INVITED PAPER

Putting the Radio in "Software-Defined Radio": Hardware Developments for Adaptable RF Systems

This paper concentrates on filtering aspects for future frequency-agile radios.

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ABSTRACT | The prospects for and the state of the art of adaptable RF hardware are reviewed, focusing primarily on the traditional frequency planning bottleneck, the filtering stages. First, a case is made that even banded systems can be greatly impacted by a modest amount of tuning. This is done by showing the results of a traditional fixed system in an unlicensed band upgraded with a programmable front-end filter. Next, a system built specifically for wideband tuning is shown that enables band selection across the 20-MHz–6-GHz-band. Cooperative operation of multiple colocated nodes is enabled by high-quality pre-LNA filtering across the bands of operation. Future capabilities of adaptable systems are shown by reviewing the state of the art of adaptable systems, heading toward a field-programmable filter array in which a sea of resonators are dynamically interconnected to create a transfer function on demand. Additionally, a novel synthesis approach is highlighted in which multiple filters can cooperate gracefully without crossover issues between the bands. This approach allows for a vast number of filter states by turning on and off passbands without affecting the adjacent bands. The advancements in adaptable hardware will enable new classes of RF systems which much more efficiently utilize the spectrum.

KEYWORDS | Cognitive radio; microstrip filters; radio spectrum management; resonator filters; software radio

I. INTRODUCTION: IMPORTANCE OF EMERGING ADAPTABLE RF CAPABILITY

While the term software-defined radio (SDR) has existed for many years [1]–[14], it has traditionally referred to a programmable software stage implemented in a field-programmable gate array (FPGA) or general-purpose processor following a fixed set of radio-frequency (RF) hardware. This hardware has fixed design choices that ultimately limit the applicability of the system. Either the SDR is a "wide open" system that receives much of the spectrum but is then subject to interference, or a "highly filtered" system that isolates the portion of the spectrum of interest but severely limits the flexibility of the system. This paper will detail recent progress on tunable and adaptable RF systems that promise to provide the best of both approaches: the performance of a specifically designed system but with the flexibility of a wide open system.

Both military and commercial systems have a need for adaptable hardware. Adaptation is of paramount importance for commercial (e.g., cellular) designers due to wireless standards that evolve quickly and continually have additional bands and radio functions that must be accommodated by the hardware. Instead of adding yet another hardware chain to handle a new standard, waveform, or frequency band, the hardware of a previously installed

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device can adapt to the specifications of a new standard. Whereas the evolution of standards is not typically the driving force for change within a military system, the needs of these systems change based on spectral conditions that evolve based on the mission, which may not be predictable at the initial time of design.

To fully realize this vision of a single widely applicable adaptable radio, the "SDR" must extend through the RF hardware, since this is where much of the system-specific components reside. Designing at RF traditionally has entailed wavelength-specific designs that result in application-specific components that often are not applicable to the next generation of standard. As an example, RF filtering is a particularly limiting component that is unique per application, and the inherent static nature of the design can be extremely limiting to the ability to port across standards or other applications. While the FPGA has showed that digital circuit hardware can be generalized such that the application layer can be added after the fabrication of the hardware, no such capability exists in the RF domain.

This shift to generalized RF systems, in which application specifics are added after the initial design, would have far reaching impacts from performance to sustainability, including even environmental effects. Embracing adaptable RF has implications on the environmental impact of the numerous wireless systems that quickly become outdated. As an alternative to the current paradigm of full replacement for upgrades, manufacturers of front–end components and systems could create reconfigurable products with longer life cycles. Consumer electronics companies could also create systems that work throughout multiple international markets with the same benefits stated above. Having a longer life cycle for a given set of RF hardware would impact the sustainability of a system, potentially alleviating the environmental challenges caused by the increasing upgrade cadence mandated by rapidly changing specifications. A more adaptable transceiver market could make a dent in the fastest growing contributor to the waste stream (consumer electronics waste in the United States measured at more than 3.4 million tons in 2011) by allowing the wireless system to be viable for multiple cycles of standards [15]–[19].

Ultimately, the wireless hardware should not only be able to gracefully move between standards, which implies a slower reaction timescale, but should also react in real time to the spectrum as it exists at that moment. By reacting to the spectrum in real time, we can avoid overdesigning the system with specifications for the worst electromagnetic environment, but instead allocate resources for the instantaneous need of the system. This adaptive approach can be applied to numerous portions of the RF system, e.g., the linearity versus power draw in the low-noise amplifier, the efficiency versus distortion in the power amplifier, and the spectral isolation versus sensitivity of the overall receive chain. This paper will focus on the role of adaptive frequency planning through advances in adaptable filtering. Efforts to create such devices started with filters with center frequency tuning [20]–[34], enabling a system to move to a free frequency band. The state of the art has moved beyond these initial results, and it is instructive to understand what is available toward dynamically creating transfer functions on demand.

Traditionally, such approaches have been limited by the tradeoff in the amount of flexibility in a transceiver versus the expected performance. However, recent progress in tunable or switchable components has changed the nature of the tradeoffs, which is highlighted through early system demonstrators showing the utility of adaptable components. Following the system demonstration discussions, we will overview recent improvements that are expected to impact the field in the future: high-quality wide tuning filters, field-programmable filter banks, and advanced filter synthesis allowing for cooperative interaction between numerous filters.

II. AVOIDING FEAR-BASED RF SYSTEM DESIGN THROUGH ADAPTATION

A. Worst Case Scenario Engineering

To motivate the importance of this field to next-generation systems, we start with a relatively simple system demonstration based on relatively unsophisticated sensor nodes. Performance of filters located before the low-noise amplifier is critical due to the importance of the loss of the filter on the system sensitivity. The filter is most effective before the amplification in order to avoid saturation of the front–end electronic system from out-of-band interferers or to avoid inducing nonlinearities in the amplifier itself. If a system cannot react dynamically to the interferers when they exist, then "worst case scenario RF engineering" is practiced, or "fear-based RF design." This fear-based engineering entails planning for the worst interference that may be experienced through the life of the system, which ensures that in most instances of operation the system is overdesigned. A static spectral mask would typically be created based on the potential existence of out-of-band interferers, and this defines the performance requirements for a static filter. For example, a specification will include the bandwidth of the passband or the slope of the filter skirts (which relates to the number of poles in the filter). Since the insertion loss, and, therefore, the sensitivity of the wireless system, is directly dependent on the bandwidth and the number of poles used to define the filter skirts, the sensitivity of the system is typically driven by the fear of interference and not the actual presence of interference.

An example of a typical spectral mask is shown in Fig. 1 with spectral isolation specifications on both sides of the filter based on the expected presence of interference. The assumption behind this mask is that the interference profile has spectral content on either side of the band, as, for example, represented by the compilation spectrum created by overlaying the two captured spectral interferers shown in Fig. 1(a) and (b). While it is true that the spectrum is increasingly crowded, this is not true that at any one location and at any one instance in time the system can expect the maximum interference from both sides of the spectrum. While this condition may occur, constraining the system performance to this worst scenario is unnecessary. Given this projected scenario, a static system designed for this mask must accept the performance reduction based on the threat of an interferer even when the interferer is not present. This approach serves to greatly reduce the sensitivity of a system or allocate too many resources to the static filtering problem, such as employing excess volume to obtain a higher quality factor (Q) filter or a many-pole filter when otherwise a lower number of poles may be acceptable.

