Abstract – Today, the largest and most desirable portion of the radio spectrum is allocated to licensed services, which has resulted in the well-known profound scarcity of this resource for emerging applications. With the rapid growth of wireless technologies, current spectrum scarcity has become a serious problem as more and more wireless applications compete for very little spectrum. On the other hand, the licensed spectrum allocated to applications such as television, cellular telephony and public safety show very little usage over time at different geographical locations. This has, therefore, seriously impaired the evolution of newer technologies because of current regulatory constraints on the operation in licensed spectrum, such as TV bands, and is being addressed by FCC through recent rule makings. With the goal of ubiquitous communication in mind, we look into spectrum agile radios as a new technology enabled by such emerging regulatory rulings and study its advantages over conventional radios. Initially, we provide a simple mathematical modeling to understand the utilization that is achievable by spectrum agile radios. Next, we investigate several issues related to spectrum sensing, as it is one of the key pillars to realize spectrum agile radios. Through sensing, the spectrum agile radio identifies the so-called “white-spaces” in the spectrum and then decides whether to occupy those white spaces opportunistically to transmit data. We also discuss the concept of interference temperature introduced by the FCC, and propose a spectrum-aware sensor network as a way to address it. Finally, we extend this spectrum-aware sensor networks to introduce a new sensing architecture to identify and locate white spaces in the spectrum.

A Introduction

Electromagnetic spectrum is a valuable natural resource, and hence is tightly regulated around the world. In the US, spectrum auction for third-generation (3G) mobile communications yielded USD 17 billion, while it yielded USD 34 billion and USD 46 billion in England and Germany, respectively. The US frequency allocations chart produced by the Office of Spectrum Management, US Department of Commerce, reveals that almost all of the electromagnetic spectrum is allocated; while recent studies indicate most of those allocations are utilized only in low duty cycles. One such spectrum measurement study, conducted by Shared Spectrum Company, indicates occupancy in less than 35% percent of the radio spectrum below 3GHz, even in the most crowded area near downtown Washington DC, where both government and commercial spectrum usage is intensive [1]. Similar results have been obtained when measurements were made in New York City during the republican convention held last year (see Figure 1) [2]. Furthermore, it is noted that spectrum usage varies dramatically in time, geographic locations, and frequency.

Figure 1: Occupancy of spectrum in 30 MHz to 3 GHz in NYC over a 24 hour period yielding 13% duty cycle (source: Shared Spectrum Company website).

These and other studies [10] have indicated that precious spectrum (especially under 3 GHz) remains unused, whereas other parts of the spectrum experience considerable overcrowding. Recognizing this, the Federal Communication Commission (FCC) is undertaking regulatory reforms to improve the overall utilization of spectrum, and thus facilitate faster deployment of new wireless applications. Such reforms rely on recent improvements in wireless communications technologies, widely known as Cognitive Radios, and referred to in this paper as Spectrum Agile Radios (or simply, agile radios) [7][8][9][14].

1st Background: Impact of spectrum regulation on the design of wireless communications systems

Today the FCC regulates radio spectrum by dividing it into frequency bands and applying one of two regulatory models to each band \(^1\). In the first model (applied to most bands), a primary user is given a license to operate, usually exclusively (in some bands multiple users may be assigned as co-primaries). Examples of primary licensed operation include television, radio and military applications. In the second model, a few remaining frequency bands are allocated for secondary users for non-exclusive,
unlicensed use\(^2\). Examples of secondary unlicensed operation include the many applications in the ISM bands, such as computer networking using WiFi.

Since primary users have exclusive access to certain parts of the spectrum, a simplified and cost effective architecture can be used for wireless communications devices operating in these bands. In addition, due to the exclusive use of spectrum, these primary users are able to provide the higher Quality-of-Service (QoS) needed for audio/video services. However, as indicated earlier, a significant part of the spectrum allocated for primary users is vacant for most of the time, resulting in inefficient use of spectrum.

On the other hand, in the unlicensed bands, a large number of wireless applications have quickly become available in recent years, especially indoors. The very success of these applications has in fact resulted in overcrowding of these bands. As a result, no strict QoS can be provided for these applications, despite the great efforts to find such mechanisms (e.g., to provide better QoS and robustness) by researchers in academia and the industry, including the IEEE 802 Standards body.

