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A survey of overlay and underlay paradigms in cognitive radio networks

Bhoopendra Kumar[1] | Sanjay Kumar Dhurandher[1] | Isaac Woungang[2]

[1]CAITFS, Division of Information Technology, Netaji Subhas Institute of Technology (NSIT), University of Delhi, Delhi, India

[2]Department of Computer Science, Ryerson University, Toronto, Ontario, Canada

Correspondence
Isaac Woungang, Department of Computer Science, Ryerson University, Toronto, Ontario, Canada.
Email: iwoungan@scs.ryerson.ca

Summary

In the recent years, wireless applications and services have grown tremendously, resulting to a shortage of radio spectrum. On one hand, most of the available radio spectrum has already been allocated to different users and service providers. On another hand, research and statistics have revealed that the spectrum utilization usability is very limited. To address this dilemma, the concept of cognitive radio has emerged, which promotes the use of overlay and underlay transmission techniques to boost the utilization of radio spectrum resources. This paper provides a comprehensive survey of these 2 techniques and compares them qualitatively based on several network parameters. Next, this paper simulates overlay and underlay transmission techniques in OMNeT++ simulator on different network parameters, namely, Primary user arrival rate, throughput, sensing duration, and energy consumption. Our findings reveal that neither the overlay nor the underlay technique is sufficient itself to fulfill the demands for future wireless systems, and adopting a hybrid access technique consisting of a joint utilization of overlay and underlay approaches is desirable. Furthermore, the key challenges and open research issues in radio spectrum resources utilization are discussed.

KEYWORDS

cognitive radio, hybrid access, network parameters, overlay, radio spectrum resources utilization, qualitative comparison, underlay

1 | INTRODUCTION

Nowadays, wireless communication has become an integral part of our daily life. In the 19th century, M.G. Marconi did the revolutionary work in the area of wireless communication by successfully establishing the first radio transmission system. Since then, wireless communication systems have experienced a steady growth while continuously improving our personal and professional life. Over the recent years, a number of wireless devices, applications, and services have been developed and launched into the market for a variety of purposes. Due to this advancement, consumers have shown an increased interest in these services. To continuously accommodate this growth in wireless services and applications, the demand for radio spectrum has grown exponentially, and in future, more radio spectrum will be required for smooth and uninterrupted functioning of new wireless services. As a result, it has become a big challenge to meet the challenges posed by future wireless systems by just applying the traditional ways of networking the world. As shown in Figure 1, the amount of wireless data traffic is expected to reach about 49 exabytes per month by the year 2021. According to this index, the global wireless data traffic is growing rapidly with an estimated compound annual growth rate[1] of 47% from 2016 to 2021. As a result, it is projected to inculcate outstrip improvements in the existing radio-frequency wireless technologies.

In Figure 2, it is shown that the growth in mobile video traffic is forecasted to reach around 55% annually up to 2021, and account for over two-third of the global mobile data traffic. These trends are accentuated by the growing use of embedded video in social media and web pages.

The trends in Figures 1 and 2 clearly emphasize for a huge demand of radio spectrum in future to meet the challenges posed by the new collective lifestyle. Wireless spectrum being a natural resource is very precious and scare, which is limited in its availability. Moreover, the majority of available radio frequencies have already been allocated. Despite this, its utilization is very poor in some frequency bands (such as TV transmission system, amateur radio, to name a few) and is intensive in consumer radio communication bands. This imbalance is a result of the current static allocation policies, which are still in use for the allocation of the spectrum. According to McHenry[4] and Martian et al,[5] the worldwide spectrum usage by the licensed (primary) users within the frequency range from 25 to 3400 MHz is very poor. Further, the frequency ranges 470 to 766 MHz and 880 to 960 MHz are currently in use by cellular phone networks. The licensed (primary) users' average utilization factor is only around 0.45 for these frequency ranges. The utilization factor for other frequency ranges is much lower. For instance, the utilization factor for the frequency range 960 to 1525 MHz is only about 0.0236. Accordingly, the mean utilization ratio covering the entire frequency range 25 to 3400 MHz was shown to be equal [5] to 0.12. The poor utilization of radio spectrum resources demands that the traditional and fixed spectrum allocation policies be reviewed by the spectrum regulatory authorities so that the radio spectrum resources can be exploited in a more effective and flexible way. The "Federal Communications Commission (FCC)" has regulated the spectrum since the 1930s, controlling the licensing of radio spectrum and providing it to the users in a particular geographical area. To overcome the shortage of radio spectrum, the FCC has been continuously proposing new ways to manage these radio resources. In this direction, one solution has been to enable any unlicensed user to use the licensed frequencies by ensuring that the interference perceived by the primary license holders will be minimal. With the advancement in software and cognitive radio (CR), there is a clear demand for the implementation of this solution in a near future. In 2003, the FCC

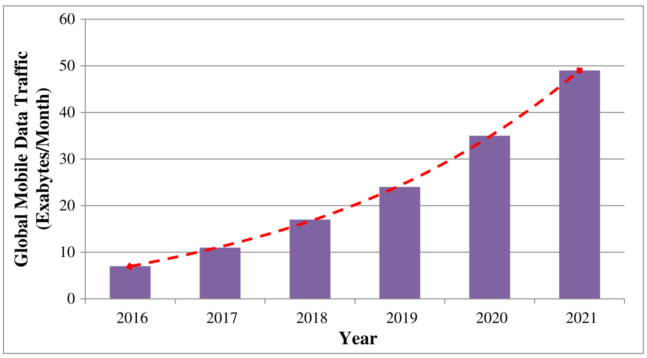

FIGURE 1 Trend in the growth of global mobile data traffic[2]

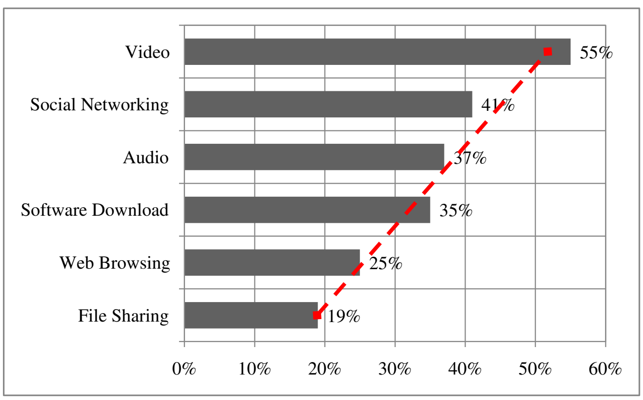

FIGURE 2 Application-wise trend in the growth of mobile data traffic[3]

released a memorandum seeking some comments on the interference temperature model for enhancing the utilization of the radio spectrum.

