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Abstract: Notables features of cognitive radios have made them a technology of choice for wireless communications and motivated the notion of cognitive radio cellular networks in which the network may also operate opportunistically on spectrum white spaces. As spectrum handover can be considered as a new cause of reliability impairment, a reliability framework for cognitive radio cellular networks is proposed in this paper to discuss how cognitive radio features may help compensating the impact of spectrum handovers. For the sake of servicing different classes of traffic, reliability differentiation is also addressed.

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1 Introduction

A recent solution to improve the spectrum usage efficiency and thus address the exponential growth of demand for spectrum resources is to deploy secondary wireless networks in parts of the licensed spectrum which are temporarily vacant from their primary users (PU). This approach is known as opportunistic spectrum access (OSA) and necessitates empowered wireless nodes able to sense the spectrum in order to detect the vacant portions. Such requirements are fulfilled by cognitive radios (CR). The fact that new generations of cellular networks are among the most spectrum demanding wireless applications motivated the notion of cognitive radio cellular networks in which the cellular networks are allowed also to opportunistically operate in some temporary vacant parts of the spectrum such as TV white spaces (TVWS) and 3.5 GHz band. It is worth noting that even though cellular networks are not limited to mobile telephony networks, without loss of generality and as the mobile telephony networks are the most important part, we focus in this paper on telephony networks.

Since long ago, wireless services have been known as unreliable services with inconsistent quality of service (QoS) in which problems (dropped connections, variable data rates, long delays, etc.) are frequent occurrences. These problems have been presented as inherent characteristics of wireless networks. However, with the deployment of wireless networks in critical applications and increased expectations of end users, the question of reliability became more important. Cellular systems are not excepted from this trend. While mobile phones have been known as an unreliable successor of fixed home phones, nowadays, a dropped call during an important job interview or a disconnection while doing a financial transaction over the phone can not be accepted.

In addition to common impairment factors in wireless communications, such as fading and interference, intercell handoffs (a.k.a, handover), mainly due to user mobility, has been a reliability concern in cellular networks such that an extensive amount of research has been conducted to improve the handoff process and to provide a smoother handoff. In cognitive radio cellular systems operating on the basis of opportunistic spectrum access (OSA), a new cause of interruption is introduced which is spectrum handoff where, even with no user mobility, the operating channel should be vacated and switched because the primary user has returned to the channel. As a result, a new reliability framework is required to address both spectrum mobility and user mobility [1].

On the other side, a cognitive radio cellular network may be empowered with several intelligent and cognitive features which can be exploited to open new doors for the notion of reliability in wireless networks [2]. It is realistic to assume that in cognitive radio cellular networks, base stations enjoy a full cognitive cycle [3] while mobile phones are equipped with limited and simple spectrum sensing and location awareness capabilities. As discussed in [2], any cognitive feature may help a cognitive radio network to prevent the occurrence of potential failures or to decrease their severity and consequence after occurrence, in a more efficient way. Therefore, ignoring these new capabilities and depending only on existing reliability frameworks is not an intelligent choice. This paper thus deals with these features to propose a new reliability framework and its extension to differentiation, which not only takes into account the new impairment factors due to spectrum mobility and unpredictability of the resources, but also proposes solutions based on cognitive features, in order to guarantee a specified level of reliability for different priority classes of traffic, from an operational point of view.

The remainder of this paper is organized as follows. Section 2 discusses why existing differentiation schemes can not address the requirements of cognitive cellular networks, focusing on cognitive radio features. In Section 3, the system model for a cognitive cellular network from the reliability point of view is investigated and the reliability impairment factors are introduced. Extension to differentiated scenarios is discussed in 4, and finally Section 5 concludes the paper.

2 Why a new differentiated reliability framework?

Nowadays as discussed, the most important objective when employing cognitive radios is in the framework of opportunistic spectrum access to solve the problem of spectrum scarcity and spectrum usage inefficiency.

Regarding the discussions in the introduction, two questions may arise. The first question is that while the CR technology seems to be a technology for lower communication layers, the Internet Protocol (IP) may be still present in the network layer, as it is the case for instance for 3GPP Long Term Evolution (LTE) [4]. Thus, why do not we trust existing solutions and differentiation mechanisms in the IP layer and leave this task to the IP Differentiated Services (DS) or other proposed methods for reliability improvement in communication networks?

