A General Perspective on Software-Hardware Defined Cognitive Radio Based on Emergency Ad-Hoc Network Topology

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Abstract: **This paper presents a different perspective on the collective concept of software-hardware defined radio (SHDR) in cognitive radio (CR) networks. The SHDR is proposed considering the multiple hardware functionalities conceived by software defined radio, which generally reflects on the adaptable recognition of network services and operational conditions. An ad-hoc network scheme is envisaged as an alternative to a conventional cellular network to accommodate for emergency situations. The connection to such emergency backup network could be established on CR engines built in normal or dedicated smart phone handsets.**

Keywords: **software-hardware defined radio, cognitive radio, ad-hoc network, smart phone.**

I. INTRODUCTION

Cognitive Radio (CR) systems in contemporary wireless networks have received considerable attention in recent years. The cognition feature in modern radio systems enhances the overall performance in terms of adapting to changes in transmission and reception environments. CR or cognitive network (CN) promotes the awareness to have more flexible and programmable hardware to cope with the communication channel and carrier variations. Accordingly, new CR built on the concept of Software Defined Radio (SDR) is envisioned as a promising multidisciplinary field of study [1-3].

Recent studies have shown that the frequency spectrum is severely underutilized in many respects [24]. One of the main reasons of this problem is due to static allocation of primary licensed users over geographical areas [3, 4]. Suburban and urban areas suffer the following spectrum deficiencies:

- Some bands in the frequency spectrum are largely unoccupied most of the time.
- Some bands are only partially occupied.
- The remaining frequency bands are heavily utilized.

Such unmanaged spectrum utilization has led to the evolvement of a new concept, termed *spectrum holes*. This calls for an efficient spectrum management and notable improvement over prevalent radio systems performance. This can possibly be achieved by allowing secondary unlicensed users to access spectrum holes, unoccupied by primary users, at the right location and time. This accordingly contributed to the emergence of CR terminology to improve the spectrum availability. Figure 1 illustrates such a time-frequency holes allocation approach, which randomly jumps in the frequency domain while being continuous in the time domain.

The CR is aware of its surrounding environment and can adapt in a real-time manner to the changing operational parameters while aiming at two important objectives:

- High level of reliability anytime and anywhere;
- Efficient frequency spectrum utilization.

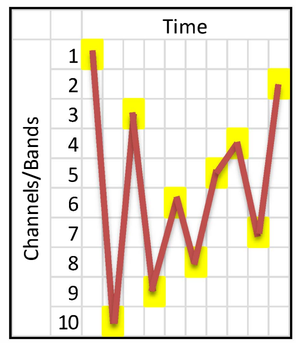

Figure 1. The Time-Frequency Allocation Random Trend.

Despite the fact that the SDR relies heavily on digital techniques, SDR is different from software-controlled digital radio. The key difference lies in the total programmability of SDR including all signal processing stages. This leads to a successful joining between software and hardware to allow various signal processing tasks, while monitoring new software services or updating details shared on the network. In either competitive or collaborative working conditions, it is apparent that there is a need for certain protocols and rules to manage the information and services' pool among all users. This control evoked new standards and advancements based on the syntax of radio knowledge representation language, which defines the SDR ontology [2, 4]. The network may coordinate the requested services or information, such as industrial, scientific, and medical channels with suitable rules in the United States. Another language has also been developed, called knowledge query and manipulation language (KQML) to readily express the pooled-spectrum management information. However, there are various standard programming languages and operating systems that can be used to develop a CR system with an efficient user interface and meet the services and performance demands.

The SHDR proposed in the following is an extension to SDR to provide a comprehensive and practical approach on software and hardware components building the CR systems and networks. The advancement in current technologies renders the system-on-the-chip realization of such SHDR feasible, excluding the analogue part of CR, which is essential for radio frequency (RF) signal filtration and amplification. The SDR, as

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was envisioned earlier, can adapt the graphical user interface (GUI) of a portable device and acknowledge updates on software and services prompted to the user. The user can opt to accept or deny any of the displayed options accordingly. From the outset, the user cannot identify nor recognize the burden consumed by the SDR engine to produce such prompts. Precise interpretation of displayed messages might be overlooked by the user occasionally, which may sometimes result in unfavorable outcomes such as missing an alert. Such software implications based on changing network parameters are heavily attached to complex hardware computing processing. Such a processor consists of vast functional components entertaining the incoming noisy signals and adjusts to variations in transmission conditions.

