Cognitive Radio: An Intellectual Network for Future Wireless Communication Systems

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***Abstract*—The fixed spectrum assignment policy becomes a bottleneck for more efficient spectrum utilization due to the rapid deployment of new wireless devices and multimedia applications. Cognitive radio technology has emerged as the key technology, which enables opportunistic access to the spectrum by using unused or less used spectrum in radio environments and will provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques. The prime objective of cognitive radio is to use scarce and limited natural resources efficiently without causing excessive interference to the primary licensed users. To provide a better understanding of cognitive radio technology, this paper at first presents the fundamentals of cognitive radio technology, cognitive radio capability, architecture of a cognitive radio network and its applications. Then several open research challenges and security issues are discussed.**

Keywords —software defined radio; cognitive radio; spectrum sensing; primary users; secondary users; wireless networks

I. INTRODUCTION

Current wireless networks are described as static spectrum allotment policy, where Regulatory bodies like federal communication commission (FCC) assign wireless spectrum for large geographical areas to license holders on long-term basis, this give rise to inefficient usage of spectrum resources. Also emerging wireless multimedia applications requiring significantly more frequency spectrum, these factors lets the spectrum regulatory bodies to think for innovative communication technology that can exploit the wireless spectrum in a more flexible and intelligent way [1]. Hence dynamic spectrum access techniques were proposed recently to resolve these spectrum inefficiency problems.

The key enabling technology providing dynamic spectrum access is the cognitive radio (CR) also known as dynamic spectrum access (DSA) networks that enables next generation communication networks. It is defined as a radio that can change its transmitter parameters on interactions with the environment in which it operates [2]. Cognitive radio differs from conventional radio devices in that cognitive radio can equip users with cognitive capability and reconfigurability, this means that cognitive radio introduces intelligence to conventional radio such that it searches for a spectrum hole [3]. Cognitive radio has the capability to sense the spectrum and determine the vacant bands and can make use of these available bands by dynamically changing its operating parameters, in an opportunistic manner surpassing the traditional fixed spectrum assignment approach in terms of overall spectrum utilization [4]. As shown in "Fig.1", a cognitive radio enables the usage of temporally unused spectrum, referred to as spectrum hole or white space which are frequency bands that are not used by the licensed users at that time within a selected area. In licensed bands, wireless users with a specific license to communicate over the allocated band are known as the primary user (PU) and has the priority to access the channel whereas cognitive radio users are called secondary users (SU) and can access the channel as long as they do not cause interference to the primary user. When secondary users coexist with primary users, they have to perform real-time wideband monitoring of the licensed spectrum to be used and when secondary users are allowed to transmit data simultaneously with a primary user, interference limit should not be violated [5]. If secondary users are only allowed to transmit when the primary users are not using the spectrum, they need to be aware of the primary users' reappearance through various detection techniques, such as energy detection, feature detection, matched filtering and coherent detection [6]. With these capabilities, cognitive radios can operate in licensed bands as well as in unlicensed bands and select the best spectrum that can be shared with other users, and exploited without interference with licensed user.

In the past few years there have been many significant developments in the field of cognitive radio technology. This paper presents an survey on cognitive radio technology and corresponding research challenges with security issues. In Section II, we discuss the fundamentals of cognitive radio technology. In Section III, we review cognitive radio capability which includes different types of cognitive capability and reconfigurable capability. In Section IV, we describe the architecture of cognitive radio network. In section V, we discuss on potential application of cognitive radio. Finally in section VI, we discuss several important challenges and security issues of cognitive radio technology.

