Emerging Cognitive Radio Applications: A Survey

Jianfeng Wang, Monisha Ghosh, Kiran Challapali (Invited Paper)

Philips Research North America

Abstract

Recent developments in spectrum policy and regulatory domains, notably the release of the National Broadband Plan, the publication of final rules for TV white spaces, and the ongoing proceeding for secondary use of the 2360 – 2400 MHz band for Medical Body Area Networks (MBANS), will allow more flexible and efficient use of spectrum in the future. These important changes open up exciting opportunities for cognitive radio to enable and support a variety of emerging applications, ranging from smart grid, public safety and broadband cellular, to medical applications. This article presents a high-level view on how cognitive radio (primarily from a dynamic spectrum access perspective) would support such applications, the benefits that cognitive radio would bring, and also some challenges that are yet to be resolved. We also illustrate related standardization that uses cognitive radio technologies to support such emerging applications.

Introduction

Current spectrum allocations are based on a command-and-control philosophy, i.e. spectrum is allocated for a particular application, e.g. TV broadcasting, and such allocations do not change over space and time. There have been several important developments in the past few years in the spectrum policy and regulatory domains to accelerate opportunistic uses of spectrum. The most recent of these are the publication of the National Broadband Plan in March 2010 [1], the publication of the final rules for unlicensed devices in the TV bands in September 2010 [2] and the ongoing proceeding for secondary use of the 2360 – 2400 MHz band for Medical Body Area Networks (MBANS) [3]. Cognitive radio (CR) technology plays a significant role in making the best use of scarce spectrum to support the increasing demand for emerging wireless applications, e.g., TV bands for smart grid, public safety, broadband cellular, and the MBAN band for medical applications. In order to take advantage of these new opportunities, a number of standards, e.g. IEEE 802.22 [4], IEEE 802.11af, ECMA 392 [5], IEEE SCC41, ETSI RRS [6] are either in development or have already been completed.

Regulation

A. *National Broadband Plan*

The National Broadband Plan (NBP) is a policy document that was the culmination of almost a year's worth of work by the Federal Communications Commission (FCC) with input from industry and government agencies on how to formulate spectrum policy in order to facilitate broadband usage for the coming years. One of the main recommendations of the NBP is to free up 500 MHz of spectrum for broadband use in the next 10 years with 300 MHz being made available for mobile use in the next 5 years. The Plan proposes to achieve this goal in a number of ways: incentive auctions, repacking spectrum, enabling innovative spectrum access models that take advantage of opportunistic spectrum access and cognitive techniques to better utilize spectrum. The Plan urges the FCC to initiate further proceedings on opportunistic spectrum access beyond the already completed TV White Spaces (TVWS) proceedings.

B. *TV White Spaces Regulation*

The major worldwide regulatory agencies involved in developing rules for the unlicensed use of TV white spaces are the FCC in the US, Office of Communications (Ofcom) in the UK and the Electronic Communications Committee (ECC) of CEPT in Europe.

The FCC released the final rules for "Unlicensed Operation in the TV Broadcast Bands" in September 2010 [2]. This was the culmination of many years of deliberations on the subject, starting with the first NPRM in May 2004 and followed by laboratory and field testing of sensing devices through 2007 and 2008 and the second report and order in 2008[7]. A recent study shows the opportunity provided by TV white spaces is shown to be potentially of the same order (~ 62MHz) as the recent release of "beachfront" 700MHz spectrum for wireless data service [8], while New America Foundation has another estimate of 15-40 channels available in major cities [9]. The main features of the rules as set forth in this order are as follows:

- TV band devices (TVBDs) are divided into two categories: fixed and personal/portable. Fixed TVBDs operate from a known, fixed location and can use a total transmit power of up to 4 W EIRP, with a power spectral density (PSD) of 16.7 mW/ 100 kHz. They are required to either have a geolocation capability or be professionally installed in a specified fixed location and have the capability to retrieve a list of available channels from an authorized database. Fixed TVBDs can only operate on channels that are not adjacent to an incumbent TV signal in any channel between 2 and 51 except channels 3, 4, and 37. Personal/portable devices are restricted to channels 21 – 51 (except Channel 37) and are allowed a maximum EIRP of 100 mW with a PSD of 1.67 mW/ 100 kHz on non-adjacent channels and 40 mW with a PSD of 0.7 mW/ 100 kHz on adjacent channels and are further divided into 2 types: Mode I and Mode II. Mode I devices do not need geolocation capability or access to a database. Mode II devices, must have geolocation capability and the means to access a database for list of available channels.

