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A Cooperative Overlay Approach at the Physical Layer of Cognitive Radio for Digital Agriculture

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A Cooperative Overlay Approach at the Physical Layer of Cognitive Radio for Digital Agriculture

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***Abstract*—In digital agriculture, the cognitive radio technology is being envisaged as solution to spectral shortage problems by allowing agricultural cognitive users to co-exist with non-cognitive users in the same spectrum on the field. Cognitive radios increase system capacity and spectral efficiency by sensing the spectrum and adapting the transmission parameters. This design requires a robust, adaptable and flexible physical layer to support cognitive radio functionality. In this paper, a novel physical layer architecture for cognitive radio based on cognition, cooperation, and cognitive interference avoidance has been developed by using power control for digital agriculture applications. The design is based on sensing of spectrum usage, detecting the message/spreading code of noncognitive users, cognitive relaying, cooperation, and cognition of channel parameters. Moreover, the power and rate allocation, ergodic, and outage capacity formulas are also presented.**

I. INTRODUCTION

The Federal Communication Chart (FCC) has permitted the use the cognitive radio devices in the spectrum range of 470 MHz to 698 MHz on farm machinery and agricultural equipment for digital agriculture applications [29]. In this area, the cognitive radio operation holds the promise for flexible, inexpensive radio devices with dynamic spectrum management techniques for digital agriculture sensing and communication applications [30]. This technology can fill the gaps in on-field radio spectrum and can also increase spectral efficiency through sensing of wireless spectrum and adaptive communications [12-28]. In 2008, FCC already had allowed the operation of unlicensed cognitive devices in UHF TV band [3]. In 2010, restriction of mandatory sensing requirements was removed [4] which has facilitated the use of the spectrum with relocation-based channel allocation.

Three paradigms namely underlay, overlay, and interweaved are used for cognitive radio implementation [1]. In overlay paradigm, the cognitive user, through knowledge of message and channel side information, can transmit simultaneously with noncognitive/primary user. Cognitive transmitter's knowledge of message/code being used by noncognitive user is utilized to cancel the interference of noncognitive users. It is also used to assist the transmission of noncognitive users by allocating some portion of power of cognitive user to further relay the noncognitive user transmission. This tradeoff increases the signal-to-interference and noise ratio (SINR) of noncognitive/primary user through relaying viz-a-viz decrease in SINR caused by interference of other cognitive users. It also helps in keeping rate of noncognitive user unaffected.

In this paper, we present a cognitive direct sequence spread spectrum (CDSSS), a cooperative overlay approach at the physical layer of cognitive radio in smart agriculture. CDSSS can be utilized for white space communications on the field. The potential of CDSSS as an overlay cognitive radio paradigm has been presented in this paper. In this collaborative protocol, the cognitive users exchange message information that is used in synchronization and improving knowledge of presence of primary users.

The Multi-user detection (MUD) is employed at cognitive receiver in order to reduce multiple access interference and inter-symbol-interference. The capacity region, merits, and challenges of CDSSS are also discussed. This paper is organized as follows: the related work is discussed in Section II. In Section III, the system model is described. The adaptive power and rate control are presented in Section IV. The results of the performance evaluations of the developed approach are presented in Section V. In Section VI, the challenges and advantages of the design are discussed. The paper concludes in Section VII.

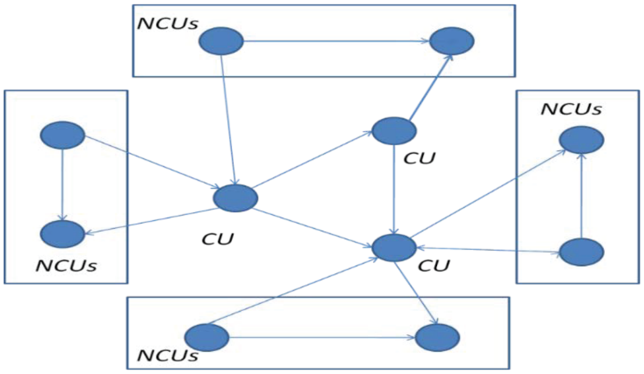

Fig. 1: The interaction among cognitive and noncognitive users.