This question has been discussed in [5]. The authors state that even though the IETF Diffserv [6] can provide some level of reliability, as it is not designed for failure management and reliability purposes, its reaction to failures is slow and inefficient, and consequently is not powerful enough to alone provide (differentiated) reliability. For this end, some collaboration between the IP and lower communication layers (in [5], they have mostly focused on the physical layer in WDM networks) is necessary, which results in cross-layer mechanisms to provide reliability in communication networks. As cognitive radios possess an adaptable cross-layer structure, new mechanisms to improve the reliability can be implemented more efficiently in cognitive radio cellular networks.

The other question that may arise after the above discussion is that when some other models have been proposed for the sake of reliability differentiation, why not apply the same models to cognitive radio cellular networks. In other words, what is the necessity of a new research on this topic? The answer to this question can be divided into two parts where both parts have been somehow discussed in the introduction. The proposed mechanisms are mainly for wired networks while, because of their nature, wireless networks are inherently more unreliable and error-prone. The study of wireless networks reliability is therefore more challenging. For the second part of the answer, we should take into account the distinction of traditional wireless networks, including traditional cellular networks, and cognitive radio cellular networks based on opportunistic spectrum access, as discussed in the introduction and will be explained in details in the following.

2.1 Cognitive radio

A Cognitive radio node is defined as an intelligent radio that can observe and learn from the environment and adapts its communication parameters based on this knowledge [3]. They are supposed to be decision maker and possess different features such as spectrum-awareness, location-awareness, learning and history-awareness, adaptability and reconfigurability. Using these features, a CR node operates in a cognitive cycle proposed by Mitola [3].

2.1.1 Spectrum-awareness

Spectrum-awareness implies that a CR node is able to sense the spectrum to find the spectrum white spaces. Based on the spectrum sensing results, the transmitter and receiver select a common spectrum hole as their operating channel. In the sensing process, the CR node attempts to detect the signal of primary users. If the CR node has some information about the interference signal characteristics, sensing can be done more accurately and faster using coherent detection mechanisms (e.g., Matched Filter Detection [7]). In cognitive radio cellular networks, the opportunistic frequencies are expected to be limited to TV white spaces (TVWS) and 3.5 GHz with knwon licensees, so the primary user signal can be assumed to be known. It also realistic therefore to assume that if an opportunistic channel is being used by the mobile network in a neighbor cell, spectrum sensing will detect that and does not consider it as primary users' activity. The task of sensing can also be distributed among mobile nodes in a collaborative manner to increase the sensing accuracy and to be able to sense a wider frequency range. The facts that cellular networks are generally infra structure networks with tight synchronization thus encourage employing *cooperative/collaborative sensing*, where the base station plays the role of a fusion center [7].

Note that when spectrum sensing capabilities are not available in mobile phones or even in base station, the base stations will be necessarily equipped with mechanisms to communicate with a spectrum database and inquiry about channels available in their geographical region. This information can then be disseminated to mobile phones. In large cells, knowing the approximate location of the mobile nodes, the base station is then able to find the channels which are common both in the mobile node and in the base station side.

2.1.2 Location-awareness

Location-awareness can greatly help a CR node to have an accurate view of the network. Since base stations are generally fixed and pre-planned, knowing the current location helps a CR node to estimate propagation delay and analyze the position of all base stations around it. A base station which knows its own location may use this information when performs inquiries about available opportunistic channels with a spectrum database. Localization of mobile nodes can be done by Geographical Positioning System (GPS), as most of the phones are now equipped with.

2.1.3 Learning and history-awareness

In the definition of the cognitive radio by Mitola [3], learning capability implies that a CR node possesses a database which can save the observation results and experienced events in order to use them to take history-aware decision in the future. The learning phase is the outcome of observation, planning and decision-making phases. Due to complexity of learning and considering the limited resources of mobile phone and their dependency on base stations, learning tasks can be left for base stations.

2.1.4 Reasoning and decision-making

In addition to selecting the best transmission parameters for the link to all mobile nodes, a base station in cognitive radio cellular networks should make some decisions on the opportunistic operating channels independent of the mobile switching center (MSC), in a distributed manner. The cognitive radio base station will thus have a reasoning unit. The reasoning unit should analyze all the possibilities in a very short time and make the best decision. Similar to learning, it may not be necessary to equip the phones with an expensive and power-consuming reasoning unit.

