INVITED PAPER

# Reconfigurable Radios: A Possible Solution to Reduce Entry Costs in Wireless Phones

*This paper examines prospective technologies for implementing fully reconfigurable radios and how they may reduce spectrum acquisition entry costs for new competitors in wireless service.*

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**ABSTRACT** | With advances in telecommunications, an increasing number of services rely on high data rate spectrum access. These critical services include banking, telemedicine, and exchange of technical information. As a result, spectrum resources are in ever-greater demand and the radio spectrum has become overly crowded. For efficient usage of spectrum, smart or cognitive radios are sought after. However, current wireless phones can only select a few specific bands. In this paper, we discuss the advantages of reconfigurable radios in not only increasing the efficiency of spectrum usage but also in potentially reducing the cost of wireless handsets and the barriers for new wireless service providers to enter the market. We review available technologies that make the implementation of reconfigurable radios possible and discuss technical challenges that need to be overcome before multistandard reconfigurable radios are put into practice. We also evaluate the ability of reconfigurable radios in reducing entry costs for new competitors in wireless service.

**KEYWORDS** | Entry cost; radio frequency microelectromechanical system (RF MEMS); reconfigurable radios; software defined radios; tunable passives; UHF communication

## I. INTRODUCTION

The U.S. wireless phone service industry is dominated by four large, national providers: AT&T, Sprint, T-Mobile, and Verizon. According to the Federal Communications Commission (FCC) Wireless Competition Report, market shares in the wireless industry are concentrated to a degree that would provoke antitrust investigation in other industries [1]. Given the concentrated industry, a large variety of benchmark economic models suggest that it is in the public interest to encourage the entry of new, nationwide competitors into this industry. A major hurdle for a new entrant is assembling a nationwide footprint of wireless licenses. The cost of assembling nationwide coverage is prohibitive, in part due to technological limitations. One particular challenge is that current radio technologies require the potential entrant to secure licenses for the same limited frequency bands in each geographic territory, because current mobile phone radios can only work on a small number of bands. However, more than a dozen new frequency bands may be opened up for broadband internet access in each territory in the near future and several open bands already exist. If future radio technologies allow an entrant to assemble a nationwide footprint from many different frequency bands, one or more for each territory, the cost of acquiring the needed licenses is likely to be lower. This will encourage new national providers to enter

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the market, increase competition, and lower costs to consumers. Therefore, multistandard radios, supporting a wide range of frequencies and capable of selecting different bands in different territories, could be possible solutions to reduce not only the entry cost for wireless providers but also the internet access cost for end-users.

By reconfiguring the radio, one can eliminate many of the redundant components which results in a smaller form factor, lower complexity, and reduction of the bill-of-materials for radios [2]. Reconfigurable multistandard radios can also mitigate the problems associated with limited spectrum availability and limited open bandwidth by tuning to the frequency and standard that is least heavily used at any given time [1].

The concept of a reconfigurable radio introduces a number of engineering and economics related challenges. This paper discusses potential hardware technologies that could be used to implement fully reconfigurable radios and also evaluates the ability of such radios to reduce spectrum acquisition entry costs for new competitors in wireless service. More specifically, this paper reviews the applicability of all-digital receivers and digital phase locked loop (PLL)-based transmitters [1]–[5], tunable filters [6]–[9], and MEMS switches [10]–[13] in implementing a reconfigurable radio. It also reviews studies about competition in the wireless phone market and discusses how reconfigurable radios may lower carrier entry costs [14], [15]. New entry would increase competition. In doing so, the paper also provides a brief review of the reconfigurable radio components.

## II. THE NEED FOR HARDWARE RECONFIGURABLE MULTISTANDARD RADIOS

Multistandard radios currently exist in the market. However, scaling the number of standards beyond today's attainable limit is very challenging using the hardware implementation and software design of the current multistandard radios. The iPhone 6 is considered a state-of-the-art cellphone sold today. It supports several cellular standards, including 2G (GSM/EDGE), LTE, and 3G (UMTS/HSDPA/HSUPA/CDMA EV-DO). These operate in several bands worldwide, including the 800, 850, 900, 1800, 1900, and 2100 MHz bands, as well as the 2500 MHz band for the higher models. Designing a common circuit board to support these bands is a time-consuming and challenging process. This is because of several factors that impact radio design in a unique way: 1) the signals operate at very high frequencies, 2) the receive signals are very weak (pico-Watts) and the transmit signals very large (Watts), 3) the desired signal is mixed in with signals from many other users, requiring precise filtering. All of these were first accomplished on the iPhone 3GS by using several separate modules from five different manufacturers that perform combinations of filtering, amplification, and multiplexing of the high-frequency signals [16]. Similar front end radio designs are found on other multiband phones. While this solution has served the cell phone industry very well to provide devices that operate worldwide, it is not easily scalable to a larger number of cellular bands. An immediate example for this is the LTE frequency standards. Today there are 44 different LTE frequency bands, and for comparison, the iPhone 6 for AT&T supports only 16 to 20 of these. Extending the number of bands and therefore the bandwidth that the phone supports is one of the main challenges of designing future radios. Therefore, a different solution is needed in order for a single device to efficiently utilize the existing bands and standards as well as those that are becoming available in the near future.

Behind the front end amplification and filtering modules, there is typically a single integrated circuit (IC) that performs additional signal processing. This approach is used by Qualcomm [17], and similar solutions are offered by other manufacturers of commercial radios [18]–[20]. The processing performed by the IC includes converting between the digital and analog domains, performing frequency translation between the RF bands and a lower frequency that is easier to process, and further amplifying and filtering the signal. These ICs "no matter from which manufacturer" have multiple high-frequency inputs/outputs, one for each band, followed by amplification and mixing stages. The mixers all share a local oscillator (LO) that can tune to each band; the low-frequency sides of the mixers converge and share a common signal path. For a quad-band phone, there would be four RF paths and mixers that converge to a single low-frequency path where analog to digital conversion takes place. However, this solution is again not scalable to a large number of bands; a different solution will be required to support a future "any-band" phone.

Software defined radios (SDRs) have been proposed as an alternative to the multiband solutions [21]–[23]. These radios directly digitize large swaths of bandwidth and use software executed on a digital signal processor (DSP) to perform all of the filtering and frequency translation. The advantage of this approach is operation over multiple bands simultaneously, similar to what cell phone base stations are required to do today, using the same circuit and signal path. Besides placing more severe constraints on the RF electronics and dynamic range [23], high power consumption of SDRs is a primary drawback of using this solution in a handheld device. High sample rates and resolutions are required, which in turn requires high-performance DSP, all of which consume large amounts of power. Many of these radios today operate on desktop computers or high-performance FPGA modules consuming several Watts [24]–[26]. Furthermore, it is unclear, given the wide bandwidths of these radios, if radio sensitivity comparable to current cellphones can be achieved.

