The current centrally controlled electrical grid is a large interconnected network that delivers electricity from suppliers to consumers. New challenges are emerging in the traditional power grid, such as rising energy demand, aging infrastructure, renewable energy sources, reliability, and security [1–4]. These challenges have become a global concern that necessitates the traditional electrical grid to evolve toward intelligence, autonomy, improved efficiency, easy control, and high security. The smart grid is widely considered to be the next-generation electricity grid. An efficient and reliable communication architecture plays a crucial role in improving efficiency, sustainability, and stability. In this article, we first identify the fundamental challenges in the data communications for the smart grid and introduce the ongoing standardization effort in the industry. Then we present an unprecedented cognitive-radio-based communications architecture for the smart grid, which is mainly motivated by the explosive data volume, diverse data traffic, and need for QoS support. The proposed architecture is decomposed into three subareas: cognitive home area network, cognitive neighborhood area network, and cognitive wide area network, depending on the service ranges and potential applications. Finally, we focus on dynamic spectrum access and sharing in each subarea. We also identify a very unique challenge in the smart grid, the necessity of joint resource management in the decomposed NAN and WAN geographic subareas in order to achieve network-scale performance optimization. Illustrative results indicate that the joint NAN/WAN design is able to intelligently allocate spectra to support the communication requirements in the smart grid.

The current centrally controlled power grid is undergoing a drastic change in order to deal with increasingly diversified challenges, including environment and infrastructure. The next-generation power grid, known as the smart grid, will be realized with proactive usage of state-of-the-art technologies in the areas of sensing, communications, control, computing, and information technology. In a smart power grid, an efficient and reliable communication architecture plays a crucial role in improving efficiency, sustainability, and stability. In this article, we first identify the fundamental challenges in the data communications for the smart grid and introduce the ongoing standardization effort in the industry. Then we present an unprecedented cognitive-radio-based communications architecture for the smart grid, which is mainly motivated by the explosive data volume, diverse data traffic, and need for QoS support. The proposed architecture is decomposed into three subareas: cognitive home area network, cognitive neighborhood area network, and cognitive wide area network, depending on the service ranges and potential applications. Finally, we focus on dynamic spectrum access and sharing in each subarea. We also identify a very unique challenge in the smart grid, the necessity of joint resource management in the decomposed NAN and WAN geographic subareas in order to achieve network-scale performance optimization. Illustrative results indicate that the joint NAN/WAN design is able to intelligently allocate spectra to support the communication requirements in the smart grid.
tions infrastructure is envisioned to be a multilayer structure that extends across the whole smart grid from the home area to the neighborhood area and the wide area (Fig. 1a). In particular, home area networks (HANs) communicate with various smart devices to provide energy efficiency management and demand response. Neighborhood area networks (NANs) connect multiple HANs to local access points. Wide area networks (WAN) provide communication links between the NANs and the utility systems to transfer information.

This three-layered structure of the communications networks provides a potential operation of the smart grid to work economically, efficiently, reliably, and securely. However, there are still many challenges imposed on the design of communication architecture for the smart grid [7].

- **Tremendous data amount**: The amount of data generated by smart meters and intelligent sensors in the smart grid will experience explosive growth in the next few years. According to the recent report of SBI Research (Rockville, Mary-
land), the volume of smart grid data that will have to be managed by utilities over the next few years is going to surge from 10,780 Tbytes of new data created in 2010 to over 75,200 Tbytes in 2015 [8]. This tremendous data amount places considerable pressure on the communications infrastructure of the smart grid.

• **Energy sources**: A unique characteristic of the smart grid is the integration of distributed renewable energy sources (e.g., solar and wind power). In a NAN, there are two power sources: the power from the utility and the distributed renewable energy. These two power sources have two essential differences: price and availability. Balancing the usage of different energy sources will be very important for power grid stability, availability, and operation cost.

