Application Note AN-003: *UAS Communications System Improvement through Proper RF Filtering*

Introduction

This application note covers the use of RF filters to improve the performance of a communications system, with examples of RF filtering solutions for unmanned aircraft systems (UAS). RF filters prevent unwanted signals from entering sensitive receivers and causing desensitization (also known as “desense”). Further, RF filters prevent out-of-band signals from transmitters that can affect other communications systems, or violate FCC rules if the out-of-band signals fall in frequency bands that the operator is not licensed to transmit.

One of the most commonly overlooked building blocks of a UAS communication system is proper RF filtering. Whether your system is for command and control or streaming sensor data such as live video, proper filtering can be the key element in achieving the communications range or data throughput desired. Unfortunately, it is often not realized that filtering is needed until the flight test phase of the development cycle – when daily costs are high and many eyes are on the project.

Figure 1. An example of an effective RF filter is NuWaves’ C-Band Cavity Filter. This filter only allows signals in the 5.8 GHz frequency band to pass through, reducing out-of-band interference received by a receiver, or radiated by a transmitter.

Why is RF filtering so important? Simply put, filters reduce the interference in the environment that affects the performance of the communication system, and reduce the interference caused by the communication system. The lack of RF filtering can affect the performance of the UAS in a number of ways:

- Communication range is reduced due to the desensitization of the radio receiver by RF signals in the environment. This interference may be caused by a multitude of sources, including other aircraft operating in the area, dense WiFi activity (especially for 2.4 GHz and 5.8 GHz systems), or other communication systems on the UAS platform.

- Interference produced by the communication system desensitizes other communication systems on the UAS platform, reducing the communication range of those systems.
- Interference produced by the communication system may interfere with the reception of GPS signals by the UAS platform, reducing the accuracy of the GPS tracking, or worst case, causing total loss of GPS reception.

RF filters reduce both the interference from other systems and the interference produced by the communication system itself by blocking RF energy outside the frequency range of operation. Think of it as trying to hold a conversation in a crowded room with several other conversations occurring at the same time. It is difficult to hear the person you are speaking to with all the noise. You have to raise your voice to be heard by the other person, which adds to the volume of noise in the room. If you take your conversation to another room away from the crowd, it is much easier hear the other person and there is no need to shout to be heard – this is the affect that filtering has on your communications system.

If your UAS communication system is not meeting the expected performance, consider adding filters to your design. Filters are easy additions to the system: filters can be small and lightweight, do not require electrical power to function, and are generally low-cost items. Filtering can make a significant difference in the performance of your UAS.

RF Filtering

Starting with the basics, RF Filtering can be defined as:

- The rejection of undesired frequencies through the system.
- The passing of desired frequencies through the system, with minimal loss or distortion to the signal.

There are four types filter responses available to the designer:

- Lowpass: all frequencies from DC to the cutoff frequency are passed through the system.
- Highpass: all frequencies above the cutoff frequency are passed through the system.
- Bandpass: only the frequencies between the lower and upper cutoff frequencies are passed through the system (example response shown in ***Figure 2***).
- Bandstop (or Notch): all frequencies between the lower and upper cutoff frequencies are rejected, while the frequencies below the lower cutoff and above the upper cutoff frequencies are passed through the system.

Each filter response serves a specific purpose in the system design. There are also trades to be considered for each response, including insertion loss, ultimate rejection, shape factor, size, and cost.

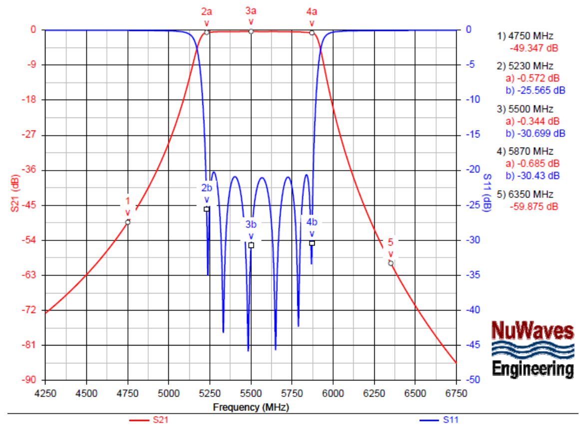


Figure 2. Frequency Response of the C-Band Cavity Filter shown in Figure 1 (Bandpass Filter). Cavity Filters provide high ultimate rejection, with low passband insertion loss.

