Reduce SWaP, Increase Performance of Phased Arrays with an Innovative Filtering Approach

The spectral environment is quickly changing today. It's becoming more crowded, which is resulting in an increase in spectral noise. This is presenting a variety of new challenges for RF designers, both in terms of the architecture and power needed to transmit and receive signals and the types of jobs filters need to perform in receivers (Rx) and transmitters (Tx). And the changes we are seeing now are just the beginning. As FCC Commissioner, Michael O'Rielly said in 2020, "In an ever-increasingly wireless world, each megahertz is being strenuously fought over. Any effort to repurpose a commercial band to new and different uses, will not occur without a huge fight."

These battles for bandwidth are happening now because many companies are creating product roadmaps for the next three to five years and they see limitations. As a result, in 2020 in the United States there were multiple high-profile conflicts over pieces of the RF spectrum. One major ongoing dispute is happening in the multichannel video distribution and data service (MVDDS) band between 12.2 and 12.7 GHz. The current use of this band is for delivering one-way direct broadcast satellite (DBS) service. However, one of the key stakeholders of this band, Dish Network, is lobbying to allow for two-way communication in this range as they build out their 5G mobile and fixed wireless broadband service. Companies such as AT&T and SpaceX are in stark opposition to this change, suggesting that two-way communications in the 12 GHz band poses an interference threat to DBS.

Another similarly controversial battle is also taking place in the mid-band at the government level between the Department of Defense (DoD) and the Federal Communications Commission (FCC) over converting portions of the S and C bands from military to commercial use. While this battle will likely intensify as more commercial space is needed in this range as 5G adoption grows, in 2020 the frequencies from 3.55 – 3.65 GHz were auctioned and auctions were set for 2021 for 3.7 – 3.98 GHz.

It's also important to note that with this second announcement, additional frequency reallocation was done as the FCC required existing satellite operators in this range to move operations to 4.0 – 4.2 GHz and that frequencies from 3.98 – 4.0 GHz were set aside a guard band.

As the number of bandwidth battles grows each year, resulting in a more crowded RF spectrum, RF designers will need to take advantage of innovative designs that minimize interference while also increasing signal transmission power. Since phased arrays can efficiently maximize gain and signal directivity and minimize interference for both Tx and Rx, adoption of this architecture by RF designers is growing. However, this means RF designers are on a quest for filtering options that can help meet the size, weight, and power (SWaP) needs and performance demands required by today's RF applications.

This white paper provides an overview of the filtering options available for phased arrays and explains how filtering in position 1 of a phased array, while a challenging task at higher frequencies, is not impossible as once believed. This paper also addresses how a solution for filtering at position 1 can minimize spectral noise and improve link budgets for phased arrays, both of which will help address the pressure RF designers are facing to continuously reduce SWaP.

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FILTERING IN A PHASED ARRAY: THREE OPTIONS

Like any RF system, a phased array needs filters that can perform three main jobs – mitigate spurious signals, meet interference compliance, and minimize system noise. In a phased array, there are three options for filter placements to perform these jobs as shown in Figure 1.

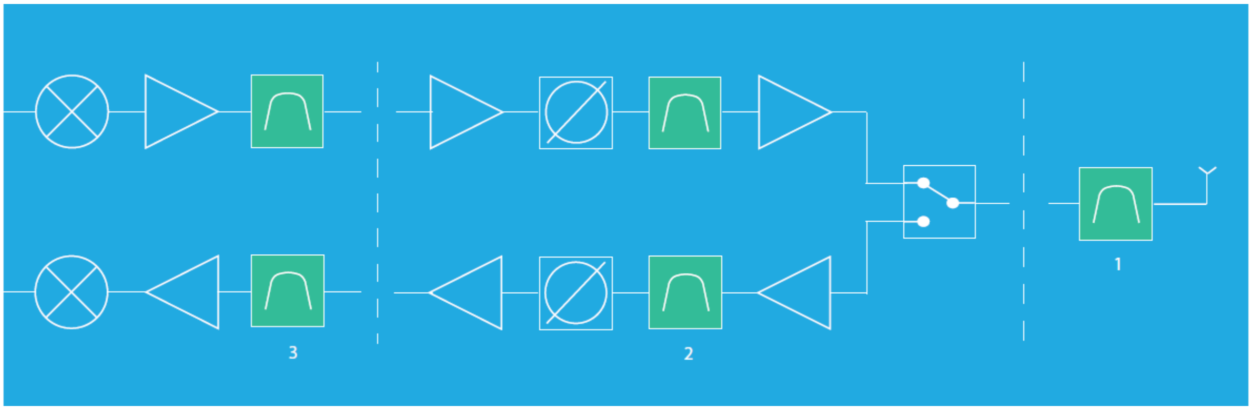

Figure 1. This single TRX path shows where filters could be added at positions 1, 2, and 3.

