Cognitive Radio for Smart Grid Communications

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***Abstract*— One of the key foundations of smart grid (SG) is a reliable communications infrastructure which is a sophisticated, multi-layer network carrying different classes of data. SG communications needs to be designed to accommodate the current energy management requirements as well as the potential demand of future applications. In this paper, we propose the application of cognitive radio (CR) based on the IEEE 802.22 standard in the SG wide area networks (WANs). We discuss the benefits of the proposed scheme including opportunistic access of TV bands, extended coverage, ease of upgradability, self-healing and fault-tolerant design. The proposed scheme can work as a secondary radio particularly in urban areas and as a backup in disaster management. In rural areas, however, a stand-alone radio based on IEEE 802.22 can effectively provide broadband access because of the wide area coverage due to the good propagation characteristics of TV bands.**

I. Introduction

Smart grid (SG) is a term referring to next generation utility networks in which the electrical power distribution and management is upgraded by incorporating advanced two-way communications and distributed computing capabilities for improved control, efficiency, reliability, and safety. Although it is too early to predict the full prospect of the SG enterprise, major features such as advanced metering infrastructure (AMI), demand-side management (DSM), fault-tolerance, and self-healing design are expected in the roadmap. The AMI smart meters use two-way communication links between the customers and the utilities and enable many new options and services such as remote meter reading, control, and detection of unauthorized usage. DSM improves system efficiency by shaping and balancing the loads either actively by shedding non-critical loads or passively through dynamic pricing. The overall system performance should not be affected by the occurance of faults and the system should automatically detect operational flaws while taking the necessary steps to repair itself. A key determining factor in establishing these features is timely access to information via a reliable communications infrastructure.

The SG communications infrastructure is expected to incorporate a hybrid mesh of different communications technologies to provide efficient and reliable access to grid components in diverse environments. Similar to existing data and voice telecommunications networks, the SG communications infrastructure is expected to be a multi-tier network that extends across multiple grid operation tiers. The SG communications networks need to spread over large geographical areas including generation, transmission, and distribution to the consumer premises [1]. The home area network (HAN) provides access to in-home appliances while the neighbourhood area network (NAN) connects smart meters to local access points, and the wide area network (WAN) provides communication links between the grid and core utility systems. Figure 1 shows a basic illustration of the electrical power grid and the SG multi-tier communications network.

The nature of each application running on these networks sets distinct requirements for data tranmission in terms of bandwidth, latency, traffic model (bursty, continuous), and priority level. Table I presents an example of different categories of data in a utility WAN [2]. The SG communications infrastructure has to accommodate the cohesive flow of different classes of data. Non-critical data features bursty traffic and moderate latency, and requires a large amount of bandwidth and resources. Further, the SG architecture has to be designed to accommodate the future growth in the numbers and types of applications and connected devices. One way to address this concern is to leave significant room for future expansions in the initial designs. However, this approach could be very costly as for example additional bandwidth needs to be acquired.

In this paper, we address the problem of additional bandwidth required for non-critical data and future applications in wireless SG communications links. In particular, these application requirements must be factored into the SG backhaul or distribution networks. Hence, our focus is on WANs that provide backhaul services and spread over large geographical areas. We discuss the application of cognitive radio (CR) systems in SG backhaul or distribution networks, which can provide opportunistic access to unused spectrum. We propose two different architectures for CR communications systems based on the IEEE 802.22 standard to accommodate the current and future needs of SG communications. One possible design is to apply the CR as a secondary link for non-critical data as well as backup connection in emergency situations. Another scenario is to use it as a stand-alone radio for rural areas.

The IEEE 802.22 standard is designed to provide broadband access to rural areas using the white space in TV bands. It employs a variety of advanced communications techniques such as orthogonal frequency-division multiple access (OFDMA) and offers extensive coverage area (33-100 km) due to the good propagation characteristics of TV bands. The application of this standard in SG WANs delivers a scalable, fault

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tolerant, and high performance broadband access. We finally discuss a practical implementation of CR-based radio using a reconfigurable and re-programmable software defined radio (SDR) technology which is easily upgradable to adapt to future needs of SG.