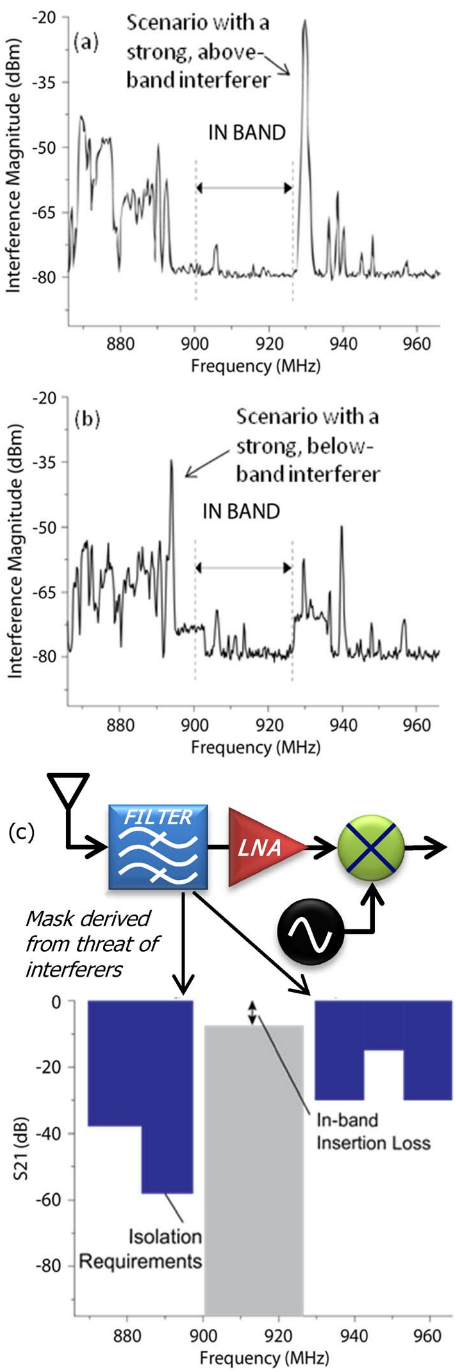

Fig. 1. ***(a) Scenario with a strong above-band interferer. (b) Scenario with a strong below-band interferer. (c) A representative RF chain and associated spectral mask defining the static filter design. Due to the static nature of the filter design, the designer must account for both scenarios in (a) and (b) occurring instantaneously, which necessitates sharp stopband transitions and high stopband attenuation that results in high in-band insertion loss and ultimately lower system sensitivity.***

B. Impact of Adaptation Even for Fixed Banded Systems

We will first show how to avoid the fear-based design through recent results that demonstrate the utility of an adaptive system, even for a traditional fixed band system where adaptability is expected to have less of an effect. While true dynamic spectral access, through which the system will hop through large regions of the spectrum, has been a goal and a research topic of much intensity, this narrowband demonstration shows that even traditional banded approaches can benefit from the intelligence of a spectrally aware system. In the case motivating this work, the ISM band from 902–928 MHz was utilized for a sensor node network. The end application for the system was the creation of a real-time sensor monitor for sewage networks for detecting overflows [35]. Regardless of the sensor application, it is representative of a system in which it is not possible to plan the network *a priori* since the location of manhole covers mandated sensor placement and not interference concerns. The sensor network nodes were placed throughout a common urban environment, and the node performance was directly correlated to the placement within the network, specifically the placement near an interfering source such as a cell tower. The receive signal strength indicator (RSSI) continued to read a robust −65 dBm, more than enough signal to continue operation with nearly 40 dB signal-to-noise (S/N) ratio; however, many of the nodes lost contact. This decorrelation between the signal strength and the packet rate was due to interference. By inserting adaptable hardware between the sensor node and the antenna [36], dynamic reaction to the spectrum was shown to recover otherwise lost nodes in the field. This addition between the antenna and the sensor node was a transparent upgrade to the rest of the sensor network system which continued to use the same signals and protocols.

It is instructive to look at the details of this use case in order to understand the benefits of the intelligent front–end system. By using high-Q filtering [36], the unlicensed band was protected from out-of-band interference by a narrow filter without unduly reducing the sensitivity of the system. The insertion loss was less than 3 dB for the roughly 25-MHz-wide filter. Two of the interfering scenarios for this sensor network were captured and shown in Fig. 2. As shown in [35], there is a sharp decrease in the packet reception rate due to an out-of-band interferer if it is larger than 40 dB, greater than the desired incident signal. Since the interference is inducing nonlinear effects, a small decrease in the interference due to a filter can have great impact on the system. So even though the closest interferer is quite near the edge of the operating band (only 6 MHz, or 0.66%, away from the edge of the band), an intelligent system can shift the front–end protection filtering to higher frequency coverage and protect from the low band interferer. By analogy, this frequency adaptation can be viewed as shading your eyes from the sun as it interferes with your ability to see.

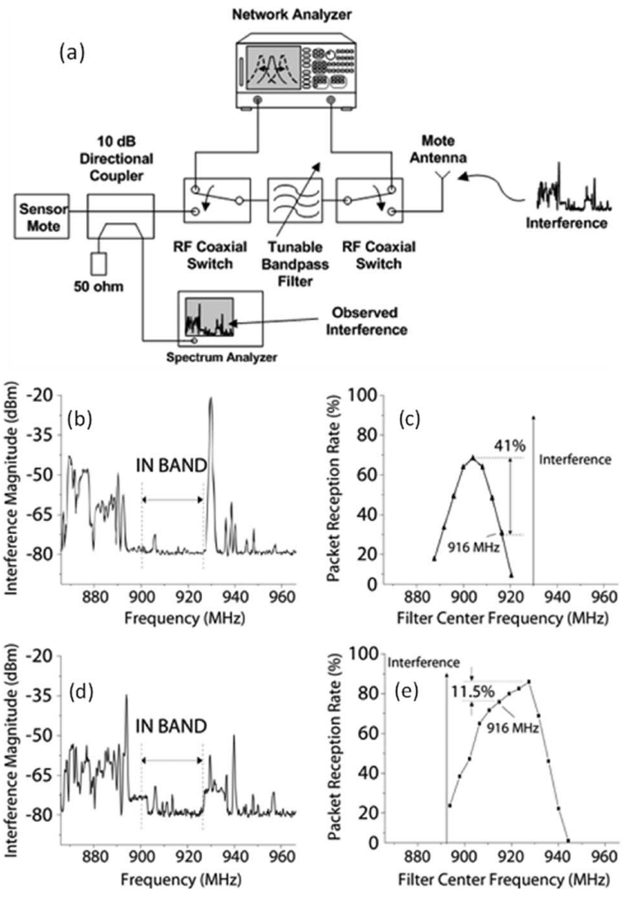

Fig. 2. ***(a) System diagram of measurement setup that allows for accurate positioning of a tunable filter and measurement of the effect of the filter on interference levels. The filter is tuned using the network analyzer and then switched into the larger circuit to attenuate interference. (b) Example interference profile used with the setup shown in (a). (c) Successful packet reception rate (PRR) versus the center frequency of the tunable filter for the interference shown in (b), showing that tuning the filter below the center of the band results in the highest PRR. (d) Another example interference profile. (e) Successful PRR versus the center frequency of the tunable filter for the interference shown in (d), showing that tuning the filter above the center of the band results in the highest PRR.***