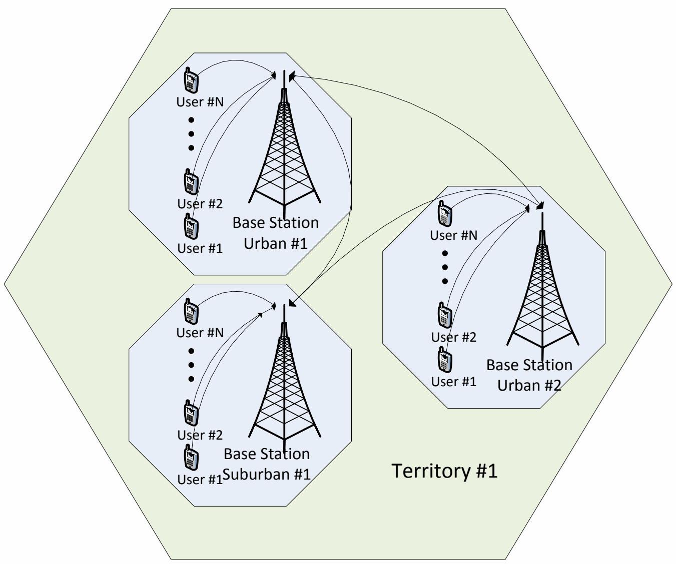

Figure 2. The Terrestrial Setting of a Wireless Network.

II. THE WIRELESS NETWORK ARCHITECTURE

Figure 2 illustrates an example of a traditional terrestrial wireless setting based on core or centric communication concepts. The specific radio domain of such a wireless network is affected by transmission bands reserved by military, police, rescue, public, fire and government agencies among others. The signal transmission is taking place using one or more multiplexing techniques, such as time, frequency or code division multiple access, in addition to space diversity (TDMA, FDMA, CDMA, and SDMA, respectively). All are aimed at better utilization of air interface resources.

From Fig. 2 the cellular structure resemblance to a conventional public mobile system is obvious. This is valid to some extent due to the nature of air transmission physics; however, they are not exactly the same. This can be attributed to the fact that the cellular mobile system has supervision and security control by the service provider, while other channels are unsupervised. The cellular mobile network covers an entire terrestrial region of particular countries and extends remotely to reach global users. Also there are rules and standards that govern such networks, namely the IEEE 802.11 standard covering the frequency bands around 2.4 GHz, 3.6 GHz, and 5 GHz using the orthogonal frequency division multiplexing (OFDM) signaling method. Communication could be maintained in half or full duplex. Such standards for CR systems and networks are still subject to intensive research [3]. The CR has the liberty to connect to any desired frequency band whenever available, whether licensed or not, and without negative impact on the licensed user. The communication range in the CR network covers the entire urban and suburban regions dedicated to a public service provider or particular operator. The base stations (BSs) in such networks perform linking and trunking between any two CR terminals regardless of their location within the same terrestrial boundaries. As such, the feature of remote access beyond terrestrial boundaries is not featured under such circumstances. Full and half duplex communications are well supported by these CR networks.

In case of emergencies, some priority precedence needs to be configured for mission critical agencies. For example, large scale emergencies like the 9/11 disaster created chaos, primarily among safety rescue and police departments, and revealed problems about legacy wireless communications systems. The responsible first responder departments strived to maintain efficient communication with each other and other involved agencies due to overwhelming occupation of the designated frequency bands and channels and also abnormal transmission parameters that might happen due to infrastructure destruction or vandalism during catastrophe. Accordingly, such poor radio communication situations motivated alternative and unconventional systems based on cognition and better investment in frequency spectrum sharing.

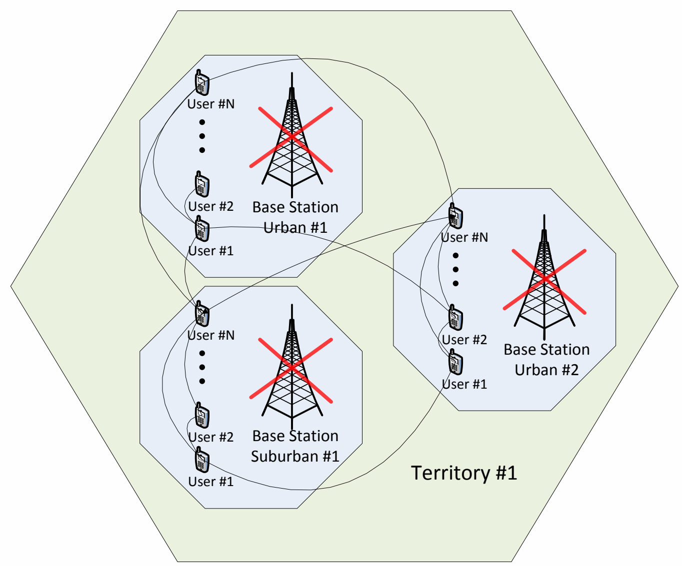

Figure 3. The Terrestrial Setting of an Emergency Ad-Hoc Wireless Network.