As indicated earlier, to alleviate these problems, the FCC is considering opening up new frequency bands, such as the television band [3], to secondary uses on a non-interference basis to primaries. This would improve spectrum utilization, and provide new spectrum for emerging applications. In addition, by regulating the emission characteristics of the radio rather than the type of service, new applications can emerge quickly unencumbered by regulatory delays. Recently, the FCC has issued a Notice of Proposed Rulemaking (NPRM) regarding Cognitive Radios [1] that requires rethinking of architectures for wireless communication, so that these radios can share spectrum with primary users without causing harmful interference to them. One such architecture is discussed in this paper. Based on the foregoing discussion, clearly, the design of wireless communications systems has been impacted by regulation.

Note that the Defense Advanced Research Projects Agency (DARPA) was the first organization in the US to develop new technologies that allow multiple radio systems to share the spectrum through adaptive mechanisms, in the form of the neXt Generation communications (XG) program [4]. The US Army has also been researching the so-called “Adaptive Spectrum Exploitation” (ASE) for real-time spectrum management in the battlefield [5][6].

The guiding principle for the design of wireless communications systems under the new regulatory framework is: if radio devices can explore the wireless spectrum and locate sparsely used spectral bands, they can exploit them opportunistically to improve not only the devices’ performance but also the overall spectrum utilization. In order to utilize the spectrum opportunistically, however, the radio must determine via advanced spectrum sensing techniques if a particular band in the spectrum is indeed an opportunity or not.

2nd Background: Spectrum sensing in agile radios

The sensing function in an agile radio is very different than those used nowadays in conventional radios, and forms an essential part of it. Agile radios need to sense the wireless medium for a number of reasons, and one of them is identifying spectrum not used by primary users (“spectrum white spaces”). It can then transmit in these white spaces with power levels such as not to cause any interference to these primary users (see Figure 2). Another reason for agile radios to sense the wireless medium is to detect the transmission of other secondary devices. In this case, the agile radio needs to share some or all of the channels occupied by other secondaries thus reducing its own blocking probability [11].

The sensing function in agile radios is different from conventional radios in another respect as well, namely, conventional radios are designed to share the medium with like devices only. As an example, consider the IEEE 802.11 wireless LAN technology. Here, all devices use the same sensing thresholds to determine if the channel is idle before a transmission. On the other hand, agile radios have to detect the presence of the primary signal at thresholds that are under signal levels (for decoding) of primary devices. In general, the detection sensitivity of the agile radio should outperform primary radio system by a large margin (say, 20-30 dB) in order to prevent what is essentially called as hidden terminal problem. This is one of the key issues that makes spectrum sensing a very challenging research problem. Meeting the sensitivity requirement in each band, which has different primary users with different characteristics, would be very difficult. This is done so that the agile radio can determine the transmit power, and the transmission and interference radius opportunistically.

![Figure 2: Agile radio spectrum utilization in the TV band.](image-url)
Contribution and outline of this paper

The rest of this paper is organized as follows. In Section B, we present an analysis of the improvements to spectrum utilization brought about by agile radios using an idealized sensing function. Next, in Section C we discuss current state-of-the-art in spectrum sensing techniques, and present results for the detection of television signals. We present agile radio architectures wherein the sensing and operational functions are collocated in Section D, followed by a discussion of certain limitations of these architectures in Section E. Then, in Section F we propose a new architecture where the sensing and operational functions are separated into different networks, and which features several desirable characteristics. Finally, we conclude this paper in Section G. The main contributions of this paper include the proposed new architectures for spectrum agile radios, results of simulations studies for the detection of television signals, and analysis of the potential increase in spectrum utilization due to an idealized sensing function in a spectrum agile radio.

B Utilization Efficiency of Agile Radios Compared to Conventional Radios

In this section we provide a simple analysis to show how the utilization of the spectrum can be improved using the spectrum agile radio. The performance metric that is considered is the utilization time that is available for the agile radio system compared to non agile radio system. Once the utilization is evaluated, one can easily translate it to channel capacity using the underlying modulation and coding technique.