Due to the poor utilization of the radio spectrum, the CR technology has become a research hotspot in recent years. Accordingly, cognitive radio networks (CRNs) have become an area of research of great importance in the last decade, in both academia and industry. In Mitola and Maguire,[6] the concept of CR was defined for the first time. On the other hand, the software defined radio (SDR) concept[7] has been the driving force for the existence of CR in the current era. It was developed for the purpose of disengaging wireless networks from the hardware dependencies. Typically, SDR adds the programming capability to the radio devices. It also increases their flexibility in working on different radio frequency bands with different transmitting parameters. An SDR transceiver is capable enough to change its operating specifications according to the radio environment in which it operates. The following key functions of CR are described in-depth in Haykin[7]:

i) Interference temperature estimation
ii) Dynamic spectrum access
iii) Channel state estimation
iv) Spectrum hole detection
v) Transmit power control

Cognitive radio has been introduced as a key technology in many areas such as machine-to-machine communication, [8] cellular networks,[9] vehicular networks,[10] to name a few. In CRNs, the primary users (PUs or licensed users) are the license holders who have been allocated the radio spectrum bands for their usage while the secondary users (SUs or unlicense users) do not possess any license for utilization of these radio spectrum bands but can use a CR technique to access the radio spectrum on a temporary basis.[11,12] The paper is organized as follows. In Section 2, representative work on spectrum utilization are presented. In Section 3, spectrum access methods are discussed. In Section 4, overlay spectrum access techniques are compared against underlay spectrum access ones with respect to a set of criteria. Section 5 highlights some of the key challenges and open research issues in radio spectrum resources utilization. Section 6 concludes the paper.

2 | RELATED WORK

Spectrum access techniques in CRNs have been extensively studied in the literature.

Giupponi and Ibars [13] reported on the benefits of cooperative communication in CRNs. They proposed a new access scheme modelled according to the theory of exact potential games, which allows for a dynamic access of radio spectrum to the SUs assuming that the SUs cooperate with the PUs in terms of transmission. Oh and Choi [14] proposed a hybrid CR system that combines the underlay and overlay access techniques to allow the SUs to change their transmission mode from overlay to underlay in a probabilistic controlled manner. It is also argued that switching the transmission mode can greatly enhance the performance of the secondary network. Manosha et al [15] introduced a new cognitive system for the multioperator scenarios. In this model, the SUs transmit the data from the PUs in addition to their own data on the same frequency band. Also, asynchronous and synchronous techniques are used by the PUs to relay their data.

Zhu and Wang [16] proposed a hybrid spectrum sharing cognitive model, in which cognitive users can dynamically switch between the overlay and underlay mode. Simulation results are provided, showing promising results in terms of improved optimal transmission power for the underlying system. Ahhmadfard et al[17] investigated the design of a hybrid access method for CRNs, with emphasis on analyzing the ergodic capacity and power allocation aspects of the SUs when not much channel information is available to these users. Ma et al[18] proposed a hybrid CR model, where the PU behavior is characterized by a two-state discrete time Markov model. The probabilities of false alarm and missed detection are used to derive the sensing capability of the SUs, as well as their transmission capacity and the outage probability of the primary network. Senthuran et al[19] considered a cognitive system in which an SU can change its access method based on the access switching features of the PUs and the throughput ratio between the overlay and underlay modes. A Markov chain analysis is used to implement the proposed system, and the results obtained in terms of system performance using Monte-Carlo simulations are promising.

Zou et al[20] presented a CRN model in which a common relay is used by the SUs to transmit their data. An auction-based power-allocation technique is proposed to resolve the power issue that may arise among multiple SUs. A method is also provided to calculate the outage probability for the SUs. Zhang et al[21] proposed an energy-constrained CR system in which the CR is able to dynamically determine in which access mode it can operate so that it can share the spectrum with the licensed systems or perform the spectrum sensing to detect spectrum occupancy. The proposed dynamic control approach is modelled as a partially observable Markov decision process (POMDP) and important properties of the derived optimal policy are highlighted. Xueyuang et al[22] proposed a hybrid access method based on double-threshold energy detection, in which an SU user can change its access method between the full and partial access methods. Markov chain framework is used to model the proposed system, and finally, authors show the considerable improvement in system interfering probability through the use of the proposed method. Chraiti et al[23] investigated the design of a secondary broadcast network based on the orthogonal beamforming technique and developed different broadcast transmission schemes. In their approach, the rate of the served secondary receivers is used as metric to analyze the performance of the secondary broadcast networks, showing that the proposed transmission schemes improve the secondary outage probability.

Song et al[24] proposed a hybrid CR system that allows an SU to probabilistically change its access mode from overlay to underlay. Through simulations, the proposed hybrid system is shown to outperform the conventional CR systems. In the same vain, Xia and Aissa[25] addressed the problem of short range communication and proposed a cooperative amplify-and-forward relaying scheme based on an underlay access technique. Chu et al[26] investigated the hybrid interweave-underlay technique of spectrum access, which uses the amplify-and-forwarding relay scheme. A continuous-time Markov chain is use to model the proposed cooperative cognitive network based on different network parameters such as outage probability, outage capacity, and symbol error rate. Simulation results show that the proposed hybrid access technique outperforms the underlay approach. Usman and Koo[27] introduced the concept of energy harvesting, where the SUs can conserve the energy not only from the transmitted primary signals but also from other natural sources such as solar and wind. A POMDP framework is used to implement the considered system. Simulation results show that the proposed system can achieve up to 60% more throughput than the overlay access technique and 43% more throughput than the conventional hybrid access technique.

Karmokar et al[28] introduced a hybrid cognitive system, in which different opportunistic spectrum access techniques are investigated. A finite-horizon POMDP framework is used to implement the considered system, and the performance of secondary networks is maximized by allowing the switching of the transmission mode from overlay to underlay or vice-versa. Wang et al[29] proposed a hybrid transmission scheme to improve the transmission quality of CRNs. Their proposed optimal transmission methods are evaluated for both underlay and overlay access modes under different types of quality of service requirements, showing promising results. Gmira et al[30] proposed a novel spectrum access model that is based on the total count of the SUs that are present in the underlay mode as well as on the access probabilities of underlay and overlay access modes. A Markov chain framework is used to implement the proposed model. Simulation results are presented, showing that the proposed method enhances the throughput of the SUs. Kordali and Cottis[31] introduced the notion of spectrum trading in CRNs to propose a two-stage spectrum access and pricing game. For spectrum access, noncoordinated SUs have the ability to maximize their utilities by selecting the access method they wish to follow. For the pricing game, the operators pricing policy is determined from an optimization problem considering the operators revenues at the SUs equilibrium. Simulations conducted using various number of SUs and associated bandwidths show promising results in terms of spectrum utilization for both PUs and SUs.

Ewaisha and Tepedelenlio[32] studied a typical CR scenario in which a single SU accesses many channels simultaneously. This problem is modelled as a SU's throughput-maximization problem under the packet delay and power interference constraints. The proposed solution is validated by simulations, showing promising results in terms of throughput. Jasbi and So[33] proposed a multicarrier code division multiple access–based hybrid transmission scheme that can be used to minimize the interference level at the primary receiver by making use of the whole spectrum for underlay transmission and the spectrum holes for overlay transmission, in such a way as to improve the efficiency of the SUs transmission. Tong et al[34] proposed a power allocation and location-aware spectrum scheme for multiuser CRNs that exploits the space and frequency opportunities to avoid unnecessary spectrum sensing, yielding some reduction in node's energy consumption. Amer et al[35] introduced a cognitive model made of underlay and cooperative spectrum access techniques, in which an SU can make use of the licensed spectrum either in the underlay or cooperative mode along with admission control. Simulation results show an improvement in the performance of the underlying system in terms of spectrum utilization.

