Exploiting TV White Spaces for Smart Grid Communications

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***Abstract*—**Although Smart Grid (SG) is conceived to be a fundamental paradigm shift in the area of power grid, it faces one major challenge which is an efficient and reliable communications structure. In this paper, we identify a possible way in which SG can exploit the use of TVWS for communications using a two-way cognitive radio-based switching procedure. This procedure enable gateways to sense and utilize TVWS channels for communication when they are declared vacant and if occupied by a Primary User (PU), the gateway can alternatively switch transmission over to an unlicensed spectrum band. The optimum sensing time that takes account of the overhead brought about by the sensing process is evaluated. The theoretical analysis are validated through the numerical results.

Index Terms—Smart grid communications, TV white spaces, cognitive radio, spectrum sensing.

I. Introduction

Over the years the conventional power grid has metamorphosed into a more intelligent, communication enabled, customer interactive electrical power system in terms of its power generation, transmission, distribution and billing method and this is called Smart Grid (SG). This smart grid incorporates a distributed networking and computing capabilities and an advanced two-way communicational abilities for the improvement of the safety, reliability, efficiency and sustainability of the grid. Apart from the smartness and self-healing design this smart grid promises, it also possesses some key functionalities like high fault tolerance level, Advanced Metering Infrastructure (AMI) and Demand Side Management (DSM) [1]. In terms of the fault tolerance level, the general output of the system is not deterred by the occurrence of any faults as the system has the ability to automatically detect faults and takes necessary action to perform a self-repair. The functionality of the DSM enables the grid to shape and balance loads either actively or passively and this is done by exuviating temporary loads or by dynamicity in pricing. Also, the AMI functionality helps in connecting the smart meters and other devices in the network of the grid through a two-way communication to ensure and enable remote meter reading, control of unauthorized usage and delivering of real-time information. An important factor necessary in incorporating these functionalities and to fulfil the potentials of smart grid is an effective, efficient and reliable communication infrastructure.

A smart grid communication network (SGCN) infrastructure should be able to provide components in a smart grid network with reliable, secure and efficient data delivery both in real-time and non-real-time situations. Hence, the communication infrastructure of a smart grid is expected to amalgamate heterogeneous communication technologies working in various standards [2] in diverse environments. The communication infrastructure is expected to deliver high volume of data and information through a multi-layer network spanning through several grid operation levels. This multi-layer network is spread across a large geographical area that encompasses generating, transmitting and distributing to the end user or consumers [3]. The home area networks (HANs) is one of the layers in the SGCN. This layer is responsible for providing communication access to smart devices and appliances together with the smart meters in the home to the gateway. It utilizes various wireless technologies and protocols for communication such as Bluetooth, Wi-Fi, ZigBee and so on. The neighbourhood area networks (NANs) is another layer that establishes the connection between the smart meters through the gateway while the wide area network (WAN) layer delivers effective communication data links between the NAN local control center, SG substations and the central control room. A typical illustration of a SG communication infrastructure is shown in Fig. 1.

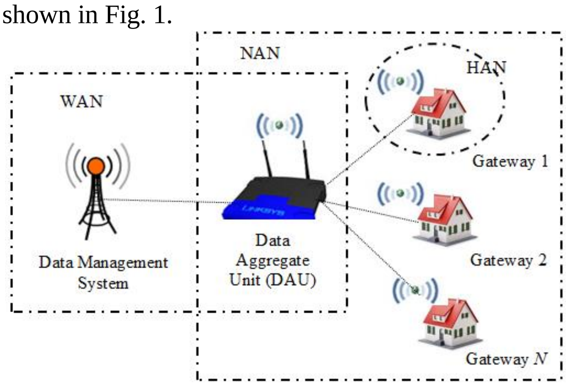

Fig. 1. SG communication procedure

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There exist some challenging issues the infrastructural communication network of a smart grid has to deal with in order to successfully deliver and exchange data and information. An important issue is the problem of high varying traffic. The amount of data exchanged during the day necessitates the smart grid communication network infrastructure to demand huge data rates and low latency to enable smooth, reliable and good Quality of Service (QoS).

Inter-operability is another issue that needs to be overcome due to the multiplicity of various technologies and standards available in the network through the multi-layered topology. The underlining issue of security is also a challenge to SGCN. Since the network communication is wireless, hence threats become more available from different utilities.

A major and pressing challenge of an SGCN is the unavailability or lack of spectrum resources for communication either due to the way it is being utilized or the fact that spectrum is scarce and always unavailable [4].