So much as that, recent research efforts have shown that centric wireless communication networks cannot accommodate heavy demands on unoccupied frequency bands and channels under distress conditions [18, 19]. Current emergency services rely much on the public networks which are not reliable in the presence of emergency overloading. Moreover, public mobile networks are susceptible to uncontrolled variation of the infrastructure. This has led researches into a new concept of reconfigurable and cooperative network components referred as ad-hoc network primarily targeting at public safety and major emergency events [18], which is depicted in Fig. 3.

Ad-hoc networking can be achieved through the implementation of a predefined common communication channel available for immediate access by rescue teams and specialized agencies. A virtual public safety wireless network can hence be established by employing un-addressed voice channels or broadcast voice channels for a talk group. This can be all realized based on the re-configurability of the medium access layer (MAC) and physical layer (PHY). The proposed ad-hoc networking objective is to make cooperative spectrum sensing possible with the contribution of multiple public safety wireless communication nodes. Accordingly, the important issue for victims and first responders to find each other becomes less critical if the core communications network is down significantly.

Another approach to alleviate the disaster situation is by using dynamic spectrum access (DSA) while keeping the land mobile radio (LMR) users intact [19]. Regardless of the spectrum owner, whether commercial, industrial or government, users would dynamically access spectrum and shared infrastructure. Again, the proposal is around making the frequency spectrum pooled and portable and can be accessed by both traditional and CN nodes designed to serve public safety, business and industry. One possibility of such network enhancement can be accomplished by the ad-hoc configuration given above.

III. THE SHDR SYSTEM ARCHITECTURE

The envisaged building blocks of a CR system are shown in Fig. 4. These blocks attain various software and hardware processing tasks on the incoming and outgoing signals. The software part is genuine to the SDR to conduct the cognition cycle by detecting, learning and building knowledge from the surrounding environment. On the other hand, such cognition becomes feasible by augmenting sophisticated hardware defined radio (HDR) supported with specialized DSP and control elements. Attributed to its conceivable versatility and multitasking features, the HDR nowadays could run 13 or 14 radios on one smart phone handset, several running at once, and without the user notice [26]. The intricate bonding between SDR and HDR appraises the SHDR as an inspiring terminology elaborating the entire real and virtual activities of a CR system. Human machine interface (HMI) devices are essential to mediate between external human kind interactions and internal chip level subroutines. The end user will benefit of such integrated technologies resulting in a product of high QoS merits and CR virtues.

The radio frequency (RF) front-end in CR is usually made of analog devices, such as low noise amplifier (LNA), multiband filters and circulator. The LNA aims at amplifying received weak signals, the multiband filters required to capture the desirable bands and reject mirror frequencies and interferences, and the circulator contributes to the isolation between received and transmitted signals. RF components and devices are commonly characterized by nonlinear responses impaired by locally generated noise. However, recent studies indicated that low-noise linear broadband transceivers suitable for 3G and 4G wireless applications are achievable [20, 27, and 28]. As for the 4G wireless technology emerging into the commercial market rapidly, alternative new front-end modules (FEMs) covering the frequency range 1.4 MHz to 20 MHz have been referenced as given above. The RF stage facilitates down conversion of incoming signals to the Nyquist dynamic range of the following analogue-to-digital converter (ADC and DCA for transmission). The common trend in CR realization is placing high speed converter chips very close to antenna [10, 13]. These chips enables direct conversion of desired signals into intermediate frequency (IF) band suitable for baseband extraction. The signal conversion and demodulation modules represent the digital front-end in CR system [10].

Different software layering and programming techniques have also been demonstrated in the literature [21, 22]. Most of the proposed software schemes were based on the standard open system interface (OSI) protocol and more emphasis have been demonstrated around the PHY and MAC layers in particular. An application programming interface (API) and extensible markup language (XML) were proposed as plausible programming tools. The Java agent development (JADE) has also been adopted as robust for distributed agent systems and can be run on personal computers (PCs) and wireless devices [21, 25]. Most common operating systems are Linux or Microsoft Windows based.