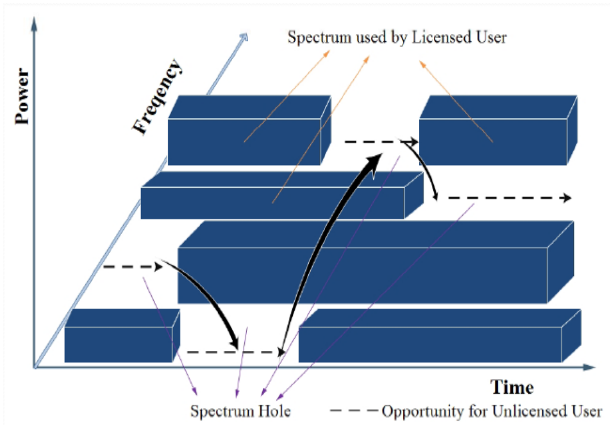

Figure. 1. Spectrum Hole

II. COGNITIVE RADIO TECHNOLOGY

The concept of Cognitive radio was firstly introduced by Joseph Mitola and Gerald Maguire [3], and they presented cognitive radio as an extension of software defined radio that will provide highly reliable communications whenever and wherever needed and efficient utilization of radio spectrum. The cognitive radio transceiver main components are the radio front-end and the digital baseband processing unit which is made by adding four blocks [7] such as sense, analyze, decide and adapt to software defined radio (SDR) as shown in “Fig.3”.

In the RF front-end the received signal is amplified, mixed and analog to-digital (A/D) converted. In the baseband processing unit, the signal is modulated or demodulated and (D/A) converted. The sense block provides the awareness of the spectrum usage in the surrounding environment about when, which bands to sense and for how long. This block also measure the electromagnetic activities due to the ongoing radio transmissions over different spectrum bands and to capture the parameters related to such bands [8]. To reach the accurate conclusions regarding the radio environment the sensed spectrum information must be sufficient for the cognitive radio. The analyze block gather existence of spectral opportunities in the surrounding radio environment based on the sensed radio environment parameters. A spectral opportunity is conventionally defined as a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographical area. In the analyze block, the cognitive radio takes in the data stream gathered by the sense block, identifies the energy patterns that might represent interference risks or signals of interest and attempts to analyze them. The decide block decide the set of transmission actions to be taken based on the outcome of the spectrum sensing and analysis procedures. The results of analyze block is then passes to the fourth distinctive adapt block. This block has the ability to re-tune its transceiver parameters dynamically according to the surrounding radio environment and is capable to configure the transmission bandwidth to adapt to the spectral opportunities of different sizes.

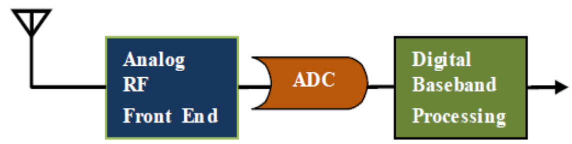

Figure 2. A practical SDR receiver

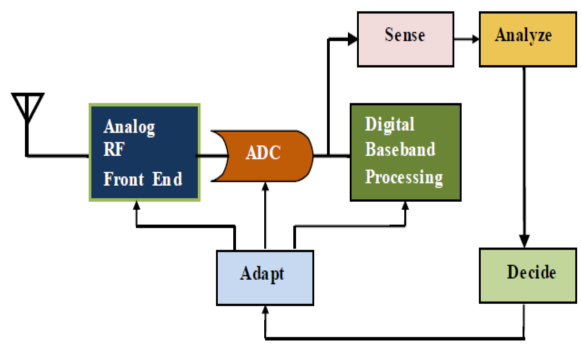

Figure 3. Cognitive radio adds Sense, decide and Adapt blocks to the SDR.

More specifically, a cognitive radio utilizes the information gathered regarding the spectrum bands identified as available spectral opportunities to define the radio transceiver parameters for the upcoming transmissions over such frequency bands. The set of transceiver parameters to be decided depends on the transceiver architecture that includes which spectrum is more favorable for an upcoming transmission, the time instant to start a transmission over a certain band, the maximum transmission power, the modulation rate, the spread spectrum hopping scheme, the angle of arrival for directional transmissions and the number and identity of the antennas to be used in multi- input- multi output (MIMO) systems [9].

III. COGNITIVE RADIO CAPABILITY

Formally, a cognitive radio is defined as a radio that can change its transmitter parameters by sensing, analyzing and interaction with its environment. From this definition two main capability of cognitive radio can be defined as cognitive capability and reconfigurable capability.

A. Cognitive Capability

The cognitive radio cognitive capability refers to the ability of the radio technology to continually observe the dynamically changing surrounding radio environment to identify the unused portions of the spectrum at a specific time or location so that the best spectrum at a specific time and appropriate operating parameters can be selected without any interference to other users [6]. The four main components of cognitive capability are spectrum sensing, spectrum sharing, spectrum decision, location identification and network discovery.