II. THE RELATED WORK

Cognitive radio has attracted a lot of research focus since its inception in 2000 [5]. Cognitive radio is a software defined radio with dynamic frequency, modulation type, and transmitted power configuration [6]. The IEEE 802.22 Wireless regional Area Networking Work Group (WRAN) WG was formed in 2004 to define cognitive radio PHY and MAC standards [7]. Its charter is to develop standards for use in TV spectrum by cognitive devices. To achieve co-existence with existing services, it uses spectrum sensing, licensed user detection, and spectrum management techniques.

The physical layer design issues unique to cognitive radio systems which can deteriorate the performance of cognitive radio are discussed in [8]. It indicates that the critical design problem related to cognitive receiver is to meet tight requirements on radio sensitivity and detection of weak signals with restricted dynamic range. In [9], interference, coordination and cooperation have been discussed as

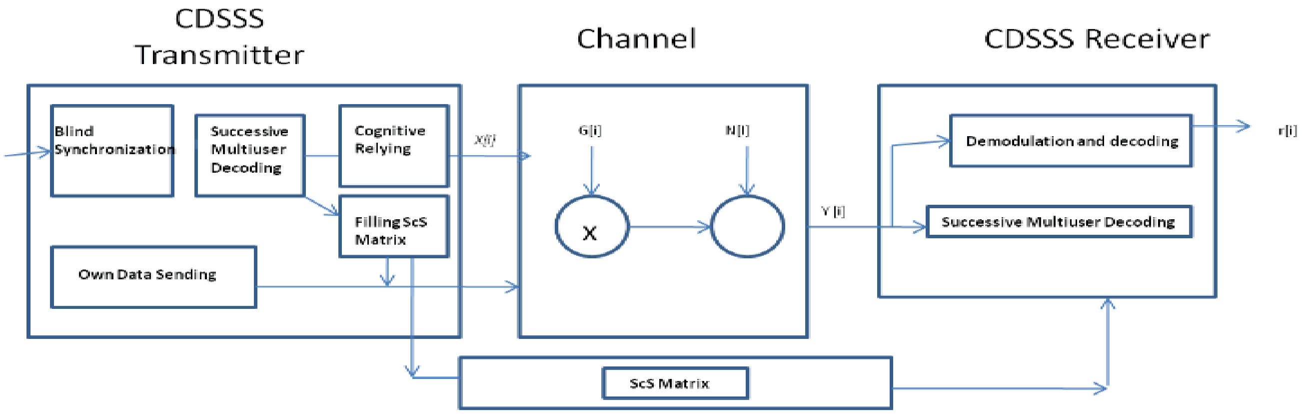

Fig. 2: The CDSSS system model.

fundamental design tradeoffs in cognitive radio systems. In [10], a strategy is formulated for noncognitive user selection based on dynamic game pricing approach. In [11] an opportunistic spectrum access scheme has been proposed which imposes restriction on cognitive user transmission power to avoid interference to noncognitive users.

To the best of our knowledge, this is the first design to consider MUD at the transmitter level. It results in enhancement of signal quality of noncognitive user and also compensate the interference that impacts the cognitive user. This novel architecture can be employed in ad hoc wireless networks and Internet of Underground Things due to its cognitive and cooperative nature [32].

III. CDSSS SYSTEM MODEL

The CDSSS operates in asynchronous fading inter-user channel. It uses nonorthogonal spreading codes that results in multiple access interference and inter-symbol interference. Orthogonal codes restrict the number of users that system can support due to which nonorthogonal spreading codes are used. Different techniques (e.g., hybrid spreading sequences, multiple spreading sequences, and quasi orthogonal spreading sequences) exists in literature to increase the capacity and to accommodate higher number of users. Hybrid concept is based on augmenting orthogonal codes with non-orthogonal codes. Multiple spreading codes concept uses two set of orthogonal codes. In this work, the non-orthogonal codes are employed. These codes do not satisfy the cross-correlation property.

In CDSSS, cognitive users share the spectrum simultaneously with noncognitive users by adapting the transmit power to keep the interference caused to noncognitive users below the noise floor of the spectrum. We assume that the cognitive users are spatially scattered according to a homogeneous Poisson point process. The power control mechanism for allocation of power to cognitive users has been developed based on interference, spectrum utilization, and the number of active noncognitive users. In the design, transmit power can be adjusted flexibly in a short time span. The mandatory constant spectrum sensing for the transmit power adaption is enforced to mitigate interference to primary users during longer transmission windows of cognitive users. Through this constant spectrum sensing mechanism, a cognitive user remains cognizant of cognitive user activation and spectrum utilization. Therefore, based on this knowledge, it adjusts its transmit power accordingly.