The paper is organized as follows. In Section II, an overview of SG WANs, CR, and the IEEE 802.22 standard is provided. A description of the proposed CR-based communications solution and their added benefits are provided in Section III. We explore the extended coverage area and the desirable propagation characteristic of the TV bands in Section IV, before the paper concludes in Section V.

II. Preliminary

In this section, we provide an overview of the infrastructure and existing communications technologies in SG WANs. We also discuss the key characteristics of the IEEE 802.22 standard.

A. Wide Area Networking in the Smart Grid

Utilities have long been operating WANs for a variety of applications such as providing information and access to their plants, offices and supervisory control and data acquisition (SCADA) systems that monitor and control the electricity grid. These legacy networks have incorporated various technologies including power line communications (PLC), fiber optics, leased lines and a variety of licensed and un-licensed wireless devices.

An SG WAN consists of two interconnected networks: the core network, and backhaul or distribution network. The core network connects the head offices and substations and commonly uses fiber optics, which can provide high data rates and minimal latency. Where fiber is unavailabe or too expensive to deploy, wireless solution using worldwide interoperability for microwave access (WiMAX) technology is a good fit due to ease of deployment and proven reliability. The backhaul or distribution network handles the broadband connectivity to NANs, mobile workforces, and automation and monitoring devices that are located on the distribution or transmission networks (e.g. sensors, monitors, SCADA systems). Technologies such as fiber optics, WiMAX, PLC, satellite and cellular communications are widely employed in WAN distribution networks.

WiMAX is a fourth generation wireless technology based on the IEEE 802.16 series of standards that offers long-range (around 5 km), high capacity wireless connections and is currently one of the front runners for SG WANs. WiMAX provides flexible broadband links and features low latency (10-50 ms) in both fixed (IEEE 802.16d) and mobile (IEEE 802.16e) versions. It also features inherent support of different levels of quality of service (QoS), allowing the SG operator to prioritize time-sensitive traffic. Figure 2 illustrates a typical SG WiMAX WAN connecting NANs to the core utility network.

B. Cognitive Radio

As the demand for radio spectrum continues to increase, the allocation of spectrum, which is a limited resource, will be an important technical challenge. Measurement-based studies of radio spectrum occupancy have also verified that wide ranges of the current licensed spectrum are sparsely used across many time and frequency slots [3]. One of the most promising solutions to improve spectrum access is the CR concept, since it enables the opportunistic usage of frequency bands that are not densely occupied by primary users (PUs) [4], [5]. In CR, PUs refer to licenced users who have higher priority or legacy rights on the usage of a specific part of the spectrum. Meanwhile, secondary users (SUs) are defined as the users that exploit this spectrum in such a way that they do not cause harmful interference to the PUs [4], [5]. More specifically, based on the definition adopted by Federal Communications Commission (FCC) in [5], CR has the ability to: detect which chunks of licensed spectrum are unused at a particular time in a particular geographic area (spectrum sensing), maximize data rate of each SU subject to RF emissions (transmit-power control), and manage distribution of available chunks fairly among SUs (spectrum management).

The IEEE 802.22 standard, which defines the air interface for a wireless regional area network (WRAN), is currently under development for CR use of the available chunks of TV spectrum (TV white space) [6]. The TV bands have superior propagation characteristics that can increase coverage and the ability to penetrate buildings at low power levels which leads to better broadband service for far-out users. IEEE 802.22 focuses on wireless broadband access in rural and remote areas as its coverage area is much greater than other wireless broadband technologies such as WiMAX.

1) FCC regulatory framework: A regulatory framework for the IEEE 802.22 standard is defined by FFC that allows cognitive users to exploit TV white space spectrum. According to FCC rules, cognitive devices operate within the very high frequency (VHF) channels and the ultra high frequency (UHF) channels. The bandwidth of these channels are 6 MHz and they range form 54 MHz to 72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz [6].

