Filter Technologies for 5G Communication Systems
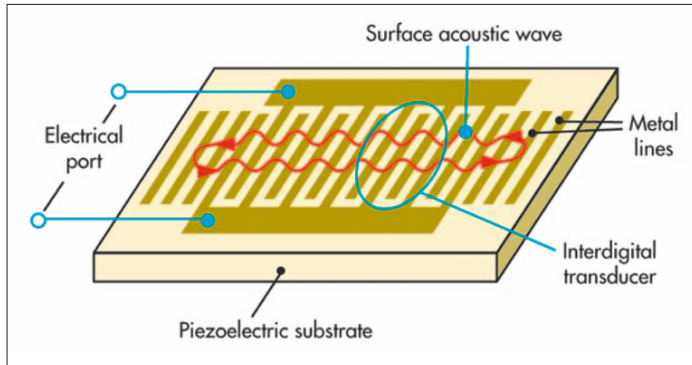

Figure 1: Basic structure of a SAW filter.

Figure 2: Cross-section of a BAW device.

This article examines the filter design challenges brought on by adopting newest radio technologies.

Systems offering large bandwidths through carrier aggregation and ubiquitous coverage through the massive overlapping of microcells will present both in-band and out-of-band interference that must be managed or eliminated. Likewise, implementation of massive MIMO will require compact filtering technology that mitigates the adverse impact of out-of-band interference on the uplink sum rate of maximum-ratio combining (MRC) receivers. This article examines the filter design challenges brought on by adopting these new technologies, the factors driving the physical, electrical, and cost restraints for 5G filters, and the supporting simulation technology that will help designers physically realize these components.

Current Mobile Device Filter Technology

Today's 4G (LTE) smartphones support in excess of 30 bands, requiring over 60 filters, many in the form of multiplexers. This number of filters consumes significant space and commands the largest share of the RF expense in the mobile ecosystem, putting considerable cost pressures on component manufacturers. The majority of these components are based on surface ac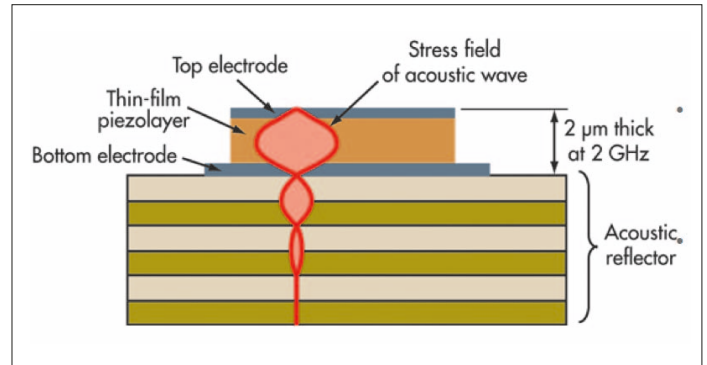oustic wave (SAW) or bulk acoustic film (BAW) technology. At the lower frequency range, SAW filters meet the requirements for low insertion loss and excellent rejection, covering broad bandwidths at a fraction of the size of traditional cavity and even ceramic filters. Meeting these requirements with the increase in frequency up to 6 GHz and mmWave bands is proving to be a challenge for these filter technologies.

A conventional filter stores the energy in the charge on capacitors and current in inductors, whereas BAW and SAW filters store the signal in acoustic resonators. As the name implies, surface acoustic waves propagate in the lateral direction with the shape and center frequency of the passband determined by the pitch, line width and thickness of the interdigital transducers (IDT) (Figure 1).

Because they are fabricated on wafers, SAW filters can be created in large volumes at low cost and filters/duplexers for different bands can be integrated on a single chip with little or no additional fabrication steps. Their key advantages are low cost, good relative bandwidth, and flexible port configurations.