Today, filter placement in phased arrays at position three (F3) between the mixer and the feed network is most common. At F3, filters are typically used to suppress LO, image, spurious, and noise emissions and for suppression of incoming interferers that accidentally fall in the IF band after the mixer. Filtering at position 2 (F2) is similar to filtering at F3 except that it is best for applications where low loss is less critical and the application needs to filter incoming interferers relatively far from the desired frequency band.

Unlike filtering at F3 or F2, filtering at position 1 (F1) is done behind or in combination with the antenna element. An F1 filter suppresses interference and emissions outside the desired channel in Rx, and in the Tx chain it prevents signals from spilling over to adjacent channels, improving spectral noise emissions. Filtering at F1 does not allow any of the additional harmonics or noises from the last stage amplifier to pass through, unlike F2 or F3 which still allows for the opportunity for the last amplifier to pick up noise, amplify it, and send it out.

THE IMPORTANCE OF DEVELOPING A FILTERING SOLUTION FOR POSITION 1

As shown above, when placing the filter at F2 or F3 in a phased array the filter is behind the amplification or even the mixer stage, which means more hardware is needed to support the filtering. Adding hardware generally increases SWaP, which is the opposite of what most applications need today, and will likely make the array more sensitive to changes in loss as additional components are added in the RF path. Additional potential performance degradations in the array when filters are used at F2 or F3 could include the following:

- Receivers that are vulnerable to out-of-band transmitters and adjacent channel power spill over
- Transmit chains that need to be run at back off conditions from peak power and efficiency to limit spectral noise

Likewise, by incorporating filters at F1, filtering is now done at the beginning of the Rx path and at the end of the Tx path of the array, which offers multiple benefits versus filtering at F2 or F3. First, this configuration promotes radiation efficiency because it minimizes loss in the path between the last amplifier and the antenna. As a result, the area of the spectrum the application is most sensitive about is cleaned up significantly, spectral noise is reduced, and the link budget is improved, resulting in overall efficiency and performance gains.

To expand on the improvements to the link budget by filtering at F1, either less amplification for a given transmission distance is needed, or by reducing RF losses in the frontend, signals can be radiated further using less power. This is crucial to the effective, or equivalent, isotropically radiated power (EIRP) of an antenna, and will directly impact SWaP as power can be greatly increased even as size and weight of the array are decreased. Cost improvements are also possible when filtering at F1 because less expensive components can be used in the rest of the system if filtering is done before the signal reaches the amplifier or mixer.

With all these potential benefits, it seems clear that the Holy Grail for phased array filtering is position 1. So, why aren't all RF designers doing this? Let's take a look at the challenges presented by this filter configuration, especially at higher frequencies.

THE CHALLENGES OF F1 FILTERING AT HIGHER FREQUENCIES

The concept of F1 filtering is not new. In the Cold War Era, UHF phased arrays the size of a commercial building were used mainly for military applications such as radar and missile detection (Figure 2). In these applications with no SWaP constraints, maximized system performance by minimizing interference and reducing system noise. But, given the scale of these arrays compared to the small cells many RF designers are working on today, this really is a different technology we are talking about now.

Figure 2. The COBRA DANE radar is a single faced ground-based, L-band phased-array radar located in northern U.S. Indio-Pacific Command (USINDOPACOM) area of operations and operated by the U.S. Air Force. Source.

Additionally, while filtering at F1 in the S and C bands below 5 GHz for Wi-Fi and cellular services and ISM radio bands is done today, higher frequencies, especially above 10 GHz, require much different approaches. This is because the technology needed to minimize path loss often conflicts with packaging and integration requirements at mmWave frequencies since antenna size and wavelength are inversely proportional to operating frequency.

To overcome these limitations, we often default to more complexity, which lends itself to the design of suboptimal packaging or suboptimal performance for path loss. In addition to path loss, more complex systems have more transitions that present greater risk for suboptimal component matching and return loss. Without well-matched components and transitions, return losses increase. The result is additional system noise and lower output power for a given reference power level. So, we can surmise that a highly integrated feed and passive component solution minimizing transitions and path losses can provide numerous benefits to system performance.