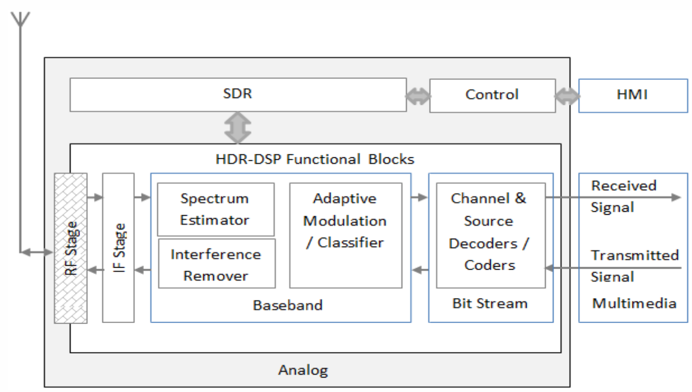

Figure 4. The Building Blocks of a CR System using SHDR Platform.

The implementation of CR systems with such challenging objectives outlined above is nowadays feasible due to the advancement made in computer software and hardware, DSP, machine learning, and networking. Moreover, the CR is also bestowed with re-configurability in addition to the cognition. That means it can incorporate new software updates and service applications as they emerge, and accommodate variations in the development of new interface standards. All the above paved the road towards SDR platform development and upon which the CR is built, due to convergence of two key technologies: digital radio, and computer software [2, 5]. The hardware implementation of such CR architecture in a flexible and energy efficient way is feasible by using the heterogeneous and reconfigurable technologies of field programmable gate arrays (FPGA), DSP, and application specific integrated circuits (ASICs).

IV. Spectrum Estimation

More emphasis has been demonstrated on the prominent use of spectrum pooling as a generic technique to overlay a secondary user on a primary user without changes in the licensing procedures [6]. The focus was dedicated to FDMA and TDMA signaling based licensed systems, claiming their coding protocols are accessible as opposed to CDMA. OFDM was suggested as a popular multicarrier transmission technique and easily attainable for spectrum sensing.

A survey on energy detection techniques for spectrum measurement in CR environment has also been conducted [7]. White Gaussian noise channels and cooperative and non-cooperative work environments were illustrated in time and frequency domains. The energy detection method has been proposed as a competent spectrum sensing compared to other methods in terms of its simplicity and practicality and especially in the presence of no prior single information.

The spectrum holes can be either detected in time base temporal, or space base spatial [8]. Temporal spectrum sensing and use by secondary users over a period of time occurs when the primary users are idle or non-operational without causing any harmful interference. Spatial spectrum reutilization by secondary users occurs when primary users are linked to another transmitter over the same channel in the same region, similar to conventional co-channel cells in mobile networks. A linear quadratic (LQ) detector has been proposed as a temporal suboptimal algorithm that uses partial statistical information to improve receiver performance [23]. Spatial spectrum sensing relies on temporal detection to determine the ON/OFF transmitter state.

Spatial sensing using a multiple-input multiple-output (MIMO) channel has been proposed for CNs to operate more efficiently by leveraging the spatial domain using multiple antennas [9]. The MIMO concept was examined to maximize the rate of the secondary link subject to the required level of primary protection using convex optimization. Three different scenarios were investigated, depending on the amount of channel state information (CSI), namely; local CSI, global CSI, and local CSI with side information. It was shown that the iterative algorithm with local CSI converges to a transceiver algorithm with global CSI when beam-forming is considered. The motivation behind joint transceiver designs, such as MIMO, was to prevent primary receivers from experiencing interference from cognitive transmitters and to remove interference caused by primary transmissions at the secondary receiver. Such problems were obvious in earlier designs, such as multiple-input single-output (MISO) cognitive radio networks, as when the primary transmitters are active; the receivers of secondary users suffer considerable interference.

V. Interference Reduction

Out-of-Band interference (OBI) is unavoidable in conventional radio receivers. The desired weak signal in certain bands is usually impaired by the existence of strong unwanted signals in neighboring bands. For this to be alleviated, signal processing techniques are usually employed at the digital front-end of SDR receivers. Baseband sampling at zero IF, followed by programmable down-sampling with embedded filtering, and all preceded by a low-noise wideband amplifier has been assumed to be the first single-chip SDR setup [10]. On the other hand, for the transmitter to be also smart and able to collaborate with dispersed receivers, the term software defined transmitter (SDT) might also be anticipated, but is still under research. The SDT has little similarity with the SDR and unfolds little details of its identity, especially in military and classified sensitive applications.