Receiver Desense

Airborne platforms create unique challenges for the communications system engineer. The close proximity of the multiple systems on the platform will cause interference that can degrade the performance. For UASs, potential for harmful interference is exacerbated by the small airframe. The interference can be mitigated through the use of RF filters.

The ability of a radio system to receive and process an incoming signal is based on a number of factors. First, the signal presented to the receiver must be of sufficient strength, which is determined by the receiver sensitivity of the radio: the minimum received power level at which a receiver can accurately decode data from a signal. Receiver sensitivity is calculated by the following equation:

Receive Sensitivity = 10 * $\log_{10}$(kTB) + NF + SNR, where

k – Boltzmann's constant = 1.38 x 10-23 Joules/Kelvin

T – Temperature in Kelvin

B – Bandwidth of receiver front end

NF – Noise Figure (dB)

SNR – Signal to Noise Ratio (dB)

Preservation of the receiver's sensitivity is critical as for every 6 dB decrease in receiver sensitivity, the communication range is cut in half. The loss receiver sensitivity due to external factors is known as receiver "desense."

Strong RF signals entering the receiver is the most significant cause of receiver desense. The affect that the interfering signal has on the receiver's ability to decode the desired signal is dependent on the receiver's bandwidth, or the frequency range over which the receiver is "listening." If the interfering signal is within the receiver's bandwidth, there are two options available to the systems engineer: use an RF filter to filter out the interfering signal, or terminate the interfering signal at its source. Note that RF filtering is only an option if the interfering signal is on a different frequency than the desired signal.

The best option to prevent receiver desense is to reduce or eliminate the interference at the source. The source of the interference is likely to be another system on the platform. Electromagnetic interference (EMI) from other radios, electric motors, and other electronics may be the cause. Radios with poor isolation between the transmit and receive paths within the radio, and unfiltered RF power amplifier harmonics that fall in the receiver's bandwidth will desense the receiver.

UAS Application Examples

Consider the following example of a UAS platform, communicating with a ground station. The UAS in ***Figure 3*** has a communications system with a receiver sensitivity of -95 dBm. The RF signal strength of the ground station is 40 dBm. As the UAS travels away from the ground station, the received signal strength decreases to the point that the signal level falls below the receiver sensitivity of the UAS communications system, and the link is lost (maximum link distance). In this scenario, the RF environment is ideal.

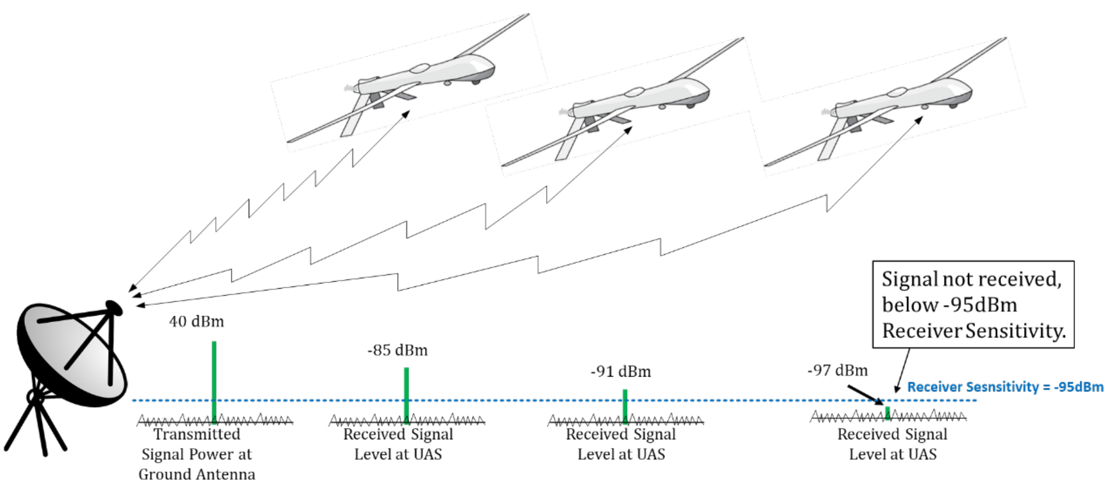


Figure 3. The UAS is traveling in an ideal RF environment, and is able to travel the maximum distance from the Ground Station before the link is lost.