A reconfigurable radio that is capable of selecting multiple bands can potentially address the problems of current multistandard radio architectures. In this paper, we discuss the hardware technologies needed to implement such reconfigurable multistandard radios. Namely, we study applicable front end passive and filter technologies, all-digital receivers, and digital PLL-based transmitter architectures. In the following sections, we review each of these units. We also evaluate the ability of reconfigurable radios to reduce entry costs for new competitors in wireless service.

Wireless carriers need licenses to have the right to transmit radio waves over certain blocks of frequencies in specified territories. If a carrier wants to offer its customers national coverage—a feature consumers value heavily [15]—it must assemble such a portfolio of licenses for almost all territories in the United States. In an ideal world, the carrier would secure more capacity in more densely populated areas. Using the prices of recent FCC spectrum auctions, the FCC's Wireless Competition Report states that "aggregating a significant regional spectrum footprint would involve an outlay of hundreds of millions of dollars and a national footprint would require billions of dollars." While there are other costs to entry, such as renting space on wireless towers, the costs of acquiring wireless licenses are a substantial barrier to entry. As mentioned earlier, current phones send and receive signals on a small number of bands. Because consumers travel, the same phone needs be able to work across the country. This technological constraint requires that the carriers secure the licenses in one of a small number of bands in each territory. Reconfigurable radios could greatly expand the number of bands that a phone can operate on. With more reconfigurable radios, new entrant carriers can patch together nationwide footprints using different licenses in each territory. With a reconfigurable radio installed on phones, the new entrant can acquire licenses in the open market for such licenses on a territory-by-territory basis. In this paper, we argue that being able to assemble a nationwide footprint through a combination of winnings from new spectrum auctions and purchases on the secondary market would ease entry costs and that the technology to use these licenses together could be a reconfigurable radio.

## III. ENGINEERING ASPECTS OF RECONFIGURABLE RADIOS

### A. Configuration of Current Multistandard Radios

For multiband transceiver implementation, a variety of architectures have been proposed. These architectures can be classified into several categories based on the type of front end filters and the topology of the transceivers. The most conventional approach uses multiple surface acoustic wave (SAW) filters and follows the superheterodyne, zero-IF, or low-IF transceiver [27], as shown in the RF front end architecture of commercialized smartphone handsets (Fig. 1) [28]. However, this approach is not applicable to flexible multiband standards, as the number of the required SAW filters will increase enormously. To cope with this, SAW-less radios, or so called SDRs, have been proposed [29], [30]. As mentioned earlier, SDR is based on wideband signal processing in the digital domain after direct-conversion into the baseband (Fig. 2) [29]. However, SDR requires high-bit rate analog-to-digital converters (ADC),

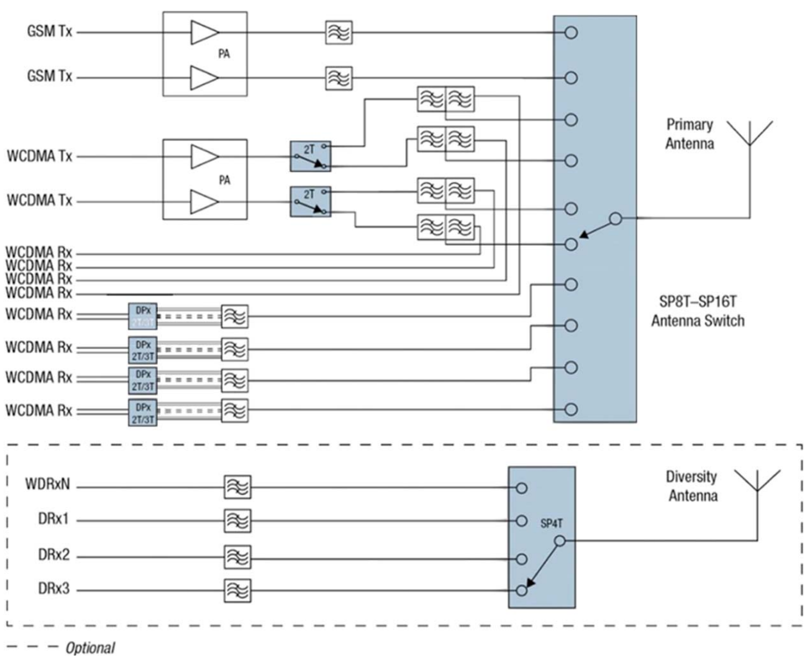


**Fig. 1.** ***The front end architecture of smart phones [28].***

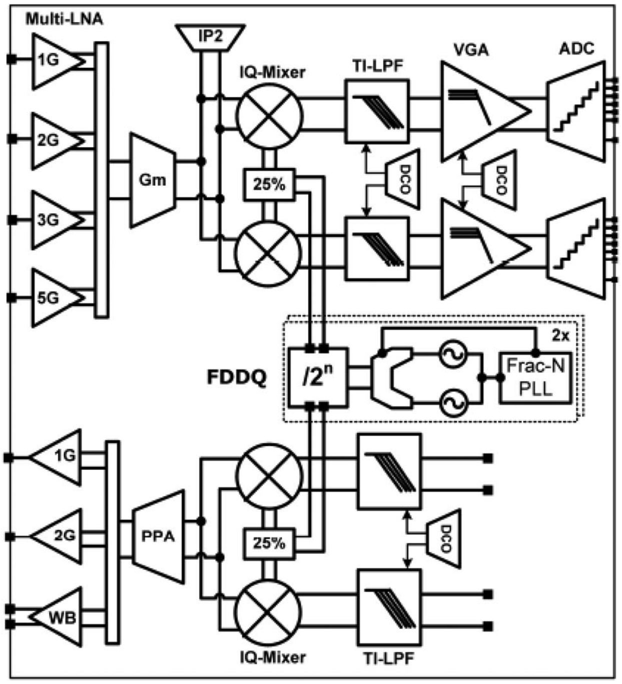


**Fig. 2.** *Transceiver block diagram of a multistandard SDR [29].*

and as such is power hungry and requires high-end, costly DSP as well as ADCs. It also suffers from blocking or saturation issues from strong interfering signals or jammers.