- Sensing was a mandatory feature to protect incumbents in the previous ruling [7] but is now an optional feature in fixed, Mode 1 and Mode II devices. Incumbent protection will be through the use of authorized databases that have to guarantee security and accuracy of all communications between it and fixed or Mode II devices. Gelocation means in Mode II devices have to be accurate within +/– 50 m. Since sensing is optional, in order to maintain up-to-data channel availability information, Mode II devices need to check their location every 60 secs and if the location changes by more than 100 m, have to access the database for an updated channel list. In order to facilitate mobility, Mode II devices are allowed to download channels for a number of locations within an area and use a channel that is available within that area without the need to access the database as long as it does not move outside the area. In addition, a new mechanism is defined in the rules to ensure that Mode 1 devices that do not have geolocation are within the receiving range of the fixed or Mode II device from which it obtained the list of channels it could operate upon. This is the "contact verification" signal, which needs to be received by the Mode 1 device every 60 secs, or else it will have to cease operation and reinitiate contact with a fixed or Mode II device.
- A sensing-only device is a personal/portable TVBD that uses spectrum sensing only to determine a list of available channels. Sensing only devices may transmit on any available channels in the frequency bands 512-608 MHz (TV channels 21-36) and 614-698 MHz (TV channels 38-51), and are allowed a maximum transmit power of 50 mW with a PSD of 0.83 mW/ 100 kHz on non-adjacent channels and 40 mW with a PSD of 0.7 mW/ 100 kHz on adjacent channels. In addition, sensing only device must demonstrate with an extremely high degree of confidence that they will not cause harmful interference to incumbent radio services. The required detection thresholds are: (A) ATSC digital TV signals: -114 dBm, averaged over a 6 MHz bandwidth; (B) NTSC analog TV signals: -114 dBm, averaged over a 100 kHz bandwidth; (C) Low power auxiliary, including wireless microphone, signals: -107 dBm, averaged over a 200 kHz bandwidth. A TVBD may start operating on a TV channel if no TV, wireless microphone or other low power auxiliary device signals above the detection threshold are detected within a minimum time interval of 30 secs. A TVBD must perform in-service monitoring of an operating channel at least once every 60 secs. After a TV, wireless microphone or other low power auxiliary device signal is detected on a TVBD operating channel, all transmissions by the TVBD must cease within two seconds.
- Safe harbor channels for wireless microphone usage are defined in all markets to be the first available channel on either side of Channel 37. TVBDs cannot operate on these channels. In addition, licensed and unlicensed wireless microphone users can register in the database if they can demonstrate that they require adequate protection from interference.

Table 1 summarizes the various parameters and potential applications of TVBDs enabled by the US TVWS rules.

Table 1 TVBD parameters and applications

	Fixed device	Mode II, Mode I	Sensing only
Channels	2~51 except 3, 4, 37. Non-adjacent channels only	21-51 except 37	21-51 except 37
Power limit	4 W	100 mW	50 mW
Incumbent protection mechanisms	Database	Database, Contact verification (Mode I)	Sensing
Potential applications	Smart grid (network gateway, smart meters), cellular backhaul (BS, relay station), MBMS (BS)	Public safety, femtocell, MBMS (CE)	Public safety, femtocell

Meanwhile, Ofcom, the regulatory body in the UK has also made significant progress in developing regulations for the TV white spaces with a first consultation released on February 16, 2009, and a further statement in July 2009 [10]. The detailed rules have yet to be released but first indications are that TVBDs will require either sensing or gelocation/database access. The sensing levels being proposed for sensing-only devices are -120 dBm for digital TV and –126 dBm for wireless microphones.

The ECC has just begun working on cognitive radio in the TV bands within its newly created group SE 43 [11] which is tasked with defining the technical and operational requirements of operating in the TV white spaces. Draft ECC report 159 [12] was released on Sept 30, 2010 for public consultation. This report will be used as the starting point for regulatory activities within the ECC.

C. MBANS Regulatory actviities in the US

The proposal to allocate the frequency band 2360 - 2400MHz for MBANS on a secondary basis was initially made in the US by GE in 2007 [13], followed by a NPRM issued by the FCC in 2009 [3]. The principal incumbent in this band in the US is Aeronautical Mobile Telemetry (AMT), which uses 2360-2390 MHz, and there are a number of proposals under consideration by the FCC that would allow MBAN devices as secondary users to coexist with the primary ATS user, without either creating interference to or being subject to interference from AMT services. These include exclusion and coordination zones as well as additional interference mitigation mechanisms, such as Listen-Before-Transmit and Adaptive Frequency Selection (LBT/AFS). Since the proposed transmit power for MBANS is quite low (1 mW in 2360-2390 MHz and 20 mW in 2390-2400 MHz), simulations have shown that these techniques would work well to protect AMT from interference while also maintaining the quality of service required for the MBANS application [14][15]. Thus, spectrum utilization is maximized by allowing opportunistic use of the underused frequency band 2360-2400 MHz for MBANS applications, instead of allocating new spectrum exclusively for this purpose. This proceeding is still under consideration by the FCC and final rules are yet to be published.

In Europe, activities have been restricted to Low Power-Active Medical Implants (LP-AMI). Draft ECC Report 149 [16] considers the feasibility of frequency bands 2360–2400 MHz, 2400–2483.5 MHz, 2483.5–2500 MHz and 2700–3400 MHz for LP-AMI, and concludes with the recommendation that the frequency band 2483.5–2500 MHz is the most promising candidate band for this purpose, based on analysis of interference between LP-AMI and existing and proposed future incumbents in these bands. External medical telemetry or MBANs, is not considered in this report, however proposals have been made to initiate an activity to explore the use of the 2360 - 2400 MHz frequency band for MBANs in Europe in order to harmonize with the anticipated regulation in the US.