Strong Signal Interference – Elevated Noise Floor

In the next scenario, shown in ***Figure 4***, a second UAS has entered the airspace near the Ground Station. The second UAS is broadcasting broadband noise across the frequency range of the receiver bandwidth of the first UAS. This broadband noise lowers the receiver sensitivity and greatly shortens the range of the communications system. A narrow bandwidth bandpass filter centered around the desired signal frequency will reduce the level of the interference in this scenario, but will not entirely eliminate the interference. The communications range will improve over the unfiltered scenario, but will still be reduced from the ideal scenario.

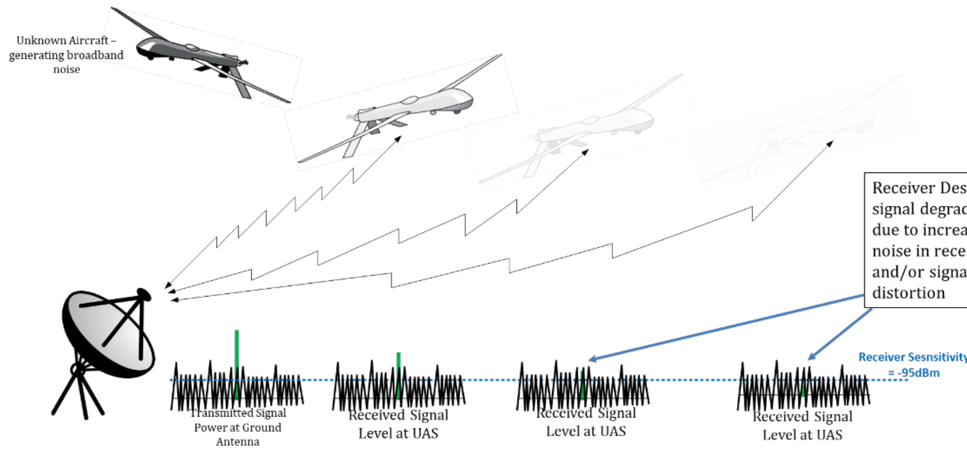


Figure 4. A second UAS, broadcasting wideband RF noise significantly reduces the communications range between the Ground Station of the first UAS. Using a narrow bandpass filter at the UAS receiver will improve system performance, but some noise will still enter the receiver and reduce the range.

In the next scenario, shown in ***Figure 5***, the GPS receiver on the UAS is desensed by the communications system on board the UAS. The transmit signal from the communications system is not filtered, and it is transmitting noise on the GPS frequency. With reliance on GPS for navigation, this situation could result in the loss of the UAS. The solution here is to place a bandpass filter immediately after the output of the communications system transmitter. This ensures any emissions from the transmitter that fall outside of the desired frequency range are attenuated, and the interference to other onboard systems is mitigated.

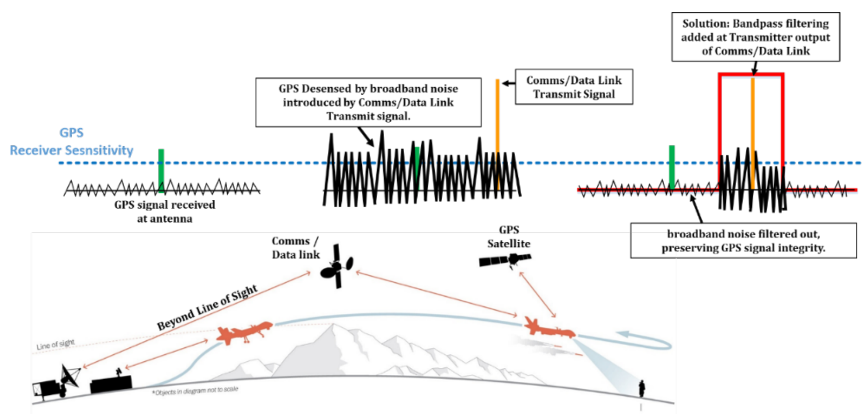


Figure 5. The transmitter on the UAS is transmitting RF noise in the GPS frequency band, causing the GPS receiver to lose GPS signals. By filtering the output of the transmitter, the interference to the GPS receiver is eliminated.