The effect of adaptation is shown in the packet reception rate for the test scenario shown in Fig. 2, in which filters react to the strong interferers by tuning the center frequency away from the interferer present just outside the operating band of interest. In this case, the sensor nodes are programmed to hop throughout the band of interest, without regard for the interferer. Thus, only the filter was changed and not the system protocol. Co-optimization of both the filter and the utilized frequencies would only serve to increase the performance, while increasing complexity. In this demonstration, we chose to show the benefit of the filter alone and not changing the sensor protocol and frequency hopping plan to isolate the effect of the filter alone. The results show a large increase in performance relative to an unprotected node without the added filter. An unprotected node had less than 10% successful packet rate, and the effect of the high-quality preselect filter is apparent in the jump to 70% and 85% packet reception rate for the two different interfering scenarios.

Of note in Fig. 2, the optimal parameters of the filter highly depend on the spectral environment and are definitively not centered on the band as would be the case for a fixed design. Counterintuitively, this optimal filter center frequency placement is entirely outside or on the very edge of the unlicensed industrial, scientific, and medical (ISM) band utilized by the sensor node. In these two representative cases, it is desirable to trade some of the signal strength of the uniformly frequency hopping signal for a reduction in the interference. Cutting the band such that the usable portion of the spectrum is on top of the skirt of the filter is preferred to having the filter centered at the band of operation. The increase in performance is dependent on the aggressiveness of the spectrum, i.e., the amplitude and location of the interferers, but the improvement is clear. Simple center frequency adjustments of merely 10 MHz to either side of the center of the band show an increase in packet reception rate of 11.5% and 41% for these two particular cases shown here. These performance increases are indicated on the graph as the change in the optimal performance point, relative to the center frequency location, which would be the default in a static design. The optimized, tuned performance in the presence of the interferer is within 4% of the performance without the interferer present at all. Clearly, the induced signal loss and distortion caused by an off-center filter is desirable in this case relative to letting the interference into the system.

While a system will typically have its own preselect filtering, due to tolerances of the static filter and issues with insertion loss, it is usually much wider than the operating band. Therefore, neighboring signals can still cause interference even if the neighbors are not violating their own allocated transmission spectra, in that their transmissions are not directly leaking into the adjacent band receive frequencies. This issue recently came to a head with the recent controversy with Global Positioning Systems (GPSs) that have an effective receive bandwidth much larger than the actual operating band. High-Q, widely tunable filters, for example, those in [37], where a single filter tunes over a frequency range greater than 3.5 : 1 with fractional bandwidths less than 1% and insertion losses less than 2.5 dB for 80% of the tuning range, give the performance needed to alleviate the design tensions and eliminate many of the difficult decisions that the crowding of the spectrum forces upon society.

This example detailed in Fig. 2 is but one of a series of tradeoffs that can be optimized for spectrum as it sensed [38]. For a more balanced interference profile, with equal interference power on each side, the operating center frequency will tend toward the center of the band. Only in the worst case scenario, in which near-in interference from both sides of the operating band exists simultaneously, will a narrow filter be needed at the center of the band. Traditionally, this case would needlessly drive the performance requirements, but even in this worst case condition, a variable bandwidth design can be employed to find the optimized operational state. Tuning center frequency and bandwidth [36] of the filter gives a rich set of optimization tools from which to choose in the field without changing the rest of the system. Employment of this type of filter, with both bandwidth and center frequency adaptation, results in graphs such as shown in Fig. 3. By optimizing both filter variables, a nearly 60% increase in packet rate is observed over the most optimistic static filter scenario. This static scenario assumes a bandwidth equal to the operation band of the sensor system centered at the middle of the band, as show in the top left corner of the graph.

The best algorithm to systematically find the optimum point in the field was beyond the scope of the initial work, which merely showed that it is worthwhile to find the optimal operation point. Integrating intelligence for optimizing the settings of adaptable filters, along with the entire RF chain which can have similar series of tradeoffs, is necessary to extract the potential benefits, and remains an open question for next-generation systems.

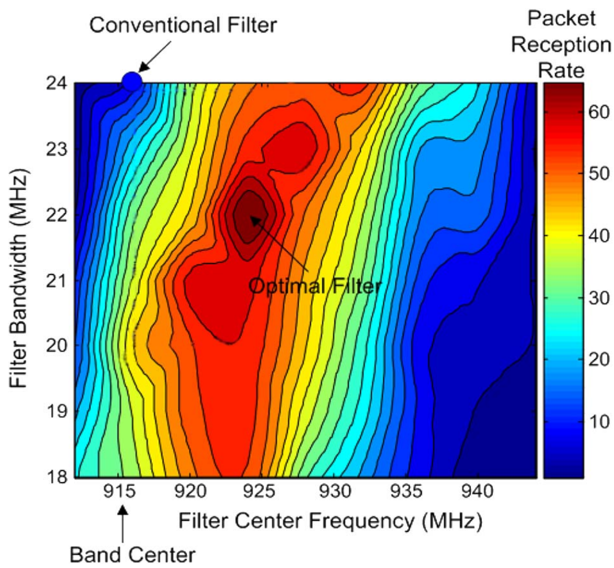

Fig. 3. ***Measured packet reception rate of a system with a filter with tunable bandwidth and center frequency in the presence of the interference, shown in Fig. 2(d). The conventional filter, shown by the blue circle and statically centered in the band at 916 MHz, produces < 10% successful packet reception rate. The optimized filter shows a slight skewing to the high-frequency side of the band and a narrower bandwidth. This optimized state shows an increase to greater than 68% packet reception rate [38].***

C. System Impact of Broadband Filter Tuning

With more aggressive tuning, much broader band coverage can be created, which allows for dynamic band allocation. As an example of the state of the art, a full receiver was designed by Rockwell Collins that has tunable components through the 20-MHz–6-GHz band. The challenge was to preserve the narrowband selection described above, but allow for scanning throughout the usable handheld spectrum. Multiple downconversion channels were demonstrated in small form factors, allowing for cooperative, simultaneous use of the spectrum from one platform. This dynamic front–end filtering allows for concurrent use of the spectrum completely independently, where one transceiver is transmitting high-power signals while another colocated system is receiving sensitive signals without prior frequency planning required.