• **Highly varying traffic**: There are large amounts of real-time and archival operational data in the smart grid. The amount of data varies tremendously during a day, so the traffic conditions change rapidly. For example, solar power is a typical kind of renewable energy source. Such renewable energy sources are only available for a certain period of time during a day. The switching orders of the renewable energy equipment are transmitted dynamically according to the availability of the renewable energy. During peak hours, the data communications require higher data rate and more reliable services.

• **Interoperability**: Data will flow over generation, transmission, distribution, and user networks in the smart grid. A variety of technologies will be used to set up the communication architecture to provide enough information to the control centers to ensure the operation of the smart grid. One of the major problems of the multilayered architecture of communications networks is interoperability among so many subnetworks.

• **Quality of service (QoS)**: Different categories of data have different QoS priorities in terms of transmission latency, bandwidth, reliability, and security [6]. Information including devices’ state, load, and power pricing should flow over the communications network accurately, effectively, and reliably. A higher priority and guaranteed QoS should be provided to the meter data, while power price data used for summarizing the monthly bill for electric usage have normal priority and QoS.

• **Security**: The smart grid will use computer networks for controlling and monitoring the power infrastructures. This in turn exposes the smart grid to outside attacks. There are many potential threats within utilities, such as indiscretions by employees and authorization violation [5]. Smart grid networks have to carry reliable and real-time information to the control centers of the utilities. Due to the unique challenges imposed on the smart grid, the existing communications network is infeasible and cannot be applied trivially. A revolutionary communication architecture is urgently demanded. In this article, we propose a cognitive-radio-based communication architecture for the smart grid (Fig. 1b). Cognitive radio refers to the potentiality that wireless systems are context-aware and capable of reconfiguration based on the surrounding environments and their own properties [11]. In the same frequency range, there are two coexisting systems: the primary system and the secondary system. The primary system refers to the licensed system with legacy spectrum. This system has exclusive privilege to access the assigned spectrum. The secondary system refers to the unlicensed cognitive system, which can only opportunistically access the spectrum holes that are not used by the primary system. We call the subscriber in the primary system the primary user (PU) and the subscriber in the secondary system the secondary user (SU). The motivations for using cognitive radio in the smart grid are summarized as follows:

  • First, the main challenge in a HAN is the increasingly intensive radio systems. There are already several types of radio systems operating in the 2.4 GHz license-free industrial, scientific, and medical (ISM) frequency band (e.g., Zigbee, Bluetooth, and WiFi). The coexistence of these systems could cause significant interference with each other. Besides, domestic appliances (e.g., microwave ovens) may leak strong electromagnetic waves. As a consequence, the spectrum in a HAN is becoming dramatically crowded and contaminated. Smart grid meters in a HAN usually operate in the 2.4 GHz ISM band for economic reasons. The severe interference and keen competition over the limited ISM band will definitely endanger reliable smart grid communications. It is beneficial to introduce cognitive radio technology in HANs. Based on the parameter-adaptive capacity of cognitive radio, the interference among different radio systems could be considerably reduced by intelligent transmission scheduling and power coordination.

  • Second, the generated energy-related data will be up to tens of thousands of terabytes in the near future. This poses a significant challenge for any existing communication network as well as the future smart grid network to collect, transmit, and store such large-scale data. The usage of cognitive radio in the smart grid potentially improves spectrum utilization and communication capacity to support large-scale data transmissions.

  • Third, the smart grid communications architecture shall cover home areas, neighborhood areas, and wide areas. Consequently, it is an essentially heterogeneous network with a number of complementary technologies, which needs intelligent devices/terminals to manage the communications within each subarea and the communications between different service ranges. For the convergence of the heterogeneous network, smart grid devices should be equipped with cognitive radio functionality to enable hardware reconfigurability and context awareness.