Since the tuning range of SAW filters is very limited—if tuning is at all possible—a more practical approach to address lack of reconfigurability is to integrate tunable passive filters in the transceiver front end (Fig. 3). Using this approach, strong interferences or blocking signals located near the target signal can be removed, to prevent the saturation of following RF circuits, such as the low noise amplifier (LNA) or mixer. This also reduces the stringent dynamic range requirement of the ADC. However, in this approach a variety of LOs with different frequencies or a tunable LO is needed, as discussed later in this paper. Another candidate is the RF bandpass filtering transceiver shown in Fig. 3(b). In this technique, RF sampling replaces the down-conversion stage and multiple channels can be processed simultaneously. Depending on the bandwidth of the preselect filter, the ADC sampling rate can be from several tens to hundreds of megahertz. Even though the required sampling rate is reduced compared to the original SDR architecture, this rate is still challenging to accomplish as the analog bandwidth of the sample-and-hold (SH) should be more than the highest input RF frequency. Therefore, the power consumption of the SH stage becomes significant. Nevertheless, the latter approach of using tunable front end filters is the most power-efficient approach and offers the highest versatility in terms of radio reconfigurability.

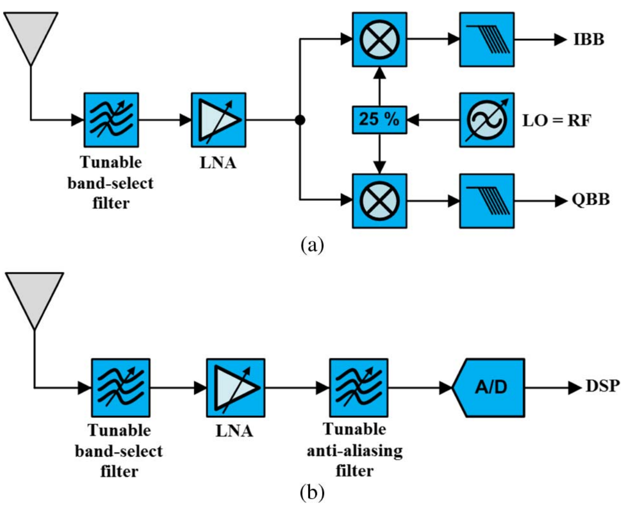


**Fig. 3.** *Candidate reconfigurable radio architectures with tunable preselect filters. (a) Direct conversion architecture. (b) RF bandpass sampling architecture; reprinted from [32].*

Integration of tunable RF filters with tunable antennas, such as those discussed in an earlier paper in this special issue, allow for tuning to the frequency of interest without jeopardizing the performance of the antenna and letting in additional unwanted and interfering signals. In the next subsection, a review on reported tunable filter architectures is provided and the required performance enhancement needed for successful insertion of these components in multistandard radios is discussed.

## B. Fully Reconfigurable Radios

*1) Tunable RF Filters:* As discussed earlier, a major obstacle in the scalability of existing multistandard radios are the preselect bandpass filters. Currently, SAW or bulk acoustic wave (BAW) filters are used as preselect filters in radios (e.g., SAW filters in Fig. 1). These filters, although small in size and high quality factor ($Q$), are not tunable and thus a number of these filters are required to select different bands (100 filters for covering the 700 MHz to 2.7 GHz range, given a bandwidth of 20 MHz for each filter). As the heart of a truly reconfigurable radio, the bandpass filter should be tunable across the frequency range of interest. Besides being tunable, the front end filter should be small in size (i.e., low profile ($<1$ mm) and small area (roughly speaking, less than 400 $\mathrm{mm}^2$)) to be an attractive candidate for cellular phone applications. The required $Q$ of the filter is defined by the cellular band to be selected. For example, for LTE bands, the signal bandwidth is usually about a few 10 s of megahertz in low gigahertz range, requiring a filter with $Q$ of $\sim$80. A few filter technologies with different levels of $Q$, size, and reconfigurability exist that offer frequency and/or bandwidth tunability, namely integrated tunable LCs [33], [34], distributed filters, and evanescent mode cavity filters [35] (Table 1).

Table 1 Comparison of Different Filter Technologies in 3 MHz–30 GHz Range

| Filter Type | Frequency Range | Q | Relative Size | Relative Loss |
|---|---|---|---|---|
| *E-Cavity* | UHF-SHF | High | Very large | Small |
| *Crystal* | IF | Very High | Large | Moderate-high |
| *Acoustic* | LF-UHF | Very high | *Very small* | Small-moderate |
| *Strip/ μstrip line* | SHF | Low-moderate | Large | Small-moderate |
| *Lumped* | HF-UHF | Low-moderate | *Small-medium* | Moderate-high |

The tuning elements in all types of filters can be implemented by semiconductor varactors or switches, radio frequency microelectromechanical system (RF MEMS) switches/varactors, variable dielectric capacitors, or the more recently developed phase change RF switches [36]. The semiconductor varactors (PIN diodes and GaAs Schottky diodes), which feature low price, low tuning voltage, and high tuning range have been demonstrated in many tunable planar filters [37]–[39]. However, the major drawbacks of semiconductor varactors are their low $Q$ of less than 150 and low linearity. Ferroelectrics with voltage tunable permittivity can also be used to implement variable capacitors. The advantage of this technique is the low voltage requirement to achieve significant capacitive tuning [40]. The main challenge, on the other hand, lies in the deposition process. Most ferroelectrics, such as barium strontium titanate (BST), are sputter deposited on small 2 inch wafers. The uniformity and quality of the deposited film suffer significantly by going to larger size wafers. Also, these films can only be sputtered in high quality on specific metals. RF MEMS technology is a promising candidate for providing tuning elements. Because of their high $Q$s, RF MEMS varactors and switched capacitors have been utilized to design tunable filters with excellent tuning performances.

From the list in Table 1, cavity filters have shown superior performance at frequencies above 1 GHz [41]. Recent research has demonstrated cavity filters with excellent tuning and low loss [42]–[48]. However, the volumetric size of demonstrated cavity filters is in the order of several cubic millimeters, thus hindering their application in handheld devices and single-chip radios. Reducing the size of cavity filters results in significant degradation of their $Q$ and performance. Lumped element and distributed filters [49]–[52], such as microstrip type filters are frequently used for lower frequencies ($<$ 10 GHz). Frequency tuning of these types of filters is usually achieved through changing the capacitance of the resonator using electrostatic [6], [34], piezoelectric [53], or thermal [54] microactuators, with the electrostatic technique having the clear advantage of fast tuning speed and ease of microfabrication. Tunable distributed type filters using MEMS technology have been extensively researched and excellent performance has been achieved at frequencies between 3 GHz and 10 GHz. Given the fact that newly open wireless bands are all between 225 MHz and 3.7 GHz [55] filter development should be focused on addressing this frequency range. At these lower frequencies, the size of distributed filters becomes considerably large [56], [57], impeding their application in a practical setting. Lumped LC filtering, although an established concept, has great potential at ultrahigh frequency (UHF) range where other techniques fall short.