1) Spectrum Sensing: Spectrum sensing is active spectrum awareness process where cognitive radio monitors its radio environment and geographical surroundings and detect the spectrum white space or spectrum holes and then utilize the spectrum .When primary users start using the licensed spectrum again the cognitive radio can detect their activity by sensing, so that no harmful interference is generated due to secondary users transmission. The sensed spectrum information must be sufficient enough for the cognitive radio to reach accurate conclusions regarding the radio environment. Therefore spectrum sensing is one of the most critical functions of a cognitive radio as it provides the awareness of the spectrum usage in the surrounding environment [10].

2) Spectrum Sharing: Spectrum sharing refers to the ability of cognitive radio for solving diverse conflicts in cognitive radio networks when more secondary users are forced to share the available spectrum at a particular time instant [11]. Since there is number of secondary users participating in usage of available spectrum holes, cognitive radio has to achieve balance between its self-goal of transferring information in efficient way and to share the available resources with other cognitive and non-cognitive users. Spectrum sharing can be classified as centralized or distributed [6]. In centralized spectrum sharing the spectrum allocation and access procedures are controlled by a central entity. The central entity can lease spectrum to users in a limited geographical region for a specific amount of time. In distributed spectrum sharing spectrum access and allocation are based on local policies that are performed by each node distributively.

3) Spectrum Decision: It is the capability of cognitive radio to decide which is the best spectrum band among the available vacant bands according to satisfy required quality of service, without causing excessive interference to the primary users. Spectrum decision is closely related to the channel characteristics and operations of primary users. Cognitive radio analyzes the sensing data and make a decision about channel and the transmission parameters such as transmission power and modulation [11]. Furthermore spectrum decision not only depends on local observations of cognitive radio users but also on statistical information of primary networks then the most appropriate spectrum band can be chosen.

4) Location Identification and Network Discovery: The ability of cognitive radio to determine its location and the location of other devices operating in the same spectrum and then selects the appropriate operating parameters such as the power and frequency allowed at its location to optimize transmission parameters for increasing spectrum reuse. Also location technology is an appropriate method of avoiding interference because sensing technology would not be able to identify the locations of nearby receivers. Furthermore to communicate cognitive radio terminal shall first discover available networks around it and these networks are reachable either via directed one hop communication or via multi-hop relay nodes [12]. For instance, when a cognitive radio terminal has to make a phone call, it shall discover if there is global system for mobile communication (GSM) base transceiver systems (BTSs) or wireless fidelity (Wi-Fi) access points (APs) nearby. If there is no direct communication link between the terminal and the base transceiver systems or access points but through other cognitive radio terminals some access networks are reachable, it can still make a call in this circumstance.

B. Reconfigurable Capability

The cognitive capability of cognitive radio provides spectrum awareness whereas reconfigurable capability enables the cognitive radio to be dynamically programmed according to the radio environment. The best operating parameters and most appropriate spectrum band can be selected and reconfigured through reconfigurable capability. The four main components of reconfigurable capability are frequency agility and dynamic frequency selection, adaptive modulation, transmit power control and spectrum mobility.

1) Frequency Agility and Dynamic Frequency Selection: Frequency agility is the ability of a cognitive radio to quickly shift its operating frequency on a continuous basis to optimize its use in adapting to the environment [11]. Such changes are automatic, and may follow a programmed algorithm. Frequency agility usually combines with dynamic frequency selection method which detects signals from other radio frequency systems with low interference levels.

2) Adaptive Modulation : Adaptive modulation is one of the key technology of cognitive radio and used in most broadband wireless communication standards such as the high speed packet access (HSPA) and the worldwide interoperability for microwave access (Wi-MAX). It is a techniques which can modify transmission characteristics and waveforms to provide opportunities for improved spectrum access and more intensive use of spectrum in the presence of other signals around [13]. In adaptive modulation, many parameters can be adjusted according to the channel variations such as the transmit power, modulation level, symbol rate, coding rate, etc Also it exploits the rapid fluctuations in wireless channels to maximize the data throughput in energy and spectral efficient ways.

