Cognitive Radio-Based Backup Protection Scheme for Smart Grid Applications

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ABSTRACT In this paper, a backup protection scheme is presented. The proposed scheme uses the concept of a cognitive radio-based wireless sensor network to implement a protection scheme without the need for conventional electric wires and/or optical fiber between current and voltage transducers, control panels, and circuit breakers. The proposed scheme uses unlicensed spectrum channels by applying spectrum sensing and frequency allocation algorithms that are used in cognitive radio based systems. The importance of the proposed scheme comes from its cost effectiveness compared to the Ethernet communication both wired and wireless if the data transfer and message exchange is done using cognitive radio_based communication for relatively long distances. The proposed scheme utilizes cognitive radio-based communication network to convey analog and digital signals within a substation. In this way, it saves the cost of the copper wires and/or optical fiber that would be used to transmit digital and analog signals. Further, it does not require the expensive spectrum licenses that would have been purchased if Ethernet long-distance wireless communications are utilized. To assess the benefits/challenges related to the application of cognitive radio_based communication, a detailed and realistic modeling of both power systems and cognitive radio_based communication systems is performed simultaneously. The proposed scheme is simulated using MATLAB/Simulink and performance of the proposed scheme was investigated under different communication scenarios.

INDEX TERMS Cognitive radio, green communication, IEC-61850-9-2 process bus, microgrids, smart grid, overcurrent protection, substation automation.

I. INTRODUCTION

Conventional power grids suffer from many problems that include, but are not limited to, transmission network congestion, increasing energy prices, degraded power quality, and conventional protection, control, and metering schemes [1], [2]. Practical and reliable solutions have to be adopted to counter these grid challenges especially with its infrastructure aging [3]. Smart electric grids are being adopted widely to solve conventional power grid problems [4]–[6]. The main features of a Smart Grid (SG) include incorporation of two-way communications, distributed computing, and automated control [7]. While they are considered as the backbone for building a smart grid, Ethernet communication systems will either require a substantial infrastructure if they use wired channels, or will incur considerable cost for purchasing a license if they use wireless channels for relatively long distances. Adopted communication systems for smart grid applications must provide vital solutions for radio spectrum high cost or extensive infrastructure complexity.

In substation automation, IEC-61850-9-2 Process Bus standard allows for the utilization of Ethernet communication, both wired and wireless, to transfer analog and digital signals [8]–[10]. While Ethernet communication is very well-established and reliable communication system in substation automation; it requires cost ineffective infrastructure for copper wires or optical fibers to transmit current and voltage signals between the transducers and the control and protection room. On the other hand, implementing IEC-61850-9-2 Process Bus Ethernet communication...
wirelessly as proposed in [11]–[14], requires the operators to purchase expensive spectrum license to transmit the spectrum within (Considering longer distances that local areas). Hence, cognitive radio-based communication systems is studied in this paper to overcome these problems. In addition, the impacts of cognitive radio-based communication on protection systems in terms of time delays and transmission errors were studied. This requires detailed analysis and modeling of both power and communication systems.

Cognitive Radio (CR) started to emerge in smart grid applications replacing licensed technologies in order to avoid the expensive or unavailable radio frequencies. In this research we will focus on CR-based power systems applications. In [15] the authors studied Supervisory Control and Data Acquisition (SCADA) that adopts CR-based IEEE 802.22 standard. The proposed system and the two examples in the paper showed that the CR based wireless control is efficient, cost effective, and with a small number of limitations. In addition, the work in [16] studied the Automatic Generation Control (AGC) problem. The research studied both the asymptotic stability and mean-square stability of two generator systems with a tie line, and the discussed results showed that CR can be used for control applications but with some compromise on the dynamic stability. However, the authors suggested that if the considered CR control scheme improves quality of the service system, the overall dynamic stability of the AGC scheme will be improved. Multiple research papers discussed the architecture, applications, and communication technologies of CR based smart grid applications [17]–[19]. The research in [17] was one of the early researches that studied the CR communication schemes applied on a microgrid testbed, while in [18] the architecture and the implementation of a design model for a CR-based smart grid application is presented. In particular, this research discusses the Low Power Wide Area Network (LPWAN) systems implementation and design. Finally, in [19] the authors discussed the communication requirement for different smart grid applications. Different Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN) SG applications are considered in the paper and the compliance of best communication network and standard of each one of these systems is presented. In [20], [21], the standards for applying CR in smart grid applications are discussed. In [20], the authors proposed an IEEE 802.11af-based NAN for smart grid application in a low voltage distribution system. The paper proposed all system specifications such as reliability, range, data rate, and latency required by each SG application (i.e., distribution automation, demand response, etc.). The simulated results showed that the proposed scheme kept at least 99% of packet delivery ratio and less than 200 ms time delay. On the other hand, the authors in [21] studied the spectrum sharing problem in CR-based SG applications. They presented the spectrum sharing algorithm with compliance with IEEE 802.11af defined on white space TV spectrum. The spectrum sharing of white space TV bands is achieved by the use of a geolocation database that contains full knowledge of licensed and unlicensed users in the band. On the other hand, the authors in [22] studied the spectrum sharing problem in CR-based SG applications. They presented the spectrum sharing algorithm with compliance with IEEE 802.11 af defined on white space TV spectrum. The spectrum sharing of white space TV bands is achieved by the use of the geolocation database that contains full knowledge of licensed and unlicensed users in the band. Finally, [23] the authors studied an IEEE 802.11 af based joint power and channel allocation scheme applied to NAN applications. The discussed results showed that the proposed scheme was successful in achieving an optimal solution for the conflicting goals of channel allocation and reduced power consumption for a desired quality of service. While the previous work demonstrated the importance and efficiency of using CR in smart grid applications, no research has studied CR schemes for communication purposes in substation automation. The purpose of this work is to apply CR-based communication for message exchange in substation automation that utilizes the IEC-61850 standard instead of Ethernet communication both wired and wireless.