Table 2 summarizes the performance of RF tunable filters in the UHF range, built with different technologies. The first two works [7], [8] describe integrated MEMS tunable capacitors on a PCB. Due to the large size of RF circuits on PCB, this type of integration [38] has larger size than complete integration of MEMS technology [58]. The customized multilayer PCB technology [9] can provide much smaller size than other technologies, but the filter implemented using this technique does not show a proper response across the entire tuned spectrum mainly due to the low $Q$ of passive components embedded in the lower PCB layers. The listed filters can be also classified into two categories based on their fractional bandwidths: wide-band filters with $>$ 10% of 3 dB-bandwidth ($BW_{3\ dB}$) and narrow-band filters with $\sim$5% of $BW_{3\ dB}$. Monolithic integration of RF components using the MEMS technology is clearly more beneficial for the narrow-band filter implementation that requires passive components with higher $Q$ values ($Q >$ 100 in UHF [59]). For wide-band filters, high-$Q$ inductors with $Q$s exceeding 150 can be soldered to the filter chip and a reasonable insertion loss can still be obtained. However, size reduction is still an issue when using off-chip elements. Therefore, a more advanced MEMS solution is necessary in order to achieve both high performance and small size [58].

Another way to classify tunable filters is by the tuning resolution. Some designs use continuously tuned MEMS capacitors for tuning the filter [8], [33], [34]. Selecting a specific band using such capacitors requires tight control over the variable gap. In other work, a bank of switched capacitors with digital states is used to reconfigure both the frequency and the bandwidth of the filters [7]. For example, for selecting 16 bands, four switched capacitors can be used in each resonator section and the value of the coupling element can be tuned as well. The disadvantage of this approach is the limited number of bands that can be selected using the same filter.

Another factor to consider when implementing filters or other radio front ends is the power handling capability. The power handling requirement of the filter depends on the application: the receiver filter does not receive much power. (The received power could be in the order of $-90$ dBm; interferences might be stronger.) Therefore, power handling is not a major concern for the receiver filter. Here, the insertion loss is the most important constraint as the receiver chain should have a small noise figure (typically less than 5 dB). Conversely, at the transmit side,

Table 2 Comparison of Reported Tunable Filters in the UHF Range

| | Brown '00 [7] | Borwick '03 [8] | S.-Renedo '05 [56] | Lee '09 [9] | Rais-Zadeh '09 [34] | Zhang '10 [38] | Shim '12 [33] | Cho '14 [57] |
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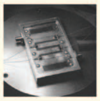
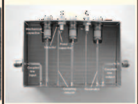
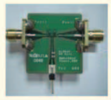
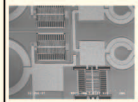
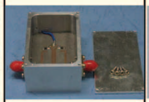
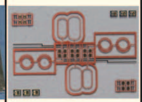
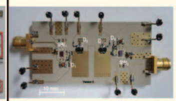
| **Picture** |  |  |  |  |  |  |  |  |
| **$f_c$ (MHz)** | 700-1330 | 225-400 | 470-862 | 510-910 | 786-836 | 680-1000 | 602-1011 | 730-1030 |
| **Filter Architecture** | 5th order discretely tunable combline filter | 2nd order filter with off-chip inductors | 3rd order continuously tunable combline filter | 2nd order filter with off-chip varactor | 2nd order continuously tunable lumped filter | 2nd order continuously tunable combline filter | 3rd order continuously tunable lumped filter | Reconfigurable 2 pole-4 pole filter |
| **Insertion Loss (dB)** | 2.0-6.0 | 4.7-6.2 | 3.0-6.0 | 1.8-2.5 | 4.0-6.0 | 1.1-1.5 | 3.0-3.6 | 5.7-7.66 |
| **$BW_{3dB}$ (% of $f_c$)** | 8-22 | 4 | 1-3 | 20 | 5-6 | 8-12 | 13-14 | ~10 |
| **$BW_{30dB}/BW_{3dB}$** | 2.0-3.0 | 5.0-6.0 | 3.0-5.0 | 4.5-6.5 | > 7.0 | 5.0-6.0 | 3.2-4.7 | < 4 |
| **Tuning Speed** | NA | < 600 µs | < 1 µs | < 1 µs | < 1 ms | < 1 µs | < 80 µs | N/A |
| **$IIP_3$ (dBm)** | 18-24 | 30-38 | 32.8 | N/A | N/A | 13 | > 20 | 20- 27 |
| **Technology** | PCB (microstrip) | PCB (SMT) + MEMS | PCB + CMOS varactor | PCB (multilayer) | MEMS (single chip) | PCB + CMOS varactor | MEMS (single chip) | Duroid+ MEMS switches and CMOS varactors |
| **Size ($mm^2$)** | < 31 × 41 | 30.0 × 44.5 | < 50 × 65 | 4.4 × 3.4 | < 5 × 6 | < 30 × 30 | 11 ×15 | < 20 × 40 |

the filter should support up to 1 W (30 dBm) of RF power. In this case, the linearity and the third-order input intercept point ($IIP_3$) of the filter needs to be better than ~35 dBm. Generally speaking, MEMS varactors and switched capacitors are able to handle high powers and are therefore suitable for use in both transmit and receive channels.

To obtain higher-performance (lower-loss, smaller-bandwidth, faster tuning range, and more linear) filters suitable for mobile RF transceivers, the Q of passive components should be increased and the resistive loss should be effectively reduced. Currently, the performance of the lumped filters is limited by the on-chip inductor. As a comparison, the highest-performance tunable filter has Q close to 25 (Table 2), limited by the inductor Q, versus Qs in excess of 200 that could be readily achieved using SAW or BAW filters. To increase the inductor Q to more 100 and reduce the interconnect loss, a fabrication technique which offers thick high-aspect ratio metal structures is desirable. Unfortunately, thick metal lines ($> 20\ \mu$m) are still not available in standard semiconductor processes. Such microfabrication techniques enable the implementation of high-Q passives as well as low-loss interconnects [59], providing a solution to scaling issues in integrated circuits.

The reliability of MEMS varactors and switches, and by extension MEMS filters, needs to be improved. Here, improved reliability requires improving the number of cycles the devices can be reconfigured; consistency in the voltage required to tune the frequency to a specific band; reliable operation over the $-40\ ^\circ$C to 85 $^\circ$C industrial temperature range; high power handling and linear operation; etc. From Table 2, it can be seen that although MEMS is a promising and perhaps the only sound solution for implementing small-size tunable RF modules, a MEMS reconfigurable filter that meets all such requirements has not been demonstrated, making the handset manufacturer hesitant to adopt this technology as yet.