2.1.5 Adaptability and reconfigurability

Cognitive radio supposed to possess a fully reconfigurable architecture which permits the node to adjust different communication parameters based on the current system state [3]. For example, at the physical layer, the frequency and the channel bandwidth, modulation and coding scheme, configuration of antennas and the transmission power are some of the adjustable parameters. Correspondingly, the sensing process parameters, e.g. the sensing duration or the threshold levels, can be customized. Due to advancements of digital signal processing, a mobile phone may also have some of these flexibilities. The most important feature is frequency agility which lets a mobile node change the operating frequency with a low overhead, motivating a seamless spectrum handover (referred as *frequency switching*). The reconfigurable architecture also enables a cognitive radio node to implement diversity techniques more efficiently in response to fading and interference, for instance by adjusting internal parameters (coding scheme, number of antennas, etc) or by switching the diversity technique on the fly (referred as *CR diversity*).

From the reliability point of view and considering the features discussed above, the cognitive cycle proposed by [3] can be modified to the one presented in Figure 1, which illustrates the inherent capability of cognitive radio networks to prevent or recover from impairments and failures, in order to improve reliability.

In this modified cognitive cycle, after the environment observation and monitoring (stages 1 and 2), in stages 3 and 4 the cognitive radio analyzes whether any new failure has occurred or may be occurring in the near future (warning). In the case of warning, the CR deploys a prevention measure. For example, if a CR mobile node is becoming farther from the base station, the frequency or the modulation and coding may be switched to prevent path loss failure. In the other case, the type of failure is analyzed to find the best solution (stages 5 and 6). The CR base station can also learn from the current experiences and observations to help it in the development of more efficient plans in the future (stage 7).

3 Operating model

Consider a cognitive radio node (a multi-band mobile phone, tablet, etc) which is operating over its designated channel, known as current operating channel, connected to a designated cognitive radio base station within

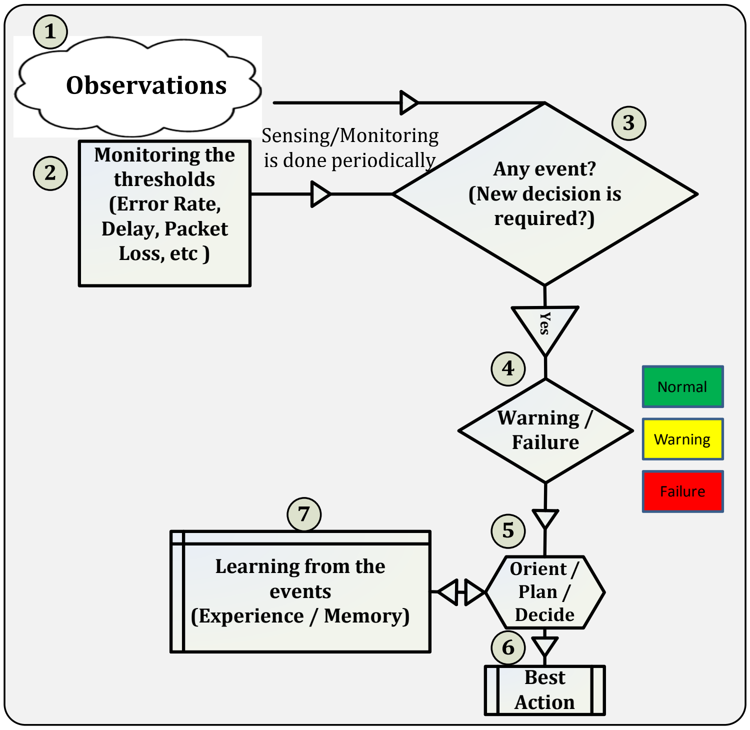

Figure 1: Reliability-oriented cognitive cycle, reproduced from [2].

a macro, femto or pico cell. As in LTE and IEEE 802.16m, OFDMA is assumed to be the medium access protocol operating over both contiguous and non-contiguous chunks of spectrum [8]. The node continues working on this channel until because of a reliability impairment factor, it vacates this channel and switches to a new channel. Channel switching may be accompanied by a cell switching. In the following, we discuss the impairment factors in a cognitive radio cellular network. Note that the factors are common between the case where the nodes operate over a licensed channel (e.g., in 900 MHz, 1.8, 2.1 or 2.6 GHz bands) and over a channel which is used opportunistically (e.g., TV VHF/UHF or 3.5 GHz). The only difference is channel switching due to appearance of primary users, which is not applicable to licensed channels. We use the term *opportunistic channel* to refer to spectrum white spaces used opportunistically.

