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Chapter 4

# Spectrum Decision Framework to Support Cognitive Radio Based IoT in 5G

Ahmad Naeem Akhtar, Fahim Arif and
Adil Masood Siddique

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### Abstract

RF Spectrum Decision in Cognitive Radio enables unlicensed users of wireless communication systems to occupy the vacant spectrum slots as a solution to scarce spectrum. Internet of Things (IoT) is a wide-reaching network of unified entities. IoT capable things will be interconnected through wireless communication technologies offering cost-effectiveness and accessibility to remote users making quality life style. IoT implementation suffers from challenges of vulnerabilities to dynamic environmental conditions, ease of access, bandwidth allocation and utilization, and cost to purchase RF spectrum. As RF spectrum is a precious commodity and there is a dearth of RF spectrum, hence IoT connections are drifting towards Cognitive Radio Networks (CRNs). Permeating things with cognitive abilities will be able to make RF spectrum decisions to achieve interference-free and wireless connectivity as per their QoS requirements. The wireless systems are rapidly advancing. The leap from packet switching along with circuit switching with 144 kbps data rate (2G and 2.5G) to Long Term Evolution Advanced (LTE-A), i.e., 4G occurred in one decade time frame. As the current wireless connectivity is aimed at higher capacity, higher data rate, low end-to-end latency, massive device connectivity, reduced cost and consistent Quality of Experience (QoE) provision, therefore, 4G is being replaced with 5G. Presently the Radio Frequency (RF) spectrum band is fully sold out and allocated to various wireless operators and applications. On the other hand, new wireless applications are emerging and there is a serious dearth of frequency spectrum to be allocated to emerging wireless services. The efficient utilization of assigned RF spectrum which is otherwise underutilized due to the typical usage by the licensed users known as Primary Users (PUs) is the one of the best possible way to implement IoT in 5G. Thus the Spectrum Decision by unlicensed users of CR holds a significance in CR-based IoT in 5G and beyond network. This chapter describes a scientific supported spectrum decision support framework for CR Network. The main goal of this chapter is to discuss how CR technology can be helpful for the IoT paradigm.

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**Keywords:** cognitive radio, internet of things, 5G/B5G, Spectrum decision framework, primary user, IoT-User

## 1. Introduction

4G provides voice, data and multimedia imparting to the wireless subscribers on every time and everywhere basis at higher data rates in Multimedia Messaging Service, Digital Video Chat Broadcasting (DVB), video chat, High Definitive TV content and mobile TV. As an application of 5G, the wireless systems are deployed to make All the people and things to be connected Any time with Anyone while being Anywhere via Any Path or Network and Any service (A6 connection). This A6 connection is known as Internet of Things (IoT). Internet of Things (IoT) is the environment where all over smart interconnected objects are connected with each other through unique addressing schemes based on specific telecommunication standards and protocols [1]. IoT based devices are to be interconnected through Base Transceiver Stations (BTSs) in wireless operations and the BTSs are linked with backhaul connectivity through Optical Fiber Transmission systems achieving higher bandwidths supplemented by Terrestrial Microwave links. The wireless Radio Frequency spectrum (WRFS) is almost completely assigned to existing wireless applications. At the same time, WRFS is underutilized due to the typical usage of mobile and other wireless services. To address this problem, Cognitive Radio (CR) has emerged as an enabling technology which offers a solution to spectrum scarcity problem. Hence, the CR-based IoT system has by default becomes a focus for researchers in wireless communication systems. CRN systems have emerged as a capable solution to the spectrum scarcity and as an enabling technology for the optimum utilization of otherwise underutilized RF spectrum, humanizing the synchronicity and interoperability in various wireless and mobile communications systems transforming into telecommunication devices and systems autonomous and self-reconfigurable. With swift shift to smart communication technologies and infrastructure, the Internet of Things (IoT) has emerged as a modern challenge in international Telecommunication industry and wireless applications. SUs access RF spectrum bands in heterogeneous manners in CRN and IoT supported smart area consists of heterogeneous devices, which are mobile as well as static in nature [1]. At the same time, the next generation mobile communication network referred to as the Fifth Generation (5G) is almost realized in the advanced telecommunication era [2]. 5G and beyond is expected to integrate the contemporary wireless technologies into an all Internet Protocol (IP) based networks which offer high performance worldwide network [3]. As the bandwidth for 5G and beyond is very large and the WRFS offers a large number of non-continuous idle spectrum slots in 5G communication as well [4], there is a requirement to identify the unused spectrum slots not being used by respective licensed users called primary users (PUs). This process is known as Spectrum Sensing (SS) in Cognitive Radio systems. Accurate SS allows the secondary users (SUs) to opportunistically use the vacant spectrum slots as per their wireless applications and vacate when the PU arrives in the network. This process is termed as spectrum decision. When optimally done, the SU along with PU will be enabled users using IoT paradigm in 5G/B5G networks. Therefore, spectrum decision is an important parameter for the deployment of CR-based IoT in 5G/B5G network.

All previously mentioned research contributions are more concept oriented for IoT in 5G network. The RF spectrum accessibility as per the wireless application for the user in IoT environment remains an open research area. Motivated by this, a comprehensive survey on 5G networks embedded with IoT applications based on CR ensuring A6 connectivity by accessing across the entire RF spectrum has been carried out in this chapter. A case study based on this survey for CR-based IoT in 5G networks has also been proposed to validate the concept.

## 2. Structure of the chapter

Introduction, related work and the motivation of the work is given in the first section. Evolution to 5G is given in Section 3. IoT in 5G network is described in Section 4. Section 5 gives an account for 5G with CRN based IoT and the need for RF spectrum management is given in Section 6. Section 7 concludes the chapter. **Table 1** given below lists the abbreviations used in this chapter.

| Abbreviation | Definition | Abbreviation | Definition |
|---|---|---|---|
| AWGN | Additive White Gaussian Noise | MF | Membership function |
| AMPS | Advanced Mobile Phone Service | MIMO | O Multiple input multiple output |
| B3G, B4G, B5G | Beyond third, fourth and fifth generations | MISO | Multiple input single output |
| BTS | Base Transceiver Station | MHz | Mega hertz |
| CCC | Common control channel | MVR | Majority vote rule |
| CDMA | Code Division Multiplexing Access | NB Narrow band | Narrow band |
| CR | Cognitive Radio | NI | National instrument |
| CRN | Cognitive Radio Networks | OFDM | Orthogonal frequency division multiplexing |
| DSA | Dynamic Spectrum Access | PC | Personal Computer |
| | | PDP | Poisson distribution process |
| DSMF | Dynamic Spectrum Management Framework | PSD | Power spectral density |
| DVB | Digital Video Chat Broadcasting | PU | Primary user |
| D2D | Device to Device | QoE | Quality of experience |
| IoT | Internet of Things | QoS | Quality of service |
| ED | Energy Detection | QPSK | Quadrature phase shift keying |
| EV-DO | Evolution Data Only/Evolution Data Optimized | RASC | Random channel assignment with single channel |
| ETACS | European Total Access Communication System | RFID | Radio frequency identification |
| FSDM | Frequency Spectrum Decision Mechanism | ROC | Receiver operating characteristics |
| HART | Highway Addressable Remote Transducer Protocol | SDR | Software define radio |
| RFID | Radio frequency identification | SDSF | Spectrum decision support framework |

| Abbreviation | Definition | Abbreviation | Definition |
|---|---|---|---|
| ROC | Receiver operating characteristics | SG | Smart grid |
| 6TiSCH | IP (IPv6 settings) integrated with Time synchronized channel hopping | | |
| SNR | Signal to noise ratio | | |
| SU | Secondary user | | |
| TDMA | Time division multiple access | | |
| UE | User equipment | | |
| URLLC | Ultra-reliable low latency communication | | |
| UWB | Ultra-wideband | | |
| WCDMA | Wide-band code division multiple access | | |
| WiFi | Wider Fidelity | | |
| WiMAX | Worldwide interoperability for microwave access | | |
| WLAN | Wireless local area networks | | |
| WWRF | Wireless world research forum | | |

**Table 1.** Abbreviations used.

## 3. Advancement of wireless technologies from 1G to 5G

Since the inception of the first generation (1G) cellular systems in telecommunication system, the entire pattern of living environment including the people's work, lifestyle and the agricultural and industrial development trends has been effected. Evolution to the fifth generation (5G) is the progressive advancement in the telecommunication industry to keep with the growing pace of mobile data traffic, huge volume of device connections and continuous emergence of latest commercial scenarios. Over the last one decade or so, the wireless communications have the capability to connect all the existing mobile technologies, to build a terminal that is to support the voice, video and data applications with respective QoS requirements guaranteed i.e., at very high data rates and users speeds making it a 5G/B5G environment. The chronological evolution to 5G/B5G [5] is listed here in the **Table 2**.

Device to device (D2D) communications in 3GPP and LTE standards offers transfer of data directly to each other without the involvement of BSs [6]. This reduces the workload and energy consumption of BS thereby offering a good platform for 5G. Emerging 5G wireless communications envision very high data rates (typically of Gbps order), extremely low latency, significant increase in BTS capacity and improvement in PUs' and SUs' perceived Quality of Experience (QoE), compared to existing 4G/3G wireless networks. The 5G/B5G implies the whole wireless world interconnection (WISDOM; Wireless Innovative System for Dynamic

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| Wireless technology generation | Applications | Standards | Data rates | Mobility offered | Time span |
|---|---|---|---|---|---|
| 1G (Analog) | 1st Generation of the mobile telecommunication technology standardized by the voice service. | NMT, AMPS, TACS, ETACS and JTACS | 14.4 kbps | Low Speed | 1995–1997 |
| 2G (Digital) | 2nd Generation of wireless telephone technology introducing a data service; SMS (short message service) | TDMA, GSM, CDMA, 2.4 GHz narrowband WLAN | 144 kbps | Low and medium speeds | 1997–2000 |
| 3G (IMT 2000) | 3rd Generation of mobile telecommunications (International Mobile Telecommunications-2000) | CDMA2000, EV-DO, W-CDMA, 802.11 PAN, Bluetooth. | 384 kbps | Medium and High Speed | 2000–2005 |
| B3G | Beyond 3rd Generation | WiBro802.16e, WiMax, 3GPP, LTE | <50 Mbps | High Speed | 2005–2010 |
| 4G | 4Th Generation of mobile telecommunications | DAB/DVB, cellular GSM, IMT-2000, WLAN, IR, UWB, DSL, LTE-A, IEEE802.16e | <100 Mbps | Very High Speed | 2010 onwards |
| 5G/B5G | 5th Generation and beyond. | 4G + WISDOM | | | 2015 onwards |

**Table 2.** Progressive evolution of Mobile services from 1G to 5G [5].

Operation Megacommunications concept), with guaranteed QoS requirements of wireless services [7]. Spectrum decision in CR would ensure spectrum scarcity problems and IoT complies wireless A6 connections for users, making CR-based IoT in 5G networks with a focus on spectrum decision framework in CR for IoT in 5G networks, an interesting study for researchers.

## 4. IoT in 5G/B5G networks

Mobile data and IoT are the future internet for everything and will be the key and motivating force in the advancement of 5G/B5G networks. In the time to come, likely by 2021–2025, 5G/B5G will not only meet the assorted requirements of people in various constituencies of daily life such as residence, work, leisure, and transportation, but also will infuse the IoT and light up the diverse specialized domains to the professional aspects of human life and the industry such as medical sciences and facilities and transportation to realize the true interconnectedness of all things [9]. The realization of IoT is dependent on internet application scenario based requirements which converge to 5G networks and are not guaranteed in 4G and LTE technologies. These requirements are listed in **Table 3**.

| Internet application situation | Mobile data provided internet to the subscribers | | IoT | |
|---|---|---|---|---|
| | **Wide and seamless coverage** | **High capacity to guarantee QoS requirements for Internet Applications** | **A6 connection** | **Low end to end latency** |
| Requirements | Seamless connectivity with high speed service in mobility of the subscriber | Enormously high data transmission rate | Provision connectivity to billions of devices with matching capability of power requirements for devices | Provision of service to users with less than millisecond end-to-end delays in transmission and in switching of spectrum slots. |