Yang et al[36] presented a generalized access strategy for a multichannel environment, for which only few channels among all the available ones are required for spectrum sensing. Simulation results show that the proposed access strategy outperforms the existing access schemes in terms of spectrum utilization and throughput. Gmira et al[37] proposed a spectrum access technique that can be used to improve the power consumption and efficiency of the SUs transmission when performing the spectrum sensing. Game theory is used to model the problem of spectrum allocation, and a Nash equilibrium is used to solve it. Do et al[38] investigated the connectivity of a hybrid CR ad hoc network and proposed an algorithmic-based technique to calculate the path probability, meant to be a measure of network connectivity.

3 | SPECTRUM ACCESS METHODS

Different models used in dynamic spectrum access approaches are shown in Figure 3. In comparison to dynamic exclusive use and open sharing models, the hierarchical access model has been reported as the most consistent radio spectrum management policies. This is further divided into spectrum underlay access and spectrum overlay access (also referred to as opportunistic spectrum access) methods.

3.1 | Overlay approach

In Figure 4, the idea of the overlay access method is illustrated, where the green color shows the PU transmission and the blue color shows the SU one.

In this access method, noncognitive users share knowledge of their messages and signal codebooks with the cognitive users. This method has a peculiar feature, namely, the SUs are only allowed to access the spectrum when it is not in use by the PUs. Whenever an SU wishes to access the spectrum, it has to sense the radio spectrum to identify the spectrum availability before starting the transmission. If the SU does not succeed to access the spectrum during the current time slot, it will sense the channel again for the next time slot, and so on. If at any point in time, a PU wishes to access the channel, all the SUs using that channel must vacate it immediately.

3.2 | Underlay approach

Figure 5 illustrates the idea of underlay access method, where green color shows the PU transmission and the blue one shows the SU transmission.

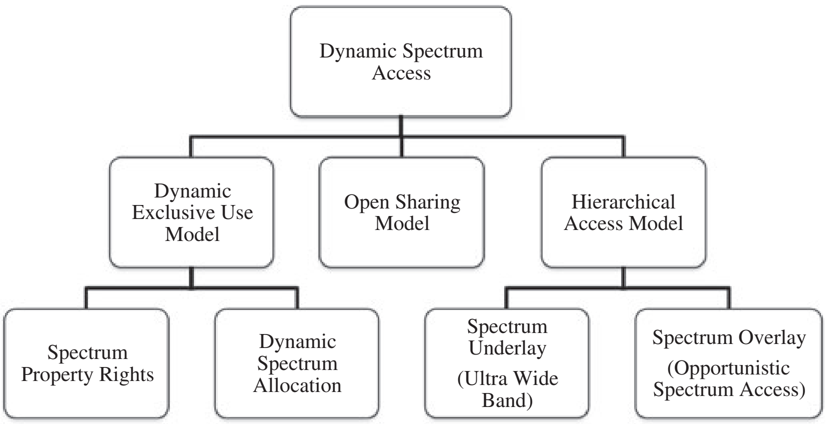

FIGURE 3 Spectrum access methods[39]

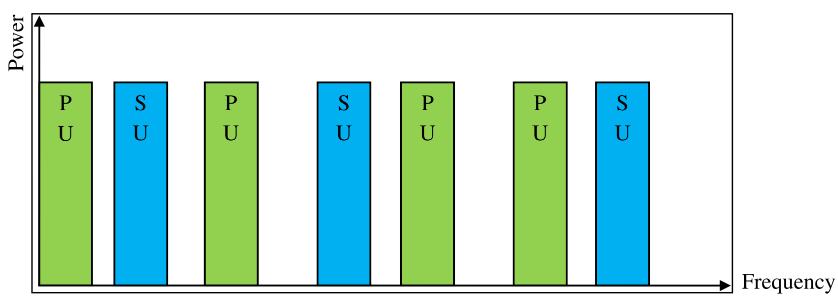

FIGURE 4 Overlay approach. PU, primary user; SU, secondary user

In this access method, simultaneous cognitive and noncognitive transmissions are allowed as long as the interference level at the PU side is kept at an acceptable level. The SUs do not have to wait for the transmission until the channel is made idle by the PUs. Rather, they can jointly transmit with the PUs by maintaining the interference level below a prescribed interference threshold limit (ITL), shown in Figure 5 by the red horizontal line. Despite the fact that the spectrum is available all the time, the spectrum bands are not fully exploited because of the restriction in the transmit power, which imposed that the predefined ITL condition be satisfied. Maintaining the interference below the threshold value at the primary receiver is a challenging task when dealing with the underlay access method. In practice, feedback mechanisms are required for updating the SUs transmitters periodically with the value of the instantaneous interference generated on the primary receivers. Because of this requirement, underlay CRNs have not been widely used for certain frequency bands such a the TV band. Indeed, these networks are more deployable in frequency bands with comparatively sparse primary receivers, for instance, in radar communication or fixed microwave communication bands. They are especially appealing when deployed in widespread cellular networks.[25]

3.3 | Hybrid approach

In conventional overlay or underlay CR systems, maintaining the stability of the SU's queue is a challenging task. This factor motivates the design of hybrid access methods. Figure 6 illustrates the idea of hybrid access method, where the green color shows the PU transmission, the blue color shows the SU transmission, and the red horizontal line shows the ITL. This access scheme[40] combines the features of overlay and underlay access methods to further capitalize the unused and underutilized spectrum bands, thereby provides a great potential to enhance the efficiency of spectrum sharing by allowing SUs to maximize their transmission rate once a spectrum opportunity is detected. Ideally, using this access method, an SU would transmit the data with higher transmit power in overlay mode if the PU is absent and would transmit the data with lower transmit power in underlay mode if the PU is present.

This method also maintains the ITL at the primary receiver's side. The SUs are aware of the status of the PU transmission, as well as the interference power they have generated at the primary receivers. Accordingly, unlike the underlay access method, the SU can transmit with maximum power by ignoring the ITL when the PU is not active. Furthermore, unlike the overlay method, an SU can transmit with limited power even when the PU is active, by maintaining the ITL. There are several ways that the benefits of hybrid access methods can be maximized. For instance, in Chakravarthy et al,[41] a cognitive user transmits the data bits over the unused frequency bands by using the overlay method and transmits the redundant bits (ie, parity bits) over the underutilized frequency bands by using the underlay method. Most of the pre-

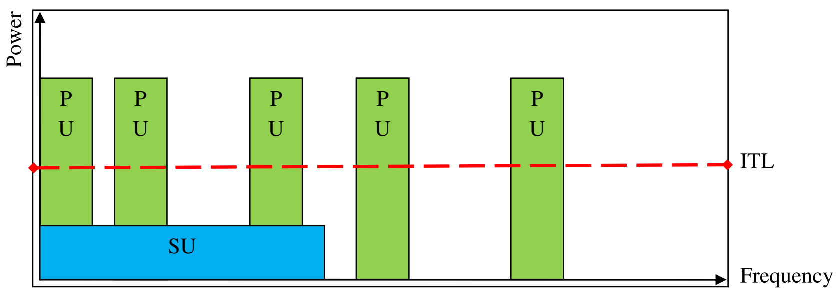

FIGURE 5 Underlay approach. ITL, interference threshold limit; PU, primary user; SU, secondary user