3.1 Reliability impairment factors

The major reliability impairment factors in wireless communications along with their root and possible solutions are listed in Table 1. Path loss, shadowing, multipath fading, interference and congestion are the major wireless channel impairments that can cause link failures. A wireless link fails completely when even with the most robust modulation scheme, the bit error rate is higher than a threshold, or equivalently the signal to noise and interference ratio (SINR) is below a threshold (depending on the diversity order).

Path loss

When the distance between the mobile node and base station increases due to the users' mobility, the received signal power decreases thereby increasing the BER and packet loss and degrading the link quality. The traditional solution to this problem is a cell handover and switching to a new base station. However, thanks to opportunistic spectrum access, it will also be possible to switch to a channel with a much lower path loss in VHF/UHF band and go on with the same cell. This solution may be used as a temporary remedy when the node link quality has degraded but still no better link can be established with a new base station. In heterogeneous cognitive radio cellular networks, the possibility of switching between macro and micro cells should also be discussed.

Table 1: Classification of reliability impairment factors.

Factor	**Caused by**	**Existing solution**	**New CR-based solution**
Path loss	Node mobility	Cell switching	Frequency switching to TVWS
Shadowing and Fading	Mobility/Environment	Diversity techniques	Frequency switching, CR diversity
Interference	Frequency reuse (Lice)	Diversity techniques	Frequency switching, CR diversity
Interference	Frequency reuse (Opp)	–	Spectrum sensing, Frequency switching, CR diversity
PU Interference	OSA	–	Spectrum sensing, Frequency switching
Congestion	Demanding traffic	Wider channels (aggregation)	More options for aggregation

- Switching from Macrocell to Femto/Pico Cell: For the sake of load balancing or to receive a better service, it is possible that a mobile node, instead of receiving service from a macro base station, joins a local femto/pico cell. Considering the frequency range of white spaces (currently TV white spaces and 3.5 GHz in future), the offered service can be even better if the node also switches to a higher frequency when joins the femto/pico cell. In other words, if the node is operating on a TV channel or 900 MHz license bands, after joining the local cell, it will operate on 2.6 GHz (licensed) or 3.5 GHz (opportunistic) range because on one side and due to higher path loss, the interference to neighbor cells will be less, and on the other side, higher frequency may support wider bandwidth and higher service rate.
- Switching from Femto/Pico Cell to Macro Cell: This is the reverse case and the concept is similar to user mobility. When the user has no option to join a femto/pico cell and thus starts communicating with the macro base station, the impact of farther distance and path loss which results in a lower rate, can be compensated by switching to a lower frequency in TV white spaces.

Environment effects (shadowing and fading)

Stochastic signal variations, such as shadowing and multipath fading, usually cause transient failures. When the node speed is high enough, so a fast fading model is applicable, it can be expected that a small displacement causes large variations in the signal, so no new solution needs to be proposed assuming that diversity techniques are already in place. When the node's velocity is low, fading may visibly affect the quality of communication. The solution will be again switching to a new channel, but the new channel should be selected far enough (in the frequency range) from the original channel considering the coherence bandwidth. Frequency agility of mobile node and the base station provides the opportunity of a seamless spectrum handoff, and possibility of operating over opportunistic channels provides more options for switching.

Interference

Interference can be seen as the most severe reliability impairment factor, which in cellular networks is mostly originated form frequency reuse in neighbor cells. The problem is addressed in a centralized manner by accurate cell planning at the mobile switching center (MSC). However, when opportunistic spectrum access comes into play, the timing scale of spectrum availability in different cells may not permit the MSC to play a major role, and the decision on the channels to be used will be mainly made by the base stations, assuming that they are equipped with spectrum sensing or database inquiry capabilities. The interference may be thus more present in cognitive radio cellular networks when the nodes are temporarily operating on white spaces, with no pre-planning. However, OSA also brings the solution which can be reactive or proactive.