**Table 3.** Modern trends and requirements in IoT [8].

## 5. 5G/B5G with CRN based IoT

The Internet of Things (IoT) envisions thousands of constrained devices with sensing, actuating, processing, and communication capabilities able to observe the world with an unprecedented resolution. According to Cisco, more than 50 billion devices are expected to be connected to the internet by 2020 and 20% of which are from the industry sector [9]. These connected things will generate huge volume of data that need to be analyzed to gain insight behind this big IoT data. Moreover, in the industrial environments (industry 4.0) as well in in smart spaces (building, houses, etc.) and connected cars communications often require high reliability, low latency and scalability. Several technologies such as BLE, Zigbee, Wireless HART, 6TiSCH, LPWAN (Lora, Sigfox, etc.) have been proposed to fit these requirements. The forthcoming 5G networks are promising not only by increased data rates but also low-latency data communication for latency-critical IoT applications. 5G will enable massive IoT devices connected via a myriad of networks and critical machine type communications. While the massive IoT is more concerned about scalability deep coverage and energy efficiency, the later requires ultra-low latency and extreme reliability (URLLC). Recently, the fog-to-thing continuum [10] is proposed to mitigate the heavy burden on the network due to the centralized processing and storing of the massive IoT data. Fog-enabled IoT architectures ensure closer processing in proximity to the things, which results in small, deterministic latency that enables real time applications and enforced security. The IoT is a modern and the state of the art archetype in the technological advancement which is evolving as a future Internet. As per the principal vision of the IoT, the further requirement is the ubiquity of the Internet, after connecting people anytime and everywhere, is to connect extinct entities. By providing objects with embedded communication capabilities and a common addressing scheme, a distributed and permeating network of impeccably connected diverse electric and electronic devices is designed, which is to be indigenously cohesive into the existing Internet connections and mobile networks. Formally, IoT can be defined as, " A worldwide network on electronically interconnected devices uniquely addressable, based on standard communication protocols and allows users to be A6 connected" [11]. Thus allowing for the development of new intelligent services available anytime, anywhere, by anyone and anything. Latest research work and

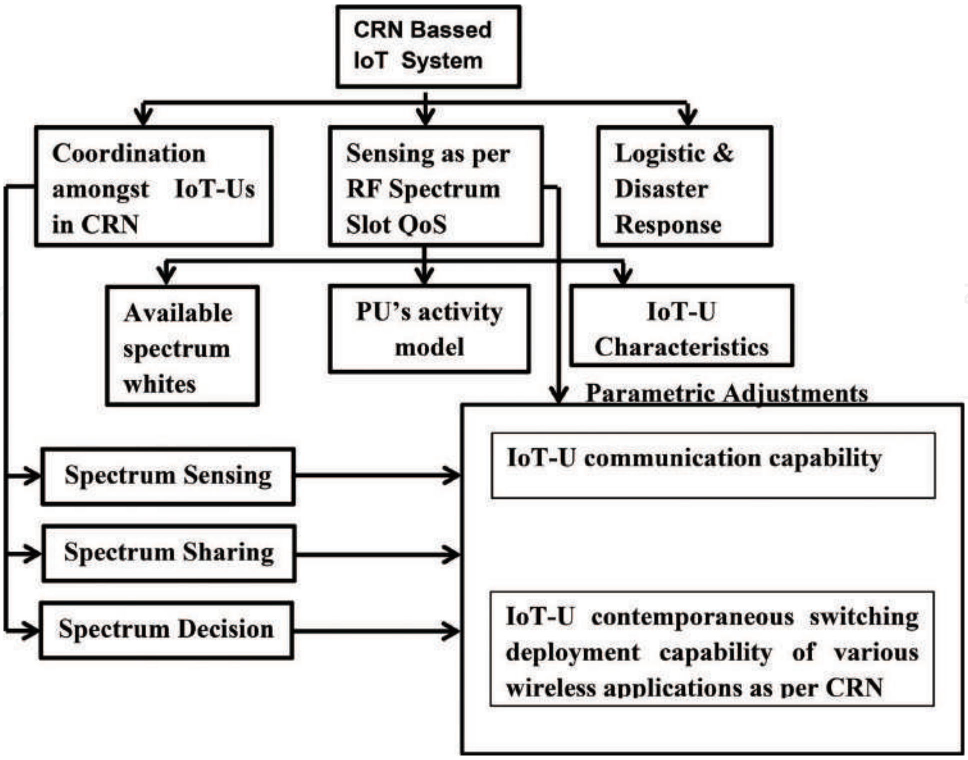


**Figure 1.** CRN system with its properties and research directions enabling it for IoT system for A6 connections by SUs.

technological systems are converging towards IoT and CRNs. Since the spectrum assignment policy involves expenditures for buying the RF spectrum, the assignment of spectrum for a huge number of devices and objects required for IoT connectivity will result in redundant cost effects. CRNs due to its typical spectrum utilization characteristic emerge in realization of IoT. The idea of a reserved spectrum slot as shared-to-reserve (SR) and reserved-to-share (RS) schemes in CR-HetNets proposed in [12] can enhance the system throughput and would offer a high bandwidth transmission for IoT-Us in CRN. A CRN properties enabling it for IoT applications is shown in **Figure 1**.

Usually, the SU operates in half-duplex mode (HD), i.e., it can either transmit or sense at any instant of time [13]. Due to this HD operation of SU, there is a possibility that harmful interference to PU is caused on unexpected arrival of PU and its activity during the transmission of SU. Hence the spectrum sensing should be a continuous process and SU must vacate the licensed channel on arrival of its PU and switch to another suitable channel as per its application, i.e., a befitting spectrum decision framework is essential.

## 6. Need for Spectrum management in IoT based 5G/B5G networks

External storage solutions offer nearly unlimited capacity, with dedicated signal processing to sort through data and find signals, interactions or events of interest. These long-duration, high-bandwidth solutions are ideal for today's crowded spectrum and advanced technologies such as cognitive radios. WRFS is characterized by PU activity modeling and accurate SS [14]. This means that the spectrum management holds a great significant in CR technologies and A6 connection. The DSA allows the users (both PUs and SUs) to optimally use the spectrum slots while guaranteeing their QoS requirements. Preserving the required QoS of the users along with their mobility requires spectrum mobility for the SUs in the network, which we now know as 5G network. Because of its mobility, an SU may change its location (cell) in a cellular network during its transmission and, therefore, will enter a new region in which the targeted RF spectrum slot is already being used by the PU [15]. The perfect SS techniques provide prior information for which SUs will work [5]. Since the primary traffic in any cell and region is always time varying and cannot be accurately predicted, therefore, the SUs must have the real time information of RF spectrum slots occupancy status to switch over to the vacant slots for resuming their transmission in case PUs arrive. Similarly, the SS errors are also required to be mitigated. The PUs use their licensed spectrum for their transmissions as per their QoS requirement and the statistical analysis says that this usage remains for a very short period of time. The decision of accessing the vacant spectrum slots would enable the SU to have A6 connections making an IoT environment. Therefore, SU is renamed here as IoT-User (IoT-U).

The allocated frequency spectrum for wireless applications is under-utilized due to the emblematic customs of wireless applications [16]. The conventional approach to spectrum management is very inflexible in the sense that each wireless service provider is assigned an exclusive license to operate in a certain frequency spectrum band. It has become very difficult to find vacant spectrum bands (to either deploy new services or to enhance existing ones) [17]. Therefore, for efficient utilization of the spectrum creating opportunities, Cognitive Radio (CR) technology allows its users called Secondary Users (SUs) to occupy the available spectrum slot for their communication (model is shown in **Figure 2**) and vacate it on arrival of the licensed user (called Primary User (PU)) [18]. The process of spectrum utilization using CR systems requires a Dynamic Spectrum Management Framework (DSMF) [19] which consists of four main components (naming Spectrum Sensing (SS), Spectrum Decision Framework, spectrum sharing and spectrum mobility). Spectrum sharing refers to coordinated access to the selected channel by the SUs. Spectrum mobility enables SU to switch over to another channel when a PU is arrived. SS involves identification of spectrum holes and the ability to quickly detect the onset of PU communications in the channels occupied by the SUs. Spectrum decision enables SUs in CR Network (CRN) to select the best available spectrum slots to satisfy SUs' Quality of Service (QoS) requirements without causing harmful interference to PUs [20]. On appearance of PU in the spectrum slot in which SU was carrying out its transmission, the SU looks for (which requires an efficient SS) and selects (which requires a suitable Spectrum Decision Framework) another QoS complying spectrum slot which is available/vacant. This implies that there are two steps (SS and spectrum decision framework) of efficient utilization of spectrum in CR-based IoT in 5G/B5G.

There are two scenarios as an overlay and underlay for spectrum sharing [21, 22]. In spectrum overlay scenario, a SU accesses a RF spectrum slot only when it is not being used by the PU [23]. This scenario is also known as opportunistic spectrum access. In other scenario the SU coexists with the PU and transmits with power constraints to guarantee the quality of service (QoS) of the PU. This scenario is known as underlay spectrum sharing [24]. The overlay mode operation is focused in this chapter.

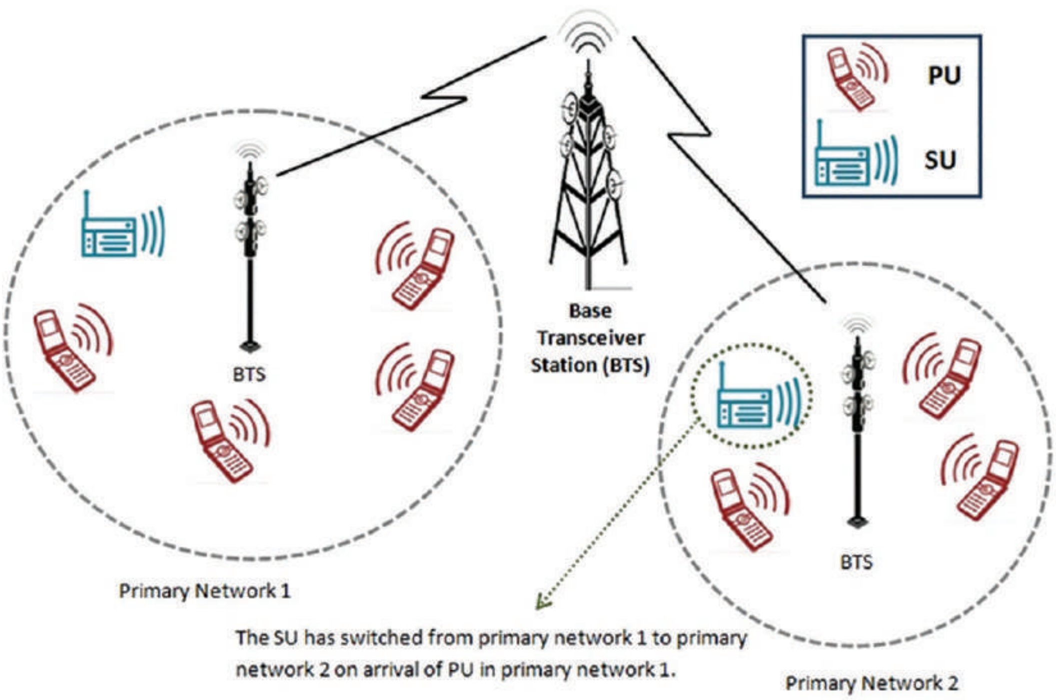


**Figure 2.** Working of a CRN model in which SU switched to another network on arrival of PU in primary network 1.

### 6.1. Spectrum sensing

CR systems offer the capability of IoT-Us to improve the spectrum utilization under the existing fixed spectrum assignment policy. IoT-Us cannot only sense the spectrum environment around and access vacant spectrum slots in the opportunity way, but also require to sense the presence of PU's signal continuously to keep the SS data updated. Hence, SS is the fundamental requirement in CR and the foundation for Spectrum Decision. The SS techniques are categorized into non cooperative (Energy Detection (ED), Matched Filter Detection (MFD) and cyclostationary detection), interference detection and cooperative (centralized SS (CSS) and non-centralized detection) [25, 26]. ED is the widely used scheme for SS due to its simplicity, easy implementation and it corresponds to the general purpose of SS for heterogeneous wireless communication systems [27]. The improved ED and CRs with multiple antennas can increase the SS performance [28]. MFD requires the exact synchronization and prior knowledge of PU signal, moreover implementation complexity of the sensing unit is large as the SU need receivers for all types of signal [29]. ED and MFD perform non coherent (by calculating the energy of the received signal samples) and coherent (comparing with the known PU signal) detection respectively [30]. Cyclostationary detection suffers from high complexity as all the cycle frequencies are required to be calculated [31]. CSS and non-centralized detection have exhibited SS errors due to time lag involved between sensing and its results [32]. Although the vacant spectrum slots are identified in SS but unless these are not simultaneously occupied through a well-defined decision process, the concept of CR cannot be realized. Therefore, it is imperative to mitigate the SS errors (false alarm and miss detection) before taking the decision to occupy the sensed vacant spectrum slot. A brief analysis of existing SS techniques [33] is given in **Table 4**.

### 6.2. PUs and IoT-Us activity model

In CRNs, there are two types of users to use the WRFS, one is PU and the other is SU, which we have renamed as IoT-U in this chapter. Since FCC has approved the access of unlicensed users (IoT-Us) to the already sold RF spectrum provided the unlicensed users do not cause harmful interference to PUs. The performance of CRNs is largely dependent on PU arrival and departure from the spectrum slots, the license of which it holds [34]. Hence, it is very important to model the PU activity for CRNs to enable IoT-Us to decide for occupation idle spectrum slots. PUs in the wide range (kHz to GHz as UWB and 5G networks operate in 3.6–39 GHz) of WRFS operate in any spectrum depending upon the specific wireless applications. **Table 5** shows the operating radio frequency bands for various wireless technologies.