SMART GRID NETWORKS

Transformation of the 20th-centrury power grid into a Smart Grid is being promoted by many governments as a way of addressing energy independence and sustainability, global warming and emergency resilience issues [17][18]. The Smart Grid is comprised of three high-level layers, from an architectural perspective: the physical power layer (generation and distribution), the communication networking layer, and the applications layer (applications and services such as advanced metering, demand response and grid management). A Smart Grid transforms the way power is generated, delivered, consumed and billed. Adding intelligence throughout the newly networked grid increases grid reliability, improves demand handling and responsiveness, increases efficiency, better harnesses and integrates renewable/distributed energy sources, and potentially reduces costs for the provider and consumers.

Sufficient access to communication facilities is critically important to the success of Smart Grids. A smart grid network would typically consist of three segments [17]: (1) the home/building area networks (HAN) that connect smart meters with on-premise appliances, plug-in electrical vehicles, and distributed renewable sources (e.g., solar panels) (2) the advanced metering infrastructure (AMI) or field area networks (FAN) that carry information between premises (via smart meters) and a network gateway (or aggregation point), which will often be a power substation, a utility pole-mounted device, or a communications tower; (3) the wide area networks (WAN) that serve as backbone for communication between network gateways (or aggregation points) and the utility data center.

While HAN can use WiFi, Zigbee, and HomePlug and WAN can leverage the fiber based IP backbone or even the broadband cellular network infrastructure, appropriate technologies for AMI/FAN are still under consideration. The dimension of an AMI/FAN could range from a few hundred meters to a few kilometers or more (for example in rural areas). Bandwidth requirements are estimated in the 10-100 kbps range per device in the home or office building [17]. This may scale up quickly with the number of devices on a premise if appliance-level data points as opposed to whole-home/building data are transmitted to the network gateway. Powerline based communication (PLC) is used in some AMI but has bandwidth and scalability problems. Moreover, the safety issues associated with ground fault currents are of concern as well. Some wireless meter readers currently use the 900 MHz unlicensed band. This is not without complications, however, since this band will soon become crowded due to the growth of unlicensed devices including smart meters. IEEE 802.15.4g, the Smart Utility Networks (SUN) Task Group, is currently working to create a physical layer (PHY) amendment for AMI/FAN by using license exempt frequency bands, such as 700 MHz to 1 GHz, and the 2.4 GHz band. It remains to be seen as to how 802.15.4g handles interference which is common to unlicensed devices operating in these bands. The cellular network is an alternative for AMI/FAN as well. However, the investment cost and operation cost could be high. Moreover, cellular networks themselves face bandwidth challenges as the cellular data traffic grows dramatically year over year. Cellular networks also have coverage issues in certain places, for example, rural areas.

Cognitive radio based AMI/FAN may offer many advantages such as bandwidth, distance and cost, as compared with other wireline/wireless technologies in certain markets. Figure 1 illustrates a CR based wide area AMI/FAN. In this case, the network gateway and smart meters are equipped with cognitive radio and dynamically utilize unused/under-utilized spectrum to communicate with each other directly or via mesh networking over a wide area with minimal or no infrastructure. The network gateway connects with a spectrum database over a WAN and serves as the controller to determine which channel(s) to use for the AMI/FAN based on the location and transmission power needed for smart meters. Taking TVWS as an example, since network gateways and smart meters are both fixed, they can operate in the fixed mode and use transmission power up to 4 W EIRP. With the high transmission power and superior TV band propagation characteristics, the network gateway may reach all the smart meters with one or two hops, e.g., covering an entire town. In rural areas, available TVWS channels could be abundant so channel availability would not be an issue.

There are several other standardization groups currently working on the incorporation of cognitive radio technologies to utilize TVWS to support applications such as smart grid networks, particularly AMI/FAN. Within IEEE, the following groups are developing standards for TVWS: IEEE 802.22 working group is nearing completion of the standard for TVWS based wireless regional area networks for ranges up to 10 – 100 km which could be used for large scale smart grid networks, an IEEE 802.15 study group (SG) has been created recently to investigate the use of TVWS and IEEE 802.11af is spearheading the development of an IEEE 802.11 amendment for TVWS operation for WLANS.

Like other unlicensed devices, CR enabled AMI/FAN devices are not immune from interference or congestion, especially if they are heterogeneous and not coordinated with each other. This may introduce issues such as reliability and delay, and limit the applicability of unlicensed devices for more critical grid control or real-time smart grid applications. CR enabled AMI/FAN should go beyond just dynamic spectrum access and develop self-coexistence mechanisms to coordinate spectrum usage, and may even prioritize spectrum use according to the class of smart grid traffic, e.g., realtime versus non-realtime, emergency report versus demand response. IEEE 802.19.1 work group is currently working on developing a standard for wireless coexistence in the TVWS and may help mitigate interference issues among CR based AMI/FANs. Furthermore, CR enabled AMI/FANs should also consider how to interoperate with other wireless technologies such as wireless cellular networks in order to make smart grid more resilient, scalable, accessible and of better quality.

PUBLIC SAFETY NETWORKS

Wireless communications are extensively used by emergency responders, such as police, fire and emergency medical services, to prevent or respond to incidents, and by citizens to quickly access emergency services. Public safety workers are increasingly being equipped with wireless laptops, handheld computers, and mobile video cameras to improve their efficiency, visibility, and ability to instantly collaborate with central command, coworkers and other agencies. The desired wireless services for public safety extend from voice to messaging, email, Web browsing, database access, picture transfer, video streaming, and other wideband services. Video surveillance cameras and sensors are becoming important tools to extend the eyes and ears of public safety agencies. Correspondingly, data rates, reliability and delay requirements vary from service to service.