2) System topology and interference avoidance: The IEEE 802.22 standard specifies that a cellular CR network is formed by base stations (BS) and customer-premises equipment (CPE). BS manages the medium access for all the CPEs in its cell. To ensure that no harmful interference is caused to the PUs, several methods are considered for CR networks. In the first method, each BS is equipped with a GPS device to transmit location information to a centralized database containing information about PU transmission in the different TV channels. The database sends back the information about available TV bands in the area of the BS. The second method to avoid interference is local spectrum sensing, where the availability of TV bands is determined by the BS. In this case, the BS relies on its sensing information and/or distributed sensing information. In distributed spectrum sensing, the CPEs perform spectrum sensing and periodically send sensing information to the BS. Then, the BS decides which TV bands are unoccupied by PUs and allocate them to the CPEs.

978-1-4244-6511-8/10/$26.00

The algorithms used for spectrum sensing can be largely classified into blind detection and feature detection. Blind detection can be applicable to all possible primary signals since it does not rely on prior information such as signal characteristics, channel, and noise power. Example of blind detection techniques are energy detection [7] and covariance-based detection [8]. On the other hand, feature detection techniques such as matched filter detector [9], waveform-based detector [10], [11], and cyclostationary feature detector [12], sense specific characteristics of a known signal. Spectrum sensing for CR is a well researched topic; a summary of well-known spectrum sensing techniques that are included in the IEEE 802.22 draft standard [6] is provided in [11].

3) The MAC and PHY: The CR-based MAC layer can adapt dynamically to changes in the environment. This layer uses a superframe that consists of many frames. The superframe has a SCH (superframe control header) and a preamble, which are located at the beginning of each superframe and transmitted by the BS in each channel that can be used for communications. The MAC layer performs two diffterent stages of sensing: fast and fine sensing. A fast sensing period, typically under 1 ms per channel, is performed by CPEs and the BS where a simple sensing algorithm is employed, e.g. energy detector. The BS initiates the fine sensing stage based on the outcome of the fast sensing, in which more powerful methods are used over a longer time period (approximately 25 ms per channel). When multiple overlapping IEEE 802.22 BSs in the same geographical region are in operation, they are synchronized based on allocating Quiet Times to perform reliable fast and fine sensing. The IEEE 802.22 PHY layer uses efficiently the available bandwidth by dynamically adjusting the bandwidth, modulation and coding schemes. OFDMA is the modulation scheme for transmission in up and downlinks as it allows flexible subcarrier allocation to CPEs.

4) Self coexistence: Since IEEE 802.22 networks are deployed by competing wireless service providers, they can access different parts of the available spectrum in a distributed manner. It is clear that every network would need to satisfy the quality of service (QoS) delivered to the CPEs. Multiple IEEE 802.22 networks can co-exist in the same area on the same channel. To ensure QoS among the IEEE 802.22 networks themselves, the IEEE 802.22 standard specifies that networks which are located within radio range of each other, must synchronize their superframes with each other. This is achieved by BSs and/or CPEs transmitting coexistence beacons. If BS receives a coexistence beacon from a neighbouring network, then it sets the start time of its superframe according to the rules specified in the standard.

III. Cognitive Radio WAN for Samrt Gird Connectivity

As we have discussed previously, SG WANs are spread over large geographical areas and have to carry reliable, and timely information to the utility core network. In this work, we propose applying CR technology based on the IEEE 802.22 standard in SG backhaul networks to enhance capacity, coverage, and scalability, and reduce cost associated with licencing spectrum.

A. Proposed Method

We propose two different architectures for CR communications systems based on the IEEE 802.22 standard according to the specific circumstances and applications.

1) Stand-alone radio: In situations where the customer density is low and/or there is more white space available in TV bands, a stand-alone radio based on the IEEE 802.22 can effectively provide broadband access. This stand-alone radio can provide the wide area coverage because of the good propagation characteristics of TV bands.

2) Secondary radio: Where we have higher customer density and capacity requirements and less availablity of unused TV bands, we propose using IEEE 802.22 CRs as a secondary radio to opportunistically transmit non-critical data, and provide a backup radio in case of a natural disaster or a security breach.