In [24] the authors proposed a CR based scheme to transfer meter data for long distances by integrating IEC 61850 Manufacturing Message Specification (MMS) with IEEE 802.22. While in [25] the authors proposed a CR based energy management system for power system emergency cases based on IEC 61850 standard. The IEC 61850 based communication modeling provides interoperability and serves for vehicles plug-and-play purposes. The suggested scheme shows the feasibility of modeling and acceptability of its performance. While the applications of these two researches are different from the one discussed here, they show that the integration of IEC 61850 using CR based systems are becoming a solution for some vital grid problems.

The paper is organized as follows section II discusses the concept of cognitive radio and its implementation details in smart grid. It also compares CR with other communication systems. Section III discusses the proposed novel concept of substation automation based on a heuristic CR approach. Section IV discusses the proposed CR based backup protection scheme. The simulation results are discussed in section V. Finally, the paper is concluded in section VI.

II. COGNITIVE RADIO FOR SMART GRID APPLICATIONS
A. DEFINITION
CR is a software-defined radio algorithm that rapidly reconfigures an SU operating parameters, such as modulation, demodulation, and encoding [1]. It allows an efficient way to transmit large data volumes without overloading the radio spectrum. In this technology, the unlicensed users (called secondary users or SUs) can utilize the spectrum allocated for licensed users (known as primary users or PUs) when these users are not using their spectrum. The major benefit of this communication scheme is to improve communication performance and throughput and to reduce interference.
between applications that use the identical or overlapping bands. While it is considered as a major solution for the congested spectrum, there are several hurdles in its implementations such as security and robustness. However, these problems are widely investigated in today’s research [21].

In this work we employ CR-based Wireless Sensor Network (CRWSN) to implement a backup protection scheme for smart grid. A CRWSN consists of a large number of SUs (sensors) located in a certain geographical area that continuously sense spectrum holes (i.e., portions of spectrum that are not being used) and then use such spectrum to transmit their transducer data [26]. SUs also apply an efficient and dynamic frequency allocation algorithm in order to choose channels that achieve maximum throughput and minimum interference.

The coexistence of the PUs and SUs on the same frequency spectrum allows the secondary users to access the network, but still requires them not to affect the PUs or cause interference. There are three major schemes that organize the concurrent use of the spectrum, these schemes are: the interweave CR, the underlay CR, and the overlay CR [22]. The interweave scheme is when the SUs access the network only when the PUs are not active. In this scheme, the SUs have to identify the frequency holes and use them when the PUs are absent, which minimizes interference. Spectrum sensing techniques are of great importance in this scheme to verify PUs inactivity. Such spectrum sensing techniques are sometimes complemented by a global database lookup for available channels. However, due to the limitations of practical database systems, and to avoid prohibitively expensive infrastructure owing to excessive database traffic, reliable and periodic sensing is always mandated for detecting PU presence [27]. The underlay scheme is when the PUs and SUs can share the spectrum but the SUs limit their transmitted power to constraint interference on PUs. Lastly, the overlay scheme also allows concurrent use of the spectrum by the primary and secondary users, but it requires advanced coding techniques because it assumes that the primary application is known for the secondary users [22].

It is worth mentioning that the interweave scheme is the one mostly applied in smart grid applications and so it is the one considered in this research paper.