On the other hand, the radio frequencies allocated for Public Safety [19] use have become highly congested in many, especially urban, areas [20]. Moreover, first responders from different jurisdictions and agencies often cannot communicate during emergencies. Interoperability is hampered by the use of multiple frequency bands, incompatible radio equipment, and a lack of standardization.

In coping with the above challenges, the US Department of Homeland Security (DHS) released its first National Emergency Communications Plan (NECP) in July 2008. The more recently released National Broadband Plan [1] clearly reflects the effort to promote public safety wireless broadband communications. The recommendations includes creating a public safety broadband network, creating an administrative system that ensures access to sufficient capacity on a day-to-day and emergency basis, and ensuring there is a mechanism in place to promote interoperability.

Cognitive radio was identified as one of emerging technologies to increase efficiency and effectiveness of spectrum usage in both the NECP report and the National Broadband Plan. With cognitive radio, public safety users can use additional spectrum such as license-exempt TVWS for daily operation from location to location and time to time. With appropriate spectrum-sharing partnerships with commercial operators, public safety workers can also access licensed spectrum and/or commercial networks. For example, the public safety community could roam on commercial networks in 700 MHz and potentially other bands both in areas where public safety broadband wireless networks are unavailable and where there is currently an operating public safety network but more capacity is required to respond effectively to an emergency.

Figure 2 illustrates public safety communications with incorporation of cognitive radio networking technologies. In this case, location-aware and/or sensing-capable CR devices together with the spectrum coordinator in the back office respond to the emergency and coordinate with users (including primary and secondary users) in/around the incident area to ensure the emergency responders have sufficient capacity and means for communications on the field and to/from infrastructure. In addition, cognitive radio can improve device interoperability through spectrum agility and interface adaptability, or network of multiple networks. CR devices can communicate directly with each other by switching to common interface and frequency. Furthermore, with help of multi-interface or software-defined radio (SDR), cognitive radio can serve as the facilitator of communications for other devices which may operate in different bands and/or have incompatible wireless interfaces. As illustrated in Figure 2, such CR devices (communication facilitators) can be located in a few powerful emergency responders' vehicles and wireless access points. This lifts the burden off the hand-held devices for each to have CR capability to mitigate the issue that different emergency responders may use different radios today and very likely in the future as well.

It remains to be seen as to how cognitive radio technologies will support priority delivery and routing of content through its own network as well as public networks, thus protecting time-sensitive, safety-of life information from loss or delay due to network congestion. This goes beyond spectrum awareness to content awareness, from the physical layer to the application layer.

Standardization remains key to the success of cognitive radio. ECMA 392 standard is the first international standard that specifies physical (PHY) and medium access control (MAC) layers to enable personal/portable devices to operate in TVWS. While ECMA 392 is not designed specifically for public safety, it may be suitable for the following reasons. ECMA 392 supports dynamic channel use by using both geolocation-based databases as well as sensing, and can be adapted to comply with local spectrum regulations. Compared to other existing standards, ECMA 392 not only supports flexible ad-hoc networking but also Quality of Service (QoS) which is required for on-field emergency communications.

CELLULAR NETWORKS

The use of cellular networks is undergoing dramatic changes in recent years, with consumer's expectations of being always connected, anywhere and anytime. The introduction of smartphones, the popularity of social networks, growing media sites such as Youtube, Hulu, flickr, introduction of new devices such as e-readers, have all added to the already high and growing use of cellular networks for conventional data services such as email and web-browsing. This trend is also identified in the FCC's visionary National Broadband Plan [1].

This presents both an opportunity and a challenge for cellular operators. The opportunity is due to the increased average revenue per user due to added data services. At the same time, the challenge is that in certain geographical areas, cellular networks are overloaded, due partly to limited spectrum resources owned by the cellular operator. Recent analysis [21] suggests that the broadband spectrum deficit is likely to approach 300 MHz by 2014, and that making available additional spectrum for mobile broadband would create value in excess of $100B in the next five years through avoidance of unnecessary costs.

With the FCC's TVWS ruling, new spectrum becomes available to cellular operators. In the long term, television band spectrum that is currently not described as white spaces may also become available to cellular operators, as discussed in the National Broadband Plan. Specifically, the plan discusses the possibility for current license holders of television spectrum to voluntarily auction their licenses, in return for part of the proceeds from the auction. The plan envisions that this newly freed spectrum could be used for cellular broadband applications (hence the name of the plan).

Many papers have investigated the application of spectrum sensing or spectrum sharing in cellular networks [6][22][23]. Figure 3 illustrates how cognitive radio technologies can augment next generation cellular networks like LTE and WiMAX to dynamically use these newly available spectrums either in the access or backhaul parts of their networks. A spectrum coordinator can be added in the non-access stratum (NAS) to allow cellular networks to dynamically lease spectrum from spectrum markets and/or identify secondary license exempt spectrum opportunities to meet the cellular traffic demand given a location and time period. The base stations (including relay stations) configure channels to operate according to the instructions of the spectrum coordinator and aggregate the spectrum for use.