As the RF spectrum band is wide range for various wireless applications, therefore, one PU activity cannot reflect the activity pattern of PU of all wireless applications as these varies from application to application. As the FCC has approved to use secondary users on licensed RF spectrum only with the condition that PU transmission will not be interfered. This implies that the licensed spectrum will only be occupied when PU is not using it, the underlay occupancy. Moreover, it is very important to ensure that PU is not harmfully interfered. That is why, the CRNs' performance is dependent on PU activity. Stochastic geometry provides a natural way of defining and computing macroscopic properties of mobile users' networks, by averaging over all potential geometrical patterns for the nodes, in the same way as queuing theory offers mobbing and the reliability, i.e., low end-to-end latency in wireless communication, average out the overall possible arrival patterns of the PUs within the networks on assigned RF spectrum. Thus PU activity modeling in wireless communication networks in terms of stochastic geometry is particularly relevant for spectrum decision framework. The PU activity, as a simplest case, in CRN can be represented as a print of a stationary random model in a probabilistic way. In particular the locations of the CRNs nodes are seen as the realizations of some point processes. When the underlying random model is ergodic, the probabilistic analysis also provides a way of estimating spatial averages which often capture the key dependencies of the CRN performance characteristics (connectivity, stability, capacity, etc.) as functions of a relatively small number of parameters [35]. Hence, the PU activity should be modeled with some stochastic arrival and departures probability expression. Poisson distribution process (PDP) provides a near to realistic probability of arrival and departure of the (primary) user in the network. PDP offers spatio-temporal representation of PU activity model. Moreover, Poisson distribution process is simple and adapts well in wireless communication scenario. The PU's arrival and departure follow the poison distribution process:

$$P(k\ events\ in\ interval) = \frac{\lambda_p^k e^{-\lambda_p}}{k!} \tag{1}$$

where $k$ is occurrence of PU arriving and takes values $0,1,2,3, \ldots.., N$ and $\lambda_p$ is the arrival rate of PU in the spectrum slot in the CRN. The existing spectrum decision techniques model PU activities without taking into account for SU (IoT-U) behavior and characterization. This is desirable in this CRN growth era as well as in CRN based IoT-U to have its model defined. This will help in ensuring no interference and will provide basics for mechanism of switching

| SS Techniques | Method Used | Main Feature |
|---|---|---|
| ED, MFD and Cyclostationary detection based SS | Based on PU's transmitter | ED does not require the prior information of the PU |
| | | MFD is related to prior knowledge of PU's signal |
| | | Cyclostationary detection relies on distinguish between the PU's signal and the noise |
| Cooperative SS | Combining the sensing results of multiple SUs to improve the detection reliability | The fusion mechanisms including reliability based cooperative decision fusion. One is described in section of this chapter |
| | | Using directional antenna |
| | | Quashing interferences |
| | | Integrates quickest detection and belief propagation framework |
| | | Guaranteeing the high sensing accuracy in vehicular networks or industrial wireless networks |
| Spectrum-database SS | Enables to find all available spectrum slots by comparing the historical information of spectrum usage pattern with the received by a base station from each SU in the network | Exploiting spectrum table for SS |
| | | A framework for determining the topology of vehicular network |
| | | An iteratively developed history processing database |
| | | A mobile crowd sensing-driven geolocation spectrum database for D2D communication |
| Compressive SS | Each SU detects and extracts the wide band signal directly to achieve efficient wide band sensing with much lower sampling rate than the Nyquist Criterion | Wideband SS scheme |
| | | Based on real time PU's signal |
| | | Analyze the sparsity of the wideband spectrum |
| | | Reducing SS errors |
| | | Spectrum occupancy status measurement |
| Full duplex SS | Each SU in the network can access the vacant spectrum slots while sensing the spectrum continuously | Listen and talk protocol |
| | | Joint mode/rate adaptation policy for WiFi/LTE-U |
| | | At low SNR values |
| | | Optimal detection thresholds |
| | | Canceling the self-interference of transceiver |

**Table 4.** List of SS techniques available in literature [33].

| Wireless applications | Frequency spectrum bands | Bandwidth |
|---|---|---|
| IEEE 802.11 g to n/WiFi | 2.4 GHz | 10 KHz |
| IEEE 802.16/LAN/2 | 5 GHz | 100 KHz |
| IEEE 802.22 | 54–862 MHz | 5–20 MHz |
| GSM | 890–915 MHz (uplink)<br>935–960 MHz (downlink) | 200 KHz |
| CDMA | 800 and 1.9 GHz | 125 MHz |
| W-CDMA | 850–2100 MHz | 125 MHz, 250 MHz |
| LTE | 1710 –1770 MHz (uplink)<br>2110–2170 MHz (downlink) | 20 MHz |
| UWB | 3.1–10.6 GHz | 500 MHz |
| 5G Cellular | 26.5–40 GHz and 30–50 GHz | All ranges of bandwidths i.e., narrow, wide, ultra wide and super ultra wide bands communication systems |

**Table 5.** Frequency spectrum ranges for various wireless applications.

to other available slot, if PU arrives. The study of opportunistic spectrum access in CRNs with SU's transmission performance reveals that the interference caused to PU can be avoided by evaluating the SU's transmission blocking [34]. When PUs appear in the multiple spectrum slots in a WRFS band denoted by '*S*', IoT-Us need to vacate the spectrum slot and switch to another suitable spectrum slot (to complete their transmission) without interfering the PUs. This transmission process for PU and IoT-U is shown in **Figure 3**. This causes IoT-Us a temporary break in transmission, which is mitigated by simultaneous access in multiple noncontiguous spectrum bands by IoT-Us for their transmission. Even if a PU appears in one of the channels, the rest of the channels will continue to allow SUs to transmit while maintaining their QoS requirements.

In the transmission process of SUs when accessing the channel in a heterogeneous manner, the transmission level measure for PU is given by the PTB as,

$$P_{TB} = P(i,j) = \frac{\lambda_p\left(P_{i-i,j}\right)\varphi(i+1.j)+(j+1)\,\mu_s\,P(i,j+1)\varphi(i.j+1)}{i\,\mu_p + j\,\mu_{s+}\,\lambda_p + \lambda_s} \tag{2}$$

where PUs and IoT-Us arrive and depart from each spectrum slot in $s$ at the rate $\lambda_p$ and $\lambda_s$ respectively. Similarly, the $\mu_p$ and $\mu_s$ are the mean values of the respective transmission durations of PU and SU in the network. The number of spectrum slots in $s$ by PU and IoT_U at some specific time are represented by $i$ and $j$ respectively, such that $i + j \leq N$. P (i,j) is the stationary probability of two dimensional Markov state which is $P_{TB}$.

The state space $\varpi$ for PUs and IoT-Us occupying spectrum slot in $S$ is given as under;

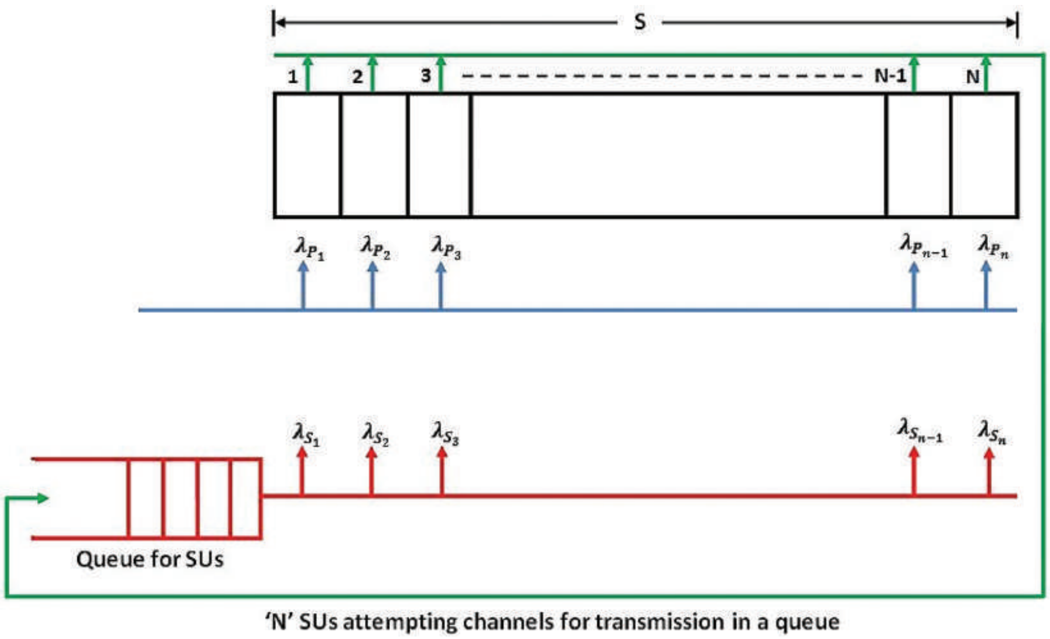


**Figure 3.** Transmission process for PUs and SUs (IoT-Us) to mitigate interference.

$$\varpi = \{(i, j) \mid 0 \le i \le N; 0 \le j \le N\} \tag{3}$$

and

$$\varphi(i, j) = \begin{cases} 1, (i, j) \in \varpi \\ 0, \text{otherwise} \end{cases} \tag{4}$$

## 7. Spectrum decision framework

CR Technology is characterize by PUs and SUs, a coordination among the IoT-Us to use the licensed bands when PUs are not using spectrum slots in the targeted spectrum slot. Although, in the recent 5 years, the researchers have carried out work in the area of Spectrum Decision, however, still this area is not yet fully explored. A survey of spectrum decision in CRNs based on RF spectrum characterization, spectrum selection and CR reconfiguration has been presented in [20]. Since then (2013) in one of spectrum decision research works, the authors have proposed a fuzzy inference-based decision strategy which is based on three key parameters, spectrum slot idle time, spectrum slot occupancy status and spectrum slot QoS [36] which provides an accurate and robust spectrum decision framework for SUs. The same and can be equally effective for IoT-Us in CR-based IOT in 5G/B5G networks as it encompasses all signal processing matrices such as Massive MIMO Antennas, varying bandwidths characteristics and wireless propagation channel models for all wireless applications (through spectrum slot QoS), required for wireless communications. Likewise, a spectrum decision scheme is

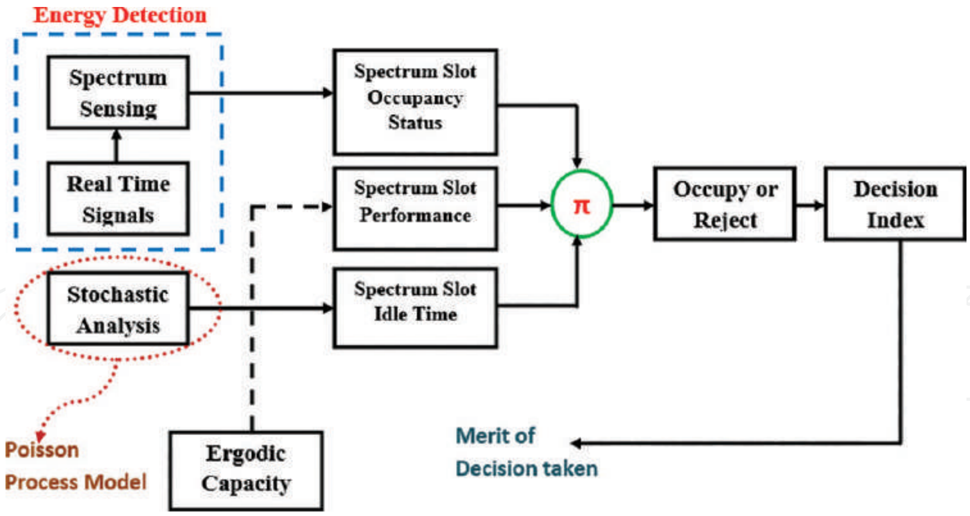


**Figure 4.** Proposed Spectrum decision framework for CRN based IoT in 5G/B5G networks.

proposed here with an analysis through Radio Operating characteristics (ROC) curves at various SNR values. This scheme is based on fusion of three separate decision of three key parameters, spectrum slot idle time, spectrum slot occupancy status and the spectrum slot performance. The spectrum decision framework first finds the idle time of the spectrum slot, spectrum slot occupancy status through SS using ED scheme and spectrum lot performance based on its ergodic capacity as shown in **Figure 4**.