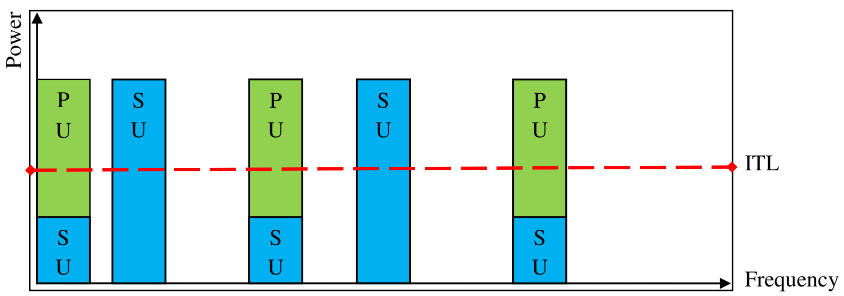

FIGURE 6 Hybrid approach. ITL, interference threshold limit; PU, primary user; SU, secondary user

vious works on hybrid methods[24,26] have reveal that these methods always outperform the overlay and underlay access methods while neglecting the recursive effects between PUs and SUs. For instance, the interference caused by an SU due to sensing errors in the overlay method or the interference generated in the underlay method due to ITL violation could degrade the PU's performance. Consequently, the PUs will attempt to balance the performance loss by raising the transmit power level or by retransmitting the data. These reflections of the PUs will again affect the SU's performance. However, in some situations, using a hybrid access scheme is not necessary appropriate.[26] For example, that is, case when the secondary transmitter and the primary receiver are situated at a distant apart and the predefined ITL is satisfied by the SU's transmission. In this case, an SU can transmit its data with the maximum available power without considering the ITL constraint. Consequently, in some situations, it is possible that the overlay method outperforms the hybrid method.

4 | OVERLAY VS UNDERLAY METHODS

Our literature review has revealed that there are several criteria for comparing the performance of overlay and underlay access methods. Table 1 summarizes these criteria with respect to their applicability to either the underlay or overlay approach. In this regard, a discussion on the relevant features follows.

4.1 | Dependency on the PU's appearance

In the overlay access method, an SU may use a particular frequency band providing that it is not being accessed by the PU. On the other hand, in the underlay access method, an SU may coexists with the PU and transmits with limited power to assure the QoS to the PU. Therefore, it is obvious that the overlay access method depends on the existence of the PU in a channel whereas the underlay access method is not dependent.

4.2 | Spectrum availability

The underlay method is more aggressive in terms of availability of spectrum since under this approach, an SU may transmit in the presence of the PU by maintaining the ITL at the primary receiver, which justifies the availability of the spectrum at all time. This is not true in the overlay access approach since the SUs can only transmit their data when the PUs are absent.

4.3 | Waiting time for transmission

In the overlay method, the waiting time for transmission depends on the PU's behavior, which in turn is intermittent in practice. Accordingly, the waiting time for the SUs vary under this method. On the other hand, in the underlay approach, an SU may experience a gain in the waiting time to further use the channels since it has the possibility to transmit at any point in time as long as the ITL is met at the primary receiver.

4.4 | Negotiation among SUs

In the overlay access approach, to achieve a reliable sensing, it is mandatory that all the SUs sense the channel during the quiet period. During this period, they must postpone their transmission activities so that each SU is able to observe the status of the primary signals. In the underlay access method, an SU does not need to negotiate with other SUs to access the spectrum.

4.5 | PU protection

An accurate detection of the PU's transmission is necessary to ensure the QoS to the PUs. In practice, this is difficult to achieve due to shadowing and fading effects.[42,43] Thus, a PU cannot be considered as completely independent from the activities of an SU. If the sensing mechanism is imperfect, which may be the case in the overlay access approach, the primary protection will be required if the PU occupies the channel. In the underlay mode, the transmit power needs to be controlled all the time to prevent the primary receiver from harmful interference.

TABLE 1 Overlay versus underlay

S. no.	Criterion	Overlay access method	Underlay access method
1	Dependency on PU's appearance	YES	NO
2	Spectrum availability	On PU absence	All the time
3	Waiting time for transmission	Vary	No waiting
4	Negotiation among the SUs	Required	Not required
5	Primary user protection	On PU appearance	All the time
6	Sharing of spectrum	Not shared	Shared
7	Type of spectrum space exploited	White space	Gray space
8	Region	Suitable for rural areas	Suitable for urban areas
9	Interference tolerance	Not required	Required
10	Power control	Not required	Required
11	Type of network side information	Spectrum holes	Interference level
12	Spectrum sensing	Required	Not required
13	High miss detection probability (P_m)	Not suitable	Suitable
14	High false alarm probability (P_f)	Not suitable	Suitable
15	Feedback-channel state information (CSI)	Not required	Required
16	High primary arrival rate	Not suitable	Suitable
	Low primary arrival rate	Suitable	Not suitable
17	High Channel idle probability	Suitable	Not suitable
	Low channel idle probability	Not suitable	Suitable
18	Long mean interarrival time of primary users	Suitable	Not suitable
	Short mean interarrival time of primary users	Not suitable	Suitable
19	Heavy primary network load	Not suitable	Suitable
	Light primary network load	Suitable	Not suitable
20	High primary network's spectrum access probability	Not suitable	Suitable
	Low primary network's spectrum access probability	Suitable	Not suitable
21	High channel transition probability	Not suitable	Suitable
22	Large number of primary channels	Suitable	Not suitable
	Small number of primary channels	Not suitable	Suitable
23	Short distance between primary user and secondary user	Suitable	Not suitable
	Long distance between primary user and secondary user	Suitable	Better
24	Transmission range	Suitable for long range	Suitable for short range
25	Delay constraint QoS	Suitable for loose delay Constraint	Suitable for stringent delay Constraint
26	High average transmit SINR	Suitable	Not suitable
	Low average transmit SINR	Not suitable	Suitable
27	High outage probability of PU	Not suitable	Suitable
	Low outage probability of PU	Better	Suitable
28	Energy consumption	High	Low
29	Low energy available at the nodes	Not suitable	Suitable
30	High interfering probability	Not suitable	Suitable
	Low interfering probability	Better	Suitable
31	Network connectivity	Not suitable	Suitable
32	Complexity	Low	High
33	Practicality	More practical	Less practical
34	Application	TV bands	Radar or fixed microwave communication bands, ultrawide bands, cellular networks

Abbreviations: PU, primary user; SINR, signal-to-interference-plus-noise ratio; SUs, secondary users.

4.6 | Sharing of spectrum

It is quite obvious that the frequency bands are shared in underlay scheme because both the PUs and SUs can simultaneously transmit their data in parallel, which is not the case in the overlay access method since at any time, either of the PU or SU is transmitting.