Strong Signal Interference – Receiver Overload

Next, the scenario shown in ***Figure 6*** involves a UAS approaching a strong shipborne transmitter near the frequency of operation of the UAS. As the UAS travels closer to the ship, the transmitter overloads the receiver, and the link to the Ground Station is lost. To mitigate the interference, a bandpass filter at the input to the receiver is used to isolate the desired signal from the interference. Note that a lowpass filter that passes the desired signal but not the interference signal is also appropriate, as well as a bandstop (notch) filter to "notch out" the interfering signal.

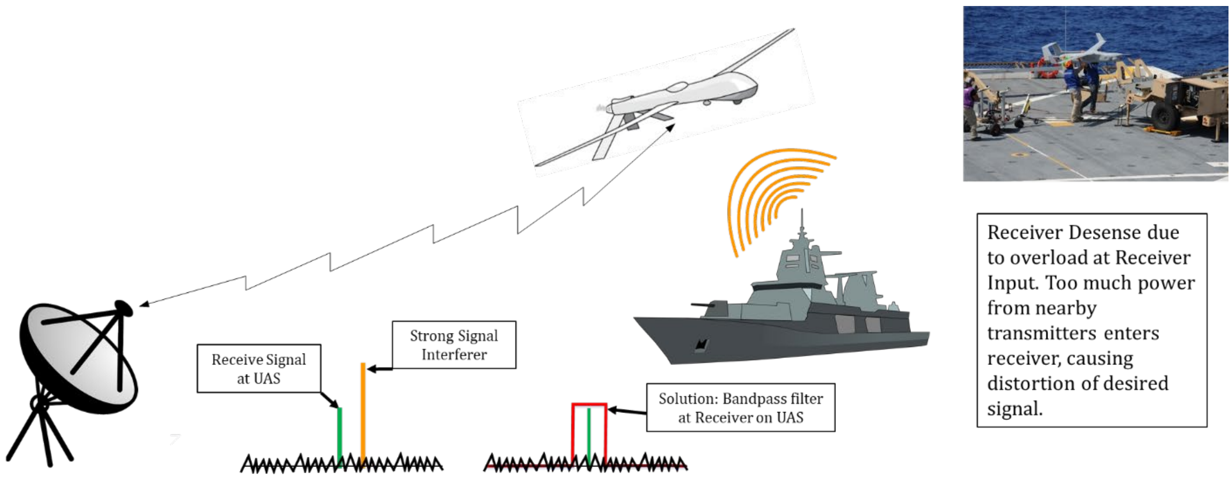


Figure 6. The presence of a strong signal transmitted from the ship overloads the UAS receiver, and the link to the Ground Station is lost. A bandpass filter on the input of the receiver filters out the interfering signal.

RF Power Amplifier Harmonics

Power amplifier harmonics can also be a source of interference, especially if a harmonic falls on or near the frequency of operation. In the scenario shown in ***Figure 7***, the UAS is receiving at 3.4 GHz, and is transmitting at 1.7 GHz using an RF power amplifier. The power amplifier is not properly filtered, and the second harmonic frequency is the same as the receive frequency. During transmissions, the receiver is unable to receive the desired signal. The solution is to place a harmonic filter at the output of the RF power amplifier. The purpose of this filter is to reduce the harmonic levels of the power amplifier and prevent interference to other systems on the platform, or in the vicinity of the UAS.