### 7.1. System model

A CRN operating in a spectrum band '*S*' with frequency ranging from 54 MHz–50 GHz covering most of the wireless applications given in **Table 5**, is considered. The other specifications to be considered (like uplink and downlink frequencies, modulation techniques used in transmission and bandwidth) are as given in [37]. Channel bandwidth is the frequency range over which a IoT-U's transceiver transmits and receives its signals in CRN. An IoT-U can carry out its transmission on either narrow, wide and ultra wide band (UWB) ranges depending on the RF environment and wireless applications. The CRN has a centralized network operator, for instance a BTS which functions as "serve to provide". A region comprising of 5 BTSs, unlimited number of mobile devices, all buildings in the neighborhood are under the coverage of all the wireless services as shown in **Figure 5**. A wide range wireless based applications, i.e., GSM, bluetooth, UWB, NB, video conferencing, IP based communication, office automation systems, building security management systems, 5G and RFID, connected through IP based communication radios. 3GPP channel model has been used owing to its typical characteristics for wireless systems, i.e., it has properties that impact on system performance by reflecting the important properties of propagation channels. Moreover, wireless networks are optimized in the region of system model. Let there be '*J*' SUs (using ED for SS) in the CRN each having its own Software Defined Radio (SDR) to exploit the multiple spectrum bands over wide spectrum ranges by adjusting the operating frequency through software operations. The BTSs exercises control over all *J* IoT-Us within its transmission range as shown in **Figure 2**. The

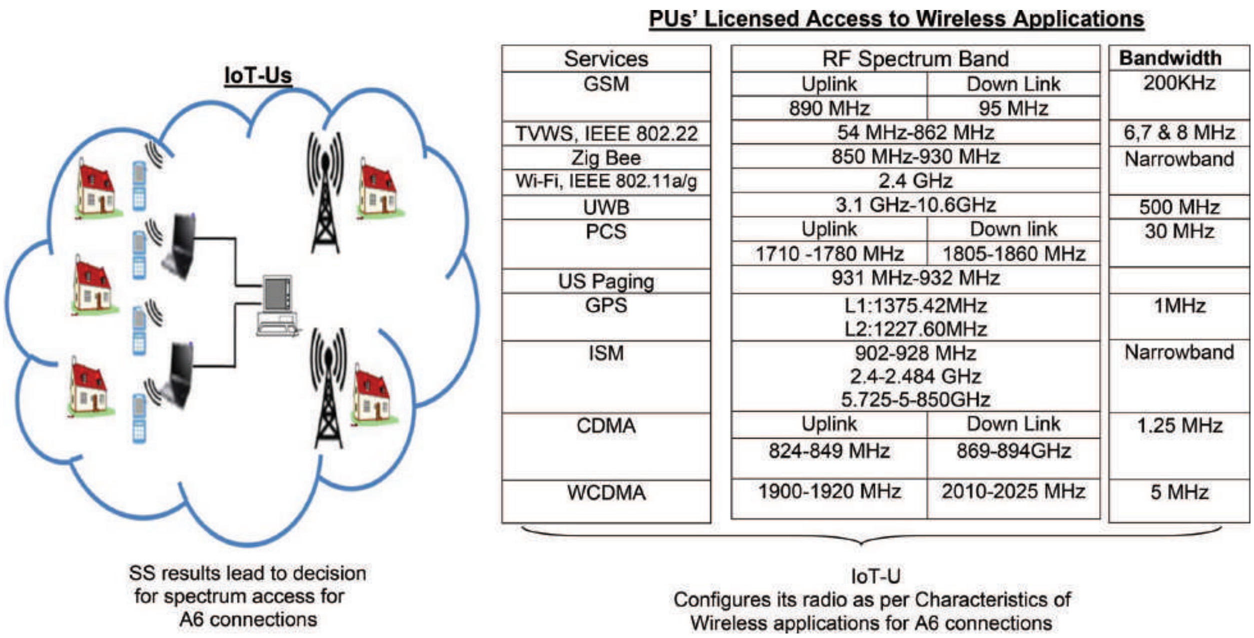


**Figure 5.** System model for proposed Spectrum decision framework.

RF spectrum slots in CRN are considered to have varying bandwidth. There are *N* PUs having rights to access same number of corresponding spectrum slots. *J* IoT-Us are attempting to access these slots for their transmission. Wireless services employ a combined FDMA/TDMA approach for air interface.

### 7.2. Performance evaluation and numerical analysis

The simulation parameters are given in **Table 6**. In finding the idle spectrum slot through the PU activity time, there can occur two types of errors. One is, false alarm and the other is the miss detection. Later is due to sensing an idle spectrum slot as occupied, and the following is due to assuming an occupied slot as idle. The performance of the proposed spectrum decision framework is assessed here through ROC curves between probability of false alarm and miss detection. These two are the inter-related parameters in the proposed decision process. To

| | |
|---|---|
| No. of BTSs | 5 |
| No of IoT-Us in CRN | *J* |
| No of PUs | 5 |
| RF spectrum range | 890–915 MHz (GSM Band) |
| Wireless channel model | 3 GPP |
| Bandwidth | 200 KHz |

**Table 6.** Simulation parameters.

have accurate data of PU(s) activity time and occupancy status, there should be low values of both the probabilities, which cannot be achieved as both are inter related to each other. Therefore, an optimal set of range must be obtained. Transmission at different values of SNR give different ROC curves for the PU's activity time and its occupancy in the spectrum slot. The lower the probability of miss detection (or higher the probability of detection) for a given probability of false alarm, the more reliable and accurate the detection would be, which is desirable for taking the decision by the SU(s) to occupy that particular spectrum slot in CRN.

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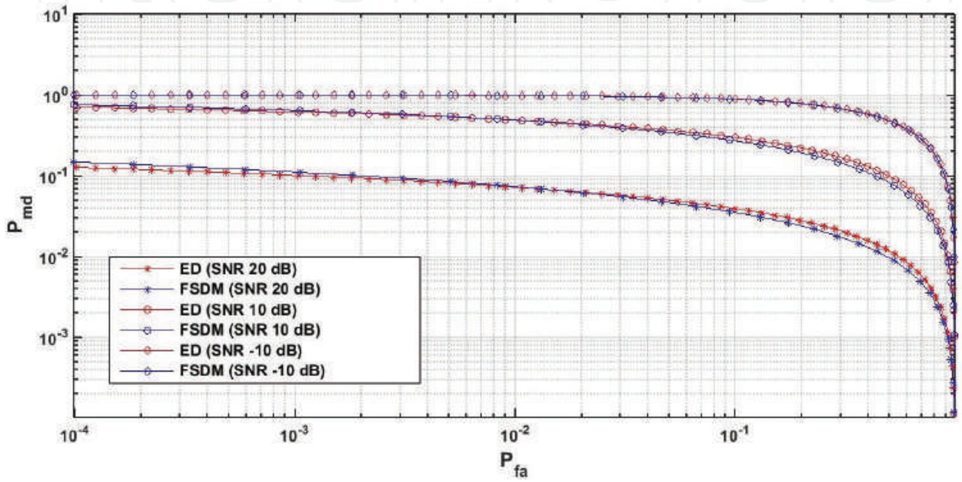


**Figure 6.** ROC curves for various values of SNR compared with ED SS results and on occupying the spectrum slots by 5 IoT-Us under proposed frequency Spectrum decision mechanism (FSDM).

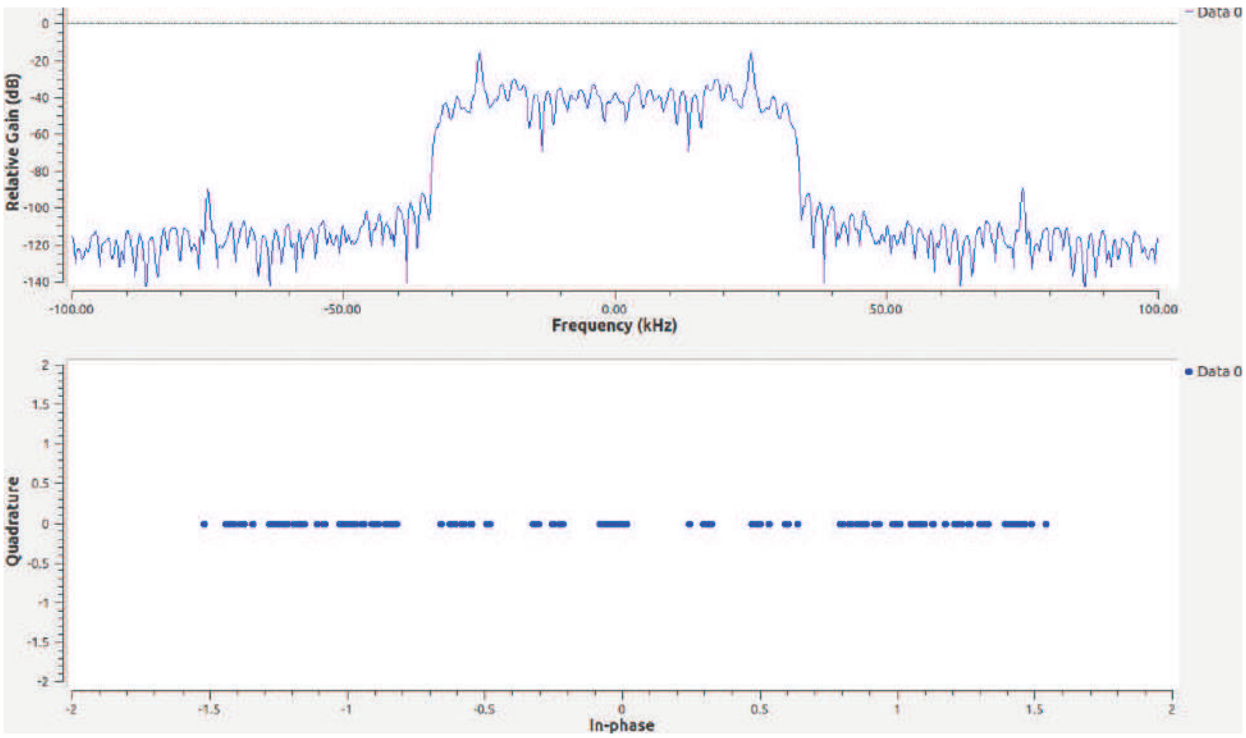


**Figure 7.** SU's transmitter transmitting low power signal around center frequency in their side lobs.

Energy Detection (ED) in SS offers a fast and reliable detection method for SUs in CRN. The detection performance of ED depends on effects of multipath fading [38]. Accordingly, the proposed decision framework has been validated by ROC curves compared with those of SS through ED method at various SNR values. ROC curves for 5 IoT-Us are shown in **Figure 6**. For the communication overhead as an outcome of information exchange required by the statistical approach, has been significantly reduced by using existing common control channels (CCC) by IoT-Us. This complexity cost is fully justified given the significant performance improvement that the proposed framework offers in terms of latency, throughput, energy efficiency, delay, and the reliability for realization of IoT in terms of A6 connections.

To ensure there is no harmful interference caused to PU by the SU, the SU's transmitter transmits less energy in the side lobs of the transmission signal as shown in **Figure 7**.

## 8. Conclusion

CR is an important measure to spectrum scarcity problem. To optimally utilize the already allocated spectrum, spectrum decision holds significance in CR. Spectrum decision enables CR users to access the spectrum slots as per their wireless application over a wide RF spectrum range. In this chapter a spectrum decision framework has been proposed which weighs the spectrum band on its idle time, occupancy status and performance and ensures A6 connection thereby providing an enable technology for IoT to support 5G/B5G networks with higher data rates.

## Author details

Ahmad Naeem Akhtar*, Fahim Arif and Adil Masood Siddique

*Address all correspondence to: ahmadnaeem.akhtar@mcs.edu

National University of Science and Technology (NUST), Islamabad, Pakistan

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Chapter 5

# Spectrum Sensing and Mitigation of Primary User Emulation Attack in Cognitive Radio

Avila Jayapalan and Thenmozhi Karuppasamy

Additional information is available at the end of the chapter

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**Abstract**

The overwhelming growth of wireless communication has led to spectrum shortage issues. In recent days, cognitive radio (CR) has risen as a complete solution for the issue. It is an artificial intelligence-based radio which is capable of finding the free spectrum and utilises it by adapting itself to the environment. Hence, searching of the free spectrum becomes the key task of the cognitive radio termed as spectrum sensing. Some malicious users disrupt the decision-making ability of the cognitive radio. Proper selection of the spectrum scheme and decision-making capability of the cognitive reduces the chance of colliding with the primary user. This chapter discusses the suitable spectrum sensing scheme for low noise environment and a trilayered solution to mitigate the primary user emulation attack (PUEA) in the physical layer of the cognitive radio. The tag is generated in three ways. Sequences were generated using DNA and chaotic algorithm. These sequences are then used as the initial seed value for the generation of gold codes. The output of the generator is considered as the authentication tag. This tag is used to identify the malicious user, thereby PUEA is mitigated. Threat-free environment enables the cognitive radio to come up with a precise decision about the spectrum holes.