The reactive solution is channel switching in case that the node along with the base station finds the link SNR below an acceptable threshold. It is worth noting that if the channel is selected by spectrum sensing, naturally the sensing mechanism becomes important because with energy sensing, it may not be possible to figure out whether the licensee has returned to the channel or another mobile user is operating opportunistically on the channel. In the proactive solution, the channel is selected in a more conservative manner and after sensing. Therefore, when some activities are found on the channel, it is not selected during the recovery process. Coordination between two base stations,e.g., over X2 interface in LTE, may also help resolving the interference. In cognitive radio cellular networks, spectrum sensing information can also be exchanged over the X2 interface to decrease the possibility of selecting the same channel in two neighbor cells.

Congestion

To afford a high volume of traffic, a wider channel is required which in LTE Advanced is satisfied by channel aggregation [4]. Channel aggregation may be done in licensed or white spaces. In case that aggregation is being done in white spaces, and channels should be found by spectrum sensing, the complexity of recovery and search algorithm increases because several channels, and preferably contiguous, should be found in a limited time. Channel aggregation may also result in blocking of new users joining the cell. So, the base station reasoning unit is responsible for a fair resource allocation.

3.2 Reliability perspective

From the reliability point of view, the node operates until a switching is required, as illustrated in Figure 2. If switching is modeled as a failure, this operating time represents *time to failure*. The time spent for channel switching, including spectrum sensing to find potential vacancies (if required), radio alignment and required negotiations with the base station(s) can be considered as a recovery period. These recovery periods are the periods in which the link is being repaired therefore they represent *time to repair/recovery* in a reliability model. Considering Eq. (1) for the node availability, availability can be increased by decreasing the mean time to repair (MTTR), the duration of recovery periods, or increasing the mean time to failure (MTTF).

$$\text{Availability} = \frac{MTTF}{MTTF + MTTR}. \tag{1}$$

In the following, we will look at the nature of these reliability metrics in a cognitive radio cellular networks and the parameters which affect them.

3.2.1 Time to failure

Once a channel is selected, the duration of operating periods, equivalent to *time to failure*, is in most scenarios dictated by the environment, e.g., fading or appearance of licensees, which is generally random and out of the control of the mobile network. Operating over a licensed channel implies that the channel will be switched either due to user mobility and leaving the cell, or fading and traffic increase which makes the current channel's quality unacceptable. Over an opportunistic channel, the new cause is the appearance of licensees. In the scenarios where there is a priori information about a channel opportunistically used, the mobile network may decide to switch to a new channel even if current channel is still available to reduce the probability of interference with the primary users and to increase the chance of having a smoother handoff.

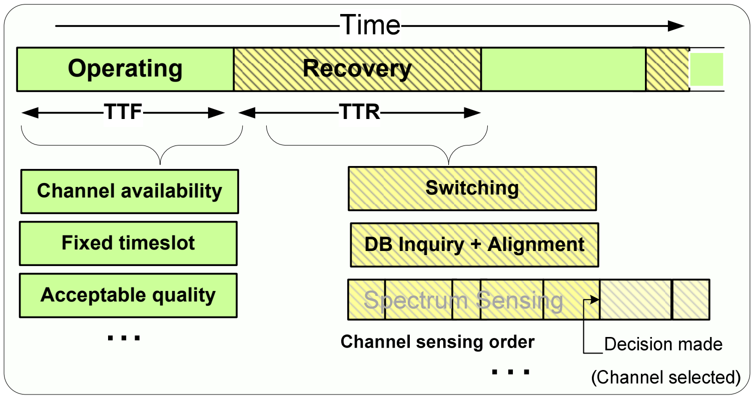

Figure 2: Operation and interruption (recovery) periods of a cognitive radio link.

In these scenarios, the duration of operating periods can thus be assumed to be deterministic (e.g., a fixed timeslot).

3.2.2 Time to recovery

The most important constraint on recovery time is that it should be short enough such that no interruption in an ongoing call is experienced. Assuming a full spectrum knowledge or no spectrum sensing capability and relying on database queries, the recovery time is the short time of decision making at the base station to select the next channel followed by negotiation and radio alignment. The recovery time will thus be almost deterministic and dependent on the processing capabilities of the base station.