An approach by using a tunable synthesizer and mixer to lock in the desired frequency band and then down-convert the signal to baseband has been suggested [11]. Two processing paths are also essential for both the desired and blocker signals. Harmonic suppression and adaptive interference cancellation techniques were also suggested in the literature as enhancements against OBI nonlinearity and harmonic mixing [12]. Other microchip ADC converters have also been addressed in recent studies as prominent tools for adaptive blocker rejection in world inter-operability for microwave access (WiMAX) mobile receivers [13]. The current trend of single-chip signal processing advancements focus on moving the ADC as close as possible to the antenna, while as much of the amplification and filtering are performed in the digital domain.

VI. Adaptive Modulation Classification

Automatic, or adaptive, modulation classification (AMC) is an intermediate step between signal detection and demodulation [14]. The AMC is awkward in a non-cooperative environment such as; multipath propagation, frequency-selectivity and time-varying channel, in addition to no prior knowledge of the incoming signal. Therefore, the blind recognition of modulated signals at the receiver side is often considered as a challenging issue in commercial communication systems, especially in SDR where coping with various modulation schemes is essential. Two steps are involved in the design of a modulation classifier; signal preprocessing and adequate classification algorithm. Preprocessing tasks may include, but not be limited to, noise reduction, estimation of carrier frequency and signal power, and channel equalization. While on the other hand, there are two main modes of classification algorithms; likelihood-based (LB) and feature-based (FB). The output of LB is the result of minimization of the probability of false classification. The complexity of such algorithms usually offsets their optimal performance. While on the other hand, the FB classifiers employ several features of the observed signals and enjoy less computational demands despite their suboptimal performance. Once the identification of the received signal has been successfully accomplished, the signal demodulation and information extraction can then be readily performed.

The different modulation schemes, such as analogue, digital, and OFDM, have been subject to recent classification researches [14]. Common classification techniques such as; the maximum likelihood (ML), waveform zero crossing, spectral feature, wavelet analysis, signal cyclostationary in addition to statistical analysis, such as higher statistical moments and cumulants, can be mentioned. A variety of algorithms has been proposed for any of the above signal classification methods; however, there are no accurate templates for perfect signal observation. Due to computational burdens, some of the classification techniques cannot be implemented in real-time situations, despite their excellent accuracy. A practical classifier should have balance between the desired performance accuracy and the processing speed and implementation complexity.

On the other hand, there are various techniques that can be adopted for the decision making stage. Among many techniques, the probability density function (PDF), Euclidian distance, binary decision tree, and neural networks are common [14, 15]. It has been shown that a single feature is not enough for recognition and hence it is necessary to combine several features for better results [15].

As for the outgoing signal, the same detected modulation scheme on the receiver side can also be implemented. However, this is not a stipulation, especially when the other side's smart transmitter keeps changing the modulation scheme to accommodate the transmission channel characteristics.

VII. Channel and Source Decoding

This functional block is attributed to the recovered bit stream to perform conventional channel equalization, source error correction decoding, frame alignment, bit stuffing, and radio link encryption [1]. Further to that, in uncooperative networking schemes the cognitive users, secondary unlicensed in this case, may face undesirable and harmful situations by the presence of intruders or selfish primary users. In such conflict of interest situations, secondary users either keep on low operational profile or allow their transmission in the primary users' absence to avoid conflicts and interferences. Although the spectrum estimation functional block can possibly assign another channel to a secondary user, however, such critical transitions may generate partial or complete data packets loss. Remedial to such poor quality of service is by having desirable anti-jamming coding techniques in CR systems. Among different encoding-decoding schemes, the rateless coding and piecewise coding can be referenced as good candidates with low complexity profiles [16].

From another perspective, the automatic repeat request (ARQ) method can be trusted whenever the receiver could not decode or receive a packet via requesting retransmission through a feedback-channel [17]. Alternatively, the receiver either collects data packets from the secondary user source or not, depending on the primary functional and signal strength measures.

Both receiver and transmitter can share the same coding scheme. However, this could not be the case if the other side's device varies the coding scheme based on transmission characteristics and other security reasons.