4.7 | Type of spectrum space exploited

Three types of spectrum bands are observed by a radio device when it scans the radio spectrum at any particular location, namely, (1) almost unused frequency bands, (2) partially used frequency bands, and (3) heavily used frequency bands. Those bands that are unoccupied most of the time have led to the notion of spectrum holes (or white spaces), ie, a range of frequencies already allocated to the PUs, but not used at a peculiar location and time.[7] Those bands that are partially used for a very short period have led to the notion of gray spaces, which promote the idea that a particular part of the spectrum that is not fully used by a PU may be used by an SU if the later can maintain the ITL generated at the primary receiver. Accordingly, in the overlay access approach, white spaces are used whereas in the underlay access method, gray spaces are used.

4.8 | Region

When the radio spectrum is not fully occupied (such as in rural areas), the SUs are more in-kind to seek for the unused spectrum bands. Thus, the overlay method would be a preferred option for data transmission. On the other hand, in urban areas where network nodes are densely deployed, chances of getting the unused spectrum bands are very rare. In those areas, the underlay access method is helpful for improving the spectral efficiency.

4.9 | Interference tolerance

The interference temperature represents the tolerable ITL at a primary receiver because of the transmission of SUs. It is equivalent to the radio frequency power available at the PU's receiving antenna per unit of bandwidth (measured in units of Kelvin), and it can be calculated[13] as

$$T_i(c_i, B_c) = \sum_{j=1}^{N} \frac{P_j^s h_{ji}^{sp} f(c_i, c_j)}{KB_c} \qquad i = 1, \dots, M,$$

where $T_i(c_i, B_c)$ is the interference temperature received by the PU's receiver i in the channel c_i, M is the transmitting-receiving PU's pairs and N is the transmitting-receiving SU's pairs, P_j^s is the secondary transmitter power, h_{ji}^{sp} is the link gain between an SU's transmitter j and a PU's receiver i, $f(c_i, c_j)$ is equal to 1 if $c_i = c_j$ or 0 or if $c_i \neq c_j$, B_c is the bandwidth, and K is the Boltzmann's constant.[44] In the underlay method, the interference tolerance is required all the time because of the parallel transmission of the PU and SU. Furthermore, the capacity of the SUs in the underlay mode increases as the ITL increases.[17] This restriction is not imposed in the overlay method since the SUs can transmit their data with the maximum available power. In Senthuran et al,[19] the interference threshold constraint (Υ_s) at the primary receiver is obtained as $\frac{P_p L(R)}{P_u L(D) + P_n} > \Upsilon_s$, where P_p is the pilot power of the primary transmitter, P_u is the power of the cognitive transmitter in the underlay mode, R is the communication range of the primary transmitter, D is the interference range of the cognitive transmitter, and $L(D)$ and P_n are, respectively, the total path loss at distance D from the transmitter and the noise power level at the primary receiver.[45]

4.10 | Power control

Power control is required in the underlay method because of the parallel transmission of cognitive users with the PU, but it is not required in the overlay method because the secondary transmission is only allowed in the absence of the PU.

4.11 | Type of network side information

For a proper utilization of the available spectrum, the network side information is required in both the overlay and underlay CRNs. In overlay networks, the SUs should know the available spectrum holes, which can be detected using spectrum sensing techniques. In underlay networks, it is required that the interference generated by the SUs at the primary receiver be known to acquire the network side information.

4.12 | Spectrum sensing

In overlay access method, an SU can use a free portion of the spectrum band that has been permanently allocated to the PUs. To achieve a successful utilization of these spectrum holes, 2 kinds of spectrum sensing must be performed by the SU, namely, out-of-band and in-band sensing. At the beginning of the transmission, the SU must perform the out-of-band sensing[46] and if a spectrum hole is detected, it can then transmit its own data on this free spectrum hole. While transmitting, the SU must also monitor the spectrum band for any potential reappearance of the PU by conducting an in-band sensing; that way, it can stop its own transmission and free up the occupied channel when the PU reappears for transmission.[47] On one hand, detecting the primary status by using spectrum sensing allows the SUs to transmit their data with a much higher transmission power, leading to performance enhancement. On the other hand, spectrum sensing necessitates a reasonable amount of time, which may jeopardize the data transmission time, resulting to a network performance degradation. In practice, in the overlay method, the SU needs to execute spectrum sensing to identify the channel's state. Suppose that at a specific time slot α, the spectrum sensing time is t_α, then the available effective transmission time is only $(T - t_\alpha)$, where T is the total available time. It should be noted that t_α depends on several network parameters and may varies greatly according to the type of sensing technique used during the spectrum sensing process. Accordingly, the available effective transmission time $(T - t_\alpha)$ for the SUs also varies, which affects the network performance. In the underlay method, spectrum sensing is not required since this form of access is allowed when the PU is present.

4.13 | High miss detection probability (P_m)

In the overlay method, the performance of the CRN depends on the accuracy of the sensing algorithm, measured by means of the missed detection probability (P_m)—ie, the probability that the SU detects that a primary channel is idle even though it is busy, and the false alarm probability (P_f). Due to the limitation imposed on the spectrum sensing time, signal attenuation and multipath fading, spectrum sensing cannot be perfect. Therefore, the miss detection may lead to interference at the PU, and a high value of P_m may disturb the primary communication, resulting to significant loss in network performance. In this particular scenario, underlay is better than overlay method. From a PU's perspective, it should be noted that lower values of P_m yields a higher protection for the PUs.

4.14 | High false alarm probability (P_f)

The false alarm probability P_f is defined as the probability that the SU detects that a primary channel is busy even though it is idle.[14] A higher value of P_f results in an underutilization of the available spectrum holes, and this justifies why using the underlay method is better than using the overlay method in this case. The false alarm probability can be improved by many means, for instance, using the double-threshold energy detection scheme proposed in Jiang et al,[22] which provides a false alarm detection performance trade-off to the near-side and far-end PUs by properly rearranging the long and short spectrum sensing durations, leading to a trade-off between decreasing the miss detection probability and decreasing the false alarm probability.[18]

4.15 | Feedback-channel state information

The feedback-channel state information (CSI) is required periodically in the case of underlay access to update the secondary transmitter with the interference level generated at the primary receiver. It is not required in the case of overlay method since the transmission takes place only in the absence of the PU. However, it is not feasible to achieve the perfect knowledge of the CSI because of the various factors (such as channel estimation errors, instantaneous channel variations, and feedback errors) that are involved in the spectrum allocation process; and the fact that an SU has to periodically sense the pilot signal transmitted by the PU to acquire the CSI between an SU and a PU. In a real wireless system, robust system design is of practical importance since all the relevant channels are not known perfectly. Therefore, any robust system design must consider the case of imperfect CSI and ensure that the generated interference to the primary receiver is well below the prescribed ITL.[25]

4.16 | Primary arrival rate

The primary arrival rate is defined as the rate by which the packets come into the input queue of a PU. When the primary arrival rate decreases, the efficiency of the overlay method is better compared to that of the underlay method because more spectrum holes will be available most of the time. The opposite is true when the primary arrival rate increases.

4.17 | Channel idle probability

The channel idle probability is directly related to the primary arrival rate. In fact, when the arrival rate is high, the channel idle probability is low and vice versa. For low channel idle probability, the underlay method may perform better than the overlay one because less opportunity will be available for free spectrum holes. The opposite is true when the channel idle probability is high.