By leveraging cognitive radio technology, the proposed communications infrastructure promises to utilize potentially all available spectrum resources in the smart grid. The radio agility allows the smart grid devices to sense the unused spectrum opportunities in the surroundings and utilize them subject to interference constraints. Dynamic spectrum access enabled by cognitive radio technology is adopted by the smart grid to exploit the underutilized frequencies in an opportunistic manner [11]. As a consequence, the flexibility, efficiency, and reliability are significantly enhanced in a cognitive-radio-based smart grid network.

This article presents key issues and solutions to cognitive-radio-based communications infrastructure for the smart grid, including the architecture, the Zigbee standardization activity, dynamic spectrum access, and sharing in HAN, NAN, and WAN as well as joint NAN/WAN scenarios. The next illustrates the network architecture, which is decomposed into three complimentary subnetworks: home areas, neighborhood areas, and wide areas. We next focus on spectrum management and sharing in each area, and then present the spectrum access in joint NAN/WAN subareas. Illustrative results indicate that the joint NAN/WAN design is able to intelligently allocate spectra to support the data communication requirements in the smart grid. The conclusion of the article is presented last.
The Proposed Cognitive-Radio-Based Communication Architecture

Figure 1b shows the proposed communication architecture based on cognitive radio for the smart grid. The communication architecture adopts the three-tiered hierarchical structure, including HAN, NAN, and WAN. Being different from the traditional architectures in the literature, the proposed architecture heavily leverages cognitive radio technology to enable the communications infrastructure more economically, flexibly, efficiently, and reliably. On one hand, cognitive communications that operate in the license-free bands are applied in the HAN to coordinate the heterogeneous wireless technologies; on the other hand, cognitive communications that operate in the licensed band are applied in the NAN and WAN to dynamically access the unoccupied spectrum opportunities. Table 1 summarizes the features and techniques in the three subareas. We explain the principles, key challenges, and potential solutions of the cognitive communications in the three subareas.

Cognitive Communications in Home Area Networks

The HAN is a fundamental component that enables two-way communications to provide demand response management services in the smart grid. The HAN provides real-time smart meter power data and load information from the user side to the utility center controls, and also provides dynamic electricity pricing information in the inverse direction. There are two necessary functionalities in the HAN: commissioning and control. Commissioning is specified to identify new devices and manage the joining/forming of the self-organizing network. Control is used to maintain the communication link between devices and ensure interoperability within the smart grid network.

Topology — Figure 2 shows the topology of a cognitive HAN. The HAN consists of a cognitive home gateway (HGW), smart meters, sensors, actuators, and other intelligent devices. A networked smart meter system is a typical instance in a HAN to offer an energy-efficient and reliable next-generation power grid. The presented HAN uses a star topology with either wired technologies (e.g., power line communications) or different wireless technologies (e.g., Zigbee, Bluetooth, and WiFi). Consequently, HAN is an essentially heterogeneous network with a number of complementary technologies, which calls for a very flexible service gateway to manage the communications within the HAN and the communications between different HANs in a NAN service range [10].

Standardization Activity — Zigbee recently defined an application layer standard for smart energy for HANs with the intention of low-cost devices and low energy use [9]. In general, Zigbee is characterized by low rate, low power, and short-range transmissions. Zigbee operates by the IEEE 802.15.4 radio specification.

The smart energy profile provides communications primarily related to efficiency, cost, messaging, and usage. The profile intends to support a diversity of devices, including in-home display, programmable communicating thermostat, load control devices (e.g., pool pumps, water heaters, appliances), and plug-in vehicles. Messaging is a key component in the profile in order to support different functionalities, in particular multiple urgency levels, security, registration, device definition, and initialization.

- From the utility companies’ point of view, ZigBee smart energy is able to offer a standards-based technology for implementing secure and cost-efficient HANs.
- From the customer perspective, they can choose interoperable devices from different manufacturers and monitor the energy consumption in real time, which will provide precise information to help reduce power consumption.
- For the regulation organizations, Zigbee smart energy offers a global open standard technology and cases the specifications of various rules. Furthermore, the Zigbee smart energy profile helps implement advanced smart meters and develop new demand response management to facilitate greener smart grids.