The ineffective and inefficient use of spectrum resources is primarily caused by the staticity in accessing the spectrum and because of this, the Federal Communications Commission (FCC) has now enabled the advancement and usage of the a software defined radio known as Cognitive Radio (CR) [5] which enables Dynamic Spectrum Access (DSA) [6]. In a CR paradigm, frequency channels or spectrum holes in licensed spectrum or bandwidth are sensed by secondary users (SU) or otherwise known as cognitive radio users for usage. When the channels have been sensed, SU can communicate in them provided that there is no presence of a Primary User (PU) or otherwise known as a licensed user in the channel or provided that the SUs do not create any interference to the PU. By doing this, a CR can intelligently and perspicaciously improve the utilization of spectrum as well as the quality of the SU's communication.

On the other hand, the availability of TV White spaces (TVWS) for communication purposes have now become a reality since the switch from Analogue to Digital Terrestrial TV (DTT) has freed numerous number of channels. TVWS is made up of fairly large frequency blocks in the VHF bands and also in the UHF bands and they have an enormous likelihood to support numerous new services and applications. The radio propagation in the TVWS is around the range of 700 MHz and it is considered to be more benign [7] when compared to others due to its ability to penetrate through buildings and structures and its easy accessibility to rough landscapes and larger coverage area. These advantages coupled with its low operational and deployment cost would be a very inviting potential for SG communications. That means the data requirements of many SG applications could be managed and supported using TVWS. In this paper, we will be focusing on the possibility of exploiting TVWS for smart grid communications employing CR.

II. Related Work

Lately, there have been quite some few works of research aimed at using white spaces for smart grid communications. The work in [8] introduces a wireless SG communication operating in TVWS. An investigation was carried out to ascertain the possibility of communicating in TVWS spectrum formerly meant for analogue TV channels for use in the rural parts of Virginia in the United States. Same investigation was also applied in [9] where the motive was to provide broadband connection to the remote Highlands and Island areas of Scotland in order to penetrate mountains, building structures and rugged terrains. One of the first works that incorporated cognitive radio into smart grid communication is seen in [10] where communication quality is improved using a spectrum sensing technique and switching of channels for smart meters in transmitting data. The energy consumption for the sensing was however not taken into account in the work. Also in [11], the authors proposed a strategy to reduce channel outages in smart grid since it plays a crucial role in Demand Response Management. In the paper, a cognitive radio based switching was employed improve the sensing time but unfortunately, the properties of TVWS was not taken into account. A cognitive radio based smart grid communication frame work was proposed in [12] to increase throughput and latency performances in AMI communications. The results show that cognitive radio improves spectrum utilization efficiency in WiMaX band as well as duty cycle of TV band. The development of smart grid communications via TVWS and ISM bands was also studied in [13] where the achievable data rate and latency in the network was maximized. This was however can be applicable only in the Home Area Network (HAN) scenario. The work in [14] proposed a multitier communication network architecture for smart metering applications in dense urban environments utilizing TVWS by small cognitive radio operators. The real-time decision support framework developed was used to ensure tradeoff between cost and QoS in the network.

In this paper, we tend to investigate how TVWS can be utilized for smart grid communications via the use of cognitive radio. Since there are regulatory rules governing the behavior of PU and the channel state information in a TVWS, there is an absolute need for the optimization of the sensing time utilized for sensing so as to cater for and improve the overall time duration over the channel.

The remainder of the paper is organized thus: In section III, a system model is described. Section IV presents our evaluation and results while in section V the paper is concluded and future work is presented.

III. System Model

We consider a smart grid communication scenario where numerous smart meters in the HANs are connected to a Gateway (GW) as depicted in Fig. 1. Each of the GW is responsible for transmitting data from the HANs to the Data Aggregate Unit (DAU). The GW utilizes a two-way CR-based communication model for the selection of channels in the TVWS for communication. The GW time is assumed to be organized into different fixed time slots with a duration T. In the model, sensing is performed by a CR user in the duration t_i and after that it transmits at a time $T - t_i = t_r$ as seen in Fig. 2.