A full receiver was created on these filtering principles, and the measured tuning results across the spectral field of regard are shown in Fig. 4. At low frequencies [very high frequency (VHF), ultrahigh frequency (UHF), and L-band], more traditional lumped element filters are utilized where the fractional bandwidth is not as aggressive and lower Q components are permissible. Due to the relatively wide bandwidth at lower frequencies, more common components such as surface mount inductors and capacitors can be used while maintaining the desired fractional bandwidth without undue loss. At higher frequencies (S-band and C-band), where a typical channel's fractional bandwidth is even less than 1%, the quality factor needs to approach 1000 to maintain a reasonable noise figure (which at room temperature for a passive component equals the insertion loss). For these frequencies, evanescent-mode cavity filters are used.

These filter banks (comprising five separate filters roughly covering VHF, UHF, L-band, S-band, and C-band) have been shown to have high performance across the composite tuning range, as shown in Fig. 5. Less than ~5-dB insertion loss is maintained across the spectrum, with the majority of the spectrum covered with approximately 2.5-dB loss or less.

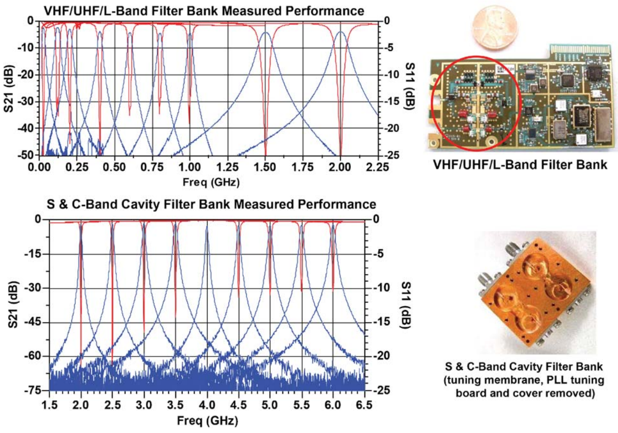

Fig. 4. ***Measured center frequency tuning capabilities for two separate filter banks developed by Rockwell Collins. The lower frequency bank is implemented with lumped elements and tunes from 20 MHz to 2 GHz, and the higher frequency bank is implemented with cavity filters tunable from 2 to 6 GHz.***

III. FUTURE PROSPECTS: FIELD-PROGRAMMABLE FILTER ARRAYS

A. Field-Addressable Transfer Functions

RF filters, described at a simplified level, are a series of resonators which are coupled together to form a specific filtering function. A single resonator has a single resonant peak which can be adjusted by the coupling to the resonator from the external ports. However, the shape of the resonance peak is exclusively set by the resonator quality factor and the external coupling value, for example, the ratio of the impedances of the resonator to the port impedance. In a two-port system for a single resonator, more external coupling means less insertion loss but at the sacrifice of a wider passband, usually described by the 3-dB bandwidth. This transfer function from a single resonator cannot be specified uniquely outside the adjustment of the quality factor and external coupling level, and more complex transfer functions are often desired. Therefore, multiple resonators are utilized in real filter designs. If two resonators are used, then two resonant peaks are formed and the frequency separation of the peaks is determined by the interresonator coupling. If there is stronger interresonator coupling, then a wider separation of the peaks is created, and thus a wider band filter can be created. Fundamentally, this separation of the peaks comes from the even and odd mode states, which exists in the symmetric pair of resonators, and the interresonator coupling coefficient is a measure of this peak separation. By adjusting the external coupling values to the two resonators, the separate resonant peaks can become the desired passband in terms of filter shape. A similar process to create multipole filters can be utilized, in which the shape of the filter is dictated by the coupling interaction between multiple resonators, and then adjustment of the external coupling to input and output ports. Control of these parameters, the interresonator coupling, the resonant frequency of the resonators, and the external coupling, gives full design control for the system.

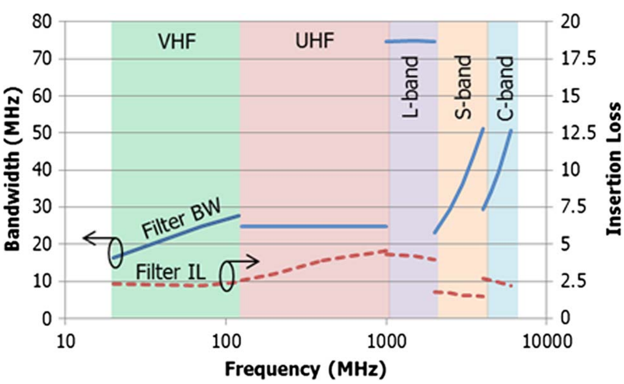

Fig. 5. ***Measured bandwidth and insertion loss performance across the radio's field of regard (shaded regions correspond to specific filters). Insertion loss was less than 5 dB over the entire 20-MHz–6-GHz composite tuning range.***

The filters in the previous sections showing the system motivation for adaptable systems were relatively simple, purely viewed from a filtering perspective. The system relied on two-pole filters that were nominally maximally flat passband shapes. While these tunable filters were meant to tune from one frequency to another, the resulting filter shape may be insufficient to cover a specific application's need since each application often has a unique spectral mask. Instead, one could imagine a sea of resonators that could dynamically reroute signals through the network of resonators to have full control of the coupling matrix used to design filters. Independent control of the center frequency of each resonator, the interresonator coupling values between the resonators, and the external coupling gives full access to the parameters required to create a desired transfer function in the field.

As switches, tuning elements, and coupling techniques advance, filters have become reconfigurable in ways beyond center frequency tuning [39]–[55]. These filters can fully adjust their filter shapes electronically. Such filters could dynamically use more bandwidth to increase data rates if the environment allowed or adjust to provide different group delay or rejection profiles that are signal dependent. The innovation that allowed these filters to more fully adapt to interference is that they often combine tunable resonators and tunable coupling structures. For example, the filter in [43] uses both tunable interresonator coupling and tunable resonators to tune in both center frequency and bandwidth.

Taken further, the concept of combining tunable resonators with tunable coupling structures would allow a system to dynamically synthesize any filter transfer function at any frequency deemed necessary for its current mode of operation (if all coupling structures could produce inductive, capacitive, and zero coupling values). Such a filter has been named the field-programmable filter array (FPFA), which consists of a "sea of resonators" that can all tune and have dynamic coupling between them. A step toward this goal is the substrate integrated filter shown in [56]. A model of this filter is shown in Fig. 6, where coplanar waveguide (CPW) transmission lines on a board couple energy from an external port to resonators integrated into the substrate. The four resonators for this design are built with vias in the substrate to form a capacitively loaded cavity, and are tuned with diaphragms that physically move on the order of 20 μm to adjust the capacitance which changes the resonant frequency.

The filter utilizes inductive waveguide irises that include vias loaded with solid-state varactors in the irises for tunable interresonator coupling. As the capacitance of the varactors increases, the vias are more strongly coupled to the iris, effectively shorting the irises and producing near-zero interresonator coupling. This process is designated in Fig. 6 as the routing between the resonators, indicated by a circle, is dynamically altered through the coupling, denoted by the line between circles. The value of this coupling is set by the coupling section varactor value, which is controlled by a bias voltage. With the ability to dynamically adjust the interresonator coupling to near-zero values, signals in the filter can be rerouted to create different response shapes. Also shown in Fig. 6 are two- and four-pole filter responses that were obtained by routing signals through different resonators to create the desired response. Such capability is useful because dynamic routing allows a host system to trade off between passband insertion loss and filter skirt slope, enabling the system to operate in a high-sensitivity mode when experiencing light interference, and a high stopband attenuation mode when experiencing stronger interference.