Dynamic Spectrum Sharing in Cognitive HANs — To autonomously adapt to different radio technologies in the HAN, the HGW shall have self-configuration or advanced cognition capability. In this sense, the HGW is able to intelligently interact with the radio surroundings, adaptively connect, and change their transmitters’ parameters. The radio agility capacity in the HGW is able to sense unused frequencies in the surroundings and can utilize them subject to interference constraints. In addition, the HGW will connect to the HAN, which in turn will connect to external networks (e.g., the Internet, NAN, or a utility). The HGW enables two-way communications in the HAN. In the forward direction, the HGW periodically collects power-related data (e.g., metered data, sensed data, and load and control information) from various machines/devices/terminals within the HAN, and then transfers the collected data outside of the NAN. In the opposite direction, the HGW acts as a central node within the cognitive NAN to receive data (e.g., pricing, demand response) from the NAN and then distribute the received data to the smart meters or display to the customers.

Within a HAN, the HGW manages the license-free spectrum bands to provide optimal data rate with low interference. An efficient solution to spectrum sharing among networked smart meters is necessary. Apart from spectrum sharing management, the HGW enables other devices and sensors to join the network, assigns channel and network addresses to each device, and coordinates the communications between the devices within the HAN.
In smart grid applications, the NANs will collect and join spectrum management. The Wide area network (WAN) is a cognitive-radio-based centralized/decentralized wireless nodes (e.g., smart meters, access control, power coordination). Hybrid dynamic spectrum access (H-DSA), which operate at the licensed band, is a hybrid dynamic spectrum access (H-DSA) paradigm is proposed to improve the spectrum efficiency. Some licensed spectrum bands are leased/bought from a telecommunication operator, and these bands are used as licensed access for the HGWs to ensure the QoS of data communications. The NGW distributes these licensed bands to the HGWs according to the transmission demand. However, licensed spectrum bands are not enough to meet the large amount of data in the smart grid. Unlicensed access is also needed for the HGWs to improve the capacity and throughput of the NAN. In unlicensed access, the HGWs and NGW could be considered SUs, and the communications link between them is set up in the unoccupied spectrum bands in an opportunistic manner. In this way, the connection between HGWs and an NGW is built up in a cost-effective way, and the information could be transferred between HAN and NAN in a hybrid access manner. To improve the spectrum efficiency and reduce the cost of buying spectrum bands, licensed and unlicensed access modes are intelligently scheduled and seamlessly switched. The smart grid user (or service) is not aware of the actual access mode it is using. A spectrum broker is deliberately deployed to manage the licensed spectrum sharing between different NANs. With consideration of the real-time change in the amount of data in the network, the spectrum broker should respond quickly to the varying channel capacity and distribute the licensed bands in an efficient manner to meet the data transmission requirements. If a WAN covers a large service area, several NANs may share the same spectrum bands without causing interference to each other. In particular, Fig. 3 shows a scenario in which there are three NANs in the WAN, and 10 spectrum bands are bought from the telecommunication operator. According to the different demands of data throughput, the spectrum broker may distribute four bands to NAN1 and six bands to NAN2. Since NAN1 and NAN3 are far from each other, the spectrum broker will distribute four bands to NAN3, which is the same as distributed to NAN1.

### Cross-Layer Spectrum Sharing in HAN

Smart meters and intelligent sensors and actuators in home areas are networked for information collection and delivery to constitute the HAN of the smart grid. As mentioned before, different wireless technologies may be adopted by various meters/sensors/actuators, and hence coexist in a HAN. The spectral overlay between these wireless systems may cause severe interference to each other and deteriorate system capacity. Thus, cognitive spectrum sharing is necessary to coordinate the spectrum access of the heterogeneous wireless systems. Here, an HGW-assisted cross-layer cognitive spectrum sharing mechanism is proposed.