However, due to the degradation in selectivity at higher frequencies, SAW filters have limited use above ~2 GHz and are mostly used for applications with modest performance requirements such as global system for mobile communication (GSM), code-division multiple access (CDMA), and 3G receiver front ends, duplexers, and filters. SAW devices are also highly sensitive to temperature as the stiffness of the substrate material decreases with higher temperatures, resulting in a diminished acoustic velocity and degraded RF performance. Typically, SAW filters operate in the mobile environment from 600 MHz to 2 GHz, whereas BAW filters operate between 1.5 and 6 GHz, putting them in the range for the lower 5G bands.

Temperature-compensated SAW (TC-SAW) filters are fabricated using a more complex and costly layer structure to increase the substrate stiffness at higher temperatures and extend their operating range. Since the process doubles the number of required mask layers, TC-SAW filters are more expensive to manufacture, but they are still less expensive than BAW filters. In comparison, BAW filters require about 10 times more processing steps than SAW filters. While BAW technology yields approximately 4 times more parts per wafer, it still has a higher cost per filter compared to SAW[1].

BAW filters fall into two general architectures, solidly-mounted resonators (SMRs) and film bulk

acoustic resonators (FBARs). With BAW filters, an electric field excites an acoustic wave which travels in a vertical direction through the body of a piezoelectric substrate, as shown in Figure 2. The resonant frequency is determined by the thickness of piezoelectric layer, which must be controlled to high accuracy. The result is a device with lower loss, higher Q, better power handling, and sharper corners (greater selectivity) compared to SAW filters operating at the same higher frequencies.

In the case of FBAR filters, the resonator is surrounded by an air interface created through etching or micro-machining. In contrast, acoustic reflectors below the bottom electrode of BAW-SMR filters allow them to be optimized for wideband performance in frequency regions where FBAR filters are more technically challenged. Although BAW-SMR and FBAR filters are more expensive to manufacture, their performance advantages are better suited for most LTE bands in addition to the PCS band, which has a narrow transition range of only 20 MHz between transmit and receive paths.

The construction of both BAW filter types allows them to handle higher RF power levels than SAW filters. They have less temperature variation than SAW devices, although not as good as a TC-SAW. The silicon dioxide (SiO_2) used in the reflector reduces the overall temperature drift of BAW significantly below what either traditional SAW or FBAR filters can achieve. Since the BAW-SMR resonator sits on a solid substrate, it can dissipate heat more effectively in comparison to FBAR, which dissipates heat laterally through a much smaller edge surface. This allows BAW devices to achieve higher power densities, allowing devices to handle upwards of 10 W, ample power for small-cell base station applications.

Leading SAW filter manufacturers include Qorvo, Qualcomm/TDK-EPCOS (RF360 Holdings), Murata, Panasonic (integra-

ted into front-end module from Skyworks), and Taiyo Yuden, whereas the high-volume BAW supply chain is dominated by Qorvo and Broadcom (Avago)[2]. Akoustis Technologies recently started shipments of its patented single-crystal BAW filter prototypes targeting 5.2 GHz for 802.11ac Tri-Band WiFi routers.

Various manufacturers use NI AWR Design Environment platform, specifically Microwave Office circuit design software and AXIEM and Analyst EM simulators to support their SAW/BAW filter design activity. With customized simulation libraries that implement acoustic wave filters using mathematical models directly in Microwave Office software, filter designers are able to focus on the combined electrical performance of the SAW/BAW devices with any off-chip resonators and electronic packaging.

Some of these devices have been implemented as PCells along laminate and low-temperature co-fired ceramic (LTCC) design kits for further product development and module integration. For SAW/BAW filter designers, NI AWR software offers:

- Complete front-to-back design flow in one integrated tool
- Integrate acoustic to electrical models
- Polymorphic/dynamic model support
- Sophisticated interconnect routing and modeling
- EM stack-ups with built-in shape pre-processing
- Integrated ACE automated circuit extraction and AXIEM and Analyst EM simulators
- Multi-technology device/module design flow