For the cases of operating opportunistically where a new channel should be discovered by spectrum sensing, the recovery time will be the random time spent on sensing a list of potential channels and finding new appropriate channel(s) followed by some constant time for negotiation and final radio alignment. The recovery time will thus be a function of the order of the channels in the list, known as *channel sensing order*. Given that channels have a different probability of being available, different sensing time (variable bandwidth) and different service capacity (variable bandwidth and fading coefficients), questions such as which channels, how many channels and in which order they should be sensed, and which channel(s) should be selected (when the recovery is finished) determine the performance of the recovery process. Efforts on improving the recovery are concentrated on improving the channel decision algorithm.

The existence of different operating frequency ranges (licensed and opportunistically) motivates the approach of hierarchical channel recovery [9] in which the base station, along with the mobile node, first selects an appropriate frequency range, based on the characteristics of different ranges, distance, availability and frequency planning already in place. Then, in the selected range, a flat spectrum sensing is performed to select a new channel in the selected range.

As discussed, the important parameter in flat spectrum sensing is the list of channels to be sensed one by one (unless base station is equipped with wideband sensing capabilities). The optimal sensing order and optimal stopping time (when to terminate the recovery and take a channel) can be found in general by solving a dynamic programming model [10]. The number of TV channels which can opportunistically be used is limited, so dynamic programming can be efficiently implemented in cognitive radio cellular networks. However in general, its complexity is too high and heuristic methods may be preferred to be implemented in base stations.

3.2.3 Blocking probability

'Network busy' is a familiar message for any mobile user when trying to make a call in a crowded region of a metropolitan city or in a rural area with limited signaling. It mostly represents the case where there is no channel to be assigned to this user, and the user is thus *blocked*. The event of blocking continues until a channel can be assigned, thus blocking increases the recovery time. As discussed, one of the main motivations of opportunistically using vacant parts of the spectrum is to reduce the possibility of blocking.

4 Differentiated reliability

Before discussing any differentiation scheme, it should be clarified how different priority levels may be assigned to mobile nodes. In current cellular and telephony networks, we can not see any service prioritization based on contract types, payments or loyalty, as can be seen in wired networks based of VLANs or in public WiFi hotspots based on additional payments. We thus propose the following rules for prioritization of mobile nodes. Any user who is blocked because no available channel exists has a higher priority to preempt a channel from a node which operates over aggregated channels. Therefore, a solution to decrease the possibility of blocking will be a fair resource allocation among the nodes. Further, as LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz, and considering the reconfigurable structure of cognitive radio mobile nodes, it is also proposed that the base station may preempt a part of the bandwidth occupied by a user and assign it to a new user joining the cell. The rate decrease for the user already in the cell may be compensated by a higher modulation scheme, if possible. We can see thus how a reasoning and decision making unit helps the base station to efficiently optimize the resources in the cell and perform admission control.

We also propose packet marking, for instance enabling IEFT Diffserv or QoS profile parameters already in place in LTE [8], on data traffic originated from the mobile node, based on application and traffic type, and then assigning a higher priority to the nodes which have an ongoing traffic with a higher importance. Naturally, the highest priority is given to the node with an ongoing voice call. Packet marking and maintaining the priority of voice calls are easier in LTE as it is an all-IP network with packet switching only. For instance, a node which has an ongoing video conferencing will have a higher priority than a node with email or web traffic. Since the base station knows the interrupted traffic of all the nodes which are looking for a new channel, it can decide how to assign priority levels to the nodes.

When the priorities are known, the recovery process is done in favor of high priority nodes meaning that the first found channel is given to the node with the highest priority to minimize the impact of interruptions. Channel sensing order can also be formed based on the priority of the nodes; i.e., if a node with a higher priority is looking for a wide channel, wider channels are put in the beginning of the list of channels to be sensed. Or, if a high priority node's link should be recovered and the node is far from the base station, low frequency channels are put in the beginning of the list.

As can be seen, the IEFT Diffserv and packet marking play a significant role in reliability differentiation of cognitive radio cellular networks however the intervention of MAC and physical layer (engaged in the recovery process) is also needed, as discussed in Section 2.

5 Conclusion

We provided a reliability framework for cognitive radio cellular networks and classified the main reliability impairment factors. Then it was investigated how cognitive radio features may provide new solutions. We saw that spectrum handover, thanks to spectrum awareness and frequency agility in cognitive radio networks, along with the reconfigurable architecture, which promotes more efficient diversity schemes, facilitate the recover from impairment factors.

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