In the CDSSS design, the noncognitive users are unaware of presence of cognitive users in the near vicinity. However, the cognitive users have the ability to facilitate the primary user transmission through relaying. On activation, cognitive users sense spectrum and detect noncognitive users. On detection of a noncognitive user, it adapts the transmit power accordingly, relay message of noncognitive user, and exchange the detected information with other cognitive users. Other cognitive users also attempt to detect the same information concurrently. This combined cognition/cooperation helps in maintaining the accurate and updated information about primary users and also facilitates synchronization. In the last step, it sends its own message with delay to destination noncognitive user. When noncognitive user is not detected, cognitive user does not adapt the transmit power and can proceed to send its own message without waiting.

In Fig. 1, an interaction among cognitive and noncognitive users is shown. Suppose D be the set of noncognitive users and C be the set of cognitive users. Let $L \varepsilon C$ be the set of relaying cognitive users that decode and forward messages of noncognitive users. In phase 1, noncognitive users in set $D = \{D_1, D_2, D_3, \ldots. D_N\}$ transmits their symbol s_l.

The CDSSS transmitter works in two steps: a cognition step, which includes blind synchronization and decoding. By cognitively relaying the message of noncognitive users, in cooperation stage, the detected information about noncognitive users is exchanged with other cognitive users. Second step also includes sending of own data by CDSSS transmitter. The CDSSS system model is shown in Fig. 2. These steps of CDSSS transmitter are discussed in the following section.

A. Cognition: Decoding and Cognitive Relaying

In CDSSS, synchronization is performed by using the blind synchronization process that works without any prior knowledge of cognitive and noncognitive transmitters. By this method of cognition, knowledge of spreading sequences is acquired. Cognitive users who cannot perform decoding acquires this knowledge through cognition process (explained in Section III-B). A knowledge of spreading sequences is required for correlation in the Successive Multiuser Decoding (SMD) and for relaying.

The CDSSS transmitter performs detection after synchronization. As an asynchronous channel is assumed, hence, unlike synchronous channel where detection can be done by focusing on one-bit interval, there is an overlap in different bit intervals. The detection process takes into account overlapping bits which consequently lead to formulation of detection problem over the whole message [25]. The received signal at cognitive transmitter can be written as:

$$r(t)=\sum_{k=1}^{K} A_k g_k\left(t-\tau_k\right) d_k\left(t-\tau_k\right)+n(t), \qquad (1)$$

where $A_k(t)$, $g_k(t)$, and $d_k(t)$ are the amplitude, signature code form and modulation of *kth* user, respectively, τ_k is delay for user k and $n(t)$ is additive white Gaussian noise.

The SMD takes a serial approach for detecting and decoding multiple users. SMD works in multiple stages. In every stage, SMD selects a user to decode in ascending order of received power, and decode by using correlation matrix R which is populated with spreading codes through cooperation and cognition. The process of information distribution and own data sending by a cognitive radio is explained in Section III-B.

The output of the first stage of SMD gives data of cognitive user *1* and a modified received signal without noncognitive user *1*. This signal then becomes input to next stage, that repeats process of stage *1* for rest of the non-cognitive users. The strongest power user is selected first in SMD because of ease of achieving acquisition and demodulation.

This multiuser decoding process can be implemented in parallel, where all the noncognitive users can sense in parallel at the cost of additional hardware. Assuming perfect amplitude and delay estimation, the received signal for noncognitive user k is given as:

$$\mathrm{r(t-T_b)}=\sum_{k=1}^{K}\left(d_k\left(t-\tau_k-T_b\right)\left(A_k\left(t-\tau_k-T_b\right)\right)g_k\left(t-\tau_k-T_b\right)\right)+n(t-T_b) \qquad (3)$$

After every decoding, decision variable of the next user under decoding is affected by multiple access interference of remaining users, Gaussian noise, and cumulative noise due to some imperfect decoding. The Gaussian approximations can be used to calculate the bit error rate (BER) of SMD while assuming Gaussian noise with zero mean. The probability of bit error after *jth* decoding, conditioned on the amplitude, can be expressed as Q function.