B. IMPLEMENTATION OF CR FOR SMART GRID APPLICATIONS

Smart grid communication architecture can span three different categories, namely: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN). HAN is the smallest of these networks. It contains in-home displays, energy management systems and smart meters. These on-premises devices collect useful data and transmit them to a local access point forming an Advanced Metering Infrastructure (AMI) [15], [28]. Another important application for HAN is the Home Energy Management (HEM) system, where home appliances communicate with smart meters for automation and control applications.

On the other hand, the coverage area of NAN application is wider and so the applications are more diverse. Some important NAN application for power and energy systems include distribution automation, power outage reporting and restoration [19], [29]. Cognitive Radio Wireless Sensor Network (CRWSN) can be efficiently employed as a NAN to perform automation and control actions like fault detection, voltage regulation, and renewable energy control. On the other hand, real time detection and restoration of power outages are possible with the spread out CR nodes that transmit and receive on-line data with acceptable delays. Finally, SCADA systems can be implemented using CRWSN based, for example, on the IEEE 802.22 CR standard.

WAN Applications are of great importance in smart grids. One of the major features of a smart grid is the implementation of renewable energy on customer side. However, the voltage and frequency of such renewable systems must be monitored in order to ensure the overall grid reliability and stability. Sensors and Phasor Measurement Units (PMU) measure the actual online values and scattered CR nodes collect such data and transfer these values through NAN and WAN in order for the system operator to take a prompt decision. This task is typically complicated and expensive if wired communication or licensed spectrum is to be used instead of CR networks. Other important applications of WAN networks is wide area protection and control [19], [28].

The proposed scheme considers communication between on-premises devices (communication between relays and Intelligent Electronic Devices (IEDs) in the control and protection room) and it also considers distribution automation based on IEC-61850-9-2 Process Bus where the devices in the control and protection room will open and close circuit breakers (CBs) and receive data from voltage and current transformers (VTs and CTs) and receive data from voltage and current transformers (VTs and CTs) in the substation field. The implementation of this scheme falls in the HAN and NAN layers as shown in Fig. 1. IEEE 802.22, IEEE 802.11af and Ecma-392 standards can be used to implement the proposed scheme. The IEEE 802.11af standard is an upgrade of IEEE 802.11 that allows it to use the TV White Space (TVWS) in the VHF and UHF bands between 54 MHz and 790 MHz [20]. Accordingly, IEEE 802.11af will cover wider ranges when compared to the 2.4 GHz and 5 GHz frequencies since it will suffer smaller path loss and attenuation. The physical layer of IEEE 802.11af is based on Orthogonal Frequency Division Multiplexing (OFDM), while the modulation considered can be BPSK, QPSK, 16-QAM, and 64-QAM. In this paper 16-QAM is considered [19]. IEEE 802.11af standard can support high data rates that may reach 18 Mbps and it may cover distances up to 10 km so it is considered as a perfect choice for substation automation where the distances required within a substation will not exceed 1 km.

C. COMPARISON OF CANDIDATE COMMUNICATION TECHNOLOGIES FOR THE SMART GRID APPLICATIONS

Both Ethernet wired and wireless communication technologies are typically used in smart grids (SGs). The number
of users/devices, the network architecture, data type, environmental conditions and cost are all factors that determine the selection of communication technology [30]. Many technologies, such as Zigbee, Bluetooth and WiFi operate in the 2.4 GHz license-free Industrial, Scientific, and Medical (ISM) band. Domestic appliances, machines, and electrical power components may produce strong electromagnetic waves that might cause interference and degrade the wireless channel conditions. This interference in the ISM band might make the SG communication unreliable [30]. Collecting and transmitting large volumes of data can be challenging for existing communication networks. CR-based SG networks can efficiently collect and transmit large volumes of data while simultaneously improving spectrum utilization. Cognitive radio can provide dedicated low-latency communication links for time-sensitive SG data [17], [31], [32]. In addition, CR-based links with the IEEE 802.22 standard in SG networks do not require initial capital investment in the licensed spectrum, as the long range (up to 100 km) of IEEE 802.22 WRANs reduces the number of required base stations [33], [34]. CR WAN architectures based on IEEE 802.22 Wireless Regional Area Networks (WRANs) can support the WAN data collection. The following points summarize why CR is a strong candidate for SG communication:

CR communication avoids the wireless spectrum licensing cost, while other communication technologies such as microwave, cellular and mobile broadband communication only support licensed users. In addition, in rural areas with low population, there has been a trend to use CR communication instead of cellular communication for SG AMI to avoid the spectrum cost [35].

The bandwidth requirements and environmental conditions vary among each SG layer, which makes it hard to implement a single communication technique. Technologies like WiMAX and WLAN can provide good coverage and high data rates. However, they cover only a limited set of the SG architectural layers and application areas. On the other hand, the highly adaptive CR communication is suitable for all SG architectural layers and a wide range of SG application areas [36].