Consider $N$ channels that are licensed to primary radio systems (incumbents). These channels can be opportunistically used by the spectrum agile radio system if they are not used by the primary radio system at any instant of time. We use a 2-state Markov chain to model the occupancy of the radio channel by the primary radio system. The “On (Off)” state of the Markov chain represents that the primary is occupying that particular channel (not occupying the channel). When the channel is not occupied by the primary, the spectrum agile radio system is allowed to utilize the channel. A non-spectrum agile radio system is statically tuned to one particular channel. This radio system is allowed to occupy the channel if and only if that channel is not occupied by the primary. Let the transition rate from “Off(On)” to “On(Off)” be represented by $\lambda$ ($\mu$). Thus, the spectral utilization is given by:

$$U = \frac{1}{M} \sum_{k=0}^{N} a_k \min(M, k)$$

Figure 3 presents the spectral utilization for the number of spectrum agile radio systems, $M$, varying from 1 to 20 for different primary loads. As we can see, when the number of spectrum agile radio systems is greater than the number of channels available, then the utilization is always less than one. This scenario is particularly interesting and one can often encounter in practice a situation when the agile radio does not find an empty spectral band in its region of operation, and hence has to share with another secondary.

![Figure 3: Spectral utilization as function of primary load for $M$ agile radio systems. Number of channels considered: $N=12$.](image)

Having studied the efficiency of agile radio systems, we now investigate various spectrum sensing mechanisms, and how sensor networks can enhance the performance of agile radios.

C Spectrum Sensing Techniques

Spectrum sensing technologies are a key component of spectrum agile radios and can, to a large extent, determine their performance. Here, we overview some of the well-known techniques used for spectrum sensing.

The most suitable sensing approach to realize a spectrum agile radio is one that quickly and reliably performs Clear Channel Assessment (CCA). The rationale for quick and reliable sensing is discussed in the following. For primary systems such as television services, the receivers are passive and their presence cannot be detected directly. However, interference is caused at the receivers. Therefore, spectrum agile radios must detect the presence of transmitters that are further away than any nominally operating television receiver in a given channel. The higher the transmit power employed by the spectrum agile radio, the further away that it must be able to detect a television transmitter. In addition, since a wideband of spectrum must be sensed, possibly one channel at a time, the sensing approaches must assess the presence of the signal rather quickly. Primarily, two techniques are used to determine whether a channel is idle or not. They are energy and feature detection.

In the energy detection approach, the wireless device measures RF energy in the channel or the received signal strength indicator (RSSI) to determine whether the chan-
nel is idle or not. But, this approach has a problem in that wireless devices can only sense the presence of a primary if and only if the energy detected is above a certain threshold. One cannot arbitrarily lower the threshold as this would result in non-detection because of the presence of noise. In addition, using the energy approach the spectrum agile radio device will not be able to distinguish between other secondary users with whom it can share the medium, and primary users that require vacation of the channel.

In the feature detection approach, which has been used in the military to detect the presence of weak signals [12], the wireless device uses cyclostationary signal processing to detect the presence of primaries. The spectral analysis of stationary random signals has been widely studied. Many random signals encountered in the field of wireless communications are more appropriately modeled as cyclostationary because of underlying periodicities due to various operations such as sampling, scanning and modulation. These underlying periodicities are more subtle than the most commonly treated case of additive sine-wave components, and their properties are, in general, not reflected in the power spectral density (PSD) function, which is a mean-square measure of spectral content. However, important characteristics of such underlying periodicity are reflected in the spectral correlation density (SCD) function. The SCD is obtained by the Fourier transformation of cyclic autocorrelation function (which is a generalization of the well known autocorrelation function).

Various (primary users’) signals exhibit varying degrees of cyclostationarity. If a signal exhibits strong cyclostationary properties, it can be detected at very low signal-to-noise ratios (SNR). Since noise is typically stationary as opposed to cyclostationary, in principle, it can be separated out in the SCD function. The cyclostationary property of the signal can be first order (i.e., periodic mean), second order (i.e., periodic variance) or higher order in nature. When the second order cyclostationarity property in a signal is used for its detection, for a given output SNR, the number of samples (time) used to detect the signal is related to the input SNR in an inverse square fashion. Rather than computing the SCD, the underlying periodicities in a signal can be converted to first order periodicity using a nonlinear time invariant transformation of the signal, such as a delay-multiply. On the other hand when the first order property is used, the number of sample varies inversely as the input SNR. For details the readers are referred to, for example, [12].