SMD requires simple multipliers and adders. The delay of the SMD is limited by the performance of the correlators. As decoding is done in the successive manner, the maximum number of decoding by a cognitive user is limited by the speed of performing correlation. In order to ensure the flow of symbols at the symbol rate *Rs*, the speed of correlator must be *N.Rs,* where *N* is the possible number of decoding. For example, in order to have at least *110* decoding assuming a bit rate of *10* kb/s, the speed of the correlator must be at least *0.17 MHz* (i.e. each correlator take less than *6.50* micro seconds). Thus, processing speed of the hardware may limit the number of possible decoding.

Other limiting factor is the number of correlators (matched filters) required for SMD front end in CDSSS transmitter (see Fig. 3). Usually number of active users is much less than total number of users. This number is further reduced in the vicinity of CDSSS transmitter performing cognition. Therefore, SMD correlates the received signal with a set of *N* correlating signals, where *N* may be dependent on the strength ranking of the user's received signal. Based on this ranking, a threshold can be defined for performing maximum correlations. Moreover, as only the SMD performs the cognition, hence, after performing the decoding up to threshold level, the remaining signal can be discarded without affecting the system performance.

In SMD, virtual multipath created by the relays are exploited by employing the RAKE for collecting multipath delayed by integer multiple of chip time. The RAKE also exploits the frequency diversity introduced by frequency selective fading and is placed before the correlator in the SMD.

In CDSSS, cognitive users also serve as relay for noncognitive users. Based on a full duplex radio operation, when these bits are being decoded these are also passed to the transmitter for relaying, simultaneously, by using the same spreading code. The spreading code vector is also populated concurrently.

A cooperative relay scheme for cognitive communication has been proposed in [22]. As an alternative to relaying same message of noncognitive user, the relays uses coded cooperation. In the code combining, the noncognitive user transmits a code word to target noncognitive radio and other cognitive radio helps the cognitive sender by sending additional redundancy bits. Accordingly, the noncognitive receiver combines the original code word and redundancy bits to decode the source message. The coded diversity was introduced in [27], [28]. Analog network coding (ANC), lattice, and dirty paper coding are other alternative techniques for coded cooperation.

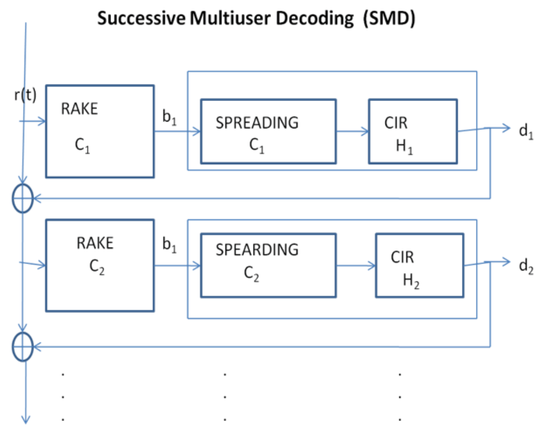

Fig. 3. Successive multiuser decoding.

Other cognitive radios populate their spreading code vector *R* by the same cognition process that is explained above. However, the cooperation comes to play a role here for other cognitive users which are unable to decode the noncognitive user due to fading or other phenomena. Information distribution process among cognitive radios through cooperation and own data sending is presented in the next section.

B. Cooperation: Information Distribution and Own Data Transmission

The cognitive users in CDSSS scheme exchange spreading codes and knowledge of amplitudes/channel gains from noncognitive users to cognitive users through a novel collaborative protocol. Although each cognitive user has the value of channel gains for a particular noncognitive user different from other cognitive users, it still helps in mapping general state of channel form cognitive to noncognitive users. Accordingly, that is used for indirect relaying based on channel state. This cooperation phase for information distribution among cognitive users is combined with own data sending.

When cognitive users start functioning, it decodes noncognitive users and populates its *R*. When *R* is populated, it selects spreading code from *R* and use it to send its own data along with collaboration protocol which is explained below.