4.18 | Mean inter arrival time of PUs

This parameter directly reflects the available load in the network at a particular time. If the mean interarrival time of the PUs is short, it means that there will be more number of PUs available in the network and less chances of spectrum being idle. This is why the underlay method may perform better than the overlay one. If the mean interarrival time of the PUs is longer, the overlay method may perform better than the underlay one for the same reason as above.

4.19 | Primary network load

The primary network load directly affects the primary network's spectrum access activities and the CRN performance. It varies with time and can be well reflected by the primary network's spectrum-occupancy probability. The heavier network load will result in high spectrum-occupancy probability; therefore, there will be less chances of getting free spectrum holes. This in turn implies that the underlay access method is a better approach for the considered scenario.[29] On the contrary, if the network load is light, the overlay access method may outperform the underlay access one.

4.20 | Primary network's spectrum access probability

The primary network's spectrum access probability will influence the efficiency of both the underlay and overlay access methods. It is not unexpected because as it increases, there will be less spectrum opportunity available for the SUs for data transmission, leading to reduced performance of the overlay method. Furthermore, when the primary network's spectrum access probability decreases, the overlay method may outperform the underlay one.[17]

4.21 | High channel transition probability

The channel transition probability reflects the rate at which a channel changes its state from one state to another. For example, a channel may switch from busy to idle, idle to busy, busy to busy, and idle to idle state. When the channel transition probability is very high, the channel jumps from one state to another very quickly. In this case, the free spectrum opportunity in overlay mode becomes intermittent and the performance of this method is not be very consistent; therefore, the underlay method may outperform the overlay one. Further, if the self state transition probability is very high and the channel is in idle state, the overlay method may provide a good performance compared to the underlay one because in that case, the selected channel will remain in the same state for an extended period. If initially, the channel is in the idle state, it will remain in that state for a longer period and there will be fewer chances of moving it into the busy state. As a result, the overlay method may perform better than the underlay one.[28]

4.22 | Number of primary channels

When there are many channels available in the network, an SU has to decide the number and order of channels that need to be sensed. Next, it senses the first channel and if the sensed channel is found to be idle, the SU stops the sensing process, otherwise it will continue sensing the next channel in a pre-decided sequence. If the number of primary channels N gets increased, the performance of the overlay method is enhanced due to the availability of more number of free channels for the secondary transmitter. However, it is opposite for lower values of N.[28] For lower N values, the underlay access method may perform better than the overlay one. Furthermore, in comparison to the single channel CRN, the gross average throughput in multichannel CRNs heavily relies on the total number of sensing channels, the order of sensing, and the sensing times, of the selected channels.

4.23 | Distance between PU and SU

It is natural for the SUs at different locations to use different spectrum access methods. For example, the SU close to/or inside the primary system cannot share the channel with the PU because of the presence of high interference, hence the overlay spectrum access should be considered, while the SUs located far from the PU system may use an underlay spectrum access in addition to the overlay one.

4.24 | Transmission range

In the underlay access method, the transmit power of the SUs is restricted by the prescribed ITL, which confines the underlay CR to short-range communications. The overlay method can also support long-range communication since the SUs can transmit with the available maximum power without considering the ITL. In Do et al,[38] the disk communication model[48] is used to define a connection between 2 nodes assuming that the distance between any 2 nodes is the only available information for the nodes to establish a connection. More precisely, assuming that a node sends a signal with transmit power P_{tx} using an omnidirectional antenna, the node's communication range R is obtained as $R = \frac{\sqrt{G_t G_r}\times c}{(4\pi f\sqrt{P_{rx}^{th}/P_{tx}})}$, where G_t and G_r are, respectively, the transmitting and receiving antenna gains, c is the speed of light, f is the operating frequency, and P_{rx}^{th} is the threshold power for receiving a signal.

4.25 | Delay constraint QoS

Quality of services (QoS) parameters should be considered when evaluating the performance of CRNs. Specifically, when the delay QoS requirement is loose (ie, the CRN can tolerate longer delay[29]), it will opt for the overlay access method to transmit its data. For stringent QoS requirements (ie, case where the CRN cannot tolerate longer delay), it needs to assure a minimum data rate for the entire duration of data transmission. Accordingly, the underlay method is a preferred choice for data transmission compared to the overlay one. For loose delay QoS constraint and delay-insensitive applications, the ergodic capacity metric[49] is often used whereas for stringent delay QoS constraint applications, the outage capacity metric[26] is often considered.

4.26 | Average transmit signal-to-interference-plus-noise ratio

A successful communication occurs only when the received signal-to-interference-plus-noise ratio (SINR) at the reference receiver is greater than a given threshold. If the SINR value perceived by the SU is high or above a threshold level, the SU can easily detect the presence of the PU. On the other hand, if the SINR value is very low, the detection of the PU presence or absence by the SUs becomes difficult and the SUs may have an incorrect status of the PUs, which may degrade the performance of their transmissions. Due to this, the overlay access method is good for higher value of SINR and the underlay access method is good for lower value of SINR.

4.27 | Outage probability of PU

This is defined as the probability that a PU n perceives an SINR subject to the following condition: $I_n < RdB$, where I_n represents the value of SINR perceived by the PU and R is the predefined threshold set according to the primary receiver's sensitivity.[13] Since a successful communication occurs only if the received SINR at the reference receiver is greater than a given threshold,[18] it is clear that for higher values of outage probability, the underlay method may outperform the overlay one.

4.28 | Energy consumption

In the overlay method, a reasonable amount of energy is consumed during the sensing process to detect the status of the primary transmission. In this sense, the detection capability of the SU is expressed by the probability of detection P_{d}. As reported in the CR standard[27] IEEE 802.22, the relationship between this probability and the overlay sensing energy threshold λ_{O} is expressed as $P_{\mathrm{d}} = Q_{\mathrm{M}}(\sqrt{2\beta}, \sqrt{\lambda_{\mathrm{O}}})$, where Q_{M} is the Marcum Q-function and β is the "signal-to-noise ratio" of the primary signal obtained at the SU. On the other hand, in the underlay method, the SU saves this energy and use it for data transmission purpose.In the literature, most of the proposed spectrum access techniques[27] try to maximize the throughput of the SUs. However, few other performance metrics deserve consideration in practice. Indeed, the throughput enhancement brings computational burden on the SUs, resulting to an increased latency and more energy consumption in the network. Accordingly, there is a requirement for an optimal solution that provides a trade-off between throughput, latency, and energy. One such solution is provided in Usman and Koo,[27] with focus on energy harvesting as a mean to further extend the life of the secondary nodes.

4.29 | Low energy available at the nodes

Wireless devices are battery operated, and energy plays a crucial role in the selection of any transmission technique. For smaller amount of available energy, the underlay method is better than the overlay one because it consumes a large amount of energy in the sensing phase. In addition, the transmission activity depends on the sensing process and the energy available at the nodes. Accordingly, if an SU does not have enough energy for sensing the spectrum, this user would sit idle in place of doing transmission and ultimately, there will be no throughput gain for this user, resulting to a significant throughput degradation for the secondary network.