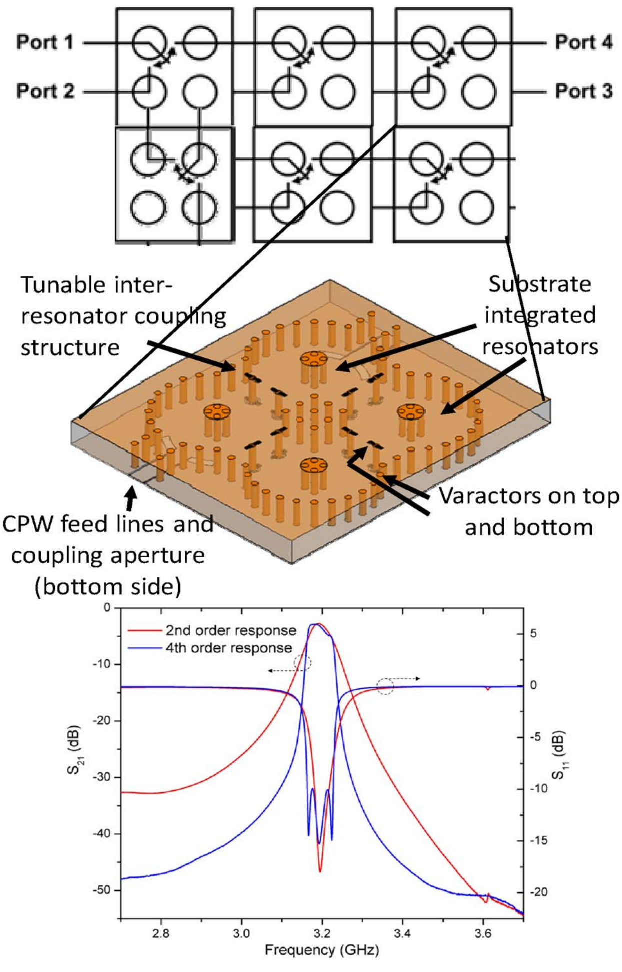

Fig. 6. ***(Top) Concept of interconnected tunable resonators with dynamic coupling. (Middle) Substrate integrated reconfigurable unit cell. (Bottom) Two- and four-pole measured responses from the same structure [56].***

While the FPFA shown in Fig. 6 used solid-state varactors to tune its interresonator coupling values, RF microelectromechanical systems (MEMS), and the emerging phase-change material switches, e.g., such as vanadium oxide or GeTe, and tuning elements offer several advantages for future systems. MEMS switches and tuning elements often have superior linearity and power handling compared with similarly sized solid-state elements at the potential cost of integration difficulty and switching/tuning speed. The reliability of MEMS components has also steadily improved over the last decade. Phase change material RF switches and tuning elements can offer superior insertion loss, linearity, and off-state capacitance compared with solid-state elements at the cost of switching/tuning speed (and static power consumption in some variants) due to their requirement for a change in temperature to cause a material transition. While this paper shows reconfigurable filters that primarily use solid-state varactors, all of the concepts are amenable to implementation with other tuning element and switch technologies.

The next step in the progression toward a fully functional FPFA was the invention of a coupling structure that could dynamically provide inductive, capacitive, and zero interresonator coupling values [57]. Such a coupling structure, with the ability to switch from positive to negative coupling, allows the design of a filter that retains the capability to route signals through desired resonators to create different responses as shown above, while adding the ability to dynamically add zeros to the transmission coefficient at desired frequencies. This negative coupling capability adds the ability to reshape the stopband or attenuate specific interfering signals, and provided capabilities similar to that shown in Fig. 8(c). Another function that this structure adds is the ability to create a filter bank without a switch to direct a signal, but rather which does

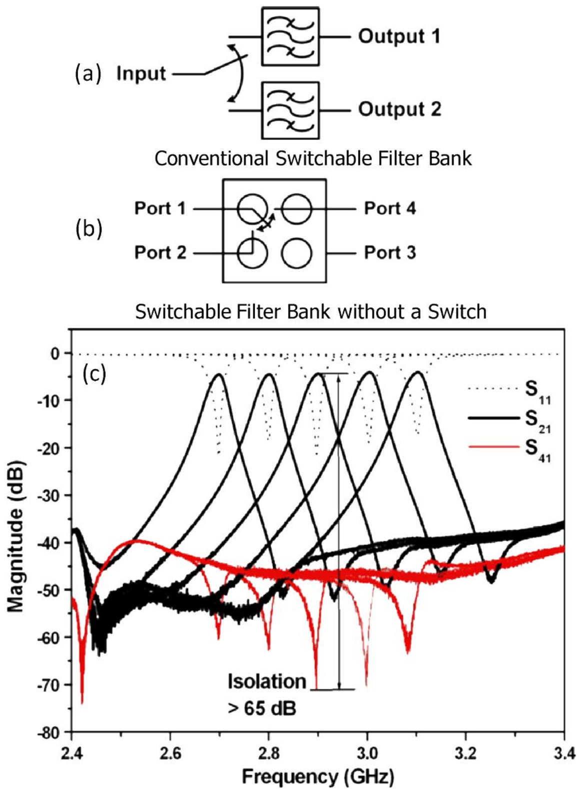

Fig. 7. ***(a) Conventional switchable filter bank. (b) Switchless filter bank enabled by tunable interresonator coupling. (c) Measured response showing > 65-dB isolation between ports 1 and 4.***

this switching internal to the filter. Fig. 7(a) shows a conventional filter bank, where a loss-inducing switch is used to switch between filters. Alternatively, Fig. 7(b) shows a four-resonator FPFA that can adjust its coupling values to route signals to different output ports. Fig. 7(c) shows a measured response of the FPFA in this configuration where > 65-dB isolation can be seen between the input port (port 1) and the isolated port (port 4).

B. Digitally Addressable FPFA

While the initial structure based on microstrip interresonator coupling [57] demonstrated a great advance in reconfigurable filter capability, the initial design could be difficult to scale to FPFAs with a large number of resonators due to the precise analog control voltages required for each interresonator coupling structure. In addition, the initial demonstrator tuned through an auxiliary resonance in the interresonator coupling structure in order to obtain inductive and capacitive coupling. This produces spurious resonances near the filter passband in some FPFA operating modes. In order to alleviate these potential issues, a digitally switchable interresonator coupling structure was devised that has the capability to provide inductive, capacitive, and near-zero coupling values while being simpler to control and having a spurious free range of over 2.5 times the passband center frequency [58]. This coupling structure is "digital" in that it changes from fixed states based on discrete values applied to the coupling section. Instead of an analog voltage to bias each coupling section, individual portions of the coupling section are turned on and off with only a single bias voltage, providing a coupling value which changes from positive to negative, and providing the important zero coupling state as well, effectively turning off the energy transferred from one resonator to the other. The 0's and 1's in Fig. 8 represent whether the discrete sections of the coupling mechanism were switched on or off.