**Keywords:** cognitive radio, spectrum sensing, PUEA, collaborator node, authentication tag

## 1. Overview

The introduction of wireless technique has led to the achievement of mobility and global connectivity through its advantages in flexibility, cost and convenience. Due to its rapid growth, there arises a demand for the spectrum. But analysis shows that there are portions

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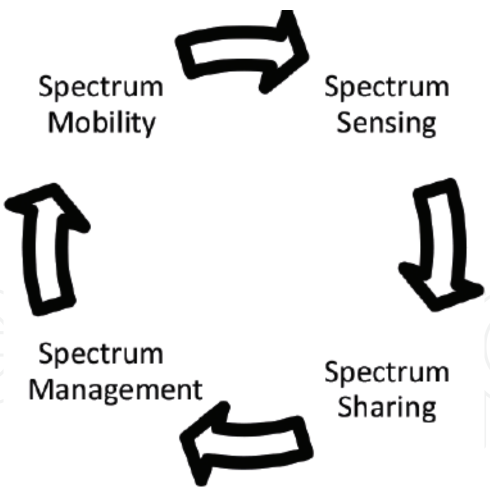


**Figure 1.** Cognitive cycle.

of the spectrum which are not effectively used and those portions of the spectrum could be exploited, whenever in need. For dynamic spectrum access, cognitive radio has risen as a favourable solution [1, 2]. Cognitive radio searches out for the free spectrum termed as 'spectrum holes'. The process of finding the spectrum holes is termed as spectrum sensing. Apart from spectrum sensing some of the other functions of cognitive radio are spectrum sharing, spectrum management and spectrum mobility. These four functions are put together termed as cognition cycle [3–6] and it is shown in **Figure 1**.

### 1.1. Spectrum sensing

The users in the wireless environment can be classified into three main groups, namely primary users, secondary users and selfish, malicious users. Primary users are those who gain ownership of the spectrum [7]. Secondary users desire to gain access in the absence of primary users [8]. Malicious users desire to own access of the spectrum by cheating the secondary users [9].

In the cognitive environment, the procedure of searching the spectrum holes by the secondary users is known as spectrum sensing. The cognitive radio not only looks for the free spectrum, but also checks for the arrival of primary users. On the homecoming of the primary users, cognitive users or the secondary users should quit the existing spectrum immediately and search for some other new spectrum hole.

### 1.2. Types

Various types of spectrum sensing schemes are available and they are shown in **Figure 2**. Some of them are energy detection method [10], cyclostationary method [11], matched filter method [12], etc. Feature detection and matched filter methods require prior knowledge about the licenced user for detection and they are time-consuming.

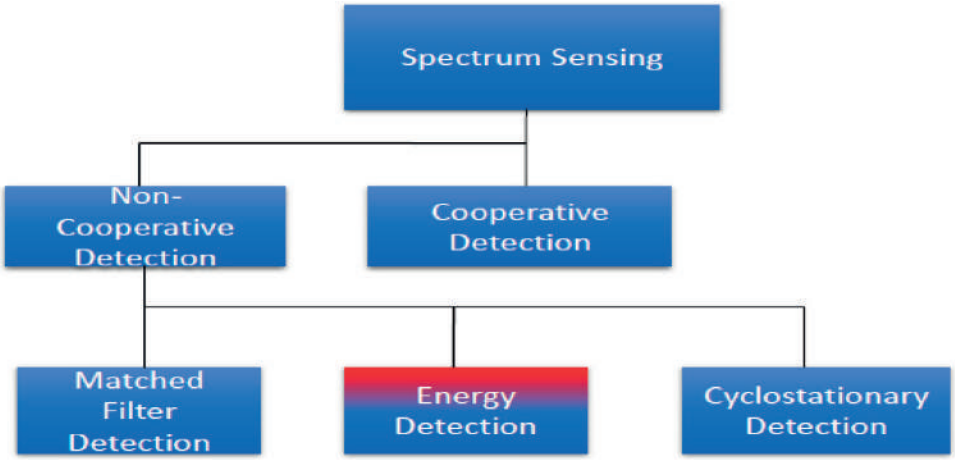


**Figure 2.** Types of spectrum sensing.

Energy detection method does not require any former knowledge about the primary user and it is simpler and quicker when compared to the previously mentioned methods. Energy detector can be classified into two types:

- Frequency domain-based energy detector
- Time domain-based energy detector

Energy detection method is not suited for places where the SNR is very low. Hence, it is a trade-off in choice of the proper spectrum sensing scheme.

### *1.2.1. Time domain*

**Figure 3** shows time domain-based energy detector. The energy of the signal is calculated and compared with the threshold.

The output of the detector is

$$Z = \sum_{n=0}^{N} y(n)^2 \tag{1}$$

where n = 1, 2, 3, …, N. N = number of samples

$$\begin{aligned} &\text{If } Z < \lambda \text{ primary user absent} \\ &\text{If } Z \geq \lambda \text{ Primary user present} \end{aligned} \tag{2}$$

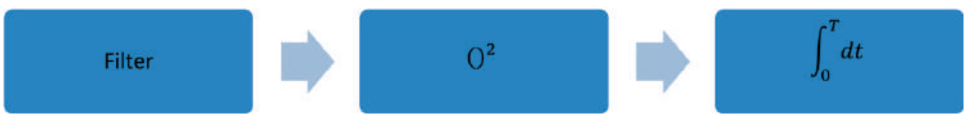


**Figure 3.** Time domain-based energy detector.

The decision hypothesis is as follows:

$$\begin{aligned} y(n) &= s\,H_0 = \text{ only the presence of noise} \\ y(n) &= x(n) + s\,H_1 = \text{ presence of both primary user signal and noise} \end{aligned} \tag{3}$$

where n is the noise, y(n) is the received signal and x(n) is the transmitted signal.

*1.2.2. Threshold*

Keeping the probability of false alarm fixed the threshold value is set according to the equation:

$$\lambda_f = \sigma_n^2\left(1 + \frac{Q^{-1}\left(P_f\right)}{\sqrt{\frac{N}{2}}}\right) \tag{4}$$

$$\lambda_d = \sigma_n^2(1 + SNR)\left(1 + \frac{Q^{-1}(P_f)}{\sqrt{\frac{N}{2}}}\right) \tag{5}$$

where N = number of samples and $Q^{-1}$ = complementary error function.

- Cooperative spectrum sensing: Group of cognitive radios, shares the spectrum sensing information. To achieve spectrum sharing and to overcome the multipath propagation effects and hidden node problems cooperative spectrum sensing scheme is utilised. The cognitive users employ less sensitive detectors, thereby reducing the cost of hardware and complexity. It is divided into two types namely
- Centralised spectrum sensing
- Distributed spectrum sensing

Centralised spectrum sensing: In this method, the central unit collects the sensing information from the cognitive users located at various places of the radio environment, analyses the received information and transmits the final decision about the existence or nonexistence of the PU to the cognitive users. Two rules are followed in deciding PU. One is AND rule and the other is OR rule.

- AND rule: All the SU's declare that the PU is present
- OR rule: If anyone SU status is high then the PU is considered present

Distributed spectrum sensing: Each node senses the PU, and a decision is made based on the earlier scenarios. Complexity is greatly reduced as there is no need of fusion center (FC). But at the same time, it increases the burden to the CR.

### 1.3. PUEA

On receiving the primary users signal, the cognitive radio compares it with a predefined threshold. If the incoming signal exceeds the primary threshold, user is assumed to be present else absent. In the absence of the primary user, the malicious user sent a fake signal almost matching with the primary user signal to the cognitive radio. The cognitive radio on receiving the fake signal compares it with the threshold. The fake signal exceeds the threshold, and hence the primary user makes a wrong interpretation that the primary user is present and does not make any attempt access the spectrum. The malicious user now utilises that free spectrum. This attack is known as primary user emulation attack (PUEA) [13], which is considered as the severe attack in the physical layer of the cognitive radio.

Various researchers have analysed the importance and impact of PUEA in cognitive radio environment, and they have come out with different solutions to overrule PUEA. Few of them are as follows. A review about primary user emulation attack has been made in [14–17]. A study about PUEA has been made in [18, 19]. To ensure end-to-end security for portable devices over cognitive radio network, two authentication protocols have been proposed in [20]. Four dimensions continuous Markov chain model to combat PUEA has been proposed in [21]. PU, secondary user, selfish misbehaviour secondary user and misbehaviour secondary user are considered to combat PUEA. In [22], a trustworthy node is taken as reference and the position of PU and emulator was found to detect PUEA. Eigenvalue-based PUEA mitigating method has been discussed in [23]. Time-synched link signature scheme to mitigate PUEA has been proposed in [24]. In [25], temporal link signature scheme to establish link between transmitter and receiver has been proposed and with the aid of signature PUEA is mitigated. Any change in the transmitter location or emulator claiming as transmitter is identified.

Integrated cryptographic and link signature-based method to mitigate PUEA has been proposed in [26]. Suspicious level and trust level calculations are carried out to mitigate PUEA in cooperative spectrum sensing environment in [27]. Mitigating PUEA and worm hold attack through sequence number generation by the helper nodes has been proposed in [28]. Multiple helper nodes-based authentication method to combat PUEA in the TV band has been discussed in [29]. Optimum voting rule and sample-based scheme in cooperative spectrum sensing to mitigate PUEA has been proposed in [30]. Advanced encryption standard (AES)-based authentication method with 256-bit key size has been suggested in [31] to overcome PUEA. Digital constellation-based authentication scheme to mitigate PUEA has been proposed in [32]. Quadrature phase shift keying was considered. Based on the tag value, the phase of QPSK modulation is rotated. Helper node-based special authentication algorithm has been suggested in [33] to mitigate PUEA in mobile networks. Location, privacy-preserving framework, has been proposed in [34]. The framework consists of two parts namely privacy-preserving sensing report aggregation protocol and distributed dummy report injection protocol.

Authentication scheme based on the transmitter called localisation based defence (LocDef) to mitigate PUEA has been discussed in [35]. In [36], neural network and database management-based scheme to mitigate PUE threat have been proposed. COOPON (called cooperative neighbouring cognitive radio nodes) technique to mitigate the selfish user attack in cooperative spectrum sensing environment has been proposed in [37, 38]. Matched filter-based spectrum sensing together with the cryptographic signature-based method has been suggested in [39]. Extensible authentication protocol and carousel rotating protocol-based authentication scheme have been proposed in [40]. Location-based authentication protocol for IEEE 802.22 wireless regional area network (WRAN) has been implemented in [41]. Double key-based encryption scheme has been proposed in [42] to overcome the attacks. Two non-parametric algorithms namely cumulative sum and data clustering-based method have been discussed in [43] to mitigate PUEA in cognitive wireless sensor networks. A study about various types of attacks and their countermeasures in wireless sensor networks has been made in [44].

In [45], Fenton's approximation and Wald's sequential probability ratio test (WSPRT)-based scheme has been proposed to mitigate PUEA. Probability of missing was the main parameter considered to set the threshold value. Modified combinational identification algorithm has been discussed in [46] to mitigate the attacks in cooperative sensing. Cluster-based technique to overcome the rogue signal intrusion in cooperative spectrum sensing has been discussed in [47]. In [48], a novel method has been suggested to mitigate the threat in cooperative spectrum sensing. It includes two phases namely identifying phase and sensing phase. In the identifying phase, reliable SUs are found and the sensing results are collected in the second phase. In [49], a trustworthy cognitive radio network has been suggested to defend against malicious users. It is based on the trust value generated and distributed among the nodes. In [50], two algorithms are derived namely encryption algorithm and displacement algorithm from overcoming PUEA. Adaptive orthogonal matching pursuit algorithm (AOMP) has been proposed in [51] to mitigate PUEA. Energy detection, cylostationary and neural network-based scheme have been reported in [52] to cancel PUEA. AND/OR rule-based sensing method has been suggested in [53] to mitigate in PUEA in cooperative spectrum sensing. Improvements in the probability of error is obtained by the OR rule than the AND rule. Nash equilibrium-based differential game method has been suggested in [54] to mitigate PUEA. A new cooperative spectrum sensing in the presence of PUEA has been offered in [55]. Based on the channel information among PU, SU and attackers, weights are derived for optimal combining in the fusion center. A hybrid defence scheme against PUEA with motional secondary users was discussed in [56]. A new spectrum decision protocol to mitigate PUEA in dynamic access networks has been discussed in [57].

### *1.3.1. Other attacks*

Some of the other attacks in the physical layer are denial of service (DOS) attack and replay attack. Any attack in the path between cognitive radio and primary user is known as DOS attack. The malicious user eavesdrop some primary user information and transmit to the cognitive radio at an irrelevant time. This confuses the cognitive radio in deciding the existence of the primary user. This attack is termed as replay attack.

A study about denial of service attack has been made in [58, 59]. Radio frequency fingerprint-based technique has been suggested in [60] to combat DOS attack. Dynamic and smart spectrum sensing algorithm (DS3) has been generated in [61] to minimise the DOS attack. Around 90% of improvement in spectrum utilisation was obtained with the inclusion of DS3 algorithm. Channel eviction triggering scheme in the presence of Rayleigh fading channel has been proposed in [62] to mitigate DOS attack in cooperative spectrum sensing environment. This mechanism is aimed at reducing the misreports and increasing the trustworthy score. A study about replay attack in cognitive radio has been made in [18, 63–65]. A study about the malicious activities in ZigBee network has been made in [66].