Spectrum and Architecture

The FCC has proposed RF bands for 5G of 3.5...6, 27...40 and 64...71 GHz. Each band will undoubtedly present its own set of issues and solutions for components in the radio design.
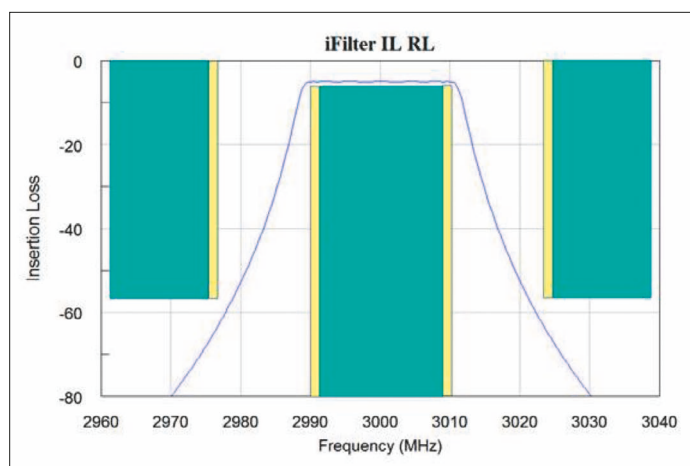

Figure 3: General filter S21 frequency mask showing passband and guard bands as simulated in Microwave Office software.

As a result, this significantly expanded spectrum is expected to result in a greater diversity of filter solutions than those serving the current mobile communication bands.

When allocating the band spacing for a new standard, the 3GPP must strike a balance between efficient use of available spectrum and the current capabilities of radio technology, including the state of filter design with regard to performance, cost and size. With 5G, the need for bandwidth has motivated the 3GPP to push for advances in radio access technology into the mmWave spectrum as well as select unused bands between frequencies that have been authorized for public safety and defense applications. As radio technology evolves, planners will look to maximize the use of this very valuable spectrum by limiting the unused space (guard bands) between adjacent bands, as shown in Figure 3.

High-performance filtering is critical as spectral crowding increases the need for interference mitigation and bandwidth utilization drives the need to reduce or even eliminate guard bands. Supporting technology will require very low-loss, raising the filters with exceptionally steep filter skirts (high selectivity), high rejection, and very little temperature drift. In addition to these stringent requirements, increased para-

sitics and substrate losses associated with the filtering device and its packaging (laminate) at mmWave frequencies will most certainly degrade performance unless properly addressed.

For the new 3.5...6 GHz 5G bands, the frequencies are close enough to the current mobile high-band that systems can employ a similar set of radio solutions. While the higher (6 GHz) frequencies will challenge the performance levels for current off-the-shelf components, the basic radio architectures employed in current systems are expected to work. From a filter perspective, the incremental higher frequency will be an additional barrier to SAW filters, which already struggle at the 2.5 GHz band. This leaves the field open for BAW and TC-BAW filters. However, the performance degradation of the current BAW technology at higher frequencies may disqualify these types of filters as well.