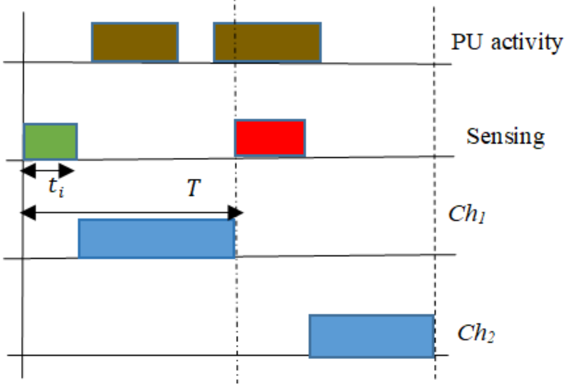

Fig. 2. Cognitive radio based two-way communication

If sensing affirms the TVWS channel to be idle, it can then be utilized for transmission once it is authorized by the White Space DataBase (WSDB) [15]-[18]. That means the GW will communicate in that sensed channel otherwise, it switches to the unlicensed band for communication. The TVWS channel is considered as $K_l(i)$ $(i = 1,2 \ldots N)$ while the channel in the unlicensed spectrum band is regarded as $K_{ul}(i)$.

The GW only switches to the unlicensed channel if there is no TVWS channel available for communication. As earlier mentioned in the previous section, the preferred option for communication is the TVWS channel due to its inherent and favourable characteristics. Therefore, the probability of switching in Eq. (1) will occur when the TVWS channel is available for communication and sensed correctly or when the TVWS channel is busy and the sensing fails.

$$P_{sw}(t_i) = P_1(i)\left(1 - P_d(t_i)\right) + P_0(i)(1 - P_f(t_i)) \quad (1)$$

where $P_1(i)$ represents the probability that at least a NAN is transmitting over the TVWS channel. $P_0(i) \cong 1 - P_1(i)$, while $P_d(t_i)$ and $P_f(t_i)$ denotes the probability of detection and probability of false alarm respectively.

The probability of detection $P_d(t_i)$ is the probability of sensing the TVWS channel as busy and that a closely related NAN is transmitting in the sensed TVWS channel. This is very practical in a smart grid scenario as the energy detector is equipped with a-priory knowledge requirement as shown in [19].

$$P_d(t_i) = Q\left(\sqrt{Wt_i}\left(\frac{\mu_i}{2Wt_i(\alpha_i+1)} - 1\right)\right) \quad (2)$$

where $Q(.)$ represents the Q-function, α denotes the Signal-to-Noise Ratio (SNR) at the selected GW transceiver, W represents the signal bandwidth and μ_i denotes the detector threshold normalized to σ^2.

Apparently, a reduced sensing time t_i, bring about a lower probability of detection $P_d(t_i)$ hence leading to a higher interference between closely located NANs transmitting over the same TVWS channel. Therefore, we can impose a constraint on the probability of detection that:

$$P_d(t_i) \geq P_d^{min} \quad (3)$$

where P_d^{min} is dependent on the smart grid requirements.

The probability of false alarm is the probability that the TVWS channel is being sensed as busy when a PU is absent and when there is no closely located NAN transmitting on the channel. Using the energy detection as in [20], it is given as

$$P_f(t_i) = Q\left(\sqrt{Wt_i}\left(\frac{\mu_i}{2Wt_i} - 1\right)\right) \quad (4)$$

The higher the probability of false alarm, the greater the amount of communication opportunities on the TVWS channels.

The probability that a channel is in a state of outage or the probability that a channel is inaccessible caused by unfavourable wireless propagation conditions is called the probability of outage. It can also be considered as the GW being unable to communicate with the DAU and this is given as

$$P_{out}(t_i) = \left(1 - P_{sw}(t_i)\right) P(K_{ul}(i)) + P_{sw}(t_i)P(K_l(i)) = [P(K_l(i)) - P(K_{ul}(i))]P_{sw}(t_i) + P(K_{ul}(i)) \quad (5)$$

$P(\mathrm{K_{ul}}(i))$ is denoted as the probability of outage for the unlicensed channel while $P(K_l(i))$ is denoted as the probability of outage for the TVWS channel. The event of an outage taking place is either a cognitive-based switching did not occur and the unlicensed channel is in a state of outage or a cognitive-based switching took place and the TVWS channel is still in a state of outage.

As discussed previously, It is however very rational to continue with the assumption that the licensed channel's quality is superior to the unlicensed channel, hence $P(K_l(i)) < P(K_{ul}(i))$ for any value of t_i. Therefore, the choice of utilizing both the TVWS spectrum and the unlicensed spectrum rather than utilizing only the unlicensed spectrum, the outage events is reduced thereby increasing the communication reliability of the smart grid. Hence we can impose the constraint on the probability of outage:

$$P_{out}(t_i) \leq P_{out}^{min} \quad (6)$$

where $P_{out}^{min} > P(K_l(i))$ so as to have an achievable constraint.