When it comes to wired communication technologies, Power Line Communication (PLC) offers high speed data transfers. However, its performance is severely affected by the noisy medium. In addition, PLC covers only HAN, NAN, and AMI. On the other hand, the Digital Subscriber Line (DSL) technology is similar to the IEEE 802.22 WRAN standard, and it covers every layer of the SG architecture. However, DSL supports only licensed users [30].

Based on the above discussion, table 1 below gives a descriptive comparison between message exchange and data transfer over wired or wireless (for relatively longer distances than LAN) Ethernet communication and the use of CR-based communication for substation automation purposes.

Finally, it is to be noted that IEC-61850 standard allows a maximum of 10 ms delay to transfer A1 tripping GOOSE messages [8], [9]. However, this time delay is irrelevant to the proposed scheme in this work where the application is focused on back-up protection which applies intentional time delays to coordinate with the main protection scheme.

### III. PROPOSED NOVEL CONCEPT OF SUBSTATION/MICROGRID AUTOMATION

Conventional protection and control schemes require wired connections between transducers (current and voltage transformers) and control and protection panels [37], [38]. However, for major substations with multiple lines, transformers and bus-bars this requires large amounts of copper wires to transfer current and voltage signals. This traditional way of analog signal transmission is very expensive. To solve this problem, the IEC-61850-9-2 Process Bus standard [8], [9] was introduced were other physical communication media like optical fiber or even wireless technologies can be implemented as shown in Fig.2.

Based on IEC-61850-9-2 Process Bus, the substation (or a microgrid) is divided into three levels: Process level that has the CTs, VTs, CBs, and the merging unit, the Bay level that

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**TABLE 1. Comparison between Ethernet and CR-based schemes.**

| System            | Wired Ethernet | Wireless Ethernet | CR-based                                      |
|-------------------|----------------|-------------------|-----------------------------------------------|
| Cost              | Expensive due to the huge cost of infrastructure and establishing optical links and/or copper wire. | Expensive due to the cost of licensed spectrum purchase | Cheap: No need for expensive infrastructure or licensed spectrum. |
| Standards         | Standards are mature and the system is already implemented | Standards are mature and the system is already implemented. However, the implementation practice is still immature | The communication standards are based on IEEE 802.22 and IEEE 802.11af |
| Complexity        | Low: based on the well known TCP/IP protocol. | Low: based on the well known TCP/IP protocol. Coverage area is a challenge | Medium: Channel allocation and spectrum sensing algorithms need to be implemented |

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contains the relays and intelligent electronic devices (IEDs), and the Substation level that contains computers and control centers. To avoid the extra cost of using copper wires between different substation components. IEC-61850-9-2 process Bus allows the use of Ethernet based communication network between process level switchyard equipment’s, and bay level protection and control (P&C). The Ethernet communication physical layer could be any wired or wireless media.

In this paper, the use of CR-based communication over IEC-61850-9-2 standard is examined. A hypothetical microgrid in an area where industrial, medical, or television primary users (PUs) exist is depicted in Fig. 3. Based on the discussion held in section II, these users are not active all the time and the substation components may act as secondary users (SUs) and utilize the radio frequencies of the PUs. It is to be noted that each substation element like current and voltage transformers, or circuit breakers must be equipped with a transmission/reception capabilities in order to communicate with other components effectively. Building such a current transformer or circuit breaker is relatively simple and cost effective. As an example, Fig. 4 shows how a current transformer with wireless transmission and reception may be built. (The same concept is applicable for other devices).

### IV. PROPOSED CR-BASED BACK-UP PROTECTION SCHEME SYSTEM DESIGN

The platform used in this research could be a low voltage microgrid or a power transmission or generation substation. It is to be noted that the location of this substation or microgrid is assumed to be in the vicinity of an area where television or medical communication applications are being used (primary users).

#### A. POWER SYSTEM

The bulk components of the power system such as the generators, power transformers, loads considered for the purpose of this research are typical components. No changes on their operation or control algorithms are required. On the other hand, the design of the transducers and circuit breakers is modified to contain wireless transmission/reception capabilities and so they are all considered as secondary users (SUs) allowed to access the spectrum available for the PUs (TV, medical, or industrial channels). In the control and protection building, the relays and the Intelligent Electronic Devices (IEDs) are also equipped with transmission and reception capabilities to receive the appropriate signals from the transducers and send tripping commands to the circuit breakers. The nature of relaying scheme in a microgrid protection is quite complicated and is out of the scope of this work. Many research papers that discuss the microgrid protection problem may be found in the literature [39]–[42]. The general philosophy is to have earth fault, negative sequence, and overload protection. Other schemes consider communication-based protection to avoid maloperation of protective relays [43], [44]. Since the purpose of this paper is to examine the cognitive radio-based back up protection and automation schemes, an overcurrent protection scheme is considered. The Inverse Definite Minimum Time (IDMT) overcurrent relay with “very inverse” characteristics is used. It is to be noted that the proposed scheme for analog and digital data transmission does not suggest any modification on the overcurrent back-up protection philosophy itself. Rather, it discusses the way that analog and digital data are transmitted within the substation.