3) Transmit Power Control : Transmit power control is one of the important feature of cognitive radio that enables a device to dynamically switch between several transmission power levels in the data transmission process. The transmission power is adapted to full power limits when necessary and reduces the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary. The function of the transmit power control is to maximize capacity of the link, maximum overall network capacity, or transmission at the minimum power level to maintain link [14]. Furthermore transmitter power level along with the attenuation of channel determines the quality of the received signal, the range of the transmission and the interference level it creates to the other receivers in the network.

4) Spectrum Mobility: If primary user starts to operate then the cognitive radio has to stop its operation or to vacate currently used radio spectrum and change its operating spectrum band, which is referred to as spectrum mobility. Spectrum mobility allows the cognitive radio to dynamically explore the available spectral opportunities. Spectrum mobility gives rise to a new type of handoff in cognitive radio networks called spectrum handoff and is a handoff mechanism that guarantees the transition to the new frequency band without breaking the communication between communicating cognitive radio terminals [15]. The purpose of the spectrum mobility management in cognitive radio networks is to ensure smooth and fast transition leading to minimum performance degradation during a spectrum handoff. Also an important requirement of mobility management protocols is the information about the duration of a spectrum handoff, this information can be provided by the sensing algorithm. After the latency information is available, the ongoing communications can be preserved with only minimum performance degradation.

IV. COGNITIVE RADIO NETWORK ARCHITECTURE

A cognitive radio network architecture consists of primary networks as well as secondary networks or cognitive networks as shown in " Fig 4". Primary network have a license to operate in a certain spectrum band and primary network comprises primary users and primary base stations. The primary users are licensed to use the spectrum and are coordinated and controlled by the primary base stations and primary users communicate among each other through the base station only [11]. Primary base-station is a fixed infrastructure network component which has a spectrum license and does not have any cognitive radio capability for sharing spectrum with cognitive radio users.

The secondary network comprises of cognitive or secondary users and cognitive base stations. Cognitive network or secondary network does not have a spectrum license to operate in the desired band and the spectrum access is allowed only in an opportunistic manner. The spectrum access is managed and handled by the secondary base station which acts as a hub or access point for the secondary user network [13]. The cognitive radio user is assumed to have the capabilities to communicate with not only the base-station but also other cognitive radio users. Cognitive radio base-station is a fixed infrastructure component with cognitive radio capabilities such as spectrum sensing, spectrum decision, spectrum handoff and cognitive radio protocols. Cognitive radio base-station provides single hop connection to cognitive radio users without spectrum access license.

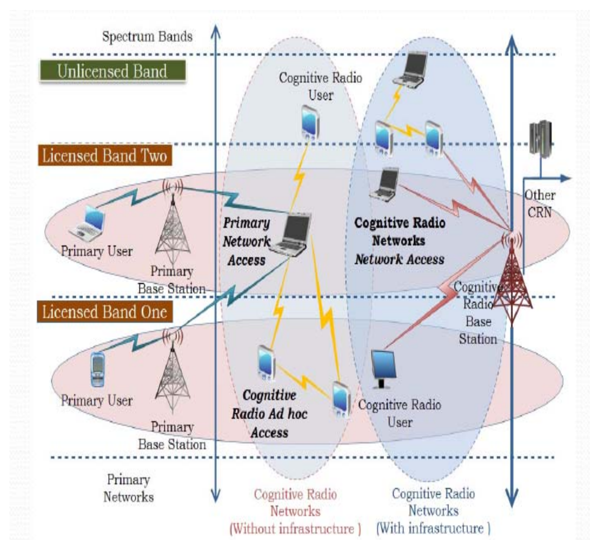

Figure 4: Cognitive Radio Architecture

From the cognitive radio network architecture, there are three different types of network access .

- *Cognitive Radio Network Access*: Cognitive radio users can access their own cognitive radio base-station both in licensed and unlicensed spectrum bands. Since all interactions occur inside the cognitive radio network, their medium access scheme is independent of that of primary network.

- *Cognitive Radio Ad-Hoc Access*: Cognitive radio users can communicate with other cognitive radio users through ad- hoc connection on both licensed and unlicensed spectrum bands. A set of cognitive radio users that connect to each other and communicate among themselves without the presence of the cognitive base station, this kind of network is called an ad-hoc network. Also cognitive radio users can have their own medium access technology.