The mechanism has two main components: the spectrum access controller and power coordinator, which operate at the medium access control (MAC) and physical (PHY) layers, respectively. Each wireless node in a HAN is allowed to access the spectrum only if it is permitted by the access controller. The power coordinator helps in the realization of a non-cooperative game among the wireless nodes to adapt their transmitting power.

### Power Coordination

Consider a HAN with $i$ wireless nodes (e.g., smart meters, sensors, or actuators) intending to transmit data. The achievable rate of the $i$th node is given by Shannon’s formula.

<table>
<thead>
<tr>
<th>Cognitive area networks</th>
<th>Home area network (HAN)</th>
<th>Neighborhood area network (NAN)</th>
<th>Wide area network (WAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum band</td>
<td>Unlicensed band</td>
<td>Licensed band</td>
<td>Licensed band</td>
</tr>
<tr>
<td>Network topology</td>
<td>Centralized/decentralized</td>
<td>Centralized</td>
<td>Centralized</td>
</tr>
<tr>
<td>Network users</td>
<td>Smart meters/sensors/actuators, HGW</td>
<td>HGWs, NGW</td>
<td>NGWs, spectrum broker</td>
</tr>
<tr>
<td>Featured strategy</td>
<td>Cross-layer spectrum sharing</td>
<td>Hybrid dynamic spectrum access</td>
<td>Optimal spectrum leasing</td>
</tr>
<tr>
<td>Key techniques</td>
<td>Access control, power coordination</td>
<td>Guard channel, spectrum handoff</td>
<td>Join spectrum management</td>
</tr>
</tbody>
</table>

Table 1. Summary of the proposed cognitive-radio-based hierarchical communications infrastructure for the smart grid.
where $B_i$ is the channel bandwidth, and $p_i(f)$ and $N_0$ are the power spectral density (PSD) function of system $i$ and noise in receivers, respectively. The average power of the $i$th system is constrained by $P_i$. The utility function of the $i$th node is defined by

$$U_i = R_i - a_i \int_B p_i(f) df,$$  \hspace{1cm} (2)

where $a_i$ is a constant with the $i$th node. The problem of transmitting power coordination among wireless nodes in a HAN can be formulated as a non-cooperative game, in which the main ingredients are defined as follows:

- **Player**: Each wireless node (e.g., a smart meter, sensor, or actuator) is an individual player in the game.
- **Action**: Each player will take an action of adjusting its transmitting power level according to that of the others.
- **Utility**: The utility for each player is defined by Eq. 2, which quantitatively reflects the player’s demand to find a satisfying trade-off between transmitting rate and energy consumption.

**Spectrum Access Control**

Within the HAN, the cognitive HGW manages the spectrum bands allocation and sharing to provide optimal data rate with low interference. The spectrum access controller aims to guarantee the QoS of all in-service wireless nodes (i.e., players) by controlling the number of new players. If the presence of a new player significantly degrades the achievable rate of one or more existing players, the new player shall be blocked. Figure 4 shows four phases in the spectrum access control:

- **Phase 1**: The access control procedure is launched by the new player that sends an access request to the HGW.
- **Phase 2**: The access controller passes the profile of the new player to the power coordinator. The profile contains the information of the specific parameters of the utility function and the PSD function of the new players.
- **Phase 3**: The power coordinator invokes the game theoretic framework discussed earlier to analyze and obtain the optimal power control of all players (including the new one). The resulting power control and achievable rate are fed back to the access controller.
- **Phase 4**: If one or more players reach an undesirable rate, the new player is denied; otherwise, it is admitted. The access controller informs the new player of the admission/rejection decision, and all the players about whether to update the transmitting power. Denied players may retry to access later.
Hybrid Dynamic Spectrum Access in NANs