For access network applications, two use cases can be envisioned. The first is hotspots, such as game stadiums and airports, where a large number of users congregate at the same time. Take the example of a stadium: users increasingly have phones equipped with cameras that can capture pictures or videos of events at the game and upload them to media sites or send them to their friends. Such picture and video data puts enormous strain on the cellular network. In Cisco's study 60% of growth is expected from such picture and video data. Today, some of this data can be offloaded to ISM band WiFi networks. However, due to the large amount of data generated in a small area ("hotspot"), both cellular networks and ISM band WiFi networks, are likely to be overloaded. If this data can be offloaded to additional spectrum, such as TVWS, the cellular network can then be used for voice applications in a more reliable fashion, thus benefiting both the user and cellular operator.

The second access network application is similar to a femtocell. Today several of the cellular operators sell a mini-cell tower (looks like a WiFi access point) that consumers may buy and install in their homes. Typical users of femtocell are those that have bad coverage in certain parts of their homes, such as basements. These femtocell devices operate on the same frequencies as those of cellular operators. However, these femtocell devices have several issues. First, due to the fact that femtocell devices and cellular networks operate on the same frequency, the quality of the network suffers when these two networks interfere with each other. Secondly, the coverage of these devices is limited. TV white space radio coverage is significantly improved due to the better propagation characteristics and in addition, there is no interference between the femtocell and main cell.

A somewhat different issue than the data overload or spotty coverage discussed above also can be noted with cellular networks. Rural areas (to be more precise, areas with low population density distribution) are known to have poor coverage. Cellular operators have rights to use their spectrum nationwide, however, choose not to deploy their networks in rural areas. The reason for this is that a significant part of the costs of a cellular operator is infrastructure costs. These costs cannot be recovered in rural areas due to lack of sufficient number of subscribers in a given area. With white space spectrum, for example, being made available for unlicensed use, cellular operators can use them for backhaul, to connect their cell towers to their backbone networks, thus reducing labor intensive backhaul cables installation, and thus provide coverage to more customers in unserved and underserved areas.

Some design considerations need to be kept in mind in using additional spectrum given that the transmission requirements associated with the additional spectrum could vary significantly from that of the primary cellular spectrum. Take TVWS as an example. The FCC rules as discussed above put certain restrictions on different device types. For data offloading between base stations and CPE, base stations would operate in the fixed mode and CPE can only operate in Mode I mode. The PSD and strict emission mask requirement may restrict Mode I personal/portable devices for uplink transmission. Therefore, for Mode I devices, a class of receiver-only white space devices might be easily possible in the near term, enabling broadcast type or mainly downlink applications with minimal return channel interactivity over cellular or another return channel. However, the economic viability of such an application remains to be seen. On the other hand, the backhaul scenario as discussed above will have fewer issues.

WIRELESS MEDICAL NETWORKS (MBANS)

In recent years there has been increasing interest in implementing ubiquitous monitoring of patients in hospitals for vital signs such as temperature, pressure, blood oxygen and electrocardiogram (ECG). Normally these vitals are monitored by on-body sensors that are then connected by wires to a bedside monitor. MBANS is a promising solution for eliminating these wires, thus allowing sensors to reliably and inexpensively collect multiple parameters simultaneously and relay the monitoring information wirelessly so that clinicians can respond rapidly [24]. Introduction of MBANS for wireless patient monitoring is an essential component to improving patient outcomes and lowering healthcare costs. Through low-cost, wireless devices, universal patient monitoring can be extended to most if not all patients in many hospitals. With such ubiquitous monitoring, changes in a patient’s condition can be recognized at an early stage and appropriate action taken. By getting rid of wires and their management, the associated risks of infection are reduced using MBANs. Additionally, MBANs would increase patient comfort and mobility, improve effectiveness of caregivers and improve quality of medical decision making. Patient mobility is an important factor in speeding up patient recovery.

Quality of service is a key requirement for MBANs, and hence the importance of having a relatively clean and less crowded spectrum band. Today, MedRadio and WMTS band are used in many medical applications but the bandwidth is limited and cannot meet the growing need [24][25]. The 2.4 GHz ISM band is not suitable for life-critical medical applications due to the interference and congestion from IT wireless networks in hospitals. By having the 2360-2400 band allocated for MBAN on a secondary basis, quality of service for these life-critical monitoring applications can be better ensured. Moreover, the frequency band 2360 - 2400 MHz is immediately adjacent to the 2400 MHz band for which many devices exist today that could be easily reused for MBANS, such as IEEE 802.15.4 radios. This would lead to low-cost implementations due to economies of scale and ultimately lead to wider deployment of MBANS and hence improvement in patient care.

MBANs communication will be limited to transmission of data (voice is excluded) used for monitoring, diagnosing or treating patients. MBAN operation is permitted either by healthcare professionals or authorized personnel under license by rule. It is proposed that the 2360 - 2400 MHz frequency band be classified into 2 bands: 2360 - 2390 MHz (Band I) and 2390 - 2400 MHz (Band II). In the 2360 - 2390 MHz band, MBAN operation is limited for indoor use only to those healthcare facilities that are outside exclusion zones of AMT services. In the 2390 - 2400 MHz band, MBAN operation is permitted everywhere - all hospitals, in-home, mobile ambulances. There are a number of mechanisms for MBAN devices to access spectrum on secondary basis while protecting incumbents and providing a safe medical implementation. An unrestricted contention-based protocol such as LBT is proposed for channel access. The maximum emission bandwidth of MBAN devices is proposed to be 5 MHz. The maximum transmit power is not to exceed the lower of 1 mW and 10logB dBm (where B is the 20 dB bandwidth in MHz) in the 2360 - 2390 MHz band and 20 mW in the 2390 - 2400 MHz band. The maximum aggregated duty cycle of an MBAN is not to exceed 25%. A geographical protection zone along with an electronic-key MBAN device control mechanism is further used to limit MBAN transmissions. Electronic key (e-key) device control is used to ensure that MBAN devices can access the 2360 - 2390 MHz frequency band only when they are within the confines of a hospital facility that is outside the protection zone of AMT sites.