- *Primary Network Access* **:** The cognitive radio user can access the primary base station through the licensed band, if the primary network allows. Unlike other access types, cognitive radio users should support the medium access technology of primary network. Furthermore, primary base-station should support cognitive radio capabilities.

V. COGNITIVE RADIO POTENTIAL APPLICATIONS

Traditional wireless network are challenged by the scarcity of the wireless bandwidth needed to meet the high-speed requirements of wireless applications whereas cognitive networks are meant be used to provide broadband access to rural, tribal, and other under-resourced areas. The application of cognitive radio networks in different fields are discussed below.

- *Public Safety Networks:* Public safety networks are used for communications among police officers, fire and paramedic personnel. Such networks are also challenged by the limited amount of allocated spectrum. Even with the recent extensions of the allocated public safety spectrum bands, the public safety personnel do not have the technology to dynamically operate across the different spectrum segments. The cognitive radio technology can offer public safety networks more bandwidth through opportunistic spectrum [16].

- *Disaster Relief and Emergency Networks:* Natural disasters such as hurricanes, earthquakes, wild fires, or other unpredictable phenomena usually cause the infrastructure based networks to collapse. This results in a set of partially or fully damaged coexistent networks that were previously deployed and then became disconnected. Meanwhile, there is an urgent need for a means of communications to help the rescue teams to facilitate organized help, rehabilitation efforts and to locate the disaster survivors [17]. Cognitive radio networks can be used for such emergency networks and will provide a significant amount of bandwidth that can handle the expected huge amount of voice, video, and other critical and time-sensitive traffic.

- *Multimedia Applications:* Multimedia applications, such as on-demand or live video streaming, audio and still images are extremely challenging because of their huge bandwidth requirements, delay intolerable and bursty in nature [18]. Also the capacity provided by the traditional sensor networks varies with the temporal and spatial characteristics of the channel. Unlike the traditional sensor networks, cognitive radio sensor networks will provide the sensor nodes with the freedom of dynamically changing communication channels according to the environmental conditions and application-specific quality-of-service requirements in terms of bandwidth, bit error rates, and access delay.

- *Real Time Surveillance Applications:* In traditional wireless sensor networks with fixed spectrum allocation ,especially if the operating spectrum band is crowded real-time surveillance applications like traffic monitoring, habitat monitoring, environmental monitoring, environmental conditions monitoring for crops and livestock, irrigation monitoring , vehicle tracking, inventory tracking, disaster relief operations, bridges or tunnel monitoring, target detection and tracking may not be always achieved [19]. Furthermore additional communication latency may occur in wireless sensor networks in case of rerouting due to a link failure caused by degrading channel conditions [20]. Also in cognitive radio sensor networks, sensor nodes may opportunistically access to the available channel in order to maintain minimum access and end-to-end communication delay for effective real-time surveillance applications.

- *Health Care:* Traditional wireless sensor networks are used In a health care system, such as telemedicine where numerous wireless sensor nodes are placed on patients body to get critical data for remote monitoring health care providers. The quality of service may not be achieved at a satisfactory level with traditional wireless sensor networks if the operating spectrum band is crowded. The use of cognitive radio wearable body wireless sensors can mitigate these problems due to bandwidth, jamming, global operability with improve reliability [21].

- *Public and Military Security Applications:* Conventional wireless sensor networks s are used in many military and public security applications, such as battlefield surveillance, command control, chemical biological radiological and nuclear (CBRN) attack detection and investigation, gathering the information of battle damage evaluation, intelligence assistant and targeting . In the battlefield or in disputed regions an enemy may send jamming signals to disturb radio communication channelshttp://www.ncbi.nlm.nih.gov/pmc/articles/PMC3821336/ - b35-sensors-13-11196 [22]. In such situations cognitive radio wireless sensor networks can handoff frequencies over a wide range and can use different frequency bands, thereby avoiding the frequency band with a jamming signal. Also cognitive radio wireless sensor networks can be a better in some military applications that requires a large bandwidth, minimum channel access and communication delays.