#### B. COMMUNICATION SYSTEM

The communication system function is to transmit analog signals from transducers (after being filtered and digitized), and digital signals to relays, IED, control panels, and circuit breakers. The communication system design is shown in Fig. 5. It consists of a transmitter, a receiver, and a communication channel. The transmitter, which is implemented within a transducer, consists of an analog-to-digital converter (ADC) to digitize the analog signals preparing them to be transmitted via the channel. A convolutional encoder (with a corresponding Viterbi decoder at the receiver) is used to protect the digital signal from noise. Quadrature Amplitude Modulation (QAM) is used for baseband modulation of the digitized signals. This type of modulation is very frequently used in radio communication applications for its high data rates compared to other amplitude and phase modulation schemes [45]. The raised cosine filter is introduced to minimize Inter Symbol Interference (ISI). Finally, the up-converter is used to convert the transmitted signal from a low-frequency into a high-frequency signal. This is done by modulating the QAM signal using a sinusoidal carrier with a certain desired frequency. The choice of the high-frequency value to be used is decided by a centralized channel allocation algorithm running at the protection and control room, which we explain next.
A single protection and control room coordinates between the different SUs, and enforces a time-slotted architecture as shown in Fig. 6. In such architecture, each time slot (of length $T$ seconds) is divided into three periods of operation: Quiet Period (QP), Control Period (CP) and Transmission Period (TP). During the first period, called QP, all SUs stop transmitting over the cognitive radio channels in order to sense any PU activity over such channels. In our proposed interweave model, operational PUs are unaware of the existence of SUs, and hence keep transmitting normally in the QP over their licensed spectrum. On the other hand, channels with no active PUs are easily detected by SUs.

The results of local sensing obtained during the QP are then sent by the different SUs to a Fusion Center (FC) that exists in the protection and control room. This is done during the next period of the time slot, named CP. The FC fuses these local sensing results (as explained shortly) to make a final decision on which channels are available for CR operation. Only channels without PU activity are utilized by our system. These channels are assigned by the protection and control room to various SUs (CT, VT, CB) based on the channel allocation strategy clarified below, and is then reported back to SUs during the same CP. In typical CR networks, an independent Common Control Channel (CCC) is used by SUs to report their local sensing data to the control room and also by the

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**Figure 3.** A typical microgrid (under study) showing primary and secondary users sharing the same spectrum.

**Figure 4.** Current transformer circuit in the proposed system.

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**C. COGNITIVE RADIO MODEL**

1) **SYSTEM ARCHITECTURE**

We consider a microgrid or a power substation that consists of a total of $C$ current transformers (named $CT_1, CT_2, \ldots, CT_C$), as well as $V$ voltage transformers (labeled $VT_1, VT_2, \ldots, VT_V$), in addition to a total of $B$ circuit breakers (called $CB_1, CB_2, \ldots, CB_B$). Such users collectively represent the population of SUs in the system. A total of $M$ spectrum channels are available for opportunistic access by the SUs so long as the channel under consideration does not include an active PU.
control room to report the channel allocation decisions back to SUs. The CCC channel can be implemented as a dedicated licensed or unlicensed channel [23].

Once the SUs receive their assigned channel frequencies, they adjust their up-converters to use such frequencies and start transmitting their transducer data to the protection and control room. This data is what the control room needs to run its power backup protection scheme. In addition, the channels assigned to CBs can be used to send tripping commands to such CBs from the control room when necessary and/or to exchange maintenance data with such devices. This final period of time, during which transmission occurs over CR channels, is the longest within the time slot, and is labeled the TP.

2) SENSING AND DATA FUSION

Accurate spectrum sensing (during the QP) plays a very important role in maintaining suitable operations over an interweave CR network [46], [47]. Sometimes a PU can be actively transmitting in its licensed channel, but is not sensed properly by the SU due to shadowing and fading effects common in the wireless medium, or sometimes this occurs due to hardware imperfections at the SU. This is a situation known as PU misdetection, and can result in the SU using a busy channel that it is not supposed to, thus causing unacceptable interference to the PU.

Alternatively, SUs can suffer from a false alarm condition, where the SU senses that a PU is active in a vacant channel. This can happen due to random bursts of noise or sudden external interference in the channel at the time of sensing. This condition can result in a wasted transmission opportunity, since the SU refrains from utilizing the spectrum band for fear of interfering with the PU.