In Figure 4, we present results of studies for the detection of digital television (DTV) signals. We evaluate the first order (cyclic correlation) and second order cyclostationary properties exhibited by the DTV signal. As the integration time increases, the confidence in detection of primaries increases, in other words, the output SNR and probability of detection increase. Note that the slope of second order detection is twice that of first order detection. Recall that the threshold of visibility of errors (TOV) for DTV that defines the minimum received signal strength for a DTV receiver is 15 dB. Thus, for a given sensitivity of the front end, a significant margin given by the difference between the chosen operating point in the figure (e.g., –5 dB) and TOV (i.e., 15 dB) is possible.

![Figure 4: Comparison of the first order (cyclic correlation) to the second order (feature based) cyclostationary detection for digital television systems.](image)

**D COLLOCATED SENSING ARCHITECTURES**

As it should be clear by now, the sensing architecture is a key component of an efficient agile radio system. While previous sections focused on specific sensing technologies, from now on we concentrate on architectures that make use of these technologies in order to perform sensing and detect spectrum opportunities (i.e., white spaces). Thus, in this section we address mainly collocated architectures. These are termed as collocated, since the sensing function and the operational function (i.e., actual data transmission) are collocated in a single device.

Before we delve into the specifics of each sensing architecture, it is important to present our proposed internal architecture of an individual agile radio, which is depicted in Figure 5.
R is the channel rate. As discussed in Section C, the more spectral bands and by estimating the duration these opportunities in those bands are, the better is the estimator but the throughput decreases as determined by the duty cycle of sensing operation, and is given by:

$$\eta = \frac{T_{\text{data}}}{T_{\text{data}} + T_{\text{sensing}}} R$$

In the above equation, $T_{\text{data}}$ represents the time that the MAC has to transmit and receive its data, $T_{\text{sensing}}$ represents the time the MAC dedicates itself for sensing and $R$ is the channel rate. As discussed in Section C, the more the time the MAC spends sensing (i.e., greater the integration time), the better is the estimator but the throughput performance is degraded and vice-versa. Additionally, it imposes a limitation on the MAC layer design. For instance, in case of collision, the MAC has no means to determine if it was due to transmission by another agile radio device or network, channel error, or because of a primary user. In case of the later, the MAC shall vacate the channel immediately.

2nd Dual radio sensing architecture

As the name suggests, there are two radios in this architecture where one of them is exclusively dedicated for sensing (using feature detection as explained before) the spectrum while the other is dedicated for data transmission. This removes the inefficiencies caused by sensing and data transmission using one single radio. On the other hand, it imposes additional complexity and power con-

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**Figure 5: Architecture of a spectrum agile radio.**

The important modules of this architecture are: (1) Opportunity identifier, (2) Policy interaction, (3) Opportunity manager, and (4) Flexible PHY layer. The opportunity identifier is responsible for determining whether a particular band in the spectrum is an opportunity or not. This is done by sensing the medium for available white spaces, and by estimating the duration these opportunities in those spectral bands [13]. The results of the identification process (i.e., spectrum measurements) are then passed to the opportunity manager. The policy interaction is responsible for understanding the policies set by the regulatory body (e.g., the FCC) for the target bands and the results of its interpretation is passed to the opportunity manager. The flexible PHY plays a critical role and is responsible for taking the inputs from the opportunity manager and shaping the waveforms so that they comply with the transmission policies set by the regulatory body for operation in the target band (this could be realized using SDR technology). The opportunity manager forms the core of this architecture. It controls the opportunity identifier by requesting measurements in target bands, specifying required accuracy of measurements and/or response (or integration) time. The opportunity manager is also responsible to receive the inputs from opportunity identifier and policy modules and then determine if the particular band is an opportunity or not. In case it is an opportunity, it would pass appropriate parameters to the flexible PHY to shape the waveforms that complies with the requirements. The opportunity manager is also responsible to map the traffic at the MAC queue to these opportunities, as some of the identified white spaces may have to be disregarded for having very little time or low duty cycle of availability. In this case, overheads such as switching and synchronizing with the receiver(s) may take more time than the actual data transfer, leading to white spaces being discarded. Additionally, one can extend the use of this opportunity manager by looking into issues like fairness that would be critical for determining the performance of agile radios.