To implement a fully reconfigurable radio, it is required to have a situation-aware hardware that is able to automatically react to changes in the communication setting. In a cognitive radio, this is done by sensing the channel using a sensing antenna, followed by dynamically reconfiguring the communicating antenna and the following filtering element to the available whitespace [60]. The tunable filter control unit basically changes the biasing condition of the switching elements or varactors to achieve the required mode of communication. Such a cognitive operation is demonstrated for antennas [60] and the concept can be extended to tunable filters.

Other filtering technologies, such as on-chip n-path filters [61]–[63], can be combined with MEMS reconfigurable filters to achieve higher performance in a practical system. However, implementation of such a system is out of the scope of this paper.

From the cost perspective, manufacturing of MEMS filters mentioned above requires only a small number of photolithography masks, much smaller than those needed in a standard semiconductor fabrication process. Therefore, improved reliability and yield of MEMS processes would result in reduced cost for tunable RF modules and would make them more attractive for use in lower cost wireless phones. Besides, a single tunable filter replaces several fixed filters currently in use and thus can reduce the bill of materials of a radio.

*2) RF Switches:* As noted, there are a number of uses for switches in radios, and even more so in reconfigurable radios. Traditional architectures have utilized mechanical relays that are not fabricated by lithographic means. Such switches are available from Teledyne, Charter Engineering, Keysight, and other companies. There has been considerable incentive to investigate switches that can be fabricated lithographically, thereby leveraging the dimensional and cost scaling advantages that have benefited other components. Semiconductor electronic switches made from p-i-n diodes or field effect transistors can meet a number of needs. For example, Peregrine Semiconductor provides RF switches based on a silicon-on-sapphire technology, whereas Triquint's switches use GaN on SiC. A high-power (43 W) switch using an AlGaN/GaN HFET was described in [64]. Despite the success of semiconductor switches in many applications, the search continues for devices that can be more easily integrated into circuits, or offer higher performance in isolation, power consumption, and other metrics. Here, we focus on two emerging approaches: micromechanical switches that actuate a movable element and those that cause a phase change between the crystalline and amorphous states of the switch material.

The interest in exploiting the change, with phase, in the electrical properties of materials traces back to the 1960s work of Stanford Ovshinsky at Energy Conversion Devices to make nonvolatile memories using GST (i.e., $Ge_2Sb_2Te_5$ - an alloy of germanium, antimony, and tellurium). Although the alloy can be varied in many ways, the simple formulation of GeTe is attractive for an RF switch because the ratio of the resistivity of the amorphous state to that of the crystalline can approach $10^6$. The RF switch may be implemented by sandwiching, between two thin films of metal, a patterned feature (via) of GeTe thin film. The resistance between the metal films is then determined by the crystalline or amorphous nature of this via. This approach was utilized in an RF switch reported in [36]. A resistive heater located in the vicinity can be used to provide the thermal pulse necessary to change the phase. Gradual cooling (over a period of about 5–30 $\mu$s) resulted in the crystalline phase, whereas rapid cooling (over about 0.5–1.5 $\mu$s) resulted in the amorphous phase. In order to guarantee phase change to crystalline state, the GeTe via must achieve about 190 °C; the return to amorphous state requires about 700 °C. Consequently, phase change switches face challenges in switching speed and power consumption. One benefit of phase change switches, particularly in comparing to electrostatically operated MEMS switches, is that the operating voltage does not need to be high and is generally compatible with standard CMOS electronics. The results reported in [36] indicate that the typical resistance of a $3 \times 3$ $\mu m^2$ via of GeTe is about 2 Ω, but that the use of five $2 \times 2$ $\mu m^2$ vias in parallel reduces the effective resistance to about 0.7 Ω. Northrop Grumman has reported some of the best results to date using a submicron gap of GeTe separating two RF ports, with insertion loss of only 0.1–0.24 dB over 0–10 GHz [65]. In this device, the thermal stimulus was provided by the thin film metal heater under the GeTe layer.

Another version of the GeTe switch uses a 4-port arrangement, in which the input and output RF ports are separated in-plane by the GeTe via [66]. The thermal stimulus is provided by passing direct current orthogonally through the via using titanium nitride (TiN) electrodes located above and below it. This reduces both the footprint of the overall device and the power necessary to switch. Crystallization can be achieved in about 400 $\mu$s using 73 mW and a drive voltage of 9 V. The on-state resistance is 3.9 Ω. The active area is $5 \times 20$ $\mu m^2$.

In the past decade, the preponderance of research related to RF switches has been directed at micromechanical devices, or MEMS. A variety of actuation methods have been envisioned and explored, including magnetic, piezoelectric, thermal, and electrostatic. Electrostatic actuation is highly attractive, in part because it does not require materials with any special transducing properties and because it offers low power operation. The primary compromise of electrostatic actuation is that the forces generated are typically in the range of 5–500 micro-Newtons (although there certainly are exceptions that fall outside this range), and even for these forces high actuation voltages (typically 50–150 V) are necessary. For contact-mode (ohmic) switches that can operate even at DC, a high actuation force is attractive because it permits relays to be mechanically stiff. A stiffer relay provides high force for retracting an actuated cantilever. High retraction forces are needed to overcome contact adhesion that may inadvertently occur at the contact tip when a high actuation force is used. A high actuation force is typically used to break through surface films and provide a low-resistance ohmic contact between the terminals of the switch.

The interest in electrostatically actuated cantilever switches dates back to work of Petersen at IBM in the 1970s [67], [68]. The basic compromises between switching speed and actuation voltage, limitations on power handling, and concerns about contact mechanics, were known even back then. The electrostatic actuation of suspended membranes of aluminum (Al) was evaluated for RF switches by Goldsmith and others at Texas Instruments in 1995 [69]. A number of early efforts are compared in [70], including those from Rockwell, Raytheon, Hughes Research Labs (now HRL), U. Michigan, Northeastern U., Siemens, OMRON, and NEC. Structural materials varied from silicon oxide and silicon nitride to silicon, epitaxial silicon, and p++ silicon, and further to Al, gold (Au), or nickel (Ni) films. Whereas most of these efforts were directed at switches that established an ohmic connection between terminals, a few were directed at capacitive connections, which are appropriate only for high-frequency signals (typically exceeding 10 GHz). An important innovation from the OMRON team was a nonlinear spring that provides a high restorative force, overcoming contact stiction [71]. The OMRON device, which used an epitaxial silicon spring and provided an ohmic contact, ultimately evolved into a commercial product that is currently available. The Northeastern U. device used an electroplated metal spring and also provided an ohmic contact [72], [73]. Although initially supported by Analog Devices, the technology was later transferred to Radant MEMS, Inc. [10]. Recent efforts by Rebeiz and collaborators at U. California, San Diego (UCSD) have also favored electroplated metal springs and ohmic contacts. One effort, in collaboration with U. Limoges (France), used a number of cantilevers arrayed in parallel in order to reduce the effective resistance of the switch [74]. Another effort used a stiff spring to provide milli-Newton forces; this feature, in combination with ruthenium-on-gold contacts, allowed high power handling [75]. High power handling was also demonstrated in an effort from U. Michigan in which stainless steel cantilevers with platinum-rhodium tips were assembled directly on printed circuit boards and encapsulated in liquid crystal polymer packages [12]. In general, for RF applications, the potential benefits of electrostatically actuated micromechanical switches include very low power consumption, low insertion loss (< 0.5 dB), high isolation (better than 15 dB), and switching times in the range of micro-seconds. While there is room for improvement, questions of reliability and power handling capability have been addressed to a large extent, and a number of companies are in the process of commercializing electrostatic switches [76], [77].