The average throughput in an ith GW can be measured by the data rate expected to be achieved during a random time slot. Also, the trade-off between the gains benefitted by improving the sensing accuracy with longer sensing times should be accounted for. Hence the optimization goal will be to achieve an optimal sensing time t_i^{opt} that can maximize the expected data rate $R(t_i)$ and also satisfy the probability of outage constraint P_{out}^{min}. Hence the optimization problem in Eq. (7).

$$t_i^{opt} = arg\max_{t_i \in R_{out}^{opt}} \{R(t_i)\} \quad (7)$$

subject to:

$$P_{out}(t_i) \le P_{out}^{min}$$

For a closed-form expression of the expected data rate $R(t_i)$ to be obtained, the probability of switching can be re-defined by setting $P_d(t_i)$ to equal P_d^{min} by substituting Eq. (4) into Eq. (1).

$$P_{sw}(t_i) = 1 - P_1(i)P_d^{min} - P_{out}Q\left(\alpha_i\sqrt{Wt_i} + Q^{-1}(P_d^{min})(\alpha_i + 1)\right) \quad (8)$$

By putting into consideration the Q-function property, it is estimated that the probability of false alarm $P_f(t_i)$ decreases as the sensing time t_i increases. Thus, the minimum probability of false alarm will be given as

$$P_f^{min} = P_f T = Q\left[\alpha_i\sqrt{WT} + Q^{-1}(P_d^{min})(\alpha_i + 1)\right] \quad (9)$$

By substituting Eq. (8) into Eq. (5) we then have:

$$P_{out}(t_i) = [P(K_l(i)) - P(K_{ul}(i))] \ . \ Q\left\{\alpha_i\sqrt{Wt_i} + Q^{-1}(P_d^{min})(\alpha_i + 1)\right\} + [P(K_l(i)) - P(K_{ul}(i))]P_1(i)P_d^{min} + P(K_{ul}(i)) \quad (10)$$

From the Eqs. (9) and (10), as (t_i) increases, there will be in improvement in the sensing accuracy. Therefore, the probability of switching $P_{sw}(t_i)$ pushes towards the maximum value $1 - P_1(i)P_d^{min}$ while the probability of being in channel outage state in Eq. (5) pushes towards the minimum value:

$$P_{out}^{min} = [P(K_l(i)) - P(K_{ul}(i))]P_{sw}^{min} + P(K_{ul}(i)) \quad (11)$$

where

$$P_{sw}^{min} = 1 - P_1(i)P_d^{min} - P_{out}Q\left(\alpha_i\sqrt{WT} + Q^{-1}(P_d^{min})(\alpha_i + 1)\right), \quad (12)$$

As (t_i) increases for an improved sensing accuracy, it results to the portion of T which is meant for transmission to decrease hence $(t_i)^{min}$ in Eq. (13).

The expected data rate $R(t_i)$ can be expressed as in Eq. (14) where C_l and C_{ul} represents the capacity of the licensed and unlicensed channel respectively.

The optimization problem in Eq. (7) can now be reformulated as t_i^{opt} in Eq. (15).

$$(t_i)^{min} = \frac{1}{\alpha_i{}^2 W}\left(-Q^{-1}(P_d^{min})(\alpha_i + 1) + Q^{-1}\left(\frac{P_{out}^{min} - (P(K_l(i)) - P(K_{ul}(i)))P_1(i)P_d^{min} - P(K_{ul}(i))}{[(P(K_l(i)) - P(K_{ul}(i)))]P_{out}(t_i)}\right)\right)^2 \quad (13)$$

$$R(t_i) = C_l(1 - P(K_l(i)))(P_1P_d(t_i) + P_0P_f(t_i)(1 - {}^{t}/_{T}) + C_{ul}\left(1 - P(K_{ul}(i))\right)P_0\left(1 - P_f(t_i)\right)\left(1 - {}^{t}/_{T}\right) \quad (14)$$

$$t_i^{opt} = arg\max_{t_i \in R_{out}^{opt}}\left\{C_l(1 - P(K_l(i)))(P_1P_d(t_i) + P_0P_f(t_i)(1 - {}^{t}/_{T}) + C_{ul}\left(1 - P(K_{ul}(i))\right)P_0\left(1 - P_f(t_i)\right)\left(1 - {}^{t}/_{T}\right)\right\} \quad (15)$$

subject to

$$t_i^{opt} \ge (t_i)^{min} = \frac{1}{\alpha_i{}^2 W}\left(-Q^{-1}(P_d^{min})(\alpha_i + 1) + Q^{-1}\left(\frac{P_{out}^{min} - (P(K_l(i)) - P(K_{ul}(i)))P_1(i)P_d^{min} - P(K_{ul}(i))}{[(P(K_l(i)) - P(K_{ul}(i)))]P_{out}(t_i)}\right)\right)^2.$$