With this internal architecture in mind, we now move to discuss the collocated sensing architectures, which are predominantly part of the opportunity identifier. Two distinct collocated sensing architectures are envisioned in this work, namely, the single radio sensing architecture and the dual radio sensing architecture.
straints on the agile radio, and so the cost per device will likely increase. Finally, this method still does not overcome the hidden node problem when primaries or owners of spectrum use directional antennas (discussed later in this paper).

E LIMITATIONS OF COLLOCATED ARCHITECTURES AND THE INTERFERENCE TEMPERATURE MODEL

The design requirement of collocated architectures (namely, sensing function and the operational function of a network have to be collocated in a single device) brings with it many limitations regarding reliability of measurements, performance, increased complexity in a single device, higher energy consumption, and so on. In this section we discuss the shortcomings of collocated architectures not only with respect to performance aspects, but we also show that these architectures do not adequately address the interference temperature model as defined by the FCC.

1st Limitations of collocated architectures

Consider, for example, the scenario where an agile radio device employing the collocated architecture model operates in an indoor environment where deep fade situations are typical. Studies reveal that in this type of scenario, 20 dB fades are possible for indoor DTV signals. Therefore, instantaneous measurements made by a single device are not reliable in low SNR cases as there is very little diversity. It is worth noticing, however, that depending of the specific application this drawback can be overcome. For example, in the new IEEE 802.22 [15] effort to define a cognitive radio based wireless standard for operation in the TV bands, a collocated sensing architecture is the option of choice. In 802.22, the sensing antenna is to be mounted outdoors to increase sensing reliability, in addition to diversity gains due to measurements made by a number of client terminals spread in a large area. These two benefits are not available in short-range (portable) wireless applications.

Secondly, spectrum agile radios based on the collocated architecture also bear “lost transmit opportunity costs”, and as a consequence performance degradation. Note that a conventional wireless device cannot sense the medium when it is transmitting, and cannot transmit when it is sensing. Thus, the incorporation of a collocated sensing mechanism in these devices would greatly impact the data transport efficiency of the operational network, as discussed in Section D.

Thirdly, the sensing operation may consume a considerable amount of power. Thus, for battery-powered devices, sensing is particularly burdensome.

Having discussed the problems, we now discuss the motivation of our approach that forms the basis for another proposal in the field of measurements.

2nd Interference temperature

Traditionally, regulatory bodies minimize interference through coordination of bands of operation, radiated power, out-of-band emissions, location of individual transmitters, and so on. In other words, interference is typically regulated in a transmitter-centric way. Recently, however, a new model for measuring interference and referred to as interference temperature has been introduced by the FCC. As opposed to current transmitter-centric approach, this model attempts to regulate interference at the receivers, which is where it is really harmful. Under this new model, a maximum noise level would be set for an entire band and new systems could be placed in service if it is anticipated that the interference temperature limit would not be exceeded. In other words, the interference temperature model accounts for the cumulative radio frequency energy from transmissions and sets a maximum cap on their aggregate level\(^3\). Figure 6 [16] depicts the interference temperature limit and concept.

Some methods have also been proposed in the FCC proceeding for monitoring interference temperature, but there is no guarantee that these theoretical systems will actually work or that licensed systems will not receive any harmful interference. Since new users would be unlicensed and use the spectrum in an opportunistic way, locating each offender and resolving interference would be very difficult. The difficulty lies in effectively measuring the interference temperature. A spectrum agile radio is naturally aware of its transmit power level and, with the availability of a positioning system, would also know its precise location. With this information, a spectrum agile radio can compute the probability that its transmission could cause significant interference to a neighboring receiver on the same frequency.