4.30 | Interfering probability

The interfering occurs when the SU creates some disturbances at the PU, ie, when an SU miss detects the PU's signal and its transmission power does not account for the ITL of the primary receiver. The interfering probability is jointly determined by the miss-detection probability and the average interference constraint violation probability.[22] When this probability is high, there will be more disturbances from the SU to the primary receiver; thus, the performance of the overlay method will be degraded. Therefore, the underlay access method would be a preferred choice for the secondary transmission with a restricted transmission power. When this probability is lower, the overlay method may perform better compared to the underlay one with increased transmission power.

4.31 | Network connectivity

Network connectivity is measured by the path probability, which is the probability that 2 randomly selected nodes in the network are connected[50] through a direct or multihop path. Different from traditional ad hoc networks, connectivity of CRNs is affected by the behavior of the PUs and the relative positions between the SUs and PUs.[38] In addition, it depends on the number of active PUs. More active PUs means lower path probability. As the network connectivity rely on the number of active PUs, the connectivity when using the overlay method varies with respect to the activity of the PUs. On the other hand, the connectivity when using the underlay method will be better than when using the overlay one, providing that the total generated interference due to the secondary transmission be less than the prescribed threshold value. Furthermore, increasing the ITL may provide a better connectivity, but this may also violate the operation of the primary network. As shown in point number 24 of Table 1, the communication range R of a node under the heading transmission range can be obtained as $R = \frac{\sqrt{G_t G_r} \times c}{(4\pi f \sqrt{P_{rx}^{th}/P_{tx}})}$, where P_{tx} is the node's transmit power, G_t and G_r are, respectively, the transmitting and receiving antenna gains, c is the speed of light, f is the operating frequency, and P_{rx}^{th} is the threshold power for receiving a signal (ie, the receiver's sensitivity). The 2 nodes establish a connection if the received power P_{rx} of the other node is larger than the threshold power P_{rx}^{th}.[38]

4.32 | Complexity

Since the PUs are licensed users that have the authority to use the spectrum permanently assigned to them, the SUs can only use these frequency bands when they are not in use by the PUs, providing that the primary transmission be protected. Thus, the utilization of these spectrum bands by the SUs is a challenging task when the parallel transmissions of SUs and PUs occur. In the underlay access method, the data transmission is more problematic for the cognitive and PUs since higher interference may occur, leading to interference mitigation.

4.33 | Practicality

Although both overlay and underlay access methods have their own practical areas, the overlay CR system is considered more functional than the underlay one because in the overlay CR method, no instantaneous knowledge about the interference level is required.

4.34 | Application

Overlay CR networks are suitable for those environments where the possibility of available spectrum holes is large, for instance, in TV bands in rural areas during the nighttime. In the underlay method, a feedback mechanism is needed to inform the CR transmitter periodically about the level of the generated interference at the primary receiver. Due to this requirement, underlay CR networks are not very handy to be used in specific frequency bands such as TV bands. These networks are most suitable for use in frequency bands with a relatively sparse primary receiver such as in radar communication or fixed microwave communication bands. On the other hand, underlay CR networks are well suited for ultrawide bands and they can be used in widespread cellular networks.

5 | SIMULATION RESULTS AND ANALYSIS

In Section 4, we revealed that there are several criteria for comparing the performance of overlay and underlay access methods. Table 1 also summarizes these criteria with respect to their applicability to either underlay or overlay approach. Here, we present and discuss the simulation results performed on different network parameters, namely, PU arrival rate, throughput, sensing duration, and energy consumption for both the access methods. We use OMNeT++ simulator[51] for the simulation purpose. Below, Table 2 shows the simulation parameters used in simulation.

To analyze the effect of the PU activity on the performance of secondary network, throughput is measured for overlay and underlay access methods in Figure 7. This figure shows the average throughput for different PU arrival rate for both the methods. From Figure 7, it is clear that when the primary arrival rate is low, the efficiency of the overlay method is better as compared to the underlay method because spectrum holes are available most of the time. Then an SU capitalizes these spectrum holes with the maximum available power to achieve higher throughput in overlay mode. Further, when the primary arrival rate increases, then the throughput in overlay mode decreases very rapidly due to the nonavailability of spectrum holes for most of the time. On the other hand, performance in the underlay mode is nearly consistent throughout the entire range of primary arrival rate, due to the fact that a secondary transmission with the limited transmission power

TABLE 2 Simulation parameters

Parameter	Value
Total simulation time	10 000 s
No. of iterations	10
No. of PUs	2
No. of SUs	2
No. of primary channels	1-2
Channel data rate	1 Mbps
Packet length	2000 Bytes
Energy consumed/sensing signal	1 mJ

Abbreviations: PUs, primary users; SUs, secondary users.

is also allowed in parallel to the primary transmission. It is worth noting that the simulation results obtained in Figure 7 support our analysis in point numbers 1 to 3, 5 to 6, 9 to 10, and 16 to 20 of Table 1.

Next, to analyze the effect of the sensing process on the performance of secondary network, throughput is considered for overlay and underlay methods in Figure 8. Figure 8 shows the average throughput for different sensing duration for both methods. This figure clearly shows that the throughput for both methods is decreasing when the sensing duration is increasing. This is due to the already mentioned fact in Subsection 4.12, that when a secondary node is consuming more time in sensing, then less time is left for the data transmission. Underlay throughput is lower than overlay for the entire range of sensing duration, because of the restriction on transmission power in the underlay mode. On the other hand, this power restriction is not applicable for the overlay mode, which ultimately contributes to the higher throughput for this mode. Finally, the trends in the Figure 8 support our analysis in point numbers 5, 9, and 10 of Table 1.

Finally, in Figure 9, we analyze the effect of sensing process on the energy level of SU. Figure 9 shows the energy consumption of SU during the sensing process for different sensing duration. This figure clearly shows that an SU in overlay mode consumes much more energy as compared to the energy consumed in underlay mode. This energy difference is the