The cognitive network is a random geometric graph *G(C,R),* where *C* cognitive users are chosen uniformly and each pair of cognitive users is connected if their Euclidian distance is smaller than some transmission radius *R*, also called the connectivity radius.

1) *For each cognitive users n, Let C(n) represent the set of neighbors of n.*

2) *User n constructs the info exchange message based on the values of ScS vector.*

3) *This message is then combined with the own data sending.*

4) *Modulation and spreading process is performed.*

5) *This message is then broadcasted with 1 bit flag that indicates the message is meant for non-cognitive user.*

6) *The broadcast value is successfully received by the nodes that are within the radius R.*

7) *All neighbors receive the broadcast value and update their ScS vector.*

8) *This procedure takes place at every cognition stage and terminates when all of ScS vector has been populated.*

Cognitive radio receiver also employs successive multiuser decoding for decoding the desired message and also for subtracting multiple access interference.

IV. COGNITIVE USER RATE AND POWER CONTROL

A power control scheme has been developed that provides protection to noncognitive users from cognitive users interference by maintaining their SINR above the required thresholds. Cognitive users are allowed to transmit data according to assigned power and rates. We derive cognitive power allocation strategies to achieve the ergodic and outage capacity under the defined noncognitive user outage probability constraint [21].

Suppose *B* is the bandwidth and *Rc* is the data rate of cognitive radio. Let P_j^c be the transmit power of the cognitive user and P_i^n be the transmit power of the noncognitive user. Let G_{ij}^{nn} be the channel gain between two noncognitive users, G_{ij}^{cc} the channel gain between to cognitive users, G_{ij}^{cn} channel gain between cognitive user *i* and noncognitive user *j* and G_{ij}^{nc} be the channel gain between noncognitive user *i* and cognitive user *j*. Due to the presence of the cognitive users and the corresponding multiple access interference, we can formulate the SINR of the i^{th} noncognitive user as:

$$\gamma_i^n = \frac{P_i^n G_{ij}^{nn} + \rho \sum_{j=1}^{N'} P_j^c G_{ji}^{cn}}{\rho \sum_{j=1}^{N} P_j^c G_{ji}^{cn} + N_0} \quad , \qquad (4)$$

where N_0 is the power spectral density of a constant background noise and ρ is interference reduction due to processing gain. Second term in then nominator of equation (4) is the power of the cooperating cognitive user which improves the SINR of the non-cognitive user by relaying the data. *N*' represents all the relaying non-cognitive users with ability to decode-and-forward message to noncognitive users.

The SINR of cognitive user is defined as:

$$\gamma_i^c = \frac{P_i^c G_{ij}^{cc}}{\rho \sum_{j=1}^{N} P_j^c G_{ji}^{cc} + N_0} \qquad (5)$$

Outage probability for noncognitive users can be defined as $p_{out}^n = p(\gamma_i^n < \gamma_i^{th})$. The outage probability for cognitive users can be defined as $p_{out}^c = p(\gamma_i^c < \gamma_i^0)$.

Ergodic capacity for cognitive users under noncognitive constraint is:

$$\begin{array}{lcl} \max \mathrm{E}\{\log_2(1+\gamma_i^c)\} & \text{such that} & p_{out}^n \le \overline{p}_{out}^c \\ P_i^c \ge 0 & & P_i^c \le P_{\max}^c \end{array} \qquad (6)$$

Outage capacity for cognitive users under noncognitive constraint is given as:

$$\begin{array}{lcl} \min p\{\log_2(1+\gamma_i^c) < R^c\} & \text{such that} & p_{out}^n \le \overline{p}_{out}^c \\ P_i^c \ge 0 & & P_i^c \le P_{\max}^c \end{array} \qquad (7)$$

where R^c is the predefined constant rate cognitive radio.

Under CDSSS power and rate optimization scheme can be formulated as follows: -

$$\max \sum_{i\varepsilon C} \gamma_i^c \qquad (8)$$

$$\begin{array}{ll} s.t. & 1)\, 0 < P_i < P_i^{\max} \forall_{i \in C} \\ & 2)\ \gamma_i^n \ge \gamma_i^{TH} < \forall_{i \in I} \\ & 3)\ \gamma_i^c \ge \gamma_0^c < \forall_{i \in C}. \end{array}$$

By solving equation (8), we get optimum SINR γ_i^c for noncognitive user. Substituting this resultant maximum SINR in equation (6) and (7), we get that ergodic and outage capacity of the CDSSS under outage constraint of noncognitive user.