Figure 4 illustrates both in-hospital solution and out-hospital solution for using 2360-2390 MHz. Any hospital that plans to use the AMT spectrum for MBAN has to register with an MBAN coordinator. The MBAN coordinator determines if a registered hospital is within protection zones of AMT sites (with possible coordination with primary users). If a hospital is outside protection zones, then the MBAN coordinator will issue an e-key specifically for that hospital to enable MBAN devices within that hospital to access AMT spectrum. Without a valid e-key, by default MBAN devices can only use the 2390 - 2400 MHz band. The distribution of e-keys to MBAN devices that are connected to the hospital IT network can be automatically done either through wired or wireless links. MBAN devices must have a means to automatically prevent transmissions in the 2360 -2390 MHz AMT band when devices go outdoors. Once a sensor in an MBAN loses its connection to its hub device, it stops transmission within the 2360 - 2390 MHz AMT spectrum or transitions to the 2390 - 2400 MHz band. The 2390 - 2400 MHz band can be used anywhere without restriction and hence without an e-key. Simulations have shown that these technologies would work well to protect AMT from interference while also maintaining the quality of service required for the MBAN applications [13][14].

The IEEE has been working on MBAN standardization. In addition to ongoing activities in IEEE 802.15.6 on body area networks, a new 802.15 Task Group 4j was started in December 2010 to specifically develop standards for MBANs in the 2360 - 2400 MHz band, by leveraging the existing IEEE 802.15.4 standard.

CONCLUSION

Many milestones, both regulatory and technical, have been reached in opening spectrum for more flexible and efficient use and this trend will continue. Cognitive radio technology plays a significant role in making the best use of scarce spectrum to support fast growing demand for wireless applications, ranging from smart grid, public safety, broadband cellular, to medical applications. Standard Development Organizations (SDOs) have begun to develop standards to take advantage of the opportunities. However, challenges still remain since CR-enabled networks have to coexist with primary as well as secondary users and need to mitigate interference in such a way that they can better support such applications from end to end.

REFERENCES

[1] Connecting America: The National Broadband Plan, http://download.broadband.gov/plan/national-broadband-plan.pdf

[2] Unlicensed Operations in the TV Broadcast Bands, Second Memorandum Opinion and Order, FCC 10-174, September 23, 2010.

[3] Amendment of the Commission's Rules to Provide Spectrum for the Operation of Medical Body Area Networks, Notice of Proposed Rulemaking, FCC, ET Docket No. 08-59.

[4] IEEE 802.22 WG on WRANs (Wireless Regional Area Networks), http://www.ieee802.org/22/.

[5] Ecma 392: MAC and PHY for Operation in TV White Space, Ecma International Standard, 1st Edition, December 2009.

[6] M. Mueck,et al, "ETSI reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards," *IEEE Communications Magazine*,Vol 48, pp 78-86, Sept. 2010.

[7] Unlicensed Operation in the TV Broadcast Bands, Second Report and Order, FCC 08-260, November 14, 2008.

[8] K. Harrison, S.M. Mishra, A. Sahai, "How Much White-Space Capacity Is There?"*2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, Singapore ,6-9 April 2010.

[9] B. Scott and M. Calabrese, “Measuring the TV ’White Space’ Available for Unlicensed Wireless Broadband,” New America Foundation, Tech. Rep., Jan. 2006.

[10] Digital Dividend: Cognitive Access, http://www.ofcom.org.uk/consult/condocs/cognitive

[11] SE 43: Cognitive Radio Systems in White Spaces, http://www.cept.org/0B322E6B-375D-4B8F-868B-3F9E5153CF72.W5Doc?frames=no&

[12] Dract ECC Report 159, ”Technical and operational requirements for the possible operation of cognitive radio systems in the "white spaces" of the frequency band 470-790 MHz”, http://www.ero.dk/D9634A59-1F13-40D1-91E9-DAE6468ED66C?frames=no&

[13] Ex-parte comments of GE Healthcare in Docket 06-135, http://fjallfoss.fcc.gov/ecfs/document/view?id=6519820996

[14] Reply Comments of Philips Healthcare Systems in Docket 08-59, http://fjallfoss.fcc.gov/ecfs/document/view?id=7020244837

[15] Reply Comments of GE Healthcare in Docket 08-59, http://fjallfoss.fcc.gov/ecfs/document/view?id=7020244842

[16] Analysis on compatibility of Low-Power Active Medical Implant (LP-AMI) applications within the frequency range 2360-3400 MHz, in particular for the band 2483.5-2500 MHz, with incumbent services, http://www.ero.dk/0FFA3C12-E787-4868-9D02-CC9CA6D5F335?frames=no&

[17] DOE, Communications Requirements Of Smart Grid Technologies, Report, October 5, 2010

[18] David J. Leeds, The Smart Grid In 2010: Market Segments, Applications and Industry Players, Gtm Research, July 2009.