In both of the proposed architectures, transmission of SG time-critical data is challenging due to inherent sensing delays and cognitive nature defined IEEE 802.22. As a solution, we propose a *dual-radio* architecture for cognitive-based transmission where one radio chain is dedicated for data transmission and reception while the other chain is dedicated for spectrum sensing. The sensing radio constantly searches for new available channels, so transceiver chain does not have to delay data communication to seek unused bandwidth. This scheme also provides higher spectrum efficiency and sensing accuracy than a *single-radio* architecture that only allocates a specific time slot for spectrum sensing.

We next point out the performance enhancements of CR-based SG WANs and discuss different application scenarios.

B. Performance Enhancements

1) Soft limit on capacity: One of key concerns for utilities is that their current investments in licensing bandwidth and equipment will be able to handle future possible applications. SG communications networks have to be designed to accommodate the upcoming applications as well as the current requirement. The proposed scheme has a soft capacity limit as it can opportunistically and dynamically use available TV channels to increase the system capacity. A total data rate of 18 Mbps in a 6 MHz TV channel has been defined by the IEEE 802.22 standard to provide CPEs with a level of performance similar to that of DSL broadband connections. To provide higher rates up to 24Mbs, the IEEE 802.22 PHY layer also employs channel bonding, using more than one TV channel for transmitting and receiving.
2) Wide coverage area: The BS coverage area for the IEEE 802.22 standard is much larger than thoes for IEEE 802 standards. For example, the maximum coverage range for IEEE 802.16a/d/e is limited to less than 5 km. However, the BS coverage for the IEEE 802.22 is 33 km if the power level of the CPE is 4 Watts EIRP.

This coverage may extend to 100 km if higher power levels are permitted. This means that less BSs would be required for wide-spread coverage. We discuss the coverage issue in more detail in the next section.

3) Fault tolerance and self-healing: The proposed scheme is inherently robust to failures. If one link is out of service because of a natural disaster or security breach, a new connection can be established to maintain connectivity. Most likely the new connection would have lower capacity, so there should be specifications in the disaster management to only transmit critical data that are important for system stability.
4) SDR architecture: CR systems are generally implemented using SDR and as a result they are more flexible and can be easily modified through software upgrades. SDR implementation has been commercially available in SG connectivity solutions both in BSs and routers, particularly for easily customizing WiMAX radios to specific licensed bands. The upgradabiliy of SDR systems is very important for utility customers because they are concerned that their capital investments on the communications infrastructure could become prematurely obsolete.

C. CR Application Scenarios in SG Communications

The proposed schemes can be applied in different situations for SG WANs both in power transmission and distribution networks. Power electric transmission networks are generally away from the population centers and as a result many of the TV channels are expected to be vacant. The large coverage area of IEEE 802.22 CR systems can be a great asset to provide connectivity in this enviroment. IEEE 802.22 CRs can also be a good solution in distribution networks. The channel characteristics, however, are substantially different in urban centers and rural areas. Urban centers have high density of customers and as a result they have to accomodate high data rates in their backhaul. The secondary radio architecture is beneficial in this scenario because of robustness and aforementioned performance enhancements. In rural areas, we have widely distributed and low density of customers. The stand-alone option based on IEEE 802.22 CR systems has a unique advantage in this situation because it has been designed for providing broadband connectivity in rural areas. We next discuss the coverage area in these different scenarios.

IV. Coverage Area

Channel propagation modeling has been extensively studied in wireless communications for decades. Classic analytical and empirical approaches have been developed to predict large-scale coverage for wireless communication system design. Path loss models are used to estimate the average received signal power as a function of distance, carrier frequency, and other transmission parameters. In this section, we study the coverage properties of TV bands and its potential benefits for SG WANs.

Consider a signal with a carrier frequency f_c that is transmitted to a receiver located at distance d from transmitter. The signal attenuation according to the free space path loss model is given by [14]

$$P_L \propto \left[\frac{1}{f_c d}\right]^2 . \quad (1)$$

It is clear from this model that lower carrier frequencies suffer from less path loss. As an example, the path loss for WiMAX transmission at 1.8 GHz is increased by 9.54 dB compared to transmission at $f_c = 600$ MHz (UHF band 470-806 MHz).