VIII. Proposed Scenario

The robust adaptability of CR features inspired innovative user-based services to the 4G wireless networks such as; relaying, cooperation, personal transfer, and internet protocol (IP) data casting, among others [29]. Hence, the requirement for person-to-person communication has become recognizable using smartphones working in 4G networking environment. Let it be assumed that a smart phone handset has the intelligent features of a CR system. The supervised frequency bands available for public use in the 3G wireless network lied in the ranges 1.7-1.85 GHz and 2.5-2.69 GHz, whereas the recent 4G wireless network it is aimed to cover conventional bands and further to 8 GHz. These frequency bands are usually reserved for public communications and subject to stringent supervisory control and monitoring by the commercial service provider. Such frequency bands and related infrastructure resources are immune against intruders external to the network, and the idea of sharing with other agencies is not foreseen in the near future. However, in case of emergency situations or when losing the building network infrastructure, then the idea of CR to reach constrained subscribers becomes crucial. This entails the base station (BS) to authenticate intercommunication among users including transmission configuration and security reassignment [29]. In the absence of the service provider broadcasting, usually the users do not know the appropriate approach to call for assistance if needed. Such a dilemma could be readily invoked automatically if the CR engine is built in to their handsets and such 4G subscriber networks can convert into an ad-hoc type. Such conversion is not always necessary, but backup support shall be attained by the remaining resources of the same network in the same urban/suburban areas at least. What is important in such uncontrollable incidents is to have the intelligent features well equipped into the users' devices and can be triggered automatically or optionally when needed. An envisioned adaptable 4G/Ad-Hoc mobile set is depicted in Fig. 5. The proposed setting is not only able to access other users on the same reserved frequency bands given above, but also can reach other users and emergency agencies on alternative networks. This is permissible as long as others put their devices in the listening mode, which is usually the case for rescuers.

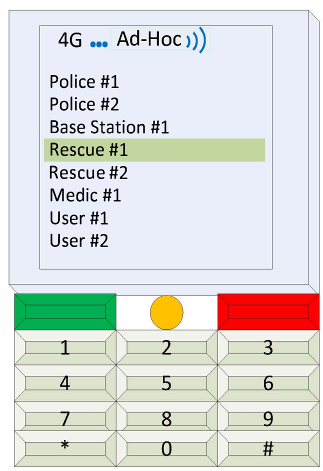

Figure 5. A Cognitive 4G/Ad-Hoc Mobile Device Module.

As is obvious from Fig. 5, in case of unforeseen 4G network unavailability, usually a weak signal is depicted on the GUI. At the same time, during such breakdown or even in normal conditions, the ad-hoc signal strength shows on the GUI as an alternative for the user to select. Upon selection of such an alternative network, other users, rescuers, first responders and also other BSs are shown. The distressed user can then freely choose any entity to communicate with as per his desire and emergency situation. Such reach out is governed by the signal strength of the user's mobile set and other devices' configurations and availability. Once the emergency call is received, the necessary intervention could be attended accordingly. Despite such communication being easily accessible in emergency situations and through uncontrolled and unsupervised network schemes, careful measures need be assessed and implemented to avoid excessive and undetermined utilization of such communications. Fraud protection against hackers and phishing also need be addressed.

As for the BS display on the caller's screen, it also could be advisable to access for help request in case such facilities equipped with adequate reply machines that can optionally transfer to a human. In case of the agent accessing the same, then reaching the services' menu could display an optional selection, such as adding service or updating software and so on. In case of unintentional skipping of the call by an agent, then the compromised caller can choose among other displayed users. As for the agent, they also have the freedom of whether to download a menu option or not. All work environments is almost similar to what is currently on normal 4G handsets, but with a cognitive processor in the background.

IX. Conclusions

This paper has illustrated the main building blocks of the SHDR in CR network environments. The software provides useful information to the user via suitable screen interfaces, while down to the chip level; it recognizes and identifies the best hardware signal processing modules and parameters. The various DSP tasks performed on the incoming and outgoing signals involve decision making relying on the knowledge learned from practice and saved as intelligent features in the hardware memory accessible and manageable through software. The SHDR bridges what is thought a gap between SDR and the DSP functionality concepts and requirements. An ad-hoc network in an emergency situation, as an alternative to conventional setups, was also envisaged as a promising proposal. Such a network can be available anytime, anywhere upon CR handsets and infrastructure resources availability. One option is to establish such a cognition feature into conventional 4G in addition to other dedicated agent devices.

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