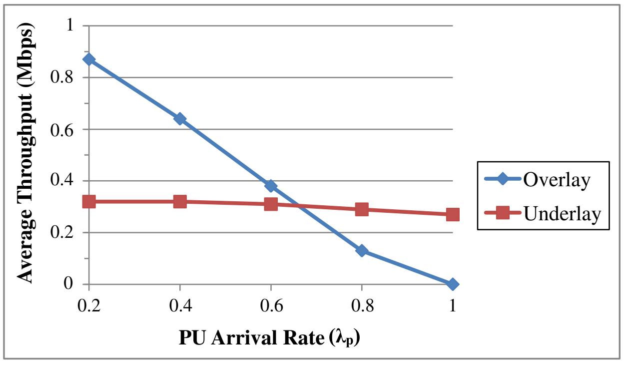

FIGURE 7 Secondary user throughput versus primary user (PU) arrival rate

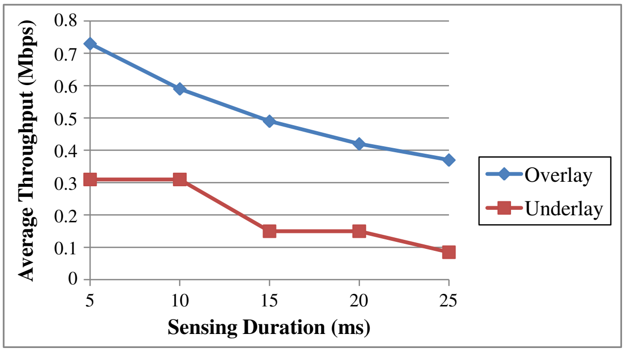

FIGURE 8 Sensing duration versus Secondary user throughput

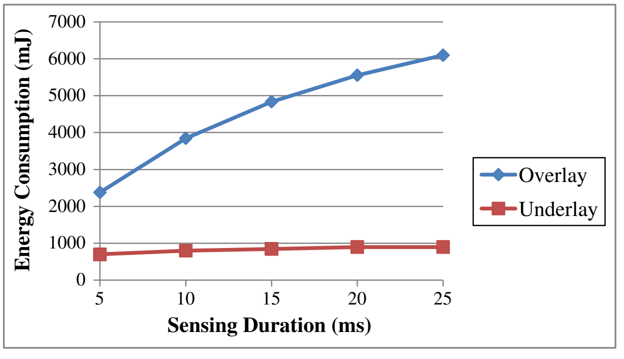

FIGURE 9 Sensing duration versus energy consumption

result of separate sensing activities in the overlay and underlay modes. As mentioned earlier in subsection 4.12, to achieve a successful utilization of the spectrum holes, an SU must perform 2 kinds of spectrum sensing, namely, out-of-band and in-band sensing. At the beginning of the transmission, an SU must perform the out-of-band sensing and if a spectrum hole is detected, it can then transmit its own data on this free spectrum hole. While transmitting, an SU must also monitors the spectrum band for any potential reappearance of the PU by conducting an in-band sensing. While on the other hand, an SU in underlay mode performs only out-of-band sensing, just to detect the presence of a PU and subsequently limits its own transmission power for further transmission in parallel to the primary transmission. Figure 9 also shows that the energy consumption for both the modes is increasing with the increasing value of sensing duration. This trend is the result of the fact that more sensing duration means more time an SU is spending in the sensing activity, which finally leads to the more energy consumption. Further, the trends in the Figure 9 support our analysis in point numbers 12, 28, and 29 of Table 1.

6 | CHALLENGES AND RESEARCH ISSUES

Spectrum assignment is considered as a key design parameter for an effective implementation of CR technology in future wireless networks.[38] In this paper, a macro view on spectrum access methods (overlay, underlay, and hybrid) is presented.

6.1 | Imperfect spectrum sensing

The performance in overlay access heavily depends upon the quality of the spectrum sensing process. It is a challenge to achieve a perfect spectrum sensing in a practical scenario. Most of the existing works assume the sensing process to be perfect, and future work in this direction includes imperfect spectrum sensing and the quest for new ways to manage the generated interference between the PUs and SUs.

6.2 | Multiple channel access

It has been reported that most of the existing access strategies[52] are applicable to single channel CRNs, where a cognitive user is allowed to access only one channel at a time. However, recent advances on physical technologies, such as orthogonal frequency division multiplexing, enable an SU to access multiple channels at a given time. One of the major challenges in a multichannel CR system is the sequential nature of the spectrum sensing, where an SU needs to decide to stop and begin its transmission or continue the spectrum sensing based on the information it has so far. This decision needs to trade-off between waiting for a potentially higher throughput and taking advantage of the current idle channel. Accordingly, designing an effective spectrum access technique for multichannel CRNs that can maximize the performance by keeping the interference below the ITL is still an open problem.

6.3 | Imperfect CSI

Achieving a perfect CSI in a practical scenario is another challenge. In fact, multiple antennas at the SUs can be used to diminish the interference level at the primary receiver and thereby extend the spatial diversity to improve the performance of the SUs. But space opportunity, which can be used to enhance the spectrum efficiency, was not considered in most of the existing work.[34] Furthermore, interference cancellation techniques can also be used to reduce the interference generated by the PUs. In a real scenario, the information received by an SU about the PUs can be used to reduce the interference level at the secondary receiver, for instance, by means of the dirty paper coding technique.[53]

6.4 | PU behavior

In most of the previous works, it was assumed that (1) the packets are transmitted on a time-slotted basis and only one packet is allowed for transmission in the each time slot[14]; (2) the channel state remains unchanged within a time slot; and (3) the state transition of the primary channel (either due to the PU's behavior or due to channel fading) only happens at the beginning or end of each time slot. These assumptions do not always prevail in a practical scenario. Some of the existing works also assumed that the PU's traffic has a positive correlation with the time, ie, when a PU occupies a particular channel, it remains in that channel for the next few slots. It is worth noticing that negatively correlated traffic may also be considered in future work on CRNs.

6.5 | Quality of service

Most existing works in CRNs focus on maximizing the throughput or capacity of the network by paying attention to the QoS in terms of data transmission. Achieving QoS (often measured delay in QoS) in a cognitive environment is a challenge. Although the capacity of a CRN can be enhanced by a proper resource allocation strategy, most existing resource allocation techniques in CRNs rely on the use of the information theory concept.[49,54-62] In these works, the network throughput is enhanced either for the case of no delay constraint (using the ergodic capacity metric) or with a stringent delay constraint (using the outage capacity metric). But, in practical scenarios, various other types of delay constraints may be required to fulfill the demand of wireless applications. Therefore, the information theory framework may no longer be directly applicable in order to achieve the delay QoS requirements. In this case, the statistical delay QoS provisioning method can be used using the *effective capacity* metric,[63] which measures the maximum constant arrival rate.

6.6 | Cooperative communication

Cooperative communication[64] is a novel paradigm in CRNs that can be used in many applications to tackle the channel fading problem, to improve the throughput, to increase spatial diversity, to name a few. In Zhu et al,[65] a cooperative diversity scheme is used by the SU for detecting the PU, and it is shown that the detection time can be improved significantly when the SUs cooperate. In practical scenarios, an SU has the ability to decide on the cooperation limit for the PUs as well as on how it can extract the maximum efficiency out of the specific spectrum bands. In addition, the amplify and forward cooperative relaying is a promising technique for improving the spectral efficiency in cellular networks. This technique is particularly useful in densely populated networks or for applications that demands for stringent QoS requirements.

6.7 | Spectrum trading

Spectrum trading goes beyond the conventional overlay and underlay access methods. It is a technique that encompasses the ability of the SUs to opportunistically acquire the spectrum access.

7 | CONCLUSION

Cognitive radio has been considered as a technology to overcome the shortage of radio spectrum in future CR wireless networks. It aims at exploiting the underutilized and unused spectrum bands, enabling the SUs to access any unoccupied portion of the spectrum band rather than restricting their accesses to some free frequencies like it is the case for existing wireless networks. In this paper, we have examined the overlay and underlay spectrum access methods on different network parameters. Our findings reveal that (1) the underlay and overlay methods have their own pros and cons under different QoS requirements; thereby, an optimal transmission method for CRNs should be dynamically adapted to either the underlay or overlay method depending on the considered QoS requirements; (2) the hybrid spectrum access combines the advantages of both overlay and underlay methods, by devising a new method to further capitalize both the unused spectrum bands and underutilized spectrum bands. Some challenges and open research issues are also highlighted, which need to be considered in future work on CRNs.

ORCID

Isaac Woungang http://orcid.org/0000-0003-2484-4649

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