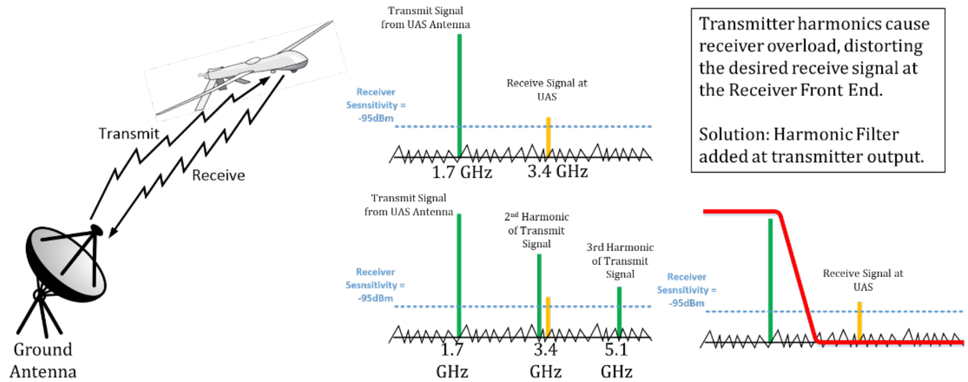


Figure 7. An onboard transmitter and RF power amplifier creates harmonic radiation that prevents the reception of the desired signal. By installing a harmonic filter on the output of the power amplifier, the interference is mitigated.

Co-located Transmitters

In the last scenario, shown in ***Figure 9***, the UAS payload includes both L-band and S-band communications systems. When the L-band system transmits, the noise received by the S-band system increases and prevents the desired signal from being received. Similarly, the S-band system increases the noise level received by the L-band system when transmitting. To mitigate the interference between the systems, it is necessary to install a filter at the outputs of both the L-band and S-band transmitters to prevent the noise from one system entering the receiver of the other.