Thermal actuation has also been explored for a number of RF switches. Like electrostatic actuation, it does not require any special transducer material. It generally provides higher actuation forces than electrostatic actuation, and requires only modest drive voltages. However, it compromises power consumption and speed. A few examples include the Cronos switch [78], [79] and the U. California, Davis switch [80]. Both efforts employed versions of the bent-bent-beam thermal actuator first reported by U. Wisconsin [81]. Peak power consumption is broadly comparable to indirectly heated phase change switches because of the thermal nature of the actuation.

Piezoelectric actuation has also been explored; it can provide relatively high forces at modest voltages and is power efficient. However, it does require the integration of piezoelectric materials. The use of lead-zirconate-titanate (PZT) ceramics for RF switches has been explored, for example, at Pennsylvania State U. [82] and LG Corporation [83], [84]. The use of AlN, which is potentially compatible with CMOS technology, has been explored at IMEC (Belgium) [85] and U. Pennsylvania [86]. For piezoelectric actuation, the switching times reported have been in the range of micro-seconds and actuation voltages have been in the range of 10 V.

Overall, current literature suggests that phase change switches offer operational frequencies extending to around 40 GHz, with on-state $S_{21}$ parameter in the range of 0.3 to 1 dB, and good linearity ($IIP_3 > 30$ dBm). In contrast, MEMS switches offer operational frequencies extending to 40 GHz or higher in some cases, with on-state $S_{21}$ value in the range of 0.2 to 0.3 dB, and excellent linearity ($IIP_3 >$ 60 dBm). Although many semiconductor switches are intended for frequencies below 20 GHz, others can operate in the 70 to 90 GHz range. On state $S_{21}$ (insertion loss) and linearity of semiconductor switches vary over ranges similar to those noted for MEMS switches above. At the system level, the selection of switches is based on a number of factors that include power consumption, footprint, packaging constraints, availability, reliability, and cost. Semiconductor and electrostatically actuated MEMS switches are already available commercially; piezoelectrically actuated MEMS switches are on the verge of commercialization, and phase change switches appear to be close behind. The investigation of RF switches remains an active pursuit in both industry and academia, and the available options will continue to grow in the coming decade.

*3) Widely Tunable Frequency Synthesizers:* Behind the RF filter and switch an IC is required to perform frequency translation and further signal conditioning. High-*Q* tunable filtering before the IC will simplify the design of RF amplification circuits and enable the use of a single, wideband RF path rather than the multipath design used in current state-of-the-art radios. However, there will still be a need for a frequency synthesizer capable of tuning over all of the frequency bands in order to provide a reconfigurable radio for nearly any frequency band currently planned for mobile communication. For example, the 44 LTE frequency bands span nearly a decade in frequency from 465 MHz to 3.6 GHz.

Mobile phone standards are designed to achieve excellent spectral efficiency (to support a maximum number of users) and therefore have some of the most strict requirements on the frequency synthesizer in the IC. A phase noise requirement of −100 dBc/Hz at a 10 kHz offset is common for LTE applications, falling to −164 dBc/Hz out-of-band, derived from the blocker requirements [87]. It is challenging to simultaneously achieve wide frequency range and high performance in a frequency synthesizer. This comes from the tradeoffs in the oscillator design, and the choice of an LC versus ring oscillator. LC oscillators provide the best performance, but are limited in tuning range. Wide range GHz LC oscillators have been recently demonstrated covering a tuning range of 2 : 1 to 3 : 1 [88], [89], but not sufficient to cover all bands. More commonly, multiple LC oscillators and frequency dividers are used to achieve wider ranges, but at the expense of performance [90]. Ring oscillators offer the widest tuning range, which would be many decades for some digital clock generator applications; however, their phase noise has not been sufficient for mobile applications. In the past decade, significant efforts have been focused on developing all-digital architectures for PLLs (ADPLLs), incorporating ring oscillators in order to push the boundaries of performance. Ultimately this could provide the best solution for reconfigurable radios because of its tuning range, if the performance can be improved enough for mobile standards. The rest of this section describes state-of-the-art for ring-based ADPLLs, and techniques for improving their performance.

A typical implementation of an ADPLL is shown in Fig. 4, which include a time-to-digital converter (TDC), digital loop filter (DLF), and digitally controlled oscillator (DCO). The performance of an ADPLL is defined by factors similar to an analog PLL, such as oscillator phase noise and loop bandwidth. However, the performance is also impacted by the resolution of the TDC and DCO. In most ADPLLs, the latter typically dominates the performance. Digitally tunable LC oscillators provide acceptable phase noise performance. However, the tuning range for such oscillators is very narrow and is often limited by the size of inductors. In addition, achieving acceptable frequency resolution in such oscillators requires sigma-delta dithering or bias voltage tuning. On the contrary, digitally controlled ring oscillators allow wide tuning range but have poor phase noise and frequency resolution. Various techniques exist to achieve wide tuning range as well as to improve the frequency resolution in ring oscillators, and these specifications are summarized in Table 3 [91]–[95], highlighting the difficulty of simultaneously achieving a wide tuning range with fine resolution. These ADPLL implementations utilize sigma-delta dithering to achieve frequency resolution below the least significant bit (LSB) of the DCO. The improved frequency resolutions are still on the order of 1 MHz, which is not sufficient to meet any cellular wireless communication standard. For most standards, 1 kHz resolution is required, along with a 10× frequency tuning range to cover all LTE bands.