In a NAN, an H-DSA strategy is proposed to significantly improve the flexibility of communications infrastructure and spectrum efficiency. Of all the spectrum bands of a NAN, some are leased and licensed from the telecommunication operator (i.e., the primary system), while the rest are used in an opportunistic/unlicensed manner. The NGW is responsible for allocating the spectrum bands to the HGWs within its area. The HGWs being allocated with unlicensed bands act as SUs. An in-service SU has to hand off to a spectrum hole once a PU appears and occupies its spectrum band. If there is no spectrum hole available to which to hand off, the SU will be dropped. For improving the QoS of SU transmissions in H-DSA, QoS-aware policies should be used.

Hybrid Guard Channel Strategy

In cognitive radio networks, the dynamic nature of spectrum availability causes a significant difficulty in stable and guaranteed QoS provisioning. The guard channel (GC) strategy is a classical but very effective approach to protect the ongoing services and maintain their QoS at a satisfactory level. In the GC strategy, a number of channels are reserved for handoff traffic. New services are not allowed to use the reserved channels.

By extending the key idea of the GC strategy, a hybrid GC (HGC) strategy is proposed here for cognitive NANs. The new feature of the HGC strategy is that both the licensed and unlicensed bands reserve a certain number of channels for the usage of spectrum handoff. Essentially, there are four types of channels in H-DSA: licensed GCs, unlicensed GCs, licensed common channels, and unlicensed common channels. The licensed GCs offer guaranteed reservation for handoff services, while the unlicensed GCs extend the opportunities for handoff services in a more resilient and efficient manner. The licensed/unlicensed common channels could be used by both new and handoff services.

We consider a NAN with a total of $N$ channels. Let $N_L^L$, $N_L^U$, $N^L_C$, and $N^U_C$ denote the number of licensed and unlicensed GCs, and licensed and unlicensed common channels, respectively. Let $N_P$ and $N_S$ denote the number of existing PU and smart grid NAN services. The main operations of our HGC strategy are explained as follows:

- A new service is allowed to access the network if $N_P + N_S < N_L^L + N_L^U$; otherwise, it should be blocked.
- The admitted new service is allocated with a licensed common channel if $N_S < N_L^C$; otherwise, it is allocated with an unlicensed common channel.
- The licensed and unlicensed GCs are only reserved for the usage of spectrum handoff. However, the licensed and unlicensed common channels could be used by new flows and handoff flows as well.

Spectrum Handoff Strategy

In a cognitive NAN, a spectrum handoff strategy is crucial to maintain the continuity and improve the resilience of the communications. An SU has to perform spectrum handoff promptly upon PU arrival. Here, the PUs can be licensed users of any telecommunications operator or TV band operators. There are two kinds of GCs in H-DSA. A fair spectrum handoff strategy is introduced to coordinate the spectrum handoff and facilitate the spectrum management in NANs. The strategy consists of the following important rules:

- If there are idle licensed or unlicensed common channels, handoff users should shift to the common channels instead of the GCs.
- If there is no common channel available but licensed GC(s), the fair approach is to allocate the licensed GCs to the handoff users following the first come first served (FCFS) rule.
- Once there is a vacancy in the licensed or unlicensed common channels due to the departure of a PU or smart grid user, one of the handoff users that is already occupying a GC has to switch back to the common channel. As a consequence, the GC could be recovered for further usage.