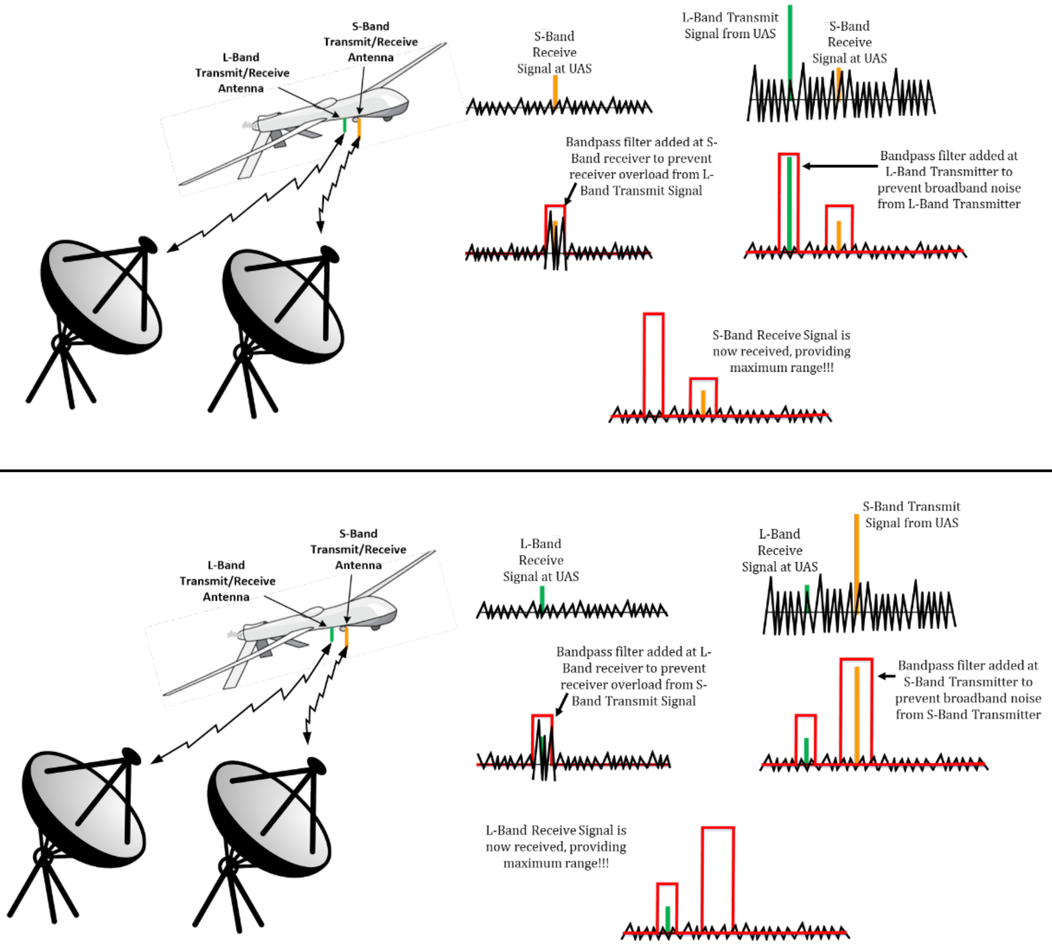


Figure 8. The broadband noise created by the L-band and S-band transmitters in the UAS payload are reducing the receiver sensitivity of the S-band and L-band receivers, respectively. By installing bandpass filters at the output of each transmitter, the interference is mitigated.

Designing-In Good Filtering

In the examples above, the RF filtering was implemented in a reactionary sense. An RF interference problem was identified, and the interference was mitigated by an external filter. While this is an acceptable solution, some of the above problems could have been avoided by incorporating filters in the design of radios, power amplifiers, frequency converters, etc. Incorporating filters into the RF module designs is more cost effective, as lower-priced filters can be used. Filters using microstrip or stripline topologies can be printed on to the printed circuit board (PCB) of the RF module, adding no appreciable per unit cost. Low cost surface mount filter “chips” are also a possibility. ***The takeaway is that multiple low-cost filters integrated into the module design will perform as well (or better) as a single, high-performance output filter, for much less per unit cost.***

Filter Topologies

The choice of filter topologies NuWaves designs falls into three major categories: cavity, microstrip or stripline, and lumped element. Cavity filters provide the lowest insertion loss and greatest ultimate rejection of the three topologies, and are capable of handling high levels of RF power (tens to watts to hundreds of watts). At radio frequencies, the materials used impact the performance of the filter. PCB materials have dielectric losses which increases the insertion loss of the filter, and reduces the Q-factor of the filter (how sharply the filter transitions from the pass-band to the stop-band). With cavity filters, the dielectric is air, which is essentially loss-less. Additionally, cavity filters are constructed from metals such as steel, aluminum, or brass, which shield the signal within the filter from other signals and interference from the outside. This provides a high amount of ultimate attenuation. Cavity filters may be installed internally or externally, depending on the space available. See ***Table 1*** below for the advantages and disadvantages of each topology.

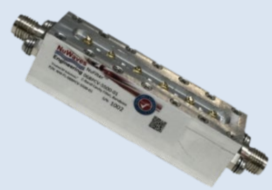
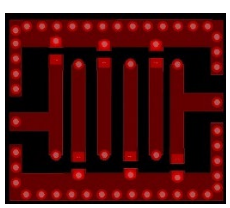
Filters that are printed on PCB substrates, using microstrip transmission lines (printed on the top or bottom layer of the PCB), or stripline transmission lines (printed on an internal layer of the PCB) are good choices for filtering between gain stages, post frequencies mixers to eliminate the image frequency, as well as output filters. The ability to integrate the filter directly into the PCB greatly reduces implementation cost and simplifies the manufacturing process. The filters may also be printed on individual daughter boards, and simply soldered to the main PCB. As described in the previous paragraph, the performance of the filter heavily depends on the PCB substrate. Low-cost FR-4 type substrates will perform adequately at frequencies up to 1 GHz, but as frequency increases, the loss due to the substrate becomes a critical factor. Therefore, higher quality low-loss microwave substrate is necessary at GHz frequencies.

Microstrip filters suffer from low ultimate rejection (-25 dB to -40 dB) due to the fact that the microstrip traces are exposed on the outer most layer of the PCB. The ultimate rejection can be improved by enclosing the filter with an RF shield. Stripline has a high ultimate rejection because the traces are sandwiched between two groundplane layers, inside the PCB. Substrate losses are greater with stripline than microstrip, because the traces are completely enclosed in substrate, where microstrip is half substrate, half air. In general, microstrip and stripline filters can handle several tens of watts. Insertion loss values are typically 1 dB to 4 dB, depending on passband bandwidth (narrower bandwidth with have more loss), and the selectivity of the filter. The physical size of these filters is dependent on frequency, where the traces are typically ¼ wavelength long. This dependency makes the filters impractically large below UHF frequencies, unless miniaturization techniques are employed.