THE LIMITATIONS OF TODAY’S COMMON FILTERS IN F1

As the FCC looks at opening more spectrum, mmWave will certainly become more crowded and these isolation and suppression problems will grow. It will also be harder to filter as more spectrum is used since there is generally just more noise to filter. As we see this shift in spectrum utilization, filtering at F1 will become more necessary. However, incorporating filters at F1 presents many new challenges that today’s array constructs and filtering technologies are not currently suited to address. To understand the current struggles with adopting F1 filtering, let’s first examine the limitations of some of the most common types of filters used today (Table 1).

Filter Technology	Max Frequency (GHz)	Frequency Tolerance (+/- %)	Qu Resonator	Relative Size	Integration Capable	Compatible with Element Level “Tile” Filtering (F3)	Practical Consideration
Dielectric Waveguide	30	1~2%	~300	2-3X	No	No	SIW - large & tolerance issues
On Chip (RFIC)	70	~2%	SOI ~25 GaN ~100	X	X	No	Not Cost Effective Not shielded/High Loss
Metal Waveguide	80	~1% @ Hi $	~2000	15X	No	No	Not Cost Effective
PCB - Stripline	~40	~4%	150	5X	X	No	Too Large for Arrays @F1 Tolerance / Yield Bad F2 & F3
LTCC	~40	2~3%	200	2X	X	No	Mech & RF Tolerance Issue with Integration
Thin Film Microstrip on Ceramic (Knowles)	70	0.3~0.5%	330	X	Yes - with “Brick” Array	No	Best Technology for F2 &F3 Filter Positions

Table 1. This table provides an overview of six of the most common filtering solutions used today and the limitations of each filter if used at mmWave frequencies in F1 of a phased array.

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Overall, in phased array applications, a solution cannot be considered unless the filter fits in the area of the antenna element grid. This is an issue with all six filters listed in Table 1 largely because as Q increase, so does the filter size. For example, RFICs are capable of meeting the small size requirement, but Q is low and cost is high. The closest possible solution shown in this table is the Knowles Precision Devices custom ceramic thin-film microstrip, which is currently a great option for filtering at F2 or F3.

FILTERING AT POSITION 1: A DIFFICULT, BUT NOT IMPOSSIBLE, TASK

Recently, at Knowles Precision Devices, our engineers developed a concept for F1 filtering at higher frequencies that provides excellent performance while also maximizing SWaP. This concept builds on existing Knowles Precision Devices technology that already offers the best tolerance, Q, and integration capabilities for filtering at F2 and F3 positions. Our design goes beyond using typical surface mount or board-integrated technologies, instead using 3D elements to create a panelized filter array (Figure 3).

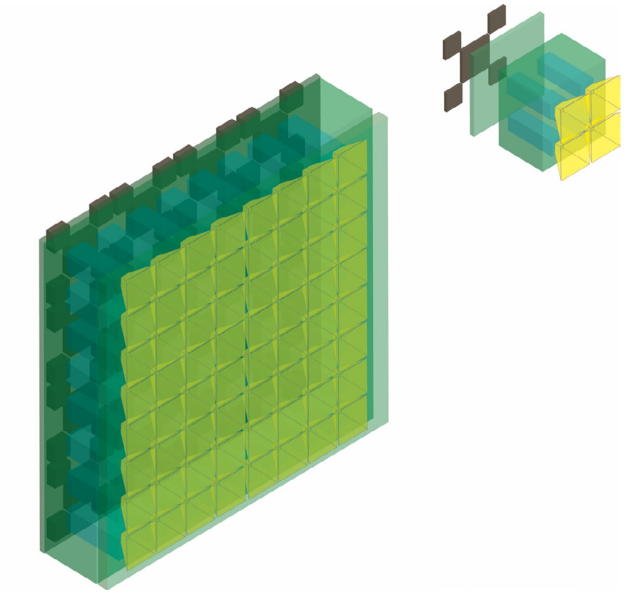

Figure 3. In this design, horn antenna elements are constructed on one side of the panel, while the feed to each antenna element from the ICs on the back of the panel is designed as an in-line filter, minimizing space and transitions.

Early prototypes have demonstrated the ability of this concept to scale in size up to 256 elements, with the possibility of larger arrays in the future. Smaller array blocks such as 2 x 2 or 4 x 4, can also be assembled in tiles, which lends itself to scalable array architectures.

As a result, our proposed filter array solution is a paradigm shift for mmWave phased arrays as we've shown that it is possible to integrate high-performance (resonator Qs on the order of 1,000), low-loss filters directly behind the antenna elements with integrated feeds and transitions. This is an ideal architecture for interference mitigation, array size reduction, and signal transmission power enhancements. The advantages of this construction are summarized in Table 2.