In a cognitive NAN, the NGW takes responsibility for coordinating the licensed and unlicensed spectrum access, dynamically adapting the HGC strategy and spectrum handoff strategy such that the H-DSA scheme operates in a low-cost and high-efficiency way. Let $P_d$ and $P_b$ denote the dropping probability and blocking probability, respectively. The NGW manages the NAN to optimize the system performance under the constraint of the spectrum leasing cost. Given the number of leased channels, $N_L$, and the requirement on $P_b$, the optimization problem can be formulated as

$$\begin{align*}
\min_{P_{d}}
P_{d}
\text{s.t. } & P_{b}(N_L^L, N_L^U, N^L_C, N^U_C) \leq P_{b}^0 \\
& N_L^L + N_L^U = N_L \\
& N^L_C + N^U_C = N.
\end{align*}$$

(3)

A discrete gradient descent algorithm can be employed to search for the solution to the optimization problem.
We observe that the proposed scheme apparently outperforms the traditional scheme by significantly reducing the dropping probability. When the budget of the utility company is relatively low, leading to a small number of leased channels, the traditional solution is not able to afford large traffic load, and the QoS constraint $P_b$ is violated. Instead, our proposed infrastructure is still able to provide a satisfactory performance with much lower dropping probability. The result is expectable because the proposed communications infrastructure employs the HDSA scheme instead of the traditional fixed access scheme. Considerable unused spectrum opportunities are utilized; hence, the system performance is clearly improved.

**Joint WAN/NAN Spectrum Management**

At the WAN level, there is a spectrum broker/server to manage the spectrum resources of the entire communications infrastructure of the smart grid. From the perspective of the utility companies, the communications infrastructure should operate economically, efficiently, and adaptively. The spectrum management of the WAN and NANs should be jointly optimized for the following main reasons:

- **In most situations, all the NANs in the same WAN operate in the same range of spectrum bands.** There are underlying competitions on spectrum resource among the NANs, which need overall coordination.
- **Different NANs have diverse demands on the amount of spectrum bands, due to the diversity in the number of HANS and traffic flows of HANS caused by the diversity in quantity and category of smart meters/sensors/actuators.**
- **The demand on spectrum bands of each NAN varies from each other.** This fact gives rise to the joint NAN/WAN spectrum management.

We consider a WAN with $K$ NANs. Let $N_{G,k}^{l}$, $N_{G,k}^{u}$, $N_{C,k}^{l}$, and $N_{C,k}^{u}$ denote the number of licensed and unlicensed GCs, and licensed and unlicensed common channels of the $k$th NAN. Let $P_{l,k}$, $P_{b,k}$ denote the dropping probability and blocking probability of the $k$th NAN, and $N_k$ the number of allocated total channels of the $k$th NAN. The joint WAN/NAN spectrum management could be formulated as the following optimization problem:

$$\begin{align*}
\min & \max_k \{P_{l,1}, \ldots, P_{l,K}, P_{b,1}, \ldots, P_{b,K}\} \\
\text{s.t.} & \sum_k N_{G,k}^{l} + N_{C,k}^{l} = N_L \\
& P_{b,k}\left(N_{G,k}^{u}, N_{C,k}^{u}\right) \leq P_{b,k}^{u}, k = 1, \ldots, K \\
& N_{G,k}^{l} + N_{C,k}^{l} + N_{C,k}^{u} = N_k, k = 1, \ldots, K \\
& \sum_k N_k \leq N
\end{align*}$$

The optimization demonstrates the constraints within NANs and WAN, and their interaction. The target is to find the optimal spectrum allocation scheme with parametric tuples $(N_k, N_{G,k}^{l}, N_{G,k}^{u}, N_{C,k}^{l}, N_{C,k}^{u})$ for all NANs.

Figure 6 shows the performance gain of the proposed cognitive communications infrastructure at the WAN level. For the sake of illustration, we consider the scenario with one WAN and two NANs. For the traditional scheme, a fixed spectrum allocation strategy is used in the WAN, and spectrum resources are managed independently in each NAN. It is observed that the proposed scheme achieves much lower blocking probability than the traditional solution. By using joint WAN/NAN spectrum management, the cognitive infrastructure is aware of the diversity of traffic load in different NANs, and consequently is able to intelligently allocate the spectrum bands. As a consequence, spectrum resources (both licensed and unlicensed) are utilized in a highly efficient manner.