One of the most common empirical models is the Hata path-loss model for large urban and rural areas. This model is applicable for the frequency range from 150 MHz to 1500 MHz. The Hata formula for empirical path loss in urban areas is [14]

$$P_{L,\text{urban}}(d)\text{dB} = 69.55 + 26.16\log_{10}(f_c) - 13.82\log_{10}(h_t) + a(h_r) + (44.90 - 6.55\log_{10}(h_t))\log_{10}(d), \quad (2)$$

where f_c is carrier frequency in MHz and d is distance in km, h_t and h_r are the effective transmitter (BS) and receiver antenna height in meters, respectively. The Hata model is restricted to the following range of parameters: 30 m $< h_t <$ 200 m, 1 m $< h_r <$10 m, 1 km $< d <$ 20 km. $a(h_r)$ is a correction factor for the mobile antenna height based on the size of the coverage area. The compensation factors for small to medium-sized cities and larger cities at $f_c > 300$ MHz are given respectively by

$$a(h_r) = (1.1\log_{10}(f_c) - 0.7)h_r - (1.56\log_{10}(f_c) - 0.8) \text{ dB}, \quad (3)$$

and

$$a(h_r) = 3.2(\log_{10}(11.75h_r))^2 - 4.97 \text{ dB}. \quad (4)$$

To obtain the path loss in rural areas, a correction factor is added to the Hata formula (2) as follows

$$P_{L,\text{rural}}(d) \text{ dB} = P_{L,\text{urban}}(d) \text{ dB} - 4.78[\log_{10}(f_c)^2 + 18.33\log_{10}(f_c)] - K, \quad (5)$$

where $35.94 < K < 40.94$. Figures 3 and 4 illustrate the path loss in dB versus distance in km for various frequency bands, assuming $h_r = 3$ m and $h_t = 30$ m. This model shows that the average large scale propagation loss is significantly lower in low-frequency TV bands. Note that some of the frequencies and distances in Figures 3 and 4 are not in reliable range of the Hata model (shown with dashed lines). In order to confirm our point, we also consider the Longley-Rice model which is valid for frequencies between 20 MHz to 10 GHz [15]. Figure 5 shows around 20 dB difference in path loss between 60 MHz and 2.4 GHz bands, assuming $h_r = 3$ m and $h_t = 30$ m.

V. Conclusions

In this paper, we proposed the application of CR communications for SG WANs. The CR links based on the IEEE 802.22 standard are desirable in SG networks since they do not require initial capital investment in licenced spectrum. They are also flexible, easily upgradable making use SDR

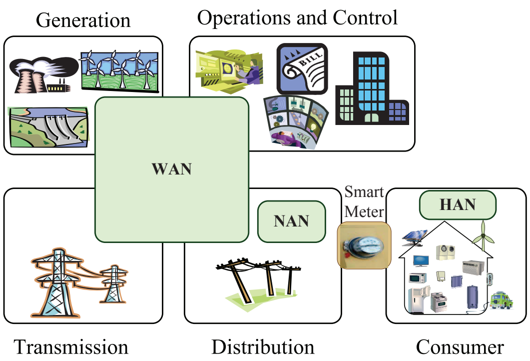

Fig. 1. Smart grid multi-tier network.

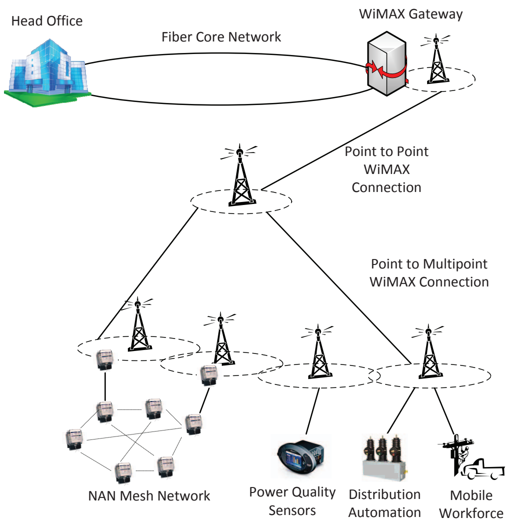

Fig. 2. A typical WiMAX WAN in smart grid communications.