[19] Doumi, T.L.; , "Spectrum considerations for public safety in the United States," *IEEE Communications Magazine* , vol.44, no.1, pp. 30- 37, Jan. 2006

[20] Leonard E. Miller, Wireless Technologies and the SAFECOM SoR for Public Safety Communications, NIST report, 2005.

[21] Mobile Broadband: The Benefits Of Additional Spectrum, FCC, OBI technical paper No. 6, Oct. 2010

[22] T. Kamakaris, M.M. Buddhikot, R. Iyer, "A case for coordinated dynamic spectrum access in cellular networks," *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, DySPAN 2005, Baltimore,USA, pp 289-298.

[23] I.F. Akyildiz, Won-Yeol Lee, M.C. Vuran, S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, Vol 46, Issue 4, pp. 40 -48, April 2008.

[24] Maulin Patel and Jianfeng Wang, "Applications, challenges, and prospective in emerging body area networking technologies," *IEEE Wireless Communications*, vol.17, no.1, pp.80-88, February 2010.

[25] B. Zhen, H. Li, K. Takizawa, K. Yazdandoost, and R. Kohno, "Frequency band consideration of SG-MBAN," IEEE 802.15-MBAN-07-0640-00, March 2007.

BIOGRAPHIES

Jianfeng Wang (jianfeng.wang@philips.com) is a Senior Member of Research Staff at Philips Research North America. He received his Ph.D. in electrical and computer engineering from University of Florida in 2006. His research interests include cognitive radio, medical body area networks, wireless tele-health, M2M, and smart grid communications. His work led to over thirty publications in journals and conferences. He has been serving as the technical editor of Ecma 392 and the coexistence group leader of IEEE 802.22.

Monisha Ghosh (monisha.ghosh@philips.com) is a Principal Member of Research Staff at Philips Research currently working on cognitive and cooperative radio networks. She received her Ph.D. in Electrical Engineering in 1991 from the University of Southern California. From 1991 to 1998 she was a Senior Member of Research Staff in the Video Communications Department at Philips Research. From 1998 to 1999 she was at Lucent Technologies, Bell Laboratories, working on wireless cellular systems. Her research interests include estimation and information theory, error-correction and digital signal processing for communication systems. She is a Senior Member of the IEEE.

Kiran Challapali (kiran.challapali@philips.com) is a Principal Member at Philips Research North America. He is with Philips since 1990. He graduated from Rutgers University with a Master of Science degree in Electrical Engineering in 1992. He currently leads CogNeA, an industry alliance to bring cognitive radio solutions to market. He has published over twenty-five technical papers in IEEE Journals and Conferences, has about twenty-five patents, issued or pending, and is a Member of the IEEE.

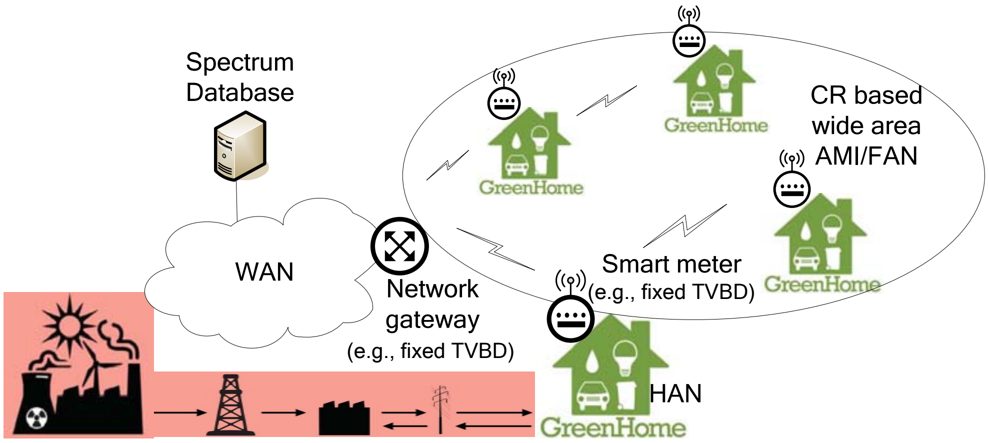

Figure 1. Smart Grid Networks.