Filter technology will also be driven by size and integration concerns, which will be influenced by the system architecture. To illustrate, consider the receiver portion of a 4G base station that could be configured along two main architectural paths: an IF sampling receiver with heterodyne mixing stages down-converting the carrier frequency to the IF sampled by the ADC and a direct down-conversion receiver in which the carrier frequency is
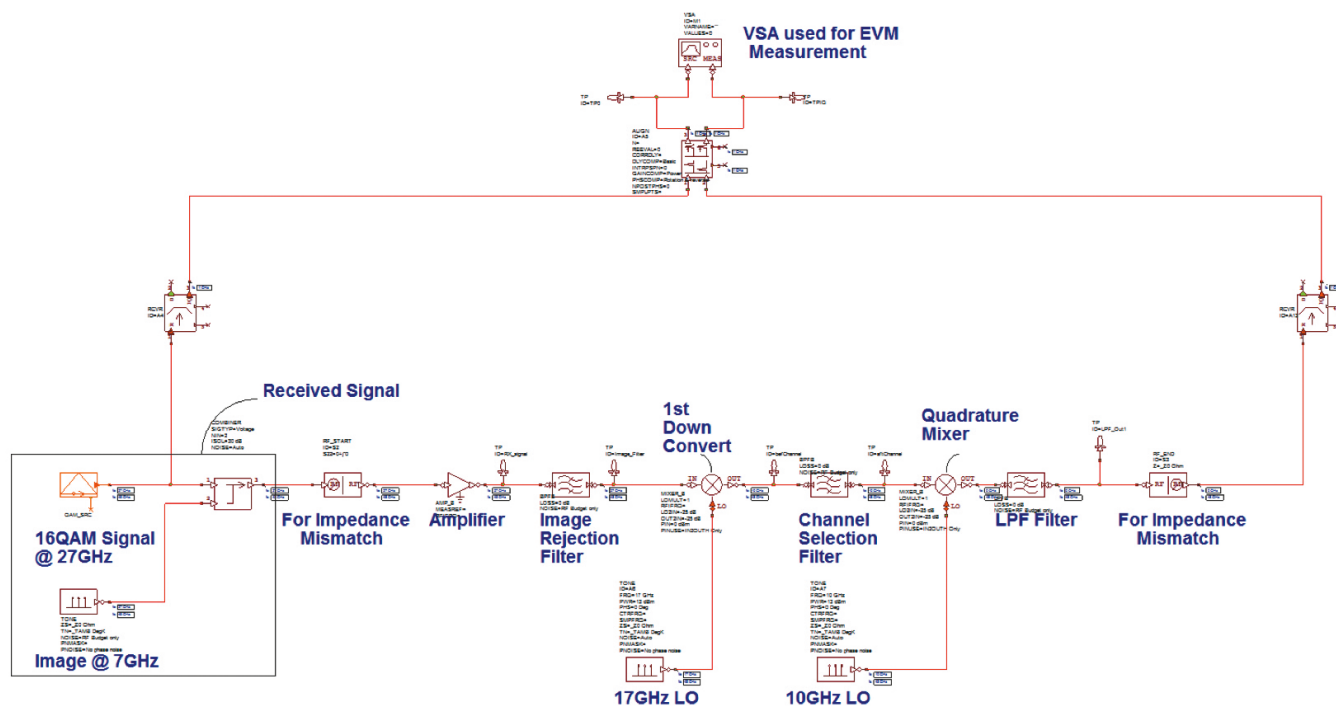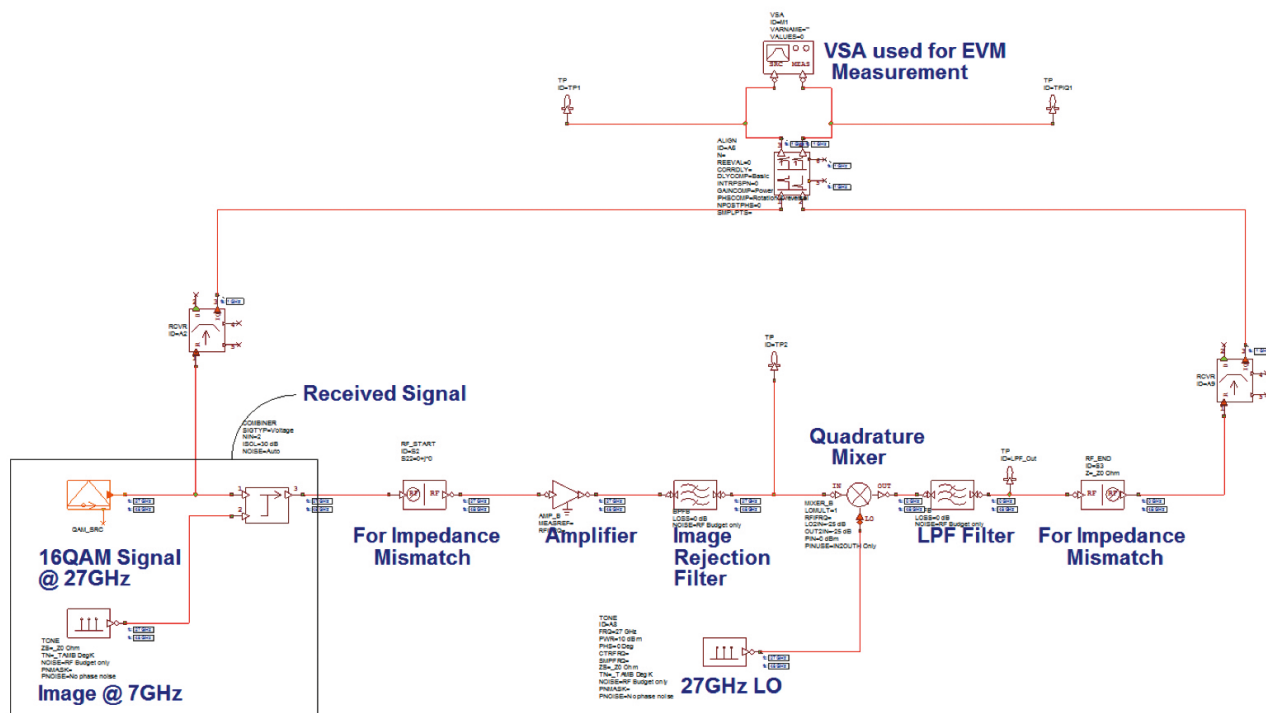
Figure 4: Two different system architectures in standard VSS example illustrate (filter) component specification impact on system performance for both a) heterodyne and b) direct-conversion receivers.
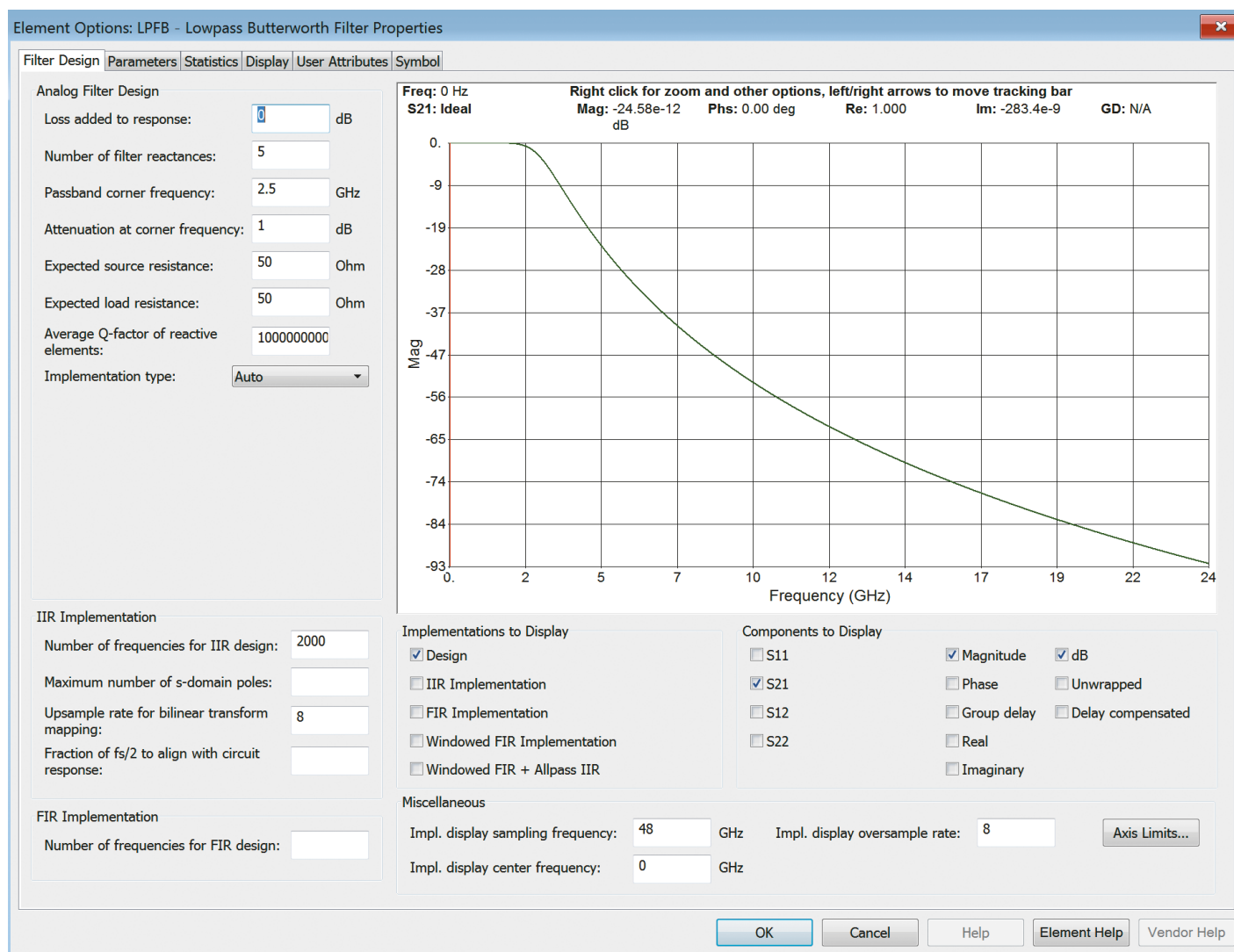
Figure 5: Properties definition for LPF element used in heterodyne and direct-conversion system architectures.