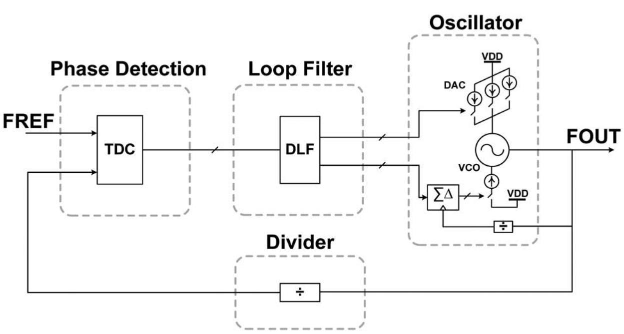



**Fig. 4.** ***A typical implementation of an ADPLL with Sigma-Delta modulation to enhance DCO resolution.***

**Table 3** Summary of Digitally Controlled Oscillators

| | Resolution | Frequency Range (MHz) | Jitter (ps) | DCO Type |
|---|---|---|---|---|
| [91] | 1.8MHz | 28-446 | 70 | Ring |
| [92] | 4MHz | 90-527 | 78 | Ring |
| [93] | 1MHz | 300-3200 | 2 | Ring |
| [94] | 1MHz | 400-3000 | 5 | Ring |
| [95] | 2kHz | 600-800 | 30 | Ring |

The next logical step for ADPLLs is to utilize digital synthesis and automatic place-and-route (APR) flows to simplify the design phase and facilitate easier integration with a system on chip (SoC). By leveraging these existing, powerful CAD tools for implementing the physical design, it becomes exponentially easier to implement reconfigurability, digital calibration, and multiple control loops into a single frequency synthesizer. Some traditionally mixed-signal systems such as ADCs and ADPLLs are already being implemented with digital synthesis tools [4], [96]–[98]. The challenge for these synthesizers is simultaneously achieving wide tuning range and sufficient phase noise performance to meet the strict requirements of cellular standards.

One technique recently demonstrated for improving the native DCO resolution, and that is amenable to a digital synthesis flow, is pulse-width modulation (PWM) control of the digital frequency control [96], [99]. This technique has several advantages over more traditional sigma-delta dithering, including lower-power operation, no spurs, and the performance improvement with Moore's Law scaling of CMOS processes.

The principle of operation of the PWM technique is described below for the DCO shown in Fig. 5. An ultrafine driver that is weaker than the main drivers is connected in parallel to each stage of the DCO. This technique enhances DCO resolution as follows: the PWM generates synchronous pulses from the DCO output at the DCO frequency, which enable all ten ultrafine drivers together for only a fraction of the RF period. As an edge propagates through the DCO, only the transitions, or fractions of transitions that overlap the PWM pulse in time will be sped up by the ultrafine driver. All other transitions will be unaffected. The DCO frequency increases as a function of the pulse width. Because the PWM signal is applied in every DCO period, the pulse modifies the DCO's internal edges the same way every cycle, thus changing its frequency by a small amount. The primary advantage of PWM control is that it finely tunes the frequency of the DCO without producing spurs, unlike traditional LSB dithering, which toggles between larger frequency steps and introduces spurs that are then rejected using a delta-sigma modulator (DSM). Therefore, this technique replaces the traditional DAC and DSM, can achieve 1 kHz DCO resolution suitable for cellular standards, and is amenable to synthesizable ADPLLs.

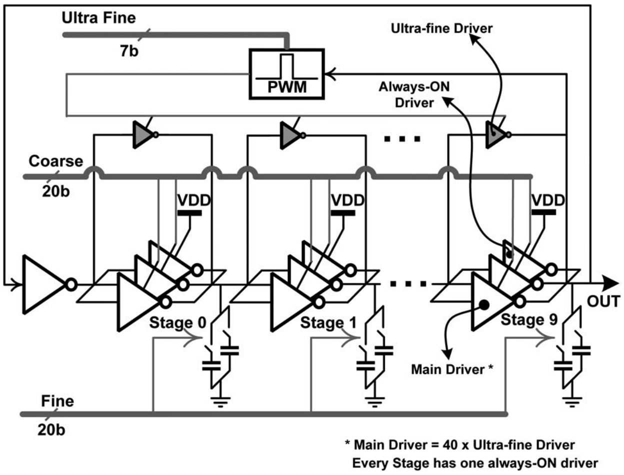



**Fig. 5.** ***Detailed schematic of the DCO and PWM based resolution enhancement technique.***

## IV. ECONOMICS ASPECTS OF RECONFIGURABLE RADIOS

### A. The Need for Increased Competition

Market power is a measure of the ability of a firm to profitably price above its costs. Competition is a measure of the absence of market power for the firms in a particular industry. A standard principle in economics is that competition is good for consumers. While there are well-known exceptions, standard theoretical models of competition predict that the prices of goods will be lower and quantities of goods sold will be higher when a market becomes more competitive (market power is decreased). An increase in competition can occur, for example, through the entry of new firms that compete with the incumbent firms. Consumer welfare will be higher with the lower prices and the higher consumption from increased competition.

The structure of the wireless phone industry in the United States in 2013 is outlined in Table 4. The numbers are before a recent merger of MetroPCS and T-Mobile. These numbers are the authors' calculations using FCC data. The column reporting total population covered sums the population of counties where the firm in question holds one or more wireless licenses in frequency blocks commonly used to provide mobile phone service. The column shows that there are four carriers with national coverage: AT&T, Sprint, T-Mobile, and Verizon. The firms with fewer people in their coverage areas are either regional carriers (Leap, U.S. Cellular) or speculators not actively selling subscriptions to consumers (Dish, Aloha, Cavalier).

Table 4 also reports on the mean total amount of spectrum held by firms in the counties where they do hold one or more wireless licenses. Counties are weighted by population in the calculations. What is most striking is that AT&T and Verizon have much larger amounts of spectrum per county, allowing them to sign up more customers with data intensive mobile devices. The dominance of AT&T and Verizon and the presence of only four national carriers characterize the industry in 2013.

**Table 4** Largest Mobile Phone Spectrum Holdings in the United States

| Wireless Carriers and License Speculators | Total Population Covered | Average MHz in Covered Counties |
|---|---|---|
| AT&T | 315 million | 96 MHz |
| T-Mobile | 315 million | 28 MHz |
| Sprint | 313 million | 17 MHz |
| Verizon | 309 million | 85 MHz |
| Echostar (Dish) | 240 million | 6 MHz |
| MetroPCS | 141 million | 15 MHz |
| Leap | 133 million | 18 MHz |
| US Cellular | 51 million | 35 MHz |
| Aloha | 48 million | 26 MHz |
| Cavalier Wireless | 26 million | 12 MHz |

Encouraging competition is currently a major issue in the U.S. wireless service (mobile phones) industry. In late 2011, the Department of Justice (DoJ) and the FCC successfully blocked the merger of AT&T and T-Mobile, two of the four national wireless carriers. These agencies blocked the merger because they predicted that the merger of AT&T and T-Mobile would give the postmerger firm additional market power and allow it to raise prices to consumers. In mid-2014, another merger between Sprint and T-Mobile was called off because of fears regulators would not approve it.