Responses from the six-resonator FPFA with the discrete tuning coupling states [58] can be seen in Fig. 8. In Fig. 8(a), four-pole responses with inductive and capacitive crosscoupling are shown that allow a tradeoff between stopband shape and group delay flatness. Two of the resonators were isolated from the response by appropriately digitally addressing the coupling structures. The output third-order intercept point (OIP3) of the filter was measured to be 37.8 dBm, and it is limited by the use of solid-state PIN diodes as switching elements. Higher linearity switches, for example MEMS switches, could improve the linearity if required by an eventual host system and application, but the design concept would be the same. Fig. 8(b) shows two-pole passband responses where the additional four resonators in the FPFA have been used to add two two-pole notches in the stopband of the filter. With this device, a six-pole response could be changed to the two-pole response with notches in the stopband, as shown in Fig. 8(b) [59]. Such a response would be useful when sensitivity is to be maximized while still highly attenuating a few targeted interfering signals. These FPFA capabilities enable a new paradigm in adaptability and predigitization signal conditioning. Future enhancements in switching and tunable components will even further advance the capability that FPFAs can add to RF and microwave systems, and the proper control/utilization of the inherent flexibility remains an ongoing research topic.

IV. INTRINSICALLY SWITCHED FILTER NETWORKS

While the manufacturing of tunable resonators has been enhanced in the past decade, there has also been progress in filter synthesis as well. These advanced synthesis approaches allow for novel filter transfer functions that have not been possible before, while minimizing the need for tunable componentry. A particular example is shown in which multiple filters in a connected bank can cooperate to cover a wide range of frequencies and be switched on and off without affecting the adjacent bands. This new class of filters relies on a new approach to operating multiple filters in the presence of each other, namely intrinsically switchable filters. As opposed to externally switching between filters, it is possible to turn off couplings

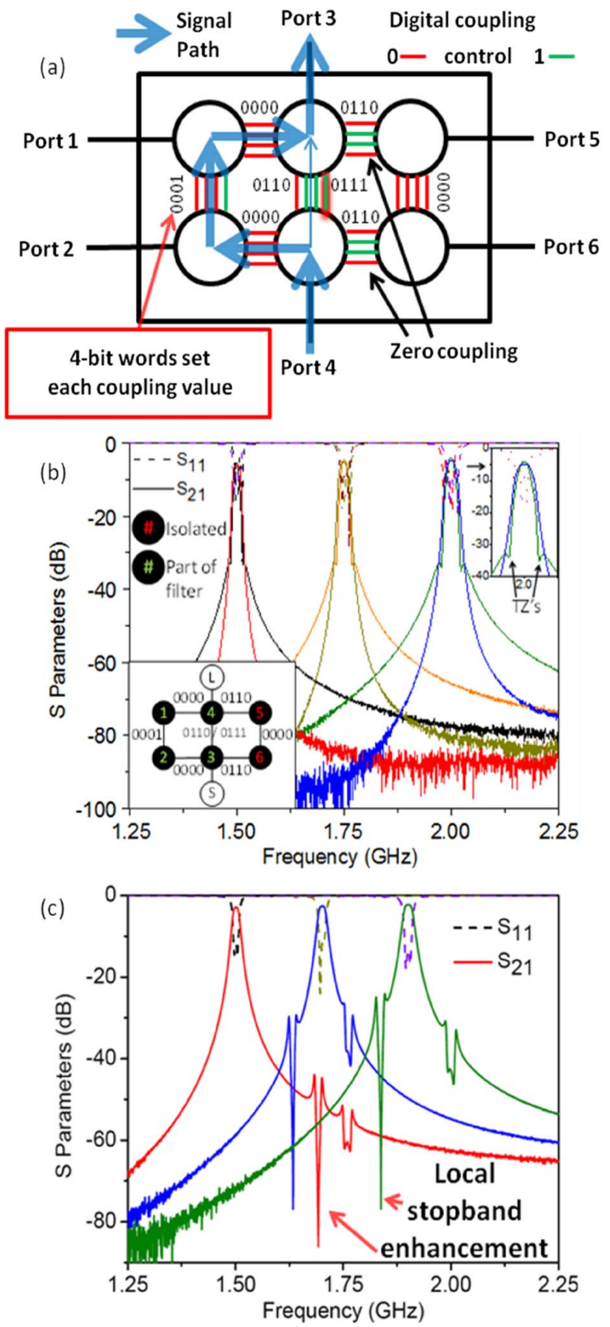

Fig. 8. ***(a) Diagram of a six-resonator FPFA with digitally addressable coupling set to produce a four-pole response between ports 3 and 4. Each interresonator coupling value is set using a 4-b word, giving 16 possible coupling values. (b) Four-pole responses of a measured FPFA switched between inductive and capacitive crosscoupling (coupling between resonators 3 and 4). (c) Measured two-pole responses using adjacent resonators for local stopband enhancement.***

internal to the filter while maintaining the out-of-band input impedance of the filter even when that path is turned off. This technique utilizes the control of internal resonator couplings to block energy flow by balancing and phasing the electric and magnetic field in the coupling mechanism, as opposed to external switches (that have inherent parasitics). Furthermore, the intrinsic switching allows for gracefully handing off between multiple filters to cover additional frequency range. Multiple filters can operate together or individually. This is expected to be important as advanced wireless system concepts such as multiband carrier aggregation become more popular.

An important, exploitable state between the positive and negative couplings of resonators exists when the coupling equals 0, which effectively shuts off energy transfer between resonators. This zero-net-coupling state exists, for example, between a pair of resonators coupled with a mixture of electric (capacitive) and magnetic (inductive) coupling. With the proper choice of resonator geometry and coupling configuration, the electric and magnetic couplings can be made to be 180° out of phase. The relative strength of electric-to-magnetic interresonator coupling can be controlled with the use of control elements (e.g., varactors or switches) weakly coupled to the resonators. When the electric and magnetic couplings are set to be equal in magnitude, zero net coupling results. This effectively allows for signal redirection between resonators. The full control of the coupling coefficient along with the ability to create a zero-coupling state enables the creation of a wide range of filter functions, as well as allowing a filter to simultaneously function as a low-loss, high-isolation switch. The resulting dual-function device, termed an intrinsically switched filter [39], improves performance by essentially eliminating extra losses associated with using external RF switches and allows for the realization of new types of reconfigurable devices, such as simultaneous band filters, that are difficult to realize using conventional RF switches.

Switched filter banks are a class of components for which intrinsic switching has direct application with significant performance benefits resulting from the elimination of RF switches. Switched-bank tunable filter configurations are often used in an attempt to extend the tuning range of tunable filters without degrading performance. Conventional switched tunable bandpass filter banks comprise a number of tunable filters with tuning ranges corresponding to bands within the desired full tuning range. To select the appropriate filter, RF switches are placed at the input and the output in the bandpass bank. The result is superior performance, in terms of either total tuning range or passband insertion loss, to that which is possible with a single tunable filter. In the conventional design, however, the switches themselves add significant passband insertion loss.