converted through quadrature demodulation into two baseband signals for digital conversion.

Because each of the radio blocks represent a discrete or lightly integrated component, the heterodyne architecture offers certain flexibility, allowing a relatively straightforward design to be easily modified for different wireless standards and carrier frequencies. While the architecture is robust and well documented, designers must still address a number of concerns that will impact the filtering. These concerns include device linearity (spurious products from nonlinear components), size constraints, and complexity. Due to the large number of discrete components required, heterodyne systems can consume large

board areas and become cost challenging with low-volume components.

These drawbacks are multiplied when designing multiple antenna systems. The challenge of addressing space and cost pressures is compounded by the complexities introduced with the architecture advances of carrier aggregation, phased array antennas and massive MIMO. As a result, the design and product development effort becomes a formidable task requiring considerable engineering support starting with simulation.

VSS system design software enables system designers to tackle these challenges with the ability to investigate different architectures and study the impact

of individual component specifications on the overall system performance. Combined with Microwave Office software and AXIEM and Analyst EM simulators, designers have a seamless path from initial system architecture development to component specification to physical realization and verification.

A standard example featuring a pre-configured single conversion heterodyne receiver and a direct-conversion receiver illustrates two popular architectures, providing system designers with an excellent guide to developing their own virtual system design bench, as shown in Figure 4. The received signal in each case is made up of a 16 QAM signal at 27 GHz (close to the 28 GHz band currently being considered

by Verizon for 5G) along with an image signal at 7 GHz. The same image rejection and LPFs are used in both the single conversion heterodyne and direct conversion top-level systems.

The desired response of the filter (low-pass Butterworth) used in both of these systems is easily defined by the user with real-time visual inspection through the property definition dialog box shown in Figure 5. Designers specify the expected or desired filter characteristics based on information from vendors or based on system requirements which can then be passed along to the filter manufacturers. Alternatively, designers can substitute real measured or data from circuit/EM level (physical model)
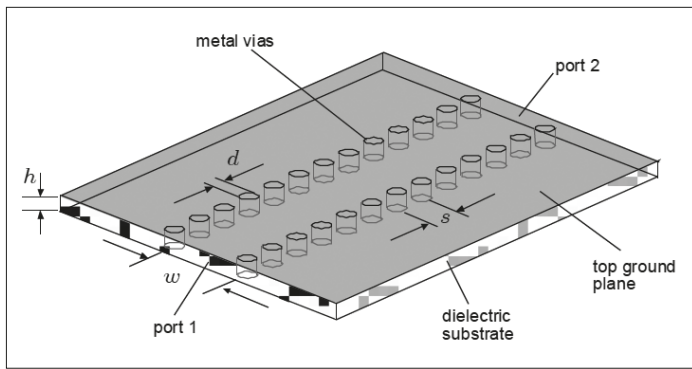
Figure 6: Typical construction of an SIW.