Reliable sensors, that can minimize the probability of misdetection (denoted by $P_{md}$) and probability of false alarm (expressed as $P_{fa}$), are typically expensive. Some sensors alternatively resort to elongating the QP portion of each time slot to collect more samples of the radio frequency energy of the spectrum being sensed to get more accurate sensing results. However, this reduces the TP time available for transmitting transducer data, which can negatively affect the proposed power system protection scheme.
Hence, to achieve a reasonable tradeoff between improving sensing accuracy while not severely affecting the length of the TP, we propose to collect local sensing results from different sensing devices at various SUs, then combine such sensing results at the FC at the control room. This combination of spatially-diverse sensing results reduces the chances of misdetection and/or false alarms [35]. To elaborate, in this work we employ a simple Energy Detector (ED) sensing device at each SU. Energy detection is a non-coherent detection method that is widely employed in the literature because it is extremely simple and it does not require any prior information about PU signals to operate properly [47], [48]. Due to the low computational complexity of an ED, this reduces the overall cost of the system [49]. In addition, we will maintain a small QP that is roughly 10% of the total time slot length, which leaves plenty of time for the TP. However, to overcome the unreliability in local sensing at a single node, the FC collects the local sensing results received from the different SUs and fuses them into one global result. Hence, the powerful spatial diversity concept in wireless systems is exploited to enhance the sensing performance due to the different locations of SU cognitive radios [50].

Fusion refers to the process of combining local sensing data to result in a finalized hypothesis testing. There are two main techniques proposed in literature for combining the local sensing results reported to the FC: soft combining and hard combining [51], [52]. Soft combining typically requires more complex hardware. In addition, it requires more bandwidth for the CCC than hard combining, since the amount of sensing data sent is higher. In hard combining, on the other hand, each SU only needs to send a one-bit decision regarding whether or not a PU was detected. The AND rule decides that a PU is present if any of the SUs has detected a PU. The Majority rule is a voting procedure that decides on the PU presence if more than half the SUs reported sensing an active PU. The final hard combining technique available is a more general voting procedure, where PU presence is declared if \( K \) out of a total of \( N \) users have detected an active PU, where \( 1 \leq K \leq N \) [53]. In this work, we employ the popular Majority rule to combine the local sensing results into one final decision with very reliable results. The obtained misdetection and false alarm events were almost zero during our restricted simulation time.

### 3) CHANNEL ALLOCATION

Radio resource allocation in our proposed technique is handled by the protection and control room, which acts as a centralized controller [54], [55]. This is a natural decision since the control room has a global view of the whole system, it has made final decisions on the availability of the cognitive channels, and its relay is the one who is going to make a final call on tripping the CB under our protection scheme. Since

The main rules that can be applied by hard decision combining are the OR, AND, Majority, and K-out-of-N rule. The AND rule decides that a PU is present if all SUs have detected a PU, the OR rule decides that a PU is present if any of the SUs has detected a PU. The Majority rule is a voting procedure that decides on the PU presence if more than half the SUs reported sensing an active PU. The final hard combining technique available is a more general voting procedure, where PU presence is declared if \( K \) out of a total of \( N \) users have detected an active PU, where \( 1 \leq K \leq N \) [53]. In this work, we employ the popular Majority rule to combine the local sensing results into one final decision with very reliable results. The obtained misdetection and false alarm events were almost zero during our restricted simulation time.

| Algorithm: Assign channels to SUs in time slot \( t \) |
| --- |
| 1. Collect sensing decisions \( d_n \) from SUs \( n \in [1,N] \), where \( N = B + C + V \), and \( d_n = 1 \) for active PU |
| 2. Identify vacant channels set \( M \) using majority rule, \( M = \{ m : m \in [1,M] \land \sum_{n=1}^{N} d_n > N/2 \} \) |
| 3. if \( |M| \geq B + C + V \) then |
| 4. /* enough available channels for all SUs */ |
| 5. Execute Typical channel assignment |
| 6. else if \( |M| \geq B + C \) then |
| 7. /* enough channels for critical devices only */ |
| 8. Execute Limited channel assignment |
| 9. else if \( |M| \geq 1 \) then |
| 10. /* not enough channels */ |
| 11. Execute Critical channel assignment |
| 12. else |
| 13. Use backup licensed low-bandwidth channel |
| 14. end |

**FIGURE 7.** The centralize channel allocation strategy used by the protection and control room.
The final case that we handle is the less-expected, but nonetheless possible, critical scenario, where for some slight amount of time the number of available cognitive channels is so small they cannot handle the transmission requirements of all critical devices in our system. As shown in the algorithm of Fig. 10, the control room starts wisely interleaving the transmission of such critical devices (CBs and CTs) over different time slots using the concept of transmission token, in a similar fashion to how time-division multiplexing (TDM) works. This ensures that the connection between such devices and the control room is never lost, even if it becomes intermittent. During any period of time when a CT cannot send its measurements to the control room, earlier samples of electric current stored previously at the control room are used as a reasonable estimate for the missing CT measurements, until of course new samples start arriving at a later time. This can delay tripping the relay slightly, but not by much, as is evident in the results section.