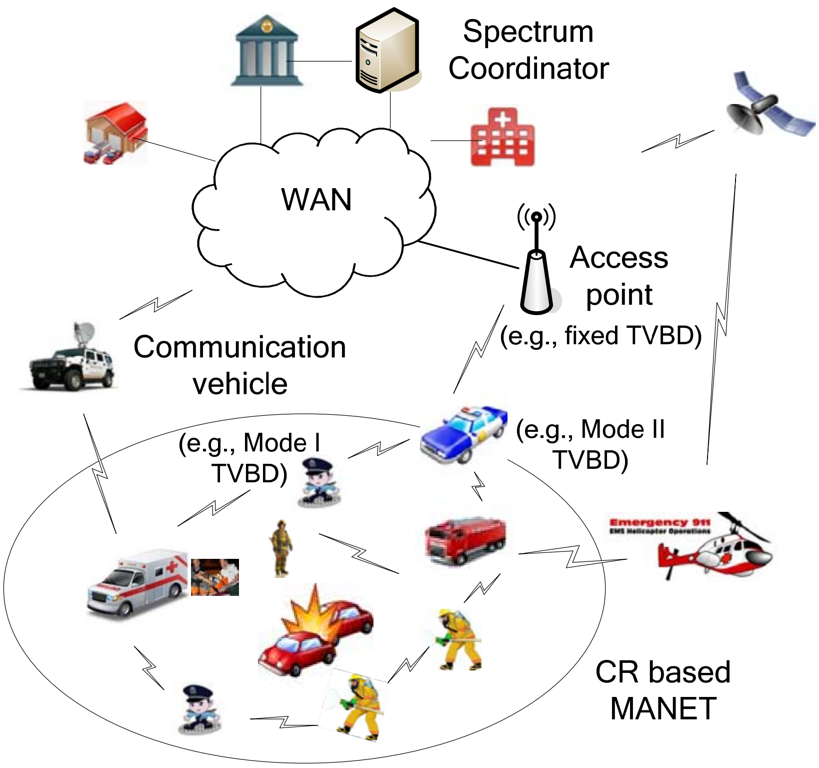

Figure 2. Public Safety Networks

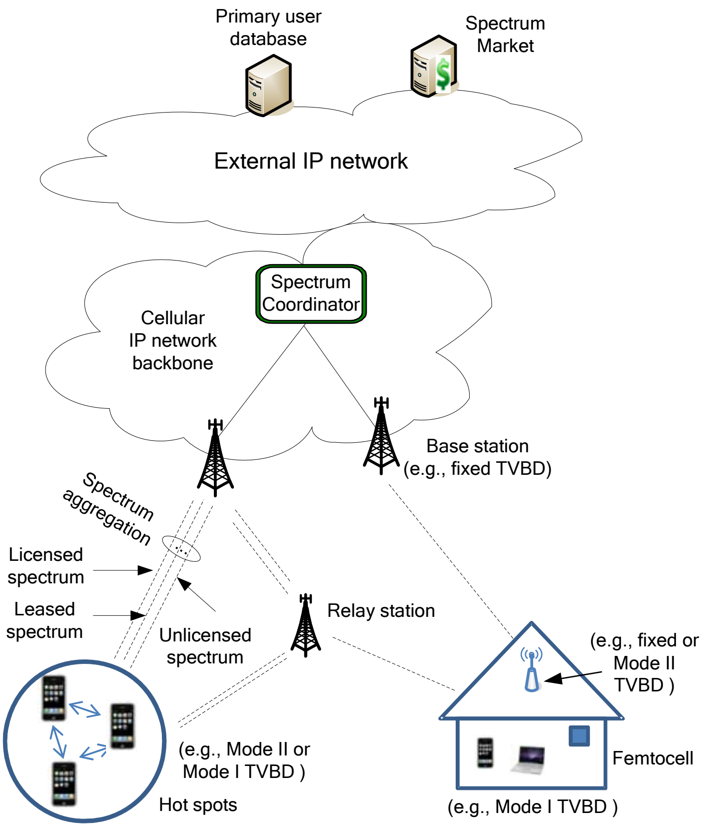

Figure 3. Cellular Networks

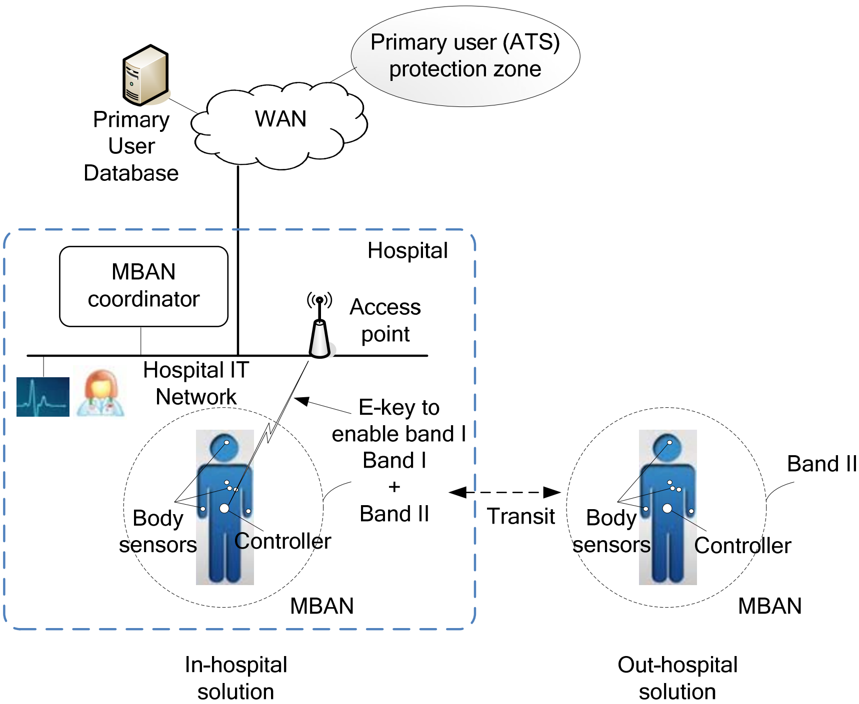

Figure 4. Medical Body Area Networks