VI. CHALLENGES AND SECURITY ISSUES

A. Challenges

Cognitive networks are inherently heterogeneous and impose unique challenges due to their coexistence with primary networks. Development of cognitive radios give rise to several open research challenges like:

- *Spectrum Sensing Challenges:* Due to the lack of interactions between primary networks and cognitive radio networks, generally a cognitive radio user cannot be aware of the precise locations of the primary receivers. Thus, new techniques are required to measure or estimate the interference temperature at nearby primary receivers. Also spectrum sensing functions should be developed considering the multi-user environment that consisting of multiple cognitive radio users and primary users, makes it more difficult to sense spectrum holes and estimate interference. Moreover novel spectrum sensing algorithms must be developed such that the sensing time is minimized within a given sensing accuracy since sensing time directly affects transmission performance [9],[21].

- *Spectrum Decision Challenges:* There are many open research challenges of cognitive radio on spectrum decision function like strategy for selecting channel for sensing or access ,design of application and spectrum adaptive spectrum decision models ,where and how the decision on spectrum availability, strategy for selecting channel for sensing or access, optimization of radio performance [23]. The other challenge is the choice of the decision algorithms. Also a cognitive radio network should support spectrum decision operations on both the licensed and unlicensed bands , hence dynamic spectrum decision operation is a major challenge.

- *Spectrum Sharing Challenges:* Cognitive radio networks a channel common to all users is highly dependent on topology and varies over time. Consequently, either cognitive common channels mitigation techniques must be devised or local cognitive common channels must be exploited for clusters of nodes [6] . In cognitive radio the secondary users should know the location and transmit power of primary users so that interference calculations can be performed easily , hence location management and transmit power control are some open challenges.

- *Spectrum Mobility Challenges*: Spectrum mobility in space is an open issue since the available bands also change as a user moves from one place to another giving rise to continuous allocation of spectrum challenge [6]. Also cognitive radio networks adapt to the wireless spectrum based on the available bands since these available channels change over time, enabling quality of service in this environment is challenging. Furthermore the primary goal of cognitive radio is to protect primary system from interference, hence detecting interference at primary receiver is an open challenge .

B.Security Issues

Traditional wireless networks are vulnerable to various types of security attacks. These attacks includes attacks on secrecy and authentication, attacks on network availability, and attacks on service integrity [24]. On the other hand the users expect that communication systems based on cognitive radio must guarantee security requirements like access control, confidentially, privacy, availability, authorization and authentication. But cognitive radio wireless networks are more vulnerable to security threats than the conventional wireless sensor networks like access to private data, unacceptable interference to licensed users, prohibiting the use of idle channels for secondary users, modification of data, injection of false data since there is no strict cooperation between primary users and secondary users communication [25]. The data collected by cognitive radio wireless sensors can be sniffed, destroyed or altered by unauthorized entities. In addition, attackers can interfere with primary users transmission or prevent the use of the channel by secondary users through spectrum sensing data falsification .

Some other possible attacks in cognitive radio wireless networks are Physical Layer Attack ,medium access control Layer Attack and Routing Layer Attack [26]. A jamming attack is one type of attack on a physical layer in which the adversary transmits radio signals on the wireless channels to interfere with cognitive radio wireless sensors normal operations. Another type of attack on physical layer is a tampering attack, in this case the attacker may damage the cognitive radio wireless sensors, replace the entire nodes, or part of its hardware. In a medium access control layer attack, the attackers violate the rules defined in the protocols and disturb the normal operation by sending undesirable packets repeatedly to disturb the normal operation and exhaust battery power, using channels selfishly, and show uncooperative behavior on the priority of a cooperative medium access control layer. This may lead to denial-of-service attacks [27] at the medium access control layer. In a routing layer, the attackers alter the information on routing packets and misguide the packet forwarding sensors on the networks. These security issues are entirely open research issues, and need to be explored further to meet its research challenges.

VII. CONCLUSION

In recent years cognitive radio technology has been proposed as a solution for current wireless network problems resulting from inefficiency spectrum usage and limited spectrum availability. By adapting operating parameters to environment variations and fine-tuning the frequency to the temporarily unused licensed band, cognitive radio technology provides future wireless devices with reliable broadband communications ,flexibility for rapidly growing data applications and additional bandwidth. In this paper the fundamental concept about cognitive radio technology, cognitive radio capability functions, architecture of cognitive radio networks and applications are presented then various challenges and security issues of cognitive radio networks are discussed. Further study can be focused on security issues and efficient spectrum management challenges.

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