We do not fail to mention that the critical scenario has a small chance of occurring in realistic CR networks, which are mainly designed and built around TV whitespace bands that are sparsely used, especially in rural and suburban areas. If there is a desire to make the system even more reliable, a licensed low-bandwidth backup channel can be used as a last resort in case the algorithm fails to find any vacant channel for the cognitive devices.

V. SIMULATED RESULTS OF THE PROPOSED SCHEME

The power and communication systems discussed in the above section are simulated in MATLAB/Simulink software with simultaneous run of SimPowerSystem and communication toolbox. The power microgrid consists of diesel generators, PV systems, a storage device, and loads in two different locations. The microgrid is connected to the utility system that is modeled as an infinite bus of 1.1 kV, 60 Hz and 10MV A short circuit capability. The two diesel generators are 50 kVA 380V, salient pole synchronous machines. The PV system is a 25 kWp system connected to the grid through
a three-phase inverter of 20 kW capacity. Finally, the transformers ratings are 1.1/0.4 kV, 25 kVA. These parameters are given in Table 2.

The very first step is to ensure that the system is running properly when the conditions were healthy. Real operating values of the current and voltage transformers were sent from the CTs and VTs and received on the other end by the protection and control room. The number of available CR-based channels was assumed to be 100. Each channel can have an active PU or it can be vacant. PUs turn on and off based on a Discrete-Time Markov Chain model with probability of \( \text{off} \) to \( \text{on} \) of 0.5 and \( \text{off} \) to \( \text{on} \) of 0.5. This means that there are roughly around 50 channels available at any time slot. Since the number of CBs, CTs, and VTs equals to five each, there are plenty of CR-based channels available. The signal transmission was successful. Figs. 11 and 12 show respectively the current and voltage transmitted (by either CT or VT) and received (by protection and control room) signals. It is to be noted that shape of the received signals is not completely identical to the shape of transmitted signals due to the existence of QP and CP mentioned in CR section above. However, this minor discrepancy in the signals shapes did not affect the proposed scheme functionality since the backup protection scheme deals with RMS values of the current signals. These RMS values are not much affected by the CR-based transmission of the signal as will be shown below.

Fig. 13 shows the RMS values of the transmitted and received current signals of the actual power systems and the calculated one received to the relay end (in primary values). As can be shown in the figure, both signals are almost identical. The RMS values of the transmitted and received voltage signals are also identical and were omitted for brevity.

A three-phase fault is simulated in the system on the PV system bus at time \( t = 0.12 \) sec and the control room and circuit breaker responses are studied. The control room received the current signal from the CT via the CR-based channel and analyzed it, when the relay part of the control room decided that it is a fault condition (the RMS value of the load current is about 70A and the RMS value of the fault current is about 180A, while the relay settings are 150A), it sends back a CR-based tripping signal to open the circuit breaker. Of great importance to ensure that the fault detection and isolation time is about 100 ms, which is an acceptable time for fault clearance considering the fault current value. Figs. 14-18 show the actual current waveform during the fault, the actual and received (by protection and control room) RMS values of the fault current, the transmitted (by CT) and received (by protection and control room) time signals, and finally the tripping signal received by the circuit breaker. These set of figures proves the adequate functionality of the proposed scheme at the time of the fault. The current signal was received and its calculated RMS value is almost the same as the actual RMS value (Fig. 15). The relay action was appropriate and the CB received a tripping signals and disconnected the faulted section of the system.

Figs. 19 and 20 show the effects of noise on the signal transmitted over the wireless communication channel. Fig. 19 shows the constellation diagram of the transmitted

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### Table 2. Power systems parameters.

| Parameter               | Value          |
|-------------------------|----------------|
| System voltage          | 1.1 kV         |
| System frequency        | 60 Hz          |
| System Short circuit    | 10 MVA         |
| Transformer ratings     | 1.1/0.4 kV     |
| PV system capacity      | 25 kW          |

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**FIGURE 11.** The transmitted (up) and received (down) current signals from the CT to the protection and control room.