Market concentration is a measure of how market shares of companies are concentrated in a few large firms. In the wireless industry, market shares are calculated for different geographic regions. This is because consumers typically buy service from carriers operating in the geographic area where the consumers live. These geographic market shares can be used as inputs into standard measures of concentration, such as the Herfindahl-Hirschman Index (HHI), which ranges from 0 to 10 000, with 10 000 representing a monopoly. The Horizontal Merger Guidelines used by the DoJ and Federal Trade Commission scrutinize mergers where the HHI is currently above 2500 (equal to four providers with equal market shares) and the merger would result in an HHI increase of 100. An HHI above 2500 is called "highly concentrated." The FCC's Wireless Competition Report divides the U.S. into 172 Economic Areas (EAs) for the purposes of computing HHIs. Using confidential subscriber data from 2011, the population-weighted average HHI was 2848, noticeably above the "highly concentrated" line.

### B. Wireless Licenses and Reconfigurable Radios

Wireless carriers need licenses that give them the right to transmit radio waves over certain blocks of frequencies in specified territories. Estimates in the literature show that consumers highly value national coverage [15]. To gain national coverage, a carrier must assemble such a portfolio of licenses for almost all territories in the United States. In an ideal world, the carrier would secure more capacity in more densely populated areas. However, using the prices of recent FCC spectrum auctions, the costs of acquiring wireless licenses are substantial barriers to entry.

As mentioned in the introduction, current phones send and receive signals on a small fraction of the available bands. Because consumers travel, the same phone needs be able to work across the country. This technological constraint requires that the carriers secure the licenses in one of a small number of bands in each territory. Reconfigurable radios would greatly expand the number of bands that a phone can operate on.

With reconfigurable radios, new entrant carriers can patch together nationwide footprints using different licenses in each territory. For example, a license in band A and territory 1 may be underutilized by its incumbent holder, while a license in band B and territory 2 may be up for sale as well. With a reconfigurable radio installed on phones, the new entrant can acquire licenses in the open market for such licenses on a territory-by-territory basis. Acquiring already issued licenses on the secondary market is a substitute for acquiring newly issued licenses in a spectrum auction, which, at current prices, may involve greater expense.

The rules for current spectrum auctions do not make it trivial to assemble a national footprint. Published estimates further indicate that FCC spectrum auctions may assign inefficiently small portfolios of licenses [14]. For a particular spectrum auction, we find empirical evidence consistent with the footprints of each winning carrier being inefficiently small. This is predicted by economic theory: the simultaneous ascending auction used in FCC spectrum auctions has collusive equilibria [100], [101]. A collusive equilibrium is in contrast to straightforward bidding, where in each round of the auction each bidder places bids on the licenses that maximize its postauction profits at the standing prices in that round of the auction. Instead, in the collusive equilibrium bidders typically split the licenses for sale during the auction at low prices to the government. This is profitable to bidders, at least in the short run, as bidders pay lower prices than under straightforward bidding, where the prices go high enough so that all but one bidder's value is lower than the closing price on each license. If bidders attempt to deviate from the collusive equilibrium, a punishment bidding war may ensue, which would lower the profits of most bidders compared to the lower prices in the collusive equilibrium. Inefficiently small spectrum footprints result from splitting licenses to ensure all colluding bidders win some licenses.

Given this institutional constraint, being able to assemble a nationwide footprint through a combination of winnings from new spectrum auctions and purchases on the secondary market would ease entry costs. The technology to use these licenses together could be reconfigurable radios.

### C. Costs of a National Footprint

How much would it cost an entrant to secure the wireless licenses for a national footprint? How would such costs change upon the introduction of reconfigurable radios? These questions motivate ongoing research into this industry by the authors. In particular, the prices of wireless licenses in the resale (say merger) market and in spectrum auctions depend on the needs of carriers as a function of the radio technology in use. As discussed previously, the introduction of reconfigurable radios will alter these license prices. Therefore, an exploration of these topics requires statistical estimates of an equilibrium model of the prices of licenses and the matching of the scarce licenses to current and potential carriers. This is a topic of active investigation.

Relatedly, it is not even possible to sum the prices of spectrum auction licenses for all U.S. geographic markets to calculate the price of a national footprint for an entrant under the current, nonreconfigurable radio technology. As discussed previously, an entrant looking to win all licenses in such an auction would disturb the possibly collusive equilibrium in such an auction, which would raise prices in the auction. Nevertheless, naïve calculations that sum auction prices across markets can provide theoretical lower bounds as to entry costs. Lower frequency spectrum is more valuable for mobile phones. In the 2008 auction of spectrum, one particular block of spectrum in the 700 MHz range, across the United States, sold for a total of \$9.1 billion. In the same auction, a nearly identical block of 10 MHz of spectrum, except for some feared interference issues from television, sold for \$4.0 billion. The hope is that reconfigurable radios will allow carriers to arbitrage away price differences across frequencies to assemble cheaper national portfolios of licenses.

## V. CONCLUSION

The increasing demand for wireless data access calls for smart usage of the radio spectrum. In addition, the highly concentrated wireless market calls for new entrants to this industry or otherwise the prices of data plans could stay high or even become higher than what they are today. A technology that could solve both problems is reconfigurable radios. If the radio is capable of selecting an increased number of bands, the service providers do not need to get licenses for the same band in every territory. This flexibility of patching together different bands to provide national coverage could result in reduced entry costs and as a result reduced prices to end-users and costumers. In this paper, we also argued that using reconfigurable radios could result in lower cost for the wireless handset itself.

Although the need for reconfigurable radios is clear, there are several challenges and unanswered questions that need to be addressed before these devices enter the wireless market. For example, what would be the new cost (using reconfigurable radios) for an entrant to secure the wireless licenses for a national footprint; are there new auction mechanisms that need to be developed by the FCC; etc. From the engineering standpoint, what is the required tuning speed to maintain connectivity, what other hardware components (besides tunable antennas, tunable filters, switches, and frequency synthesizers) may be needed. These issues need to be addressed before reconfigurable radios enter the market. ■

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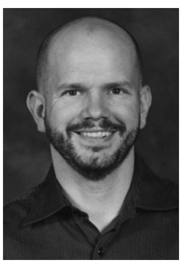

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