Here it should be noted that a cognitive user can increase its rate by increasing its power but in the process it decreases the rate of other cognitive users due to multiple access interference it causes to them. Accordingly, by decreasing the power of a particular cognitive user, the date rate of other cognitive users is increased by reduction in multiple access interference.

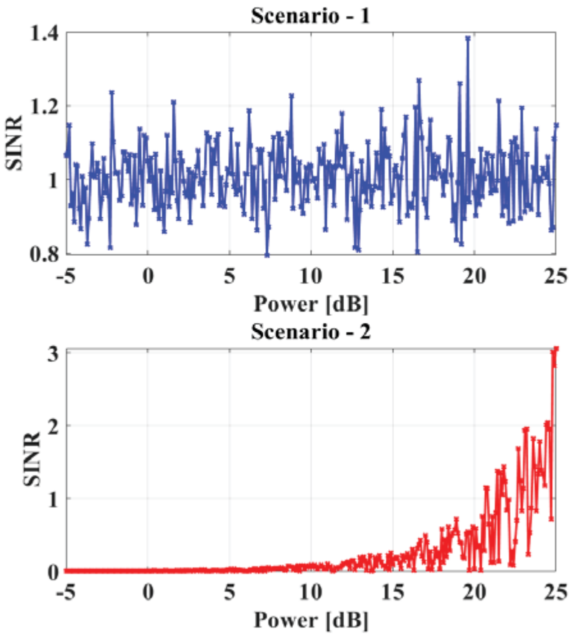

Fig 4: SINR vs. Power [dB] Plot. Noncognitive user transmission is assisted by cognitive users. Scenario -2 is no-assistance.

V. PERFORMANCE EVALUATIONS

In this section, we present the performance evaluation of the proposed approach. The CDSSS simulations are done using the MATLAB. Three cases are considered and in each case two scenarios are presented. In Section V-A, the results for maximum cognitive cooperation case are presented. The limited cognitive cooperation case is discussed in Section V-B. The third case of cognitive interference is evaluated in Section V-C.

A. Maximum Cognitive Cooperation Case

In this case, the primary user's transmission is assisted by cognitive users. In Fig. 4, the SINR vs. Power [dB] graph is shown. It can be seen in maximum cognitive cooperation case (Scenario – 1) even at low power, a 1.4 increase in SINR is observed as compared to the no assistance (Scenario – 2). This SINR increase of noncognitive users results because of relaying of cognitive users as more cognitive users contributed to increase in SINR of noncognitive user. Another factor is because the power of interference cognitive users is also low, hence, higher SINR is achieved. The case of no or very weak cognitive relay under low interference is discussed in the next section.

B. Limited Cognitive Cooperation Case

A case of limited relaying assistance from noncognitive user to cognitive transmission is shown in the Fig. 5. Due to cognitive user's limited assistance through relaying, there is only marginal increase in SINR of noncognitive users as depicted in Fig. 5. It can be observed that because cognitive users' contribution is minimal, the increase in SINR of noncognitive user is low as compared to the maximum cognitive cooperation scenario. Even, in this case, the power of interference cognitive is comparable to the maximum cognitive cooperation scenario. The impact of increase of the cognitive interference on the primary user is presented in the next section.

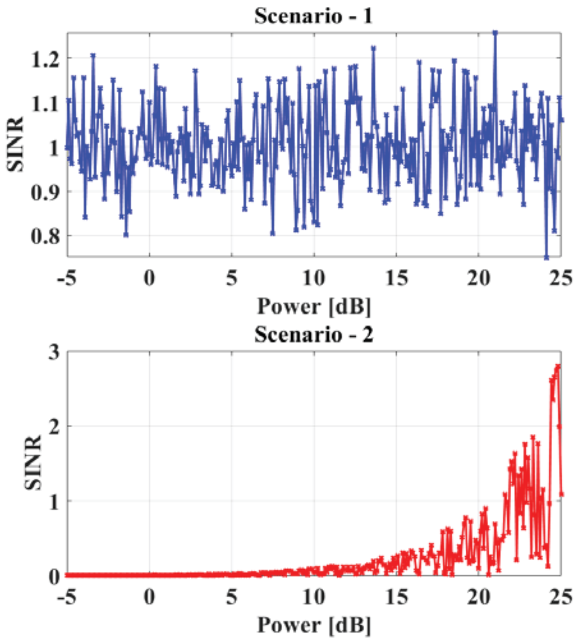

Fig 5: Limited relaying assistance from noncognitive user to cognitive transmission. In Scenario-2 there is no-assistance.