**FIGURE 12.** The transmitted (Up) and received (down) voltage signals from the VT to the protection and control room.

**FIGURE 13.** The actual calculated (Up) and received (down) RMS values of the current signals from the CT to the control room.
current waveform (from the CT), which indicates a typical 16-QAM modulated signal. The constellation diagram of the received current signal under healthy power system conditions is shown in Fig. 20, which clearly shows the effects of Additive White Gaussian Noise (AWGN) superimposed by the wireless channel. In this simulation, we assume the CT experiences a signal-to-noise ratio (SNR) of $E_b/N_0 = 11$ dB, which we intentionally set to a small value compared to realistic short to medium-distance wireless scenarios. This is done in order to test the robustness of our proposed CR network.

As can be concluded from the figures, the amount of noise added by the channel is significant. However, due to the benefits of using convolutional encoding at the transmitter paired with a Viterbi decoder at the receiver, we managed to reduce the Bit Error Rate (BER) to virtually zero, even under such low SNR conditions, which results in reliable transmission of waveforms from SUs to the control room.

On the other hand, we note that the CR based proposed scheme is not causing excessive time delays for the protection algorithm. We calculate the delay between different
SUs and the control room due to the communication system in Table 3. The Modem delay in the second column of the table includes several components, such as the delay introduced by the Viterbi decoder buffer, the delay due to digital filtering in pulse shaping, buffering in ADC and DAC blocks, etc. The propagation delay, on the other hand, is dependent on the distance between the SU and the control room, and is quite limited in our application. The total delay results clearly indicate that the communication system delay does not adversely affect the performance of our protection and control scheme. The total delay is calculated based on the following equation:

$$\text{Total Delay} = \text{Modem delay} + \frac{\text{Distance}}{\text{Light speed}}$$ (1)

The modem delay results due to several factors including buffering the received bits to accumulate one sample in the Digital-to-Analog converter, due to the delay in digital raised-cosine filtering, and due to the Viterbi decoder trace back depth of 34 bits, which is needed in order to perform forward error correction (FEC) on the received bits.

Since the back-up overcurrent protection used in this paper is an IDMT with “very inverse” characteristics, the required delay for the relay action is (in worst case) about 300 ms. Please note that this value depends on the time multiplier settings and the fault current value. In any means, this value will be very far from being affected by the communication delay calculated in Table 3 which is less than 4 ms.

Finally, we examine the proposed CR algorithm under two more scenarios, where we vary the number of available cognitive channels and the number of SUs in the system. The first case considered is when the number of secondary users are increased to a total of 150 SUs (where $B = 50$, $C = 50$ and $V = 50$). The number of available channels is kept at 100. However, due to the fact that each PU is active within its own channel for about half the time, the number of available cognitive channels is closer to an average of 50 channels at any point in time in the simulation. This is the case we named the limited scenario. As expected, in this case, the CT signal was correctly recovered by the control room, while the VT signal was ignored (see Fig. 21). It is to be noted that priority was given to CTs because the application of this research is back-up overcurrent protection.

The second case that was considered is the critical scenario, where we pushed the system to extreme limits. Here, we set the number of secondary users to a total of 150 SUs (where $B = 50$, $C = 50$ and $V = 50$), and we also reduce the number of available channels to 5. Again, only half of these channels' capacity was available to SUs due to the activity of the PUs. In this case, the voltage signal was again disregarded for the reason mentioned above. In addition, the current signal was distorted due to the fact that the control room was interleaving the transmission from different CTs and CBs over the limited set of available cognitive channels (see Fig. 22). Notably, this behavior did not prevent the control room from the detecting
the fault and responding accordingly, albeit with an added negligible delay. While the above two scenarios are less likely to happen in real life, it is to be noted that an extra small-bandwidth licensed channel can be added in this scheme for emergency situations.

VI. CONCLUSION
In this paper, a cognitive radio-based back-up protection scheme is proposed. The scheme uses unlicensed radio spectrum to transmit analog signals from a power yard to a control and protection room. The purpose of this scheme is to avoid the expensive infrastructure of copper wires needed by conventional power systems or optical fibers implemented in IEC-61850 to transfer the voltage and current signals. On the other hand, since the proposed scheme uses unlicensed spectrum, it will also save the considerable cost of the radio spectrum licensing, which gives it an extra advantage over wireless IEC-61850. With relative comparison, the proposed scheme will cut the costs for building back-up protection systems in substation. The simulation results showed that the transmitted signals were recovered correctly and no incorrect decisions were made. The studied scenarios include healthy and fault conditions and the communication time delay was acceptable in all cases. The future work of this research will include detailed study of the transmitted and received signals in the microgrid environment under various wireless channel conditions. On the other hand, different more complex spectrum sensing and channel allocation algorithms will be considered to enhance the reliability and efficiency of the cognitive radio model.

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