\(^3\) Note that the interference temperature concept is somewhat analogous to Ultra Wide Band (UWB), in which transmit power is kept low enough that damaging interference would not occur.
effectively address the interference temperature model. Only overcomes the issues identified, but which is able to produce a sensor network based sensing architecture that not and applications in the unlicensed bands. Next, we introduce a sensor network based sensing architecture to deal with the proliferation of both devices and applications in the unlicensed bands including 802.11, Bluetooth, UWB and future applications including smart dust [17], the spectrum usage over smaller areas will be heavily congested. This motivates the need to share spectrum not only with like systems, but also with other technologies such as IEEE 802.22, IEEE 802.16 and broadcast systems.

For a variety of reasons, including informed regulatory policy, intelligent equipment design, efficient system operation and the identification and location of illegal emitters, it has become necessary to better understand the spectrum environments in which these devices operate. This is in sharp contrast to the stable and well-defined environments of licensed systems. In the newer environments created by unlicensed and upcoming smart dust networks, spectrum deregulation and opportunistic use is a very important aspect. These growing numbers of short-range emitters are mixed together in a local area, using varied radio technologies at unknown locations and exhibiting unforeseen traffic patterns. The resulting spectral environment is thus sharply variable, even over short distances and brief time periods, so that time-limited measurements carried out in sites at a distance from the local area under study, cannot characterize local conditions. Furthermore, collocated architectures do not address the problem as the devices themselves use a variety of technologies, which make the individual systems incapable of recognizing themselves and adapting to local conditions.

For the first time in the long history of radio systems, a fundamentally new approach to spectrum measurement and analysis is needed. This new approach must be able to make sense of the emissions of multiple systems and evolving technologies within the confines of a single street or building, and produce a fine-grained spatial and temporal picture of the radio spectrum.

2nd The proposed architecture

The architecture we propose here to address the issues found in existing measurement approaches when applied to emerging short-range applications, is based on sensor networks. The idea behind this sensor network based sensing architecture is to have a separate sensor network fully dedicated to perform spectrum sensing. In this architecture, at least two types of networks are identified:

In the wireless network evolution, the practice of spectrum management for conventional licensed systems is straightforward as base stations operated in well-known locations, which allowed operators to use this information to minimize interference. In this case, any type of measurement could be potentially done in a simple manner by the base stations themselves (thus following the collocated architecture model).

Figure 6: This figure [16] shows the power that is received from the licensed transmitter as a function of distance. The spectrum agile radio has opportunities represented by the right-hand side (green) box.

However, the fact is that, currently, there is no practical way for spectrum agile radio to locate all receivers of communications from the transmitter in question or to assess the capabilities of those receivers. Some may generate significant internal noise and, as a result, tolerate little interference. Some may be located so far from the transmitter that their reception is marginal to begin with. Some others may use directional antennas. Unless a spectrum agile radio can measure the effect of its transmission on all possible receivers, taking a useful interference temperature measurement may not be feasible. Thus, interference temperature concepts alone cannot effectively protect the licensee in many types of situation.

F A SENSOR NETWORK BASED SENSING ARCHITECTURE

To address the need for a reliable, efficient, and evolving spectrum management approach, and to provide a path for the implementation of the interference temperature concept, here we introduce a sensor network based sensing architecture (i.e., a spectrum-aware sensor network). This architecture is based on the observation that in recent years we have experienced an explosive growth of unlicensed services, which has spawned an impressive variety of important technologies and innovative uses, from cordless phones, wireless LANs, and wireless PANs to toll takers, meter readers and home entertainment products. So, in this section we first motivate the proposed architecture by discussing the inability of the collocated architecture to deal with the proliferation of both devices and applications in the unlicensed bands. Next, we introduce a sensor network based sensing architecture that not only overcomes the issues identified, but which is able to effectively address the interference temperature model.

1st Suitability of existing measurements

In the wireless network evolution, the practice of spectrum management for conventional licensed systems is straightforward as base stations operated in well-known
the sensing network and one or more operational networks. The sensing network would be comprised of a set of sensors deployed in the desired target area and which would sense the spectrum (either continuously or periodically) and communicate the results (which may be subjected to some processing such as data fusion, etc.) to a well-known sink node. The sink node may, in turn, further process the collected data and will eventually make the information about the spectrum occupancy in the sensed target area available to all operational networks. The operational networks, on the other hand, are responsible for traditional data transmission and opportunistic use of the spectrum, and would accept the information about the spectrum occupancy map in order to determine which channel to use, when to use, and for how long. Figure 7 depicts a possible indoor deployment scenario of this sensing network architecture, where different floors in a building are comprised of sensors and operational networks.