simulation directly into a system analysis.

Two alternative radio approaches gaining attention include cognitive and reconfigurable software defined radios (SDRs) and tunable filters. With SDRs, all the filtering is done after the A/D conversion on the receive side and before the D/A on the transmit side. The current state of the art in silicon can address the filtering, however this approach consumes power (tens of watts) in contrast to passive filters which consume zero power. In addition, the front-end amplifier would be vulnerable to any potentially strong out-of-band signals and the ADC would be converting the entire received spectrum. A tunable band select filter before the LNA would address out-of-band signals, while a tunable anti-aliasing filter before the ADC would greatly improve the power efficiency[3].

In addition to the use of CA and mmWave spectrum, 5G networks will make use of greatly improved antenna array technology, requiring additional filter solutions. Massive MIMO, which may contain 100 or more antenna elements may offer an order of magnitude improvement in spectral efficiency (60-110 of bit/s/Hz/cell, under ideal conditions, compared to ~ 3 bit/s/Hz/cell) over a 4×2 MIMO[4]. One concern for massive MIMO implementation is the complexity and quantity of components per RF chain including broadband high-resolution analog digital converters (ADC and DACs), highly linear PAs with lineari-

zing control circuits, and a large number of filters with strong out-of-band suppression to address any interfering signals. Reducing interference as early as possible in the receiver chain is a favorable approach to achieving the objectives of MIMO antennas, simultaneously increasing interference robustness while decreasing power consumption.

As the number of MIMO base-station antennas (M) increases, studies have shown that the necessary out-of-band attenuation provided by the bandpass filters (BPFs) increases proportionately to the square root of the M[5]. This implies a practical limit on the number of broadcast satellite (BS) antennas due to the increase in BPF design complexity and power consumption. Insufficient out-of-band attenuation would result in aliasing of the filtered out-of-band interferers into the useful band at the output of the analog-to-digital converter (ADC), thereby corrupting the received baseband signal.

Physical Design at mmWave

Taking advantage of mmWave spectrum will require addressing poor individual component performance and the technological challenges of applying current mobile radio solutions above 20 GHz. Compounding these issues, when the mm-wave specific bands are defined, the standards will most likely require the filters to preserve as much bandwidth as possible, calling for high selectivity.

FBARs operating in frequency range of 5-20 GHz have been reported in literature[6,7]. Due to their high Q factor, these filters offer low insertion loss for decent system performance and can be designed integrated with MMIC and other technologies to reduce cost and size and provide low-power consumption. In general, the use of mmWave frequencies will likely require different filter technology than the acoustic wave filters currently used in mobile devices at cellular frequencies. Due to the need for RF chain optimization and proper addressing of the interactions between elements, there will be more integrated approaches for filtering – and the overall jump in complexity for 5G subsystems will place greater demands on design teams.

As frequencies increase toward the mmWave range, the RF wavelength becomes small enough that filters based on EM techniques are feasible. Waveguide and cavity filters are two most common high performing filter types between 20 and 80 GHz. These filters have dimensions in centimeters rather than the required millimeters, However, there are many efforts to miniaturize these filters at mmWave frequencies.

The wavelength size for the EM wave being filtered is still large with respect to the filter's physical size requirements so it is likely that these mmWave filters will be larger than the lower band acoustic filters, which may be permissible if a different radio architecture can reduce the quantity of filters required. Otherwise, alternative construction must be developed.