**Conclusion and Future Work**

In this article, we first identify the fundamental challenges in the design of a communications architecture for the smart grid. Then we present the cognitive-radio-based communications architecture for the smart grid, which consists of three layers: HAN, NAN, and WAN. Different solutions are proposed to address the dynamic spectrum access and sharing in each subarea, including cross-layer spectrum sharing in the HAN, hybrid spectrum access in the NAN, and joint NAN/WAN spectrum management. Illustrative results indicate that the joint NAN/WAN design is able to intelligently allocate spectra and that the proposed infrastructure significantly improves the performance of the system.

The proposed architecture and solutions have yielded significant results and momentum for further developments. Several challenges lie ahead before the cognitive-radio-based communications infrastructure for the smart grid can be deployed. The spectrum regulations should be specified in the new communications paradigm in the smart grid. Different spectrum management schemes have been investigated in different subareas. Reliability-driven solutions need further consideration in the mission-critical smart power grid. Privacy is an interesting research topic in order to protect customers’ energy usage data and patterns. Cooperative relay techniques [12] may be incorporated into the communications infrastructure for QoS enhancement.

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References

[10] SHENGLI XIE (shlxie@gdut.edu.cn) received his M.S. degree in mathematics from Central China Normal University in 1992 and his Ph.D. degree in control theory and applications from SCUT in 1997. He is presently a full professor and head of the Institute of Intelligent Information Processing at Guangdong University of Technology (GDUT). In November 2010 he joined the Institute of Intelligent Information Processing at Guangdong University of Technology (GDUT), where he is now an associate professor. His research interest mainly focuses on wireless communications and networking, including cognitive radio, wireless sensor networks, and home networking. He is the co-inventor of over 10 patents and author or co-author of over 50 journal and conference papers. He is a member of China’s home networking standard committee. He leads the standardization work of three standards.

Biographies

YAN ZHANG (yanzhang@simula.no) received his Ph.D. from Tsinghua University, China, in 2007. After that, he worked in the School of Electronic and Information Engineering of South China University of Technology (SCUT). In November 2010 he joined the Institute of Intelligent Information Processing at Guangdong University of Technology (GDUT), where he is now an associate professor. His research interest mainly focuses on wireless communications and networking, including cognitive radio, wireless sensor networks, and home networking. He is the co-inventor of over 10 patents and author or co-author of over 50 journal and conference papers. He is a member of China’s home networking standard committee. He leads the standardization work of three standards.

MOHSEN GUIZANI [F’09] (mguizani@ieee.org) is currently a professor and the associate vice president of graduate studies at Qatar University. He was the associate dean of academic affairs at Kuwait University. He also served as the chair of the CS Department at Western Michigan University from 2002 to 2006 and chair of the CS Department at the University of West Florida from 1999 to 2002. He held other academic positions at the University of Missouri-Kansas City, University of Colorado-Denver, and Syracuse University. He received his B.S. (with distinction) and M.S. degrees in electrical engineering, and M.S. and Ph.D. degrees in computer engineering in 1984, 1986, 1987, and 1990, respectively, from Syracuse University, Syracuse, New York. His research interests include wireless communications and mobile computing, computer networks, and optical networking. He currently serves on the editorial boards of six technical journals, and is the founder and Editor-in-Chief of Wireless Communications and Mobile Computing Journal (WCMC). He is also the founder and Steering Committee Chair of the Annual International Conference of Wireless Communications and Mobile Computing (IWCMC). He is the author of seven books and more than 200 publications in refereed journals and conferences. He has guest edited a number of special issues in IEEE journals and magazines. He also served as member, Chair, and General Chair of a number of international conferences. He served as the Chair of TNC (2009-2010) and the Chair of TACOS (2007-2009) ComSoc Technical Committees. He was an IEEE Computer Society Distinguished Lecturer from 2003 to 2005. Dr. Guizani is a Senior Member of ACM.

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