![Figure 7: Example of a deployment scenario of the spectrum-aware sensing network architecture](image)

Since the sensing and operational networks are now distinct, the internal architecture of nodes belonging to this spectrum-aware sensor network is slightly different from the one depicted in Figure 5. In this proposed architecture, spectrum sensors will not typically need a flexible PHY and policy interaction modules since they do not participate in the operational network. On the other hand, depending on the desired level of complexity of sensors, the opportunity identifier and some aspects of the opportunity manager may be needed. Figure 7 depicts the architecture of the spectrum-aware sensor nodes.

It is important to highlight that the architecture of these nodes (as shown in Figure 5) may change according to the desired application area. For example, if designed specifically for TV bands, these would most likely have to incorporate specific feature detection techniques, and hence the inclusion of the opportunity identifier and some aspects of the opportunity manager is needed. On the other hand, wideband (e.g., from 0 to 3 GHz) spectrum sensors spanning multiple licensed bands may not be able to include all feature detection algorithms necessary to identify all incumbents operating in the measured band. In this case, it may be preferred to design the sensor to perform energy detection only, and leave up to other specialized nodes to collect the sensed data from multiple sensors and then determine spectrum opportunities in the various bands. Therefore, spectrum-aware sensors would also not need the opportunity identifier module, further decreasing the implementation complexity. This type of sensor would not include a policy interaction and flexible PHY module, but may comprise opportunity identifier and manager as shown in Figure 5.

The proposed spectrum-aware sensor network architecture addresses all the limitations of collocated architectures discussed in Section E. Firstly, measurements made in a network provide the needed diversity to cope with multipath fading. Secondly, by separating the sensing and operational functions, no lost transmit opportunity costs are incurred. Finally, since operational networks need to be mobile and may be power limited, whereas the sensing function does not need to be mobile, this architecture brings unique power advantages, especially to low power portable/mobile applications.

We also note that this proposed sensor network architecture has numerous advantages as compared to traditional spectrum analyzer (SA) devices available in the market today. Traditional SAs are bulky, extremely expensive, consume high power, and are typically few in number, while sensors in a spectrum-aware sensor network are inexpensive, with small form factor, are very energy efficient, and hence can easily exceed SAs in number. Where traditional SAs are generally specialized to answer a limited set of questions about a particular system, the proposed sensing architecture can be designed to serve a wide and evolving range of purposes. These purposes will most often be related to the short-range uses and unregulated bands, but once such sensor-based measurements are available they may also offer new measurement capabilities for the older, regulated bands as well. Localizing illegal emitters is another advantage of this architecture, as the spatial diversity it provides allows for such feature to be supported. Finally, it is important to note that this proposed architecture can also be used to implement the interference temperature model, as sensor nodes can measure and provide accurate information on the interference temperature at various locations. This information would be used by the nodes in the operational network to decide when it is safe to transmit (i.e., interference temperature limits are not exceeded as a result of a transmission).
G CONCLUSIONS

In this paper, we discuss the concept of spectrum agile radio systems and show how these systems provide advantages compared to conventional systems. We provide a simple analytical model that characterizes the benefits of agile radios, and show that spectrum utilization can be considerably increased. Next, we analyze spectrum sensing techniques and architectures, which form a key component of an agile radio system and dictate its performance to a large extent. We then propose the spectrum-aware sensor network architecture. As discussed, this architecture offers many benefits as compared to existing approaches, and addresses all the limitations of colocated architectures. Firstly, measurements made in a network provide the needed diversity to cope with multipath fading. Secondly, by separating the sensing and operational functions, using this architecture, no lost transmit opportunity costs are incurred. Finally, since operational networks need to be mobile and may be power limited, whereas the sensing function does not need to be mobile, this architecture brings unique power advantages, especially to low power portable/mobile applications.

REFERENCES

[17] Smart Dust Project, Berkeley University, http://robotics.eecs.berkeley.edu/~pister/SmartDust/.