Likely candidates are filters based on substrate integrated waveguides (SIW), shown in Figure 6, which offer a planar construction that can be easily incorporated into monolithic microwave integrated circuit (MMIC), RFIC, and PCB substrates with existing interconnect structures, and have also been demonstrated using standard CMOS technology. GaAs and

indium phosphide (InP) technologies offer better performance than the CMOS process because of higher breakdown voltages, higher electron mobility, as well as high cutoff frequencies (f_T) and good noise performance. MMICs also offer high quality passives. However, major drawbacks of the III-V semiconductor technologies include high cost, a low level of integration, and high-power dissipation.

The main advantages of CMOS include low cost, integration of digital, analog, and RF functionality into a single IC, plentiful number of manufacturers, and cutoff frequencies beyond 100 GHz. Because of the low resistivity of Si substrates and metal losses, on-chip passive components exhibit low Q-factors and suffer from high losses in mmWave circuits, degrading BPF insertion loss and out-of-band rejection.

The size of a mmWave passive filter based on distributed transmission (example filter in Microwave Office software is shown in Figure 7) is smaller than a filter at microwave frequencies, supporting integration with other circuits on a single chip. The Q-factor of a monolithic transmission line (TL) is directly proportional to the square root of its operating frequency. As a result, the Q-factor of a TL is enhanced with increasing frequency. Consequently, TLs are broadly used and preferred as resonators for mmWave passive filter design. At mmWave frequencies, reactive elements required for matching networks and resonators become very small. Quasi-transverse EM (quasi-TEM) TLs are easily scalable in length and can realize small reactances.

Conclusion

For 5G filter designers, the challenges are compounded by an increase in potential interferers due to the adoption of massive MIMO and network cell densification, guard-bands that are reduced or eliminated, and carrier aggregation demands of greater selectivity and mmWave spec-
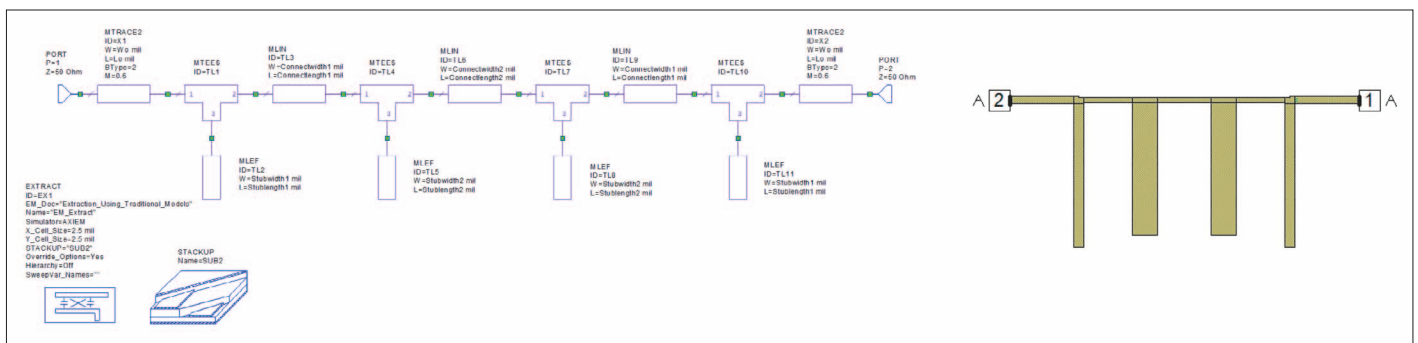
Figure 7: Microstrip bandpass filter example based on transmission lines and open-circuited stubs which reduces in size at mmWave frequencies.

trum. As current radio and acoustic filter technologies struggle with performance at these higher frequencies, designers will need to explore a wide range of alternatives. Simulation software, which includes system, circuit, and EM analysis will play a critical role in the success of these new filter technologies.

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