C. Cognitive Interference Case

In this case, the power of interfering users is increased such that that the sever impacts are observed. The case of interfering users overpowering the noncognitive user transmissions is shown in Fig. 6. It can be observed that it eliminated the positive effects of relaying, resulting in poor system performance as shown in Fig. 6. Here, the CDSSS power control mechanism (Section IV) can be employed as a solution to keep the power of cognitive users under a thresh hold in order to ensure that the operation of non-cognitive users can continue unhampered.

VI. CHALLENGES

The successive multiuser detection CDSSS, cognitive relaying, and cooperation among cognitive users make it a candidate transmission technology for cognitive radio systems in digital agriculture applications. It can effectively decode multiple noncognitive users with successive multiuser detection technique which leads to effective spectrum utilization. In CDSSS, the cognitive users adapt to different transmission environments with the help of its effective power and rate control algorithm that has been developed by keeping in view the outage and power constraints of noncognitive users. Many IEEE standards use direct sequence spread spectrum as their physical layer. Therefore, the CDSSS can easily interoperate with existing systems as compared to other technologies. In CDSSS, the support for multiuser access and immunity from narrowband interference is already inherent in the system design.

One major challenge to CDSSS is synchronization. The success of CDSSS depends greatly on the fact that cognitive user achieves fine synchronization with noncognitive user for accurate decoding. Synchronization errors can jeopardize the reliability of the whole system. Cooperation among cognitive users is very important. Therefore, the correct information exchange among cognitive users is also crucial to success.

Another challenge to CDSSS is noncognitive user emulation attack. In this attack, another cognitive user can

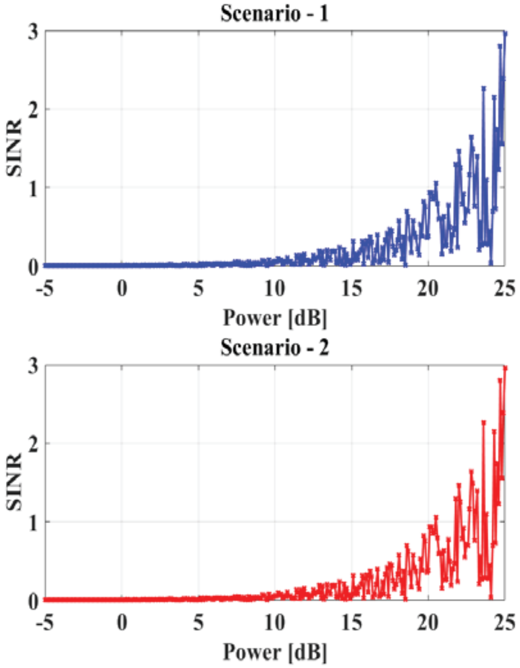

Fig. 6: Interfering users overpowers noncognitive user transmissions. In Scenario-2 there is no-assistance

emulate the characteristics of noncognitive user and consume resources. In [26], a transmitter verification scheme has been proposed which provides defense against primary user emulation attack in cognitive radio network.

A noncognitive user may be hidden due to multipath fading and shadowing, which leads to difficulties in detection, decoding and relaying and consequently cognitive users have only incomplete information about presence of noncognitive users in the network.

VII. CONCLUSIONS

The CDSSS approach works by acquiring blind synchronization, successive multiuser decoding, relaying, and cooperation by information exchange among noncognitive users. It holds promise for efficient spectrum utilization and solution to spectrum scarcity problem in the field of digital agriculture. The CDSSS also realizes the cognitive novel radio concept and introduce new capabilities to effectively utilize the white spaces in agricultural farms. More emphasis should be given to solve challenges to CDSSS implementation. Further in-depth research is needed to solve challenges identified in this paper.

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