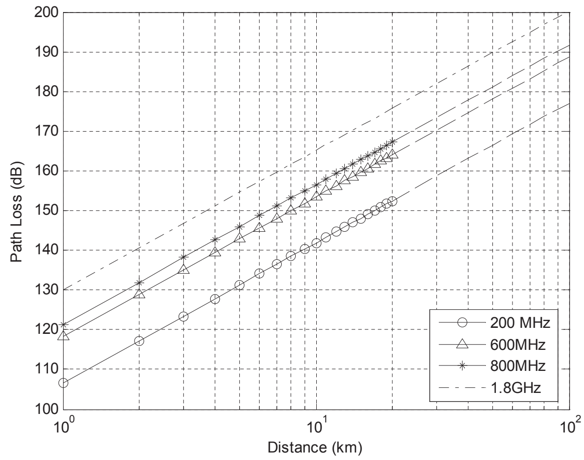

Fig. 3. Path loss in urban centers (Hata model).

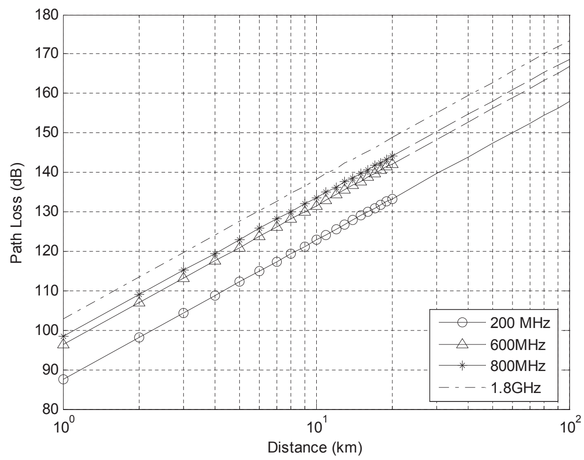

Fig. 4. Path loss in rural regions (Hata model).

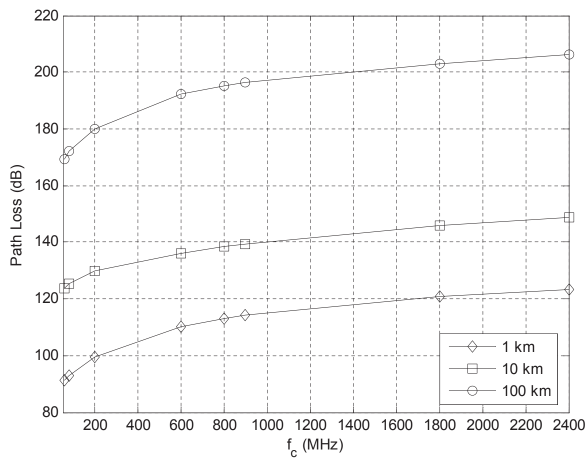

Fig. 5. Path loss comparison based on the Longley-Rice model.

implementation, and they provide an increased coverage area due to the opportunistic use of TV bands.

We proposed two different architectures for stand-alone and secondary CRs based on the IEEE 802.22 standard. The stand-alone option can provide broadband access to the widely-spread customers in rural area. In urban areas, IEEE 802.22 transceivers can be applied as a secondary radio to handle high volumes of non-critical data and they can act as a backup radio in emergency situations. Massive efforts are underway by stakeholders around the world to standardize different aspects of the SG vision, and in particular an SG communications architecture. We believe that the CR technology could become an important element of this architecture as it provides many benefits in SG applications.

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TABLE I
DATA CATEGORIES FOR UTILITIES BASED ON BC HYDRO DATA [2].

Protection data	**Operational technology data**	**Information technology data**
Critical for power system stability	Essential for utility operation	Essential for enterprise operation
Critical	Maybe critical	Non critical
Extremely low latency $<$ 1ms	Low latency 2ms-2s	Low to moderate latency 10ms-100ms
Low bandwidth	Medium bandwidth, bursty traffic	High bandwidth, bursty traffic
Extremely high reliability and security	high reliability	Enterprise class reliability and security

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