This loss tends to increase as the number of filters in the bank increases, which significantly diminishes or eliminates the insertion loss improvement provided by reducing the tuning range of each of the individual constituent filters. In addition, the switches increase the size, weight, power consumption, and control complexity, and

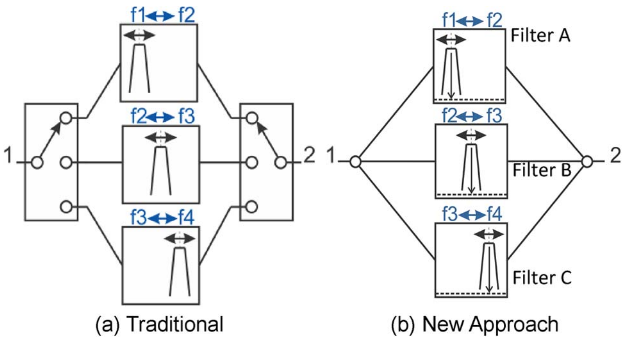

Fig. 9. ***(a) Conventional switched tunable bandpass filter bank. (b) Switchless tunable bandpass filter bank utilizing intrinsically switched tunable bandpass filters.***

they can degrade the linearity of the filter bank. Intrinsically switched tunable filters, by performing the switching function themselves, completely eliminate the need for switches in filter banks (Fig. 9) and in other applications where a switchable filter is needed. The intrinsically switched bank approach removes the switch-loss-imposed upper limit to the number of filters that can be used, and so realizing low-loss tunable filter banks comprising large numbers of low-loss narrow-tuning-range filters becomes a problem of manifold design rather than the much more difficult problem of realizing low-loss high-throw or cascaded switches. The measured results for a three-filter intrinsically switched tunable bandpass filter bank prototype demonstrating this concept are shown in Fig. 10. It has a constant 50-MHz bandwidth response continuously tunable from 740 to 1644 MHz (122%) with less than 5 dB of passband insertion loss and more than 40 dB of isolation between bands. The use of a common manifold allows for the elimination of the switch and for cooperative operation, as shown in Fig. 10(b), where each of the filters sharing the common manifold cooperatively operates to form a triband filter.

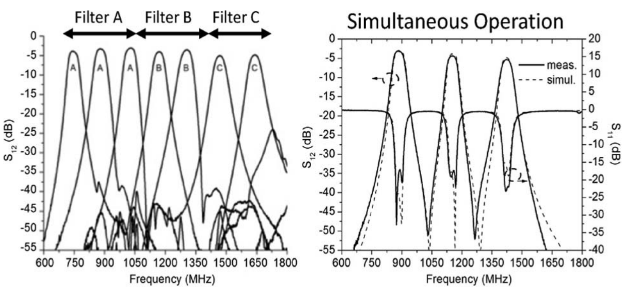

Fig. 10. ***Intrinsically switched tunable three-channel bandpass filter bank prototype: (a) measured full tuning range of each individual filter (labeled A, B, and C, corresponding to Fig. 9(b); and (b) measured response for all filters on simultaneously.***

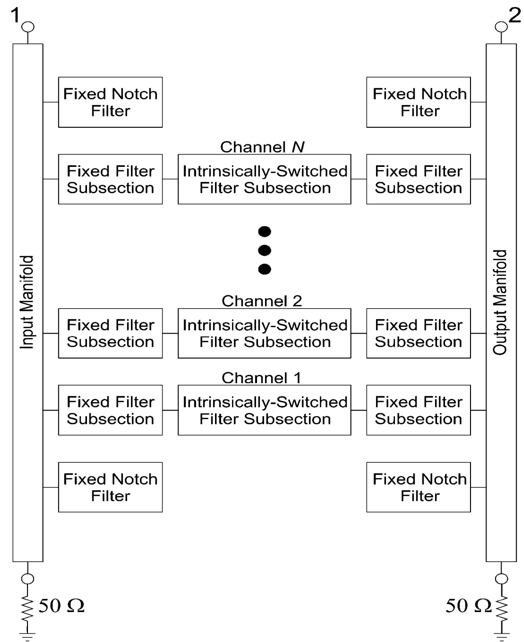

Fig. 11. ***Scalable intrinsically switched multiplexer architecture. The input and output manifolds are terminated in matched loads. The channel filters comprise intrinsically switched subsections and fixed subsections to maintain the impedance seen to other channels. Fixed notch filters serve as ''dummy'' channels to terminate the filter array above and below in frequency.***

The controlled cancellation of interresonator coupling also enables the realization of intrinsically switched multiplexers [60]. An intrinsically switched multiplexer is a generalized version of a switched filter bank, comprising a number of independently switched contiguous bandpass filter channels that form a continuous passband or passbands when two or more adjacent channels are on, resulting in 2^N states for N channels. In order to avoid blind spots in the spectrum, it is a requirement that when two or more adjacent filters are switched on, that they form a continuous passband with flat insertion loss and group delay through the crossover frequencies, which had not been previously demonstrated.

A scalable intrinsically switched multiplexer architecture is shown in Fig. 11. The channel filters are attached to transmission-line manifolds at the input and the output. The manifolds are terminated in matched loads to avoid unwanted resonances. The channel filters are arranged descending in center frequency from the input/output to the matched terminations, in a similar fashion to log-periodic and cochlear-based arrangements [61], [62]. The channel filters are switched internally such that the out-of-band impedances looking into the input and output ports of the filters are minimally affected. Permanently switched-off channel filters in the form of fixed notch filters are used to terminate the array of filters above and below in frequency.

The channel filters must be designed carefully to ensure that they act cooperatively when adjacent channels are switched on. An effective way of accomplishing this is to begin by assuming an infinite number of channels, in which case the all-channels-on transfer function is equivalent to that of a well-matched transmission line [60], which, in turn, is equivalent to a network comprising an infinite array of transversally coupled resonators. The resonators of this equivalent transversal coupled-resonator network can then be partitioned by frequency into filter channels of arbitrary order. Due to the initial assumption of infinite channels, partitioning channels to be of the same order will result in a set of identical filter networks scaled in frequency. Furthermore, it is shown in [60] that the topology of these filter networks can be simplified significantly by partitioning the transversal coupling matrix such that resonances are "shared" between channel filters, in effect allowing the channels to overlap slightly.

The results for the three-channel intrinsically switched multiplexer prototype are also shown in Fig. 12. The prototype gives 6.7 dB of passband insertion loss and 0.15-ns p-p group delay ripple over 72% of the passband for the ON-state. The insertion loss for this prototype comes primarily from the large number of surface-mount components attached with silver epoxy, most of which are trimmer capacitors. Most importantly, this first design proof of concept establishes the ability to have multiple filters connected at a common node, which allows for filters to cooperatively span a frequency range or create 2^N filter shapes between them. The transfer function is altered by merely changing the number of filters that are active within the filter bank.