Characteristic	Description	Current "Tile" Arrays	New Filter-Array Technology	New Filter Array Technology w/Integrated Antenna Elements
Integration of Filter/ Element in Array (E.g. EESS-spec)		No Solution	256 Element Filter Panel	256 Element Panel (Filters + Antenna Elements)
Filter Frequency Tolerance Capability (+/- %)		------	0.1%	0.1%
Resonate Q (Filter Loss)			~1000 (~0.5dB)	~1000 (~0.5dB)
Antenna Feedline Loss		~0.5dB	N/A	~0
Radiating Element Gain (λ/2 x λ/2)	60^0 (Az &El)	5-6dBi Patch	N/A	~10dBi W.G. Horn
Radiating Element Gain (0.54λ x 0.74λ)	+/- 60^0 Az +/- 20^0 El	5-6dBi Patch	N/A	~14dBi W.G. Horn
Adjacent Channel Power, Filter can Reduce Spill-Over	Option to Run Less Linear?		Higher Tx Pwr. & η ??	Higher Tx Pwr. & η ??

Table 2. This table summarizes the benefits of the Knowles Precision Devices' 3D tile array solution for filtering at F1.

One of the biggest performance advantages of this 3D tile array is the increased element gain that comes from the integrated horn antennas. These antennas provide an inherent gain benefit over many common printed antennas, such as patches and dipoles. Horns also exhibit excellent wideband return loss, when compared to resonant antennas, further minimizing match losses in the system. This offers a positive benefit to the link budget versus using patch elements by 4 dB and up to 8 dB if a ± 20° elevation scan is adopted. An increase like this is significant because a 6 dB gain can double base station link range and increase coverage area by 400 percent, which will translate to needing fewer base stations, and ultimately lower costs for companies adopting this technology (Figure 4).

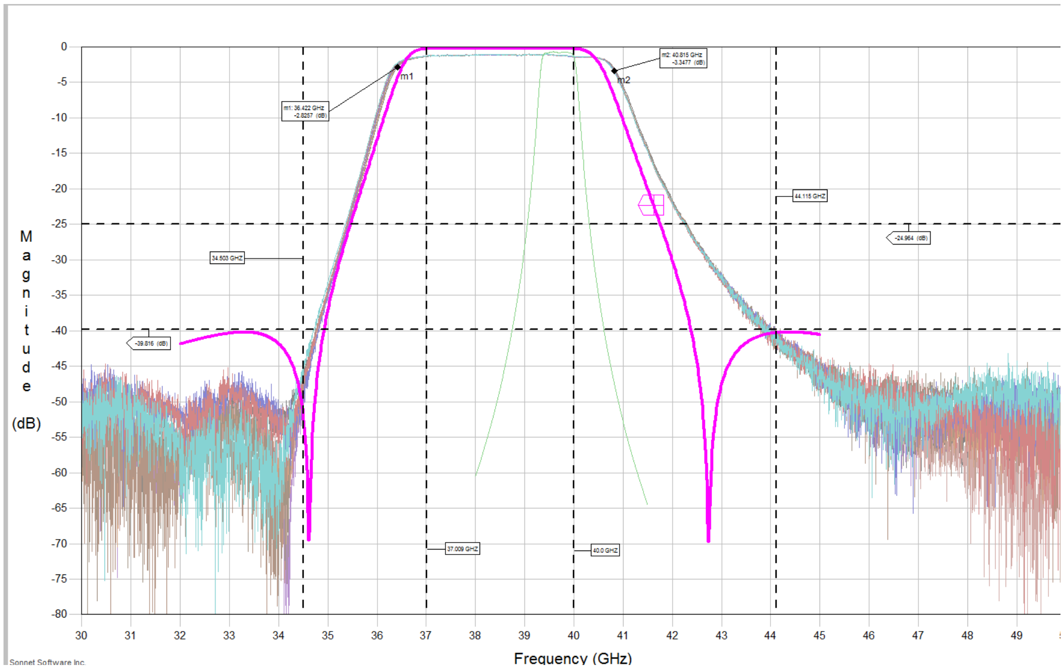

Figure 4. Typical performance of today's best filtering technology compared to a panelized filter array.

Said another way, we believe we can get equivalent EIRP with fewer elements, further improving the system's link budget. Fewer elements for a given EIRP will address SWaP concerns since a smaller array with fewer power divisions reduces power consumption and minimizes path loss, circuit complexity, cost, and size. A smaller array also reduces the size of the feed network and the number of costly ICs needed (Figure 5).

