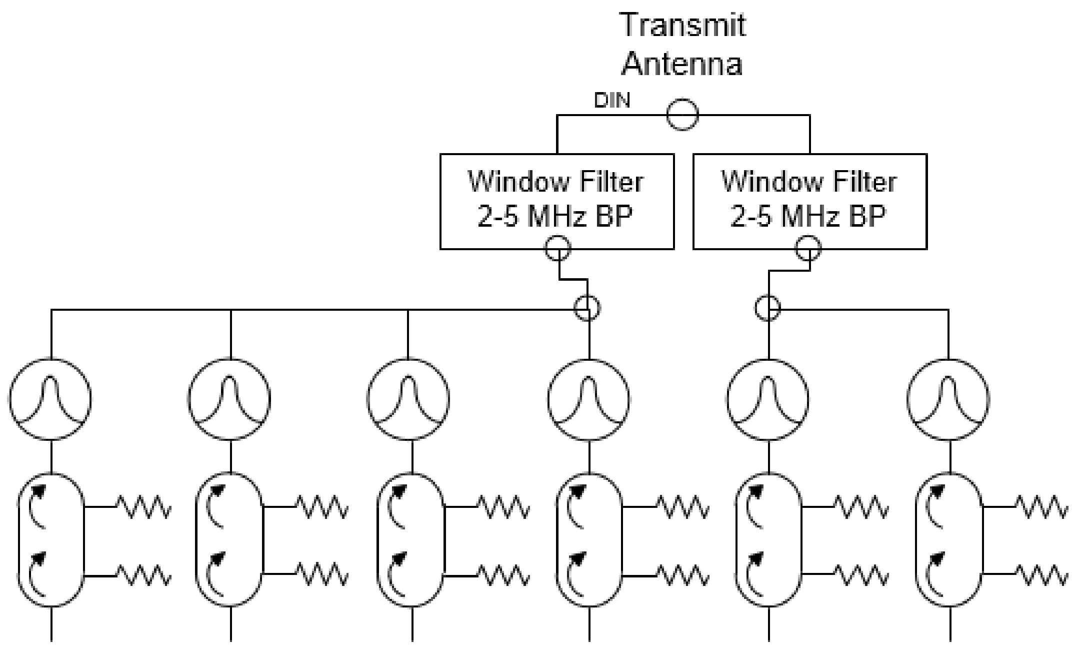

***Figure 9*: Guard band/ Bandpass definition**

<u>Transmitter Combiner Specifications</u>

- Frequency range: 450-470 MHz
- Dual Sub-band Diplexer
- Minimum TX-TX separation: 100 kHz (60 kHz with 100 W loads)
- Insertion loss
- Isolation at receive frequencies: >45 dB
- Dual stage isolators
- Antenna to TX and TX to TX isolation: >50 dB
- Connectors:
  - Input: N Female
  - Output: DIN Female

***Figure 10*: Guard band/ Bandwidth definition**

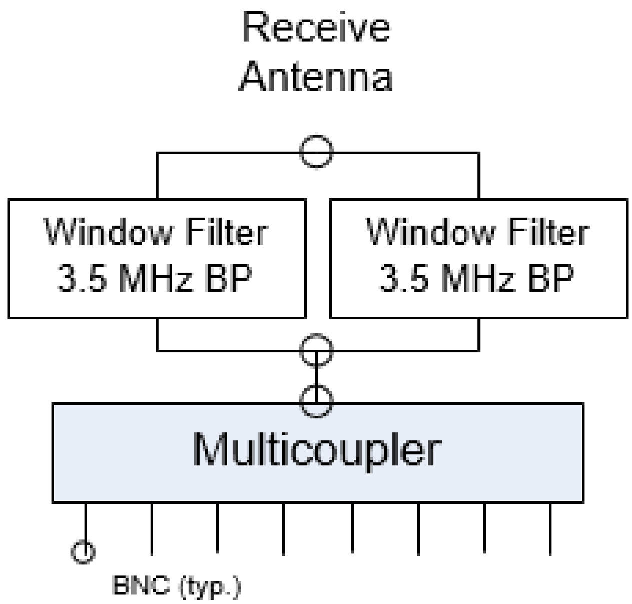

Figure 11: Receive distribution system

This same technique should be used for designing any VHF or UHF RF distribution system. VHF will be more difficult because the frequency plan is disorganized and not uniformly laid out. In some cases the transmit and receive frequencies may be interlaced, creating a complex filter design requirement. There may be multiple bandwidths to consider and the guard bands can be very small. For this reason, the hardware for VHF is many times custom and designed to the frequency plan. When working at VHF expect larger filters, more filters per frequency, and higher costs.

Best Practice RF Distribution Design Rules of Thumb

- No 3rd order IM on a site
- Use PIM rated components throughout transmit antenna network.
- Transmitter and receiver antenna isolation: > 45 dB
- Transmitter noise attenuation at the receive frequencies: > 45 dB
- Receiver isolation at transmit frequencies: > 45 dB
- Total isolation: > 90 dB with combination of filters and antenna isolation
- Ensure RF signals entering the receiver are below -35 dBm
- Keep number channels in a VHF or UHF transmitter combiner to six or less due to PIM risk.
- Keep number of channels in a 700/800/900 MHz combiner to less than 12 channel due to power risk.
- No high power multi-channel duplexing, use separate transmit and receive antennas.
- Use 7/16 DIN connectors on transmit antenna network
- Use proper torque values for all 7/16 DIN connectors
- Use PIM rated transmit antennas
- Use PIM rated lightning protection devices

Release History

Release 1.0 – March, 2017

Release 2.0 – September, 2019

Notes