IV. NUMERICAL EVALUATION AND RESULTS

This section evaluates the results obtained from the studied analysis detailed in section III. The probability of detection P_d^{min} is taken to be 0.95, while $P(K_l(i))$ and $P(K_{ul}(i))$ is taken as 0.2 and 0.5 respectively. The probability P_1 is equal to 0.4 and the time slot duration is set at 300μs while C_l and C_{ul} is taken as 11 and 26MBps respectively.

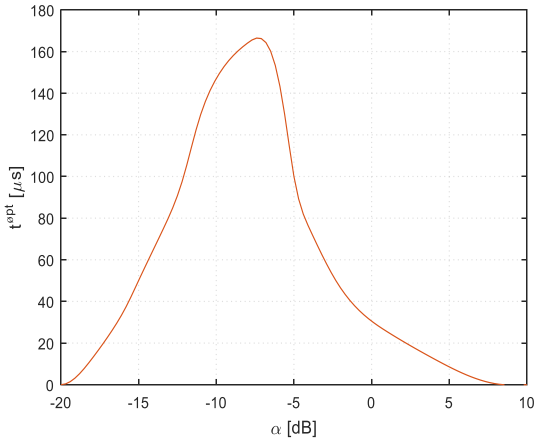

Fig. 3. Optimum sensing time vs SNR

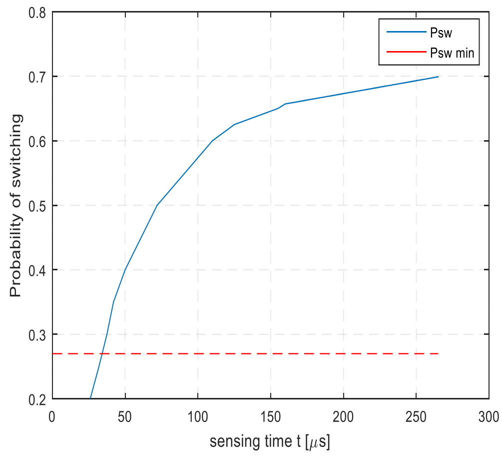

Fig. 4. Probability of channel switching vs sensing time

In Fig. 3, we report the optimal value of t as it relates to the SNR α. It is seen that optimal sensing time increases to a certain maximum value of α before decreasing gradually with α. This occurrence can be explained thus: the optimal sensing time increases for smaller values of SNR since larger sensing times provides the benefit of a better sensing accuracy. In other words, the overhead brought about by the sensing process is dominated by the detection events. When a certain threshold is reached on the SNR, the optimal sensing time then decreases because the overhead brought about by the sensing process dominates the benefits from the sensing process.

In Fig. 4, we show the probability of channel switching as a function of the sensing time. As expected, it can be noticed that the probability of channel switching increases as the sensing time increases.

This is so due to the fact that the probability of false alarm decreases as the sensing time increases. This is expected since a longer sensing time increases the accuracy of the spectrum channel sensed hence providing the smart meter or GW chances to switch data transmission to the licensed channel.

V. Conclusion and Future Works

With the introduction of cognitive radio and spectrum sensing in smart grid communications, it is expected to fully utilize and take advantage of TVWS for efficient and quality communications and reduction in channel outages. In this paper, we investigated how TVWS can be utilized for smart grid communications. We propose a procedure that enables gateway to sense TVWS channels for efficient usage and where it is not available, unlicensed spectrum bands are used for transmission. We also analyze the outages in a two-way based cognitive radio switching communications and the optimal sensing time that achieves the best sensing performance. In future works, the data rate achieved will be explored and various factors that impedes on the performance will be considered.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

E. Orumwense and K. Abo-Al-Ez conducted the research; E. Orumwense and K. Abo-Al-Ez analyzed the data; E. Orumwense wrote the paper; all authors had approved the final version.

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