Lumped element filters are a good option for filtering below 1 GHz, where cavity filters and microstrip/stripline filters may be prohibitively large. The term “lumped element” refers to the use of capacitors and inductors (i.e., physical components or “lumps”) to create the filter response. The physical size of lumped element filters is mostly driven by the power handing required: a low power handling requirement, such as < 10 mW, may be constructed of the smallest components available (0201 or 0402 sized components for example), while a requirement for hundreds of watts would require inductors and capacitors capable of handling the high current and voltage of the system. Similar to the microstip/stripline filters, lumped element filters may be integrated into the PCB design, integrated as a surface mount daughterboard, as a drop-in component, or a connectorized package for internal or external integration.

Passband insertion loss of lumped element filters varies greatly depending on the quality of components (Q-factor), selectivity required, and type of filter response (highpass, lowpass, bandpass, etc.). Therefore, the passband insertion loss is typically in the range of 0.5 dB to 5 dB. Ultimate rejection also varies, from up to 70 dB for a filter with a traditional Butterworth or Chebyshev response filter, to 25 to 35 dB for a bandpass filter with an elliptical response (high selectivity and low passband insertion loss (~1.5 dB typical) with lower ultimate rejection). A disadvantage to lumped element filters is high frequency performance, as capacitors and inductors are limited by the self-resonance frequency of the component. Self-resonance frequencies become a design concern above 1 GHz, and very few components have self-resonance frequencies above 6 GHz.

Table 1. RF Filter Technologies

Filter Technology	Example	Advantages	Disadvantages
Cavity Filter	 2.1” x 0.66” x 0.61”	- High rejection - Low insertion loss - Small size above 5 GHz - High power handling - High repeatability - Supports narrow band filters	- Large size below 5 GHz - Higher weight - Can only support bandwidths up to 30%
Microstrip and Stripline		- Light weight - Supports both narrow and wide bandwidths - Flexibility in design shape - High repeatability	- High insertion loss - Limited ultimate rejection - Low power handling
Lumped Element	 1.0” x 0.75” x 0.5”	- High design flexibility - Small size with low power handling requirements	- High insertion loss - Difficult to manufacture above 2 GHz - Large components necessary to handle higher powers - Repeatability is highly dependent on component tolerances

Summary

RF Filtering is a key component of any communications system to eliminate interference and out-of-band emissions. On small UAS platforms, the close proximity of multiple communications systems greatly increases the risk of harmful interference between the systems. The best engineering solution is to integrate RF filtering into the RF modules to ensure a spectrally clean transmit signal, or to block out-of-band emissions from desensing a receiver. However, this is often not possible when integrating COTS RF components, as the integrator has no control over the filtering within the module. Therefore, external filtering is required. With proper filtering, multiple communications systems can be employed on a single platform, with little to no degradation in performance.

NuWaves Engineering offers a full spectrum of RF filtering solutions to able the systems integrator to achieve the highest performance from their RF communications systems. From custom cavity filters designed and delivered in as little as two weeks, to microstrip/stripline and lumped element filters designed to meet stringent filtering requirements, NuWaves has a solution to advance your mission.

NuWaves Engineering is a premier supplier of RF and Microwave solutions for Department of Defense (DoD), government, and industrial customers. An RF engineering powerhouse, NuWaves offers a broad range of design and engineering services related to the development and sustainment of key communications, telemetry and electronic warfare systems, as well as a complete line of commercially available RF products. NuWaves' products include wideband frequency converters, high-efficiency and miniature solid state power amplifiers and bidirectional amplifiers, high intercept low noise amplifiers and miniature RF filters. NuWaves Engineering…Trusted RF Solutions™.

Contact Ryan Foster, Director of Product Solutions, at (513) 360-0800 ext. 154, or visit www.nuwaves.com for more information.