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### 1.4. Performance metrics

Performance metrics are used to analyse the system's behaviour and performance. They are used to confirm and validate the specified system performance requirements and to identify the performance issues in a given system.

The important performance metrics for cognitive radio are

- Probability of detection ($P_d$): Probability of detection is the time during which the primary user is detected.
- Probability of false alarm ($P_f$): the erroneous detection of the primary user
- Probability of missed detection: failing to detect the primary user. Probability of false alarm: A study about the performance metric has been made in [67–69].
- Receiver operating characteristics (ROC): It is the graph plotted between sensitivity and false positive rate. Here, it is plotted between probability of missed detection and probability of false alarm.

This chapter gives a brief idea about the working of frequency domain-based energy detection spectrum sensing scheme and provides a solution to mitigate PUEA through the authentication tag generated by the collaborator cognitive radio. The sample graphs are plotted between probability of detection and signal to noise ratio, $P_d$ versus $P_f$.

## 2. Method to mitigate PUEA

### 2.1. Collaborator node

To ensure proper spectrum sensing, cognitive radio does not carry out spectrum sensing of its own. Instead, it depends on the third party called collaborator node. It is assumed that the collaborator node is very close to the primary user. The purpose of choosing collaborator node is due to Federal Communication Commissions (FCC) decision 'no modifications must be done to the primary user signal'.

The sample graph is shown in **Figure 4**. The collaborator node senses the availability of the primary user and in the absence of the primary user conveys the message to the cognitive

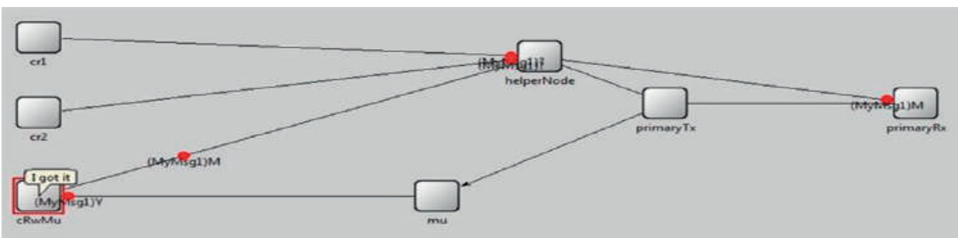


**Figure 4.** PUEA mitigation.

radio along with the authentication tag. To elude interference with the primary user, the collaborator node communicates with the cognitive radio only in the absence of the primary user. The key to decode the authentication tag is already known to the cognitive radio. The cognitive radio accepts the information only with authentication tag and discards other information. By this way, PUEA is mitigated.

### 2.2. Spectrum sensing

The collaborator node senses the availability of the primary user with the aid of energy detection method. The block diagram of frequency domain-based energy detection method is shown in **Figure 5**. The incoming signal is filtered and passed to fast Fourier transform block. The output of FFT block is fed to windowing function block. This is done so to reduce the irregularities and to reduce the side lobes. Various windows like Hanning window, Hamming window, Blackman window and Kaiser window could be utilised. Every window has its own advantage and disadvantage. By adjusting beta parameter of Kaiser window, side lobes can be reduced when compared to other windows; but at the same time, the width of main lobe is wider. By adjusting the size of the windows, better output could be obtained. Hence, proper choice of window becomes necessary. The output of windowing block is fed to magnitude square block. The average energy of the signal is then compared with the decision threshold [70–73].

If the incoming signal falls below the threshold, it is null hypothesis ($H_0$). Only noise is present in the channel and the primary user signal is absent. The spectrum is vacant and could be utilised by the cognitive radio. On the other hand, if the incoming signal exceeds the threshold the decision made is 'primary user present'.

**Table 1** summarises the simulation parameters of the graph plotted below. **Figure 6** shows the sample result plotted between $P_d$ versus SNR. SNR is considered as x-axis and $P_d$ as y-axis. For the probability of detection of 0.9, the SNR is −14 dB. The negative scale indicates that the cognitive radio can pick up the primary user signal in a week SNR environment.

**Figure 7** shows the output of energy detector for different values of SNR with AWGN noise present in the channel. From the figure, it is clear that as the SNR increases error reduces. Probability of missed detection is lesser for SNR of −5 dB when compared to −20 dB. Lesser the SNR, more is the noise which makes it difficult to detect the presence of the primary user.

### 2.3. Authentication tag generation by the collaborator node

Once the sensing process is complete, the second step is to generate the authentication tag. The authentication tag is generated in three ways. First method is logic map algorithm-based sequence generation. Second method is by means of DNA-based cryptographic algorithm

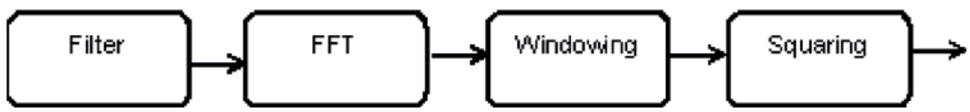


**Figure 5.** Energy detection method.

| | |
|---|---|
| Number of samples | 300 |
| Probability of false alarm | 0.1 |
| Window function | Hanning |
| Channel | AWGN |
| FFT size | 128 |

**Table 1.** Simulation parameters.

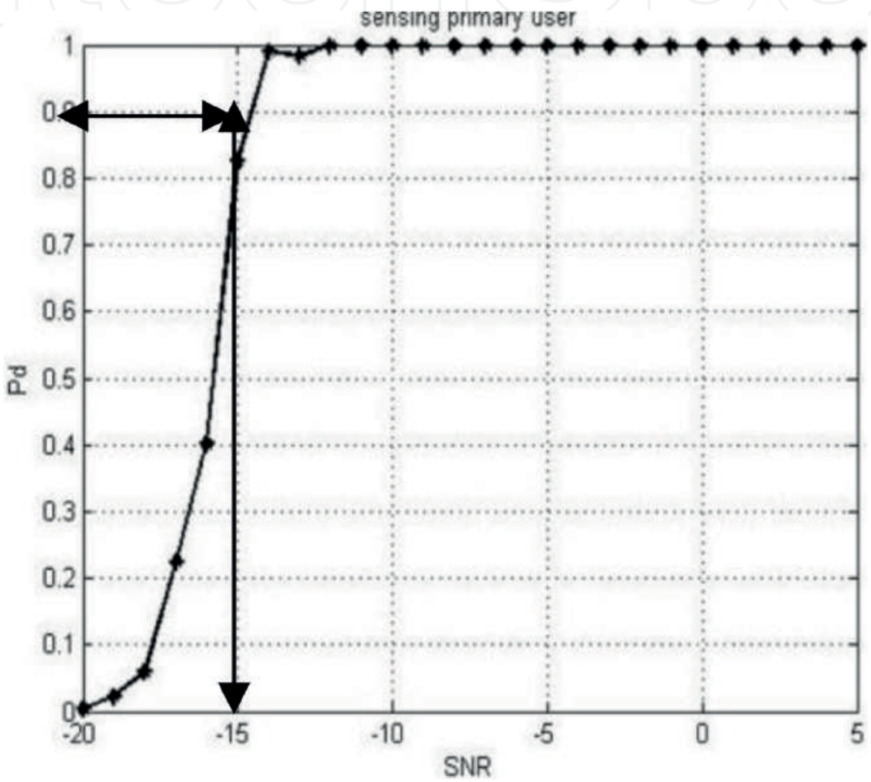


**Figure 6.** Spectrum sensing.

the sequence is generated. Third method is based on gold code. Utilising gold code generator gold codes are generated. In this, the initial seed value for the gold code is the sequences obtained from the first two methods. The final output from the gold code is treated as the authentication tag to mitigate PUEA.

*2.3.1. Chaotic sequence*

Chaotic sequences help to retrieve the data from intruder in many ways:

**a.** It changes the transmitted signal into unwanted noise, and therefore it will provide great confusion to the intruder.

**b.** Code sequences will not repeat for each and every bit of information so it causes the malicious user to take long time to find the sequences.

**c.** Developing chaotic sequence is simple for both transmitter and receiver who knows the data and parameters used in that transmission, the exact regeneration of data is difficult for a receiver those who wrongly estimate the value. A slight deviation in estimation leads to increasing the error. This is because of sensitivity of chaotic system on their initial condition.

*2.3.1.1. Logistic chaotic sequence*

1-D logistic chaotic sequence is widely used in communication because of their fast computation process, and simple nature.

Logistic chaotic sequence can be generated by using an expression

$$x(j+1) = r \times x(j) \times (1 - x(j)) \tag{6}$$

where r is called as control parameter and constant, it ranges from $3.57 < r < 4$, $x(1) = 0.99$.

One of the main properties of this sequence is extreme sensitivity to initial condition and good correlation property.

**Figure 8** shows the signal to noise ratio versus primary user detection graph plotted with and without authentication tag. The overlapping of both the graphs shows that there is no significant change in the performance of the collaborator system when an authentication tag is inserted. The authentication tag and the spectrum-free information are transmitted to the cognitive radio. The probability of false alarm is fixed as 0.1 and the number of samples chosen is 300. Additive white Gaussian noise (AWGN) is considered as the channel noise.

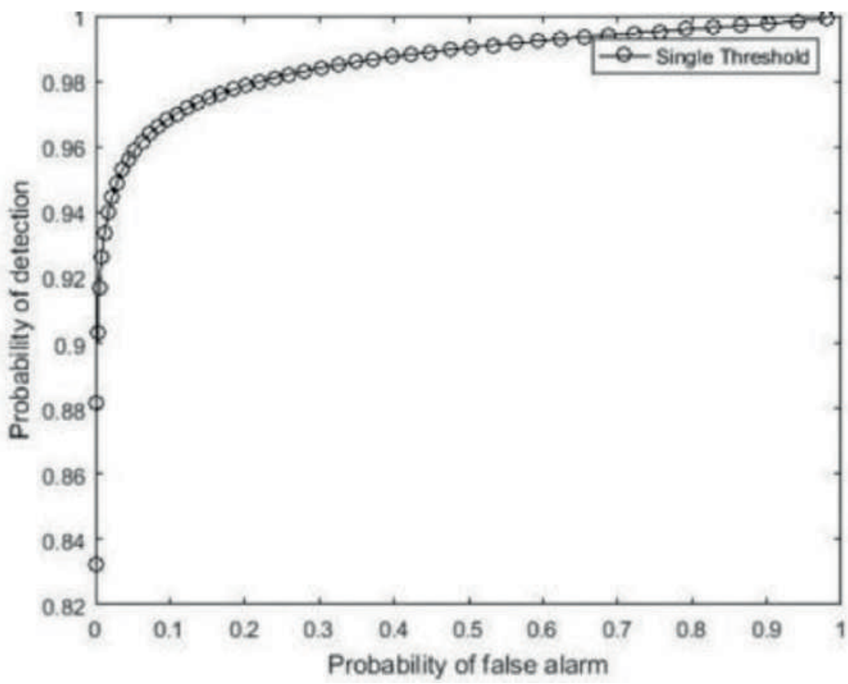


**Figure 7.** Comparison between various SNR.

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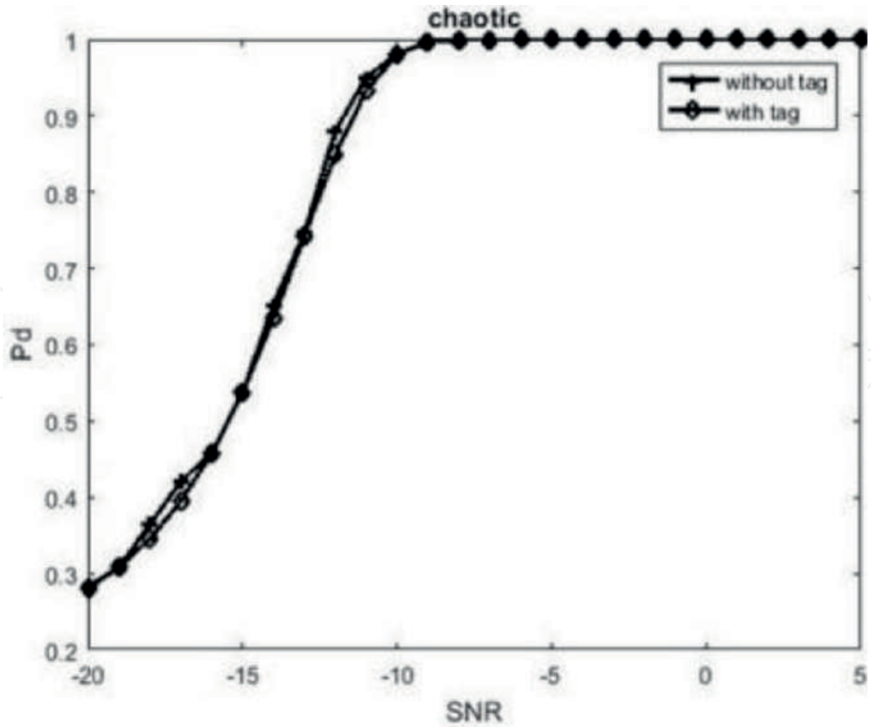


**Figure 8.** Chaotic-based tag generation.

*2.3.2. DNA*

DNA algorithm has been utilised in this work to generate the authentication tag because the storage and processing of data is very secure. One single DNA can be split into four basic units. They are Adenine (A), Thymine (T), Cytosine (C) and Guanine (G). So, it is also known as quaternary encoding. Binary values are assigned to these units for encoding purpose as follows:

A—00, T—01, C—10 and G—11.