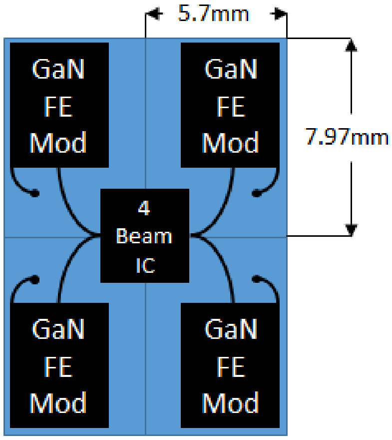

Figure 5. This configuration shows four GaN FE modules feeding into one IC in a compact form factor.

Another advancement increasing in popularity for phased array applications is channelization through dual polarization. Although isolation between these channels can be a challenge at times, this technology supports two orthogonally polarized signals being transmitted and received by a single antenna element simultaneously. This effectively doubles throughput in many applications while maintaining the same array footprint. Behind the antenna, the array system complexity effectively doubles to handle the additional channels. The panelized filter array may support dual-polarized applications, also within the intended array pitch. Size constraints are overcome by the design freedoms enabled by the core technology already discussed.

A PRACTICAL EXAMPLE FOR USING FILTER ARRAY TECHNOLOGY IN POSITION 1

One of the more severe interference issues we are already seeing today in mmWave occurs between 5G transmit channels adjacent to bands allocated to Earth Exploration Satellite Services (EESS). These satellites operate globally between 23.6 and 24 GHz, which is directly adjacent to the 5G n258 band that operates between 24.25 and 27.5 GHz. To prevent interference with the EESS, the International Telecommunication Union (ITU) placed limits on how much radiation may “leak” from 5G operations into the EESS band. Current solutions to this interference are to use some of the licensed 5G bandwidth as guard band, reducing channel capacity and revenue.

However, instead of using guard band as the solution, a future solution with high selectivity would be to incorporate this proposed Knowles Precision Devices 3D tile array for F1 filtering in 5G base stations for devices operating at 24.25 GHz. This would minimize spectral noise radiated by these base stations, which is good for all devices operating in and around this frequency, and also free up bandwidth that would no longer be needed as guard band.

PHASED ARRAYS WITH FILTERING AT POSITION 1: A GREAT FIT FOR MILITARY AND AEROSPACE APPLICATIONS

SWaP is critical for applications in mobile, shipborne, and airborne installations. This means companies like Ball Aerospace are manufacturing flat phased array terminals that operate in the Ku band. These phased arrays can be mounted flat on military equipment such as planes and tanks to deliver high data rate communication capabilities anywhere. Additionally, the ability to potentially implement this type of technology will become more important in the future as the 3.5 GHz band will be reallocated from military to telecom applications, and some military applications will likely need to move to higher frequencies.

HANDLING AN INCREASINGLY CROWDED SPECTRUM WITH PHASED ARRAYS AND AN INNOVATIVE FILTERING APPROACH

As the RF spectrum becomes more crowded, RF designers are challenged with addressing issues stemming from increased spectral noise and interference and figuring out how to enhance signal transmission power, all while reducing SWaP. While this sounds like a nearly impossible task, if filter manufacturers can develop a method to address the challenges of adding a filter in position 1 of a phased array, all these requirements can be met.

As discussed, this is a complex task because F1 filters need to perform multiple jobs since they are in both the Rx and Tx paths, and the filters cannot just perform one of these jobs well. But solving these complex challenges is where Knowles Precision Devices excels. We thrive on doing the hard things and developing innovative specialty components, which is why we are well-positioned to be the first-to-market with a viable solution to the challenges of using filters at F1 for mmWave applications.

We know this filter will need to act as Atlas holding up the rest of the system. As a result, our proposed filter array solution is a paradigm shift for mmWave phased arrays that integrates high-performance, low-loss filters directly behind the antenna elements with integrated feeds and transitions. For applications ranging from lower-frequency military and aerospace devices that need to focus on SWaP concerns to densely packed mmWave devices, this 3D panelized filter array solution is an ideal architecture for interference mitigation, array size reduction, and signal transmission power enhancements.

Instead of using F3 filtering like many RF designers are doing today, with this filtering solution for position 1, these arrays could also offer an improvement in link budget through increased coverage and enhanced performance while also seeing a reduction in size and weight of the array. The 3D panelized construction of the filter array supports weight and size reduction while the build technology and design reduce the number of elements needed. Fewer elements and transitions will reduce system power consumption. In the end, our solution will help RF designers relax some of the most difficult design challenges they are facing today.

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