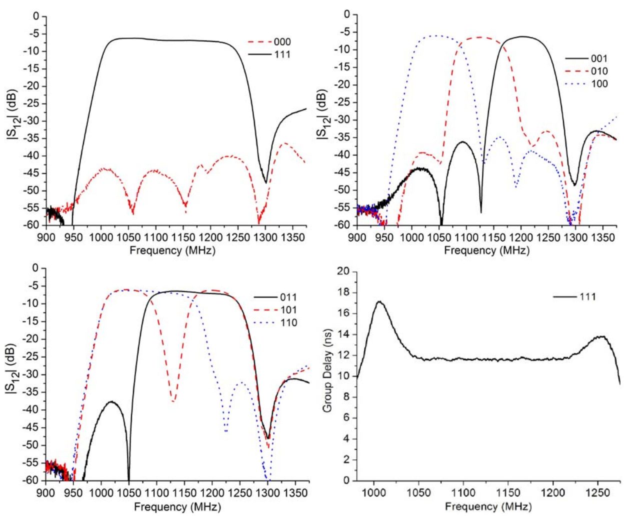

Fig. 12. ***Various states of the three-channel multiplexer with various channels dropped in or out. The filter states for each measurement are identified with a binary code, one bit per channel, with the most significant bit corresponding to the lowest frequency channel, i.e., "011" corresponds to a state in which the lowest frequency channel is deactivated while the remaining two channels are activated.***

V. FUTURE WORK AND PROSPECTS

While this paper heavily focused on tunable filters, the concepts of adaptability can cascade to any RF component. Each component in the RF chain has a drawback of having a static performance profile. However, as the digital capabilities get better every year, the influence of digital components on RF systems will continue to grow. Even if direct digital sampling of an RF signal before downconversion becomes reality, a few RF components will always be necessary: the RF filter, amplification, and the antenna. There is currently not a path to an analog-to-digital converter (ADC) with a noise figure that is compatible with operation without an amplification stage, and this amplification stage will need to be frequency isolated from interferers within the spectrum. A review of current state-of-the-art wideband ADCs reveals an average noise figure of 30 dB, which implies substantial amplification for any realistic wireless sensitivity.

The role of the filter, however, may change its nature. Instead of just fully isolating a banded system from the rest of the spectrum, the RF filter may play the role of a "frequency equalizer" such that the imbalance of signals incident on the ADC is limited adaptively. Instead of avoiding image frequencies and eliminating saturation of the other RF components, a heavily digitally sampled spectrum will need to avoid overloading the sampling stage and prepare the spectrum for digitization. Whether the RF is based on direct sampling or more traditional downconversion architectures, spectral protection is expected to still be necessary. Particularly, as modern systems utilize scaled technology nodes, such as advanced CMOS, for the circuit designs with lower bias voltages, this leads to lower power handling capabilities. The protection or isolation of the advanced circuitry must be intelligent enough to not limit the flexible operation which is inherent in the digital domain. While we have focused on the filtering in this paper, numerous antennas have many of the same properties of having coupled resonances. The concepts covered here can be nearly directly applied for the antenna as well. The antenna can be optimized for frequency transfer function as well as radiation properties, and participate in the spectral isolation.

For electromagnetic filters, as opposed to acoustic approaches, the recent advance of high-quality, linear varactors or switched capacitor banks only promises to increase the viability of the adaptable filter space. MEMS-based varactors and/or more exotic materials such as silicon on sapphire, barium strontium titanate (BST), or phase change RF switches show great promise in the near future. This area of high-Q, linear RF switches and varactors has matured, or is maturing rapidly, in the past few years, and advanced applications and components based on these new devices promise to greatly enhance this field. Most of the concepts demonstrated within this paper are agnostic to the technology which provides the tuning, and, therefore, will be able to quickly absorb the new advances in the underlying technologies independent of which technology proves most worthy.

As the underlying components mature, the prospect of high-Q adaptable filters will only become more significant, and the system adoption of these capabilities needs to be the focus of future work. Historically, tunable filters have been used to solve current problems for systems, such as blocking an incoming interferer to allow a banded system to continue working, as opposed to enable new capabilities from a system built explicitly to exploit their advantages. The codesign from the adaptable system and the adaptable component point of view is a ripe area of research that promises to show new capabilities that have never been achieved previously.

Translating these initial concepts into smaller form factors would be essential to wide adoption across applications. In the electromagnetic domain, filters similar to the substrate-integrated filters shown in this paper are currently under development in all-silicon fabrication technologies [63]–[65]. Such an advance would allow smaller tolerances due to the high accuracy of silicon micromachining developed for the integrated circuit industry. Silicon integration may make it possible to develop an entire integrated reconfigurable RF chain on a single piece of silicon; however, the size of the filter will always be the dominant component. Higher frequency applications, greater than 20 GHz, would be a more suitable frequency region for combined circuit and filter silicon integration.

For smaller integration or lower frequencies, the design concepts from the electromagnetic domain (such as lumped elements, transmission lines, and/or cavities such as those shown in these examples) can directly translate to the acoustic domain, where even more resonators and higher Q's are potentially possible due to their small size and beneficial material properties. While it is not expected that each acoustic resonator can have octave tuning as in the electromagnetic resonators, the creation of a sea of acoustic resonators with dynamic coupling coefficients is an exciting vision for the future for both academic and practical implications. The translation of these design concepts to the acoustic filter domain, whether it be adaptable acoustic technologies or mixed domain designs utilizing acoustic resonators with adaptable RF components, is potentially a next progression of research in RF filtering.

The belief of the authors is that the RF hardware will soon not be the limit of the level of adaptability that we can expect within a system. Instead, the complexity of the operation of a bandless system and the infrastructure needed to enable infield decision making for the system will become the bottleneck to progress. With flexibility comes the ability create or control chaos, and the intelligent utilization of these technologies will have to be well thought out so that we do not obstruct progress due to the inherent complexity of operation.

VI. CONCLUSION

This paper has reviewed the state of the art in adaptable RF filtering components. We initially motivated the need for adaptable hardware to complement the traditional SDR. Simple filter adjustments were shown to be effective to dramatically decrease the bit error ratio in the presence of an interferer for a fixed, banded system. Furthermore, an example was described where these same capabilities were extended to wideband coverage that allowed many radios to peacefully coexist without interference. The efforts to extend the tunable filters to "FPFAs" where the transfer function can be nearly arbitrarily dialed in for the application were overviewed. Finally, a new approach to cooperative filter interaction, intrinsically switched filter banks, was described in which many filters could act in concert. These can cooperatively operate to cover a wide tuning range or simultaneously create multiple bands without crossovers and penalty in the group delay at the filter edges. Whether these exact filters described are useful in the next generation of spectral allocation remains to be seen. However, these new advances point to a bright future in the area of tunable systems and dynamic RF systems where aggressive adaption to the spectrum is possible, expanding the already robust capabilities demonstrated with digital reprogramming of SDR systems. ■

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