**Algorithm**

Step 1: Transform message bits into binary

Step 2: Assign A, T, G and C to binary(a)

Step 3: Get key value from server(b)

Step 4: Take one's complement to step 2 and 3

Step 5: Do XOR operation between output from step 4(a' and b')

Step 6: Transform bits from step 5 into DNA form

Step 7: Transform DNA form into ASCII values

Step 8: Transform into binary form(encrypted)

**Figure 9** shows the signal to noise ratio versus probability of detection graph plotted with and without authentication tag. The overlapping of both the graphs shows that there is no notable

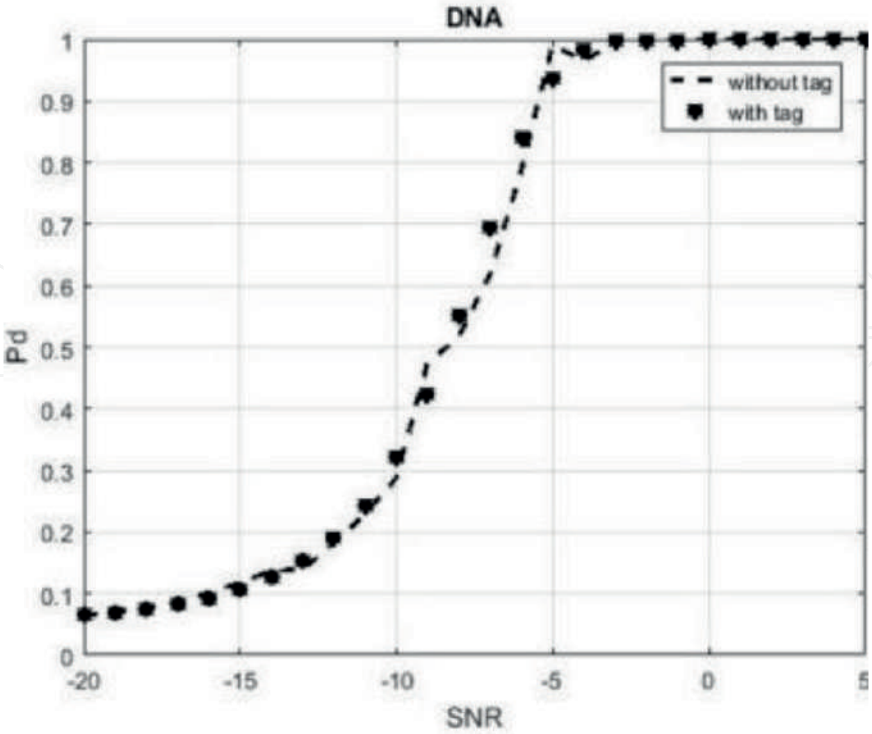


**Figure 9.** DNA algorithm-based tag generation.

difference in the performance of the collaborator system when an authentication tag is added along with the primary user availability information.

*2.3.3. Gold code*

Pseudonoise (PN) is a signal similar to noise but generated with a definite pattern. In cryptography, PN sequences are widely to ensure data protection from intruders. The PN sequences are added with the message signal so that it appears as noise to the malicious users. Various types of PN sequences are available. Their auto- and cross-correlation properties decide the choice of PN sequences. Some PN sequences have good autocorrelation property but not cross-correlation property. Some have good cross-correlation property but not autocorrelation property. Gold code is chosen because of its good auto and cross-correlation property. Gold codes are obtained by mod-2 addition of shifted pairs of m-sequences with length m. The autocorrelation and cross-correlation function of gold code, $2^t - 1$, is

Autocorrelation function:

$$\begin{gathered}\varphi_{GC}(\mathrm{h}) \\ \text{Where } \varphi_{GC}(\mathrm{h}) = \{\pm 2^t - 1, h = 0 \\ \pm 1, h \neq 0\end{gathered} \tag{7}$$

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Cross-correlation function:

$$\psi_{GC}(h)$$
$$\text{Where } \psi_{GC}(h) = (2^{t} - 1, h = \lambda \tag{8}$$
$$\pm 1, h \neq \lambda$$

*2.3.3.1. Trilayered authentication*

The proposed work is to integrate all the three algorithms and to generate a trilayered authentication tag to mitigate PUEA. Both the LFSRs required a seed value for their functioning. Hence, the initial seed value of one LFSR is the sequence generated utilising DNA algorithm and for the second LFSR it is a chaotic sequence. The outputs from the LFSRs are XORed, and the resulting gold code sequence is considered an authentication tag. It is as shown in **Figure 10**.

**Figure 11** shows the sample signal to noise ratio versus probability of detection graph plotted with and without authentication tag. From the figure, it can be depicted that there is no drastic change in the performance of the collaborator system when an authentication tag is add along with the primary user availability information.

**Figure 11b** shows the graph plotted by increasing the size of the window function. Here, Hamming window of size 10 has been utilised.

**Figure 11c** shows the plot of signal to noise ratio versus probability of detection graph plotted with and without authentication tag. Here, the FFT size of the energy detector has been raised from 64 to 128.

**Figure 11d** shows the graph plotted with the probability of false alarm fixed as 0.01.

*2.3.3.2. Hardware implementation*

Universal software-defined radio peripheral (USRP) is a universally accepted test bed for cognitive radio. The USRP software-defined radio device is a tuneable transceiver. It is used as a prototype for wireless communication systems. It offers frequency ranges up to 6 GHz with up to 56 MHz of instantaneous bandwidth. It allows advanced wireless applications to be created with LabVIEW, enabling rapid prototyping.

The prototype of energy detection-based spectrum sensing scheme is developed using LabVIEW tool. LabVIEW is a modelling, simulation and real-time implementation tool which

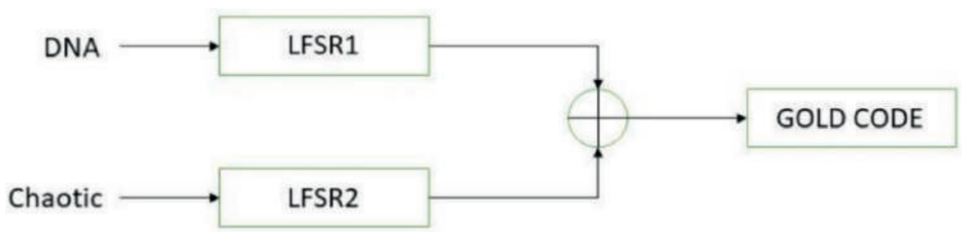


**Figure 10.** Trilayered authentication.

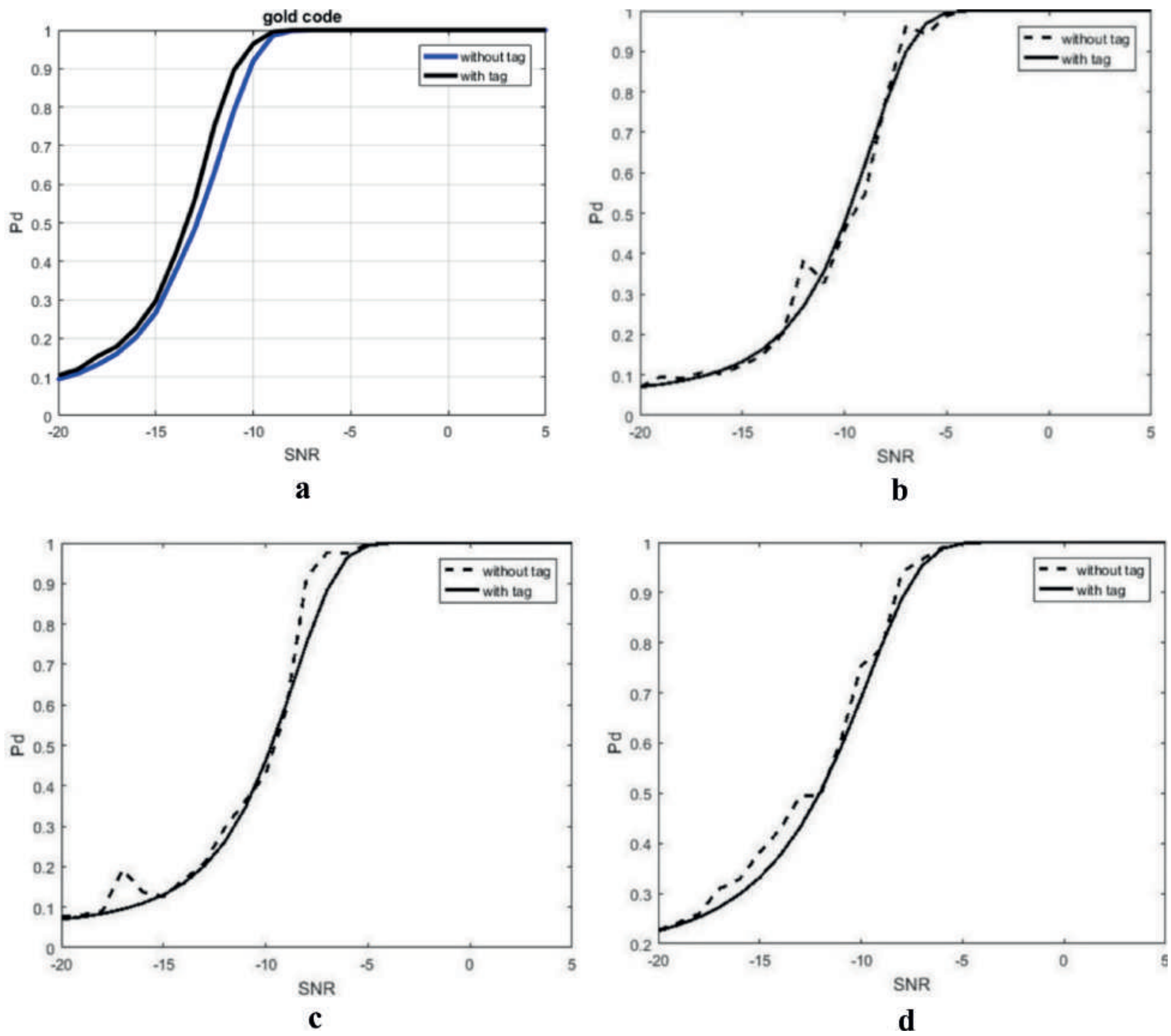


**Figure 11.** (a)–(d) Trilayer-based tag generation.

is being used around the world for implementation development through software. It uses runtime engine to simulate the designs. Front panel and block panel support the graphical user interface (GUI) structure of LabVIEW. Front panel comprises of controls and indicators, whereas block panel has functions, structures, Sub-Vis and terminals to execute the required design.

The transmitter and the receiver blocks are developed using LabVIEW software. **Figure 12** shows the block diagram of energy detector. Once the blocks are developed using LabVIEW software then the physical connections are made. Ethernet cable is used to connect USRP with the computer in which the blocks are developed.

Then, the signal is transmitted using USRP. **Figure 13** shows the USRP front panel.

**Figure 14** shows the experimental setup using USPR. Out of two USRPs, one USRP is treated as transmitter and the other USRP is treated as receiver. Additive white Gaussian noise (AWGN) is considered as the noise in the channel.

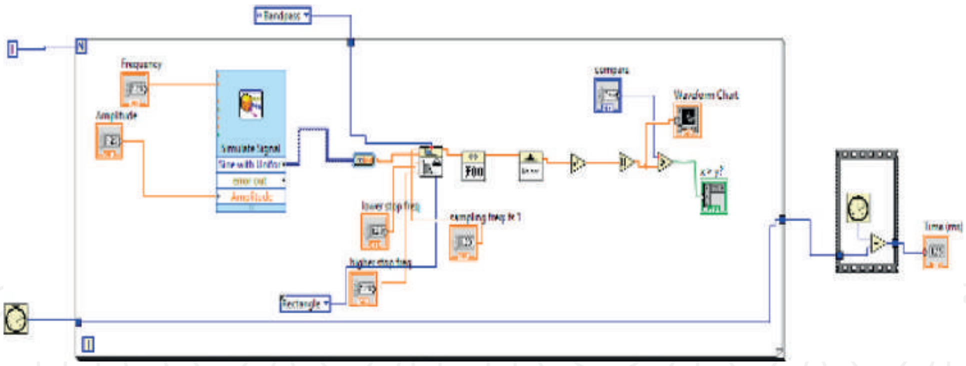


**Figure 12.** LabVIEW-based energy detector.


**Figure 13.** Front panel of USRP.

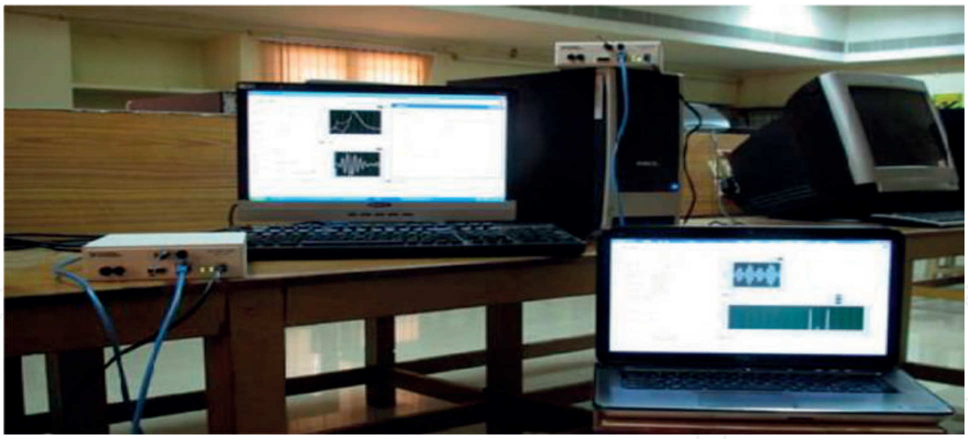

**Figure 14.** USRP experimental setup.

**Table 2** shows the specification of USRP. For transmission, the IP address is 192.168.10.1 and for reception the IP address is set as 192.168.10.2. The USRPs are connected to the computer via Ethernet cable. The distance between the two USRPs is set as 100 cm.

**Figure 15a** shows the transmission of primary user signal at the transiting end and **Figure 15b** shows the detection of primary user signal at the receiving end. The received signal is now compared with the threshold value. The incoming signal exceeds the threshold value. The presence of primary user is detected and plotted. For an SNR of −5 dB, the probability of detection is 0.9.

| | |
|---|---|
| Frequency range | 50 MHz–2.2 GHz |
| Gain range | 0–31 dB |
| Frequency accuracy | 2.5 ppm |
| DAC | 2 channels, 16 bit |
| Noise figure | 5–7 dB |
| Maximum I/Q sampling rate | 16-bit sample width at 20 MHz, 8-bit sample width at 40 MHz |

**Table 2.** USRP specifications.

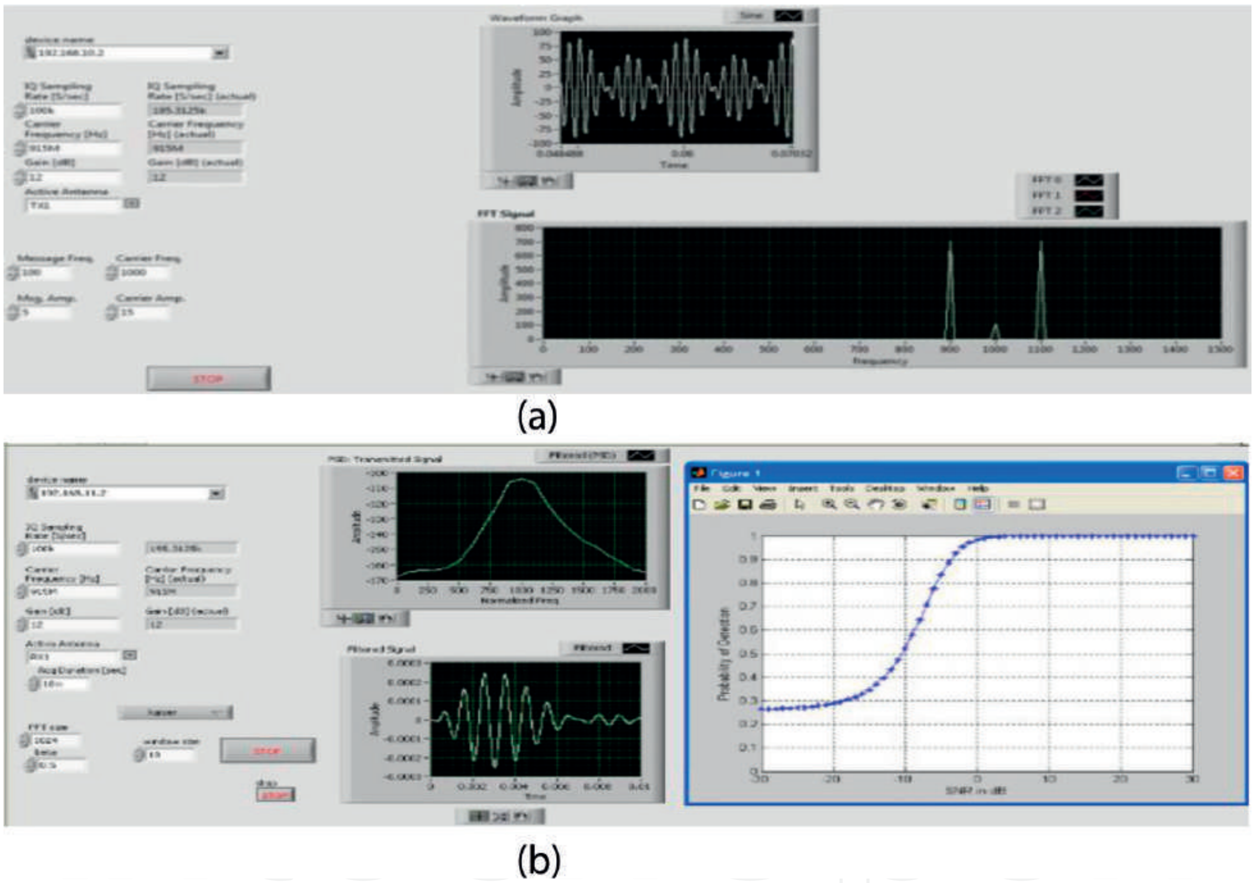

**Figure 15.** (a) Transmission using USRP. (b) Reception using USRP.

## 3. Conclusion

To avoid wastage of bandwidth and to achieve dynamic spectrum access cognitive radio is the best solution. To achieve dynamic spectrum access, the most important function of cognitive radio is spectrum sensing.

In this chapter,

- Energy detection-based spectrum sensing scheme has been discussed to detect the existence of the primary user by the collaborator node. This method has been chosen because of its simple nature.
- To combat PUEA, a collaborator node-based approach has been suggested. The cognitive radio requests the collaborator node to sense the free spectrum. The collaborator node senses the availability of the primary user.
- Once the availability of the free spectrum is confirmed, the message has been conveyed to the cognitive radio in a secure manner. Hence, a trilayered method has been suggested to generate the authentication tag. The message along with the tag is accepted by the CR and others are rejected. By this way, the PUEA attack has been overruled. Threat-free environment makes the cognitive radio to arrive at a proper conclusion about the presence of spectrum holes and utilise it.

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## Author details

Avila Jayapalan* and Thenmozhi Karuppasamy

*Address all correspondence to: avila@ece.sastra.edu

SASTRA Deemed to be University, Thanjavur, Tamil Nadu, India

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Chapter 6

# Interference Alignment in Multi-Input Multi-Output Cognitive Radio-Based Network

Arif Basgumus, Mustafa Namdar, Hakan Alakoca,
Eylem Erdogan and Lutfiye Durak-Ata

Additional information is available at the end of the chapter

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## Abstract

This study investigates the interference alignment techniques for cognitive radio networks toward 5G to meet the demand and challenges for future wireless communications requirements. In this context, we examine the performance of the interference alignment in two parts. In the first part of this chapter, a multi-input multi-output (MIMO) cognitive radio network in the presence of multiple secondary users (SUs) is investigated. The proposed model assumes that linear interference alignment is used at the primary system to lessen the interference between primary and secondary networks. Herein, we derive the closed-form mathematical equations for the outage probability considering the interference leakage occurred in the primary system. The second part of this study analyzes the performance of interference alignment for underlay cognitive two-way relay networks with channel state information (CSI) quantization error. Here, a two-way amplify-and-forward relaying scheme is considered for independent and identically distributed Rayleigh fading channel. The closed-form average pairwise error probability expressions are derived, and the effect of CSI quantization error is analyzed based on the bit error rate performance. Finally, we evaluate the instantaneous capacity for both primary and secondary networks*.

**Keywords:** 5G wireless communication systems, average pairwise error probability, CSI quantization, cognitive radio networks, interference alignment, MIMO, outage probability performance, two-way amplify-and-forward relaying

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# 1. Introduction

The rapidly growing number of mobile devices, higher data rates and cellular traffic, and quality of service requirements trigger the development of mobile communications. It is expected that the next-generation cellular networks (5G and beyond) will meet the advanced technology requirements. 4G networks are not powerful enough to support massively connected devices with low latency and high spectral efficiency, which is critical for next-generation networks. 5G networks are characterized by three fundamental functions in general: connectivity for everywhere, low latency for communication, and very high-speed data transmission [1].

In the near future, a large number of mobile devices will connect to one another in everywhere and provide a seamless mobile user experience. Real-time applications and critical systems and services (medical applications, traffic flow, etc.) with zero latency are expected to be offered over 5G cellular networks. Besides, the fast data transmission and reception will be ensured by supporting zero latency using a high-speed link. For this reason, the scope of 5G cellular networks bring the emerging advantages, new architectures, methodologies, and technologies on telecommunications such as energy-efficient heterogeneous networks, software-defined networks (SDN), full-duplex radio communications, device-to-device (D2D) communications, and cognitive radio (CR) networks. An increasing number of mobile devices and the bandwidth requirement for large amounts of data require the development of the new technologies and infrastructures in addition to the existing technology. It is inevitable that the number of smart phones, high-definition televisions, cameras, computers, transport systems, video surveillance systems, robots, sensors, and wearable devices produces a huge amount of voice-data traffic in the near future. To meet the growth and to provide fast and ubiquitous Internet access, several promising technologies have been developed. Regarding the deployment of the 5G wireless communication systems, the corresponding growth in the demand for wireless radio spectrum resources will appear. The capacity of the communication networks will be increased by using the energy-efficiency techniques with the evolving technology in 5G networks [2–5].

One of the candidates for solving the problem of spectrum shortage is the CR network which will be a key technology for 5G networks. CR has attracted considerable interest as it can cope with the spectrum underutilization phenomenon. Performing spectrum sharing using a CR network is an important issue in wireless communication networks. There are three main ways for a primary network user to share the frequency spectrum with a cognitive user: underlay, overlay, and interweave. In the underlay method, the secondary user (SU) transmits its information simultaneously with the primary user (PU) as long as the interference between SU and PU receivers is within a predefined threshold. In the overlay approach, SU helps PU by sharing its resources, and in return, PU allows SU to communicate. In the interweave technique, SU can use the bandwidth of PU if PU is not active. In this model, SU should have perfect spectrum-sensing features to analyze the spectrum [6–9].

Among the various methods of solving the interference problem, interference alignment (IA) is one of the most promising ways to achieve it. IA is an important approach for CR to recover the desired signal by utilizing the precoding and linear suppression matrices which consolidates the interference beam into one subspace in order to eliminate it [10–13]. In the literature, linear IA is adopted in CR interference channels in [14–20] and the references therein. In [14], adaptive power allocation schemes are considered for linear IA-based CR networks where the outage probability and sum rate were derived. In [15], adaptive power allocation was studied for linear IA-based CR using antenna selection at the receiver side. Ref. [16] enhances the security of CR networks by using a zero-forcing precoder. Moreover, in [17], a similar work was proposed to improve the overall outage performance of the interference channel by using power allocation optimization. These studies have shown that interference management is a critical issue to be handled in all multiuser wireless networks.

CR technology can be capable of utilizing the spectrum efficiently as long as the interference between PU and SU is perfectly aligned as shown in **Figure 1**. A set of studies discussing IA is presented in the literature [21–29].

Motivated by the above works, in the first part of this study, we examine the impact of interference leakage on multi-input multi-output (MIMO) CR networks with multiple SUs. Specifically, a closed-form outage probability expression is derived to provide the performance of the primary system. Then, in the second part of our work, we investigate the performance of IA in underlay CR networks for Rayleigh fading channel. Moreover, unlike the mentioned papers, the effect of CSI quantization error is taken into account in our analysis. Then, a two-way relaying scheme with amplify-and-forward (AF) strategy is studied. Finally, the effects of the relay location and the path loss exponent on the BER performance and system capacity and CSI quantization on the average pairwise error probability (PEP) performance for this two-way AF system are presented.

The main simulation parameters and their descriptions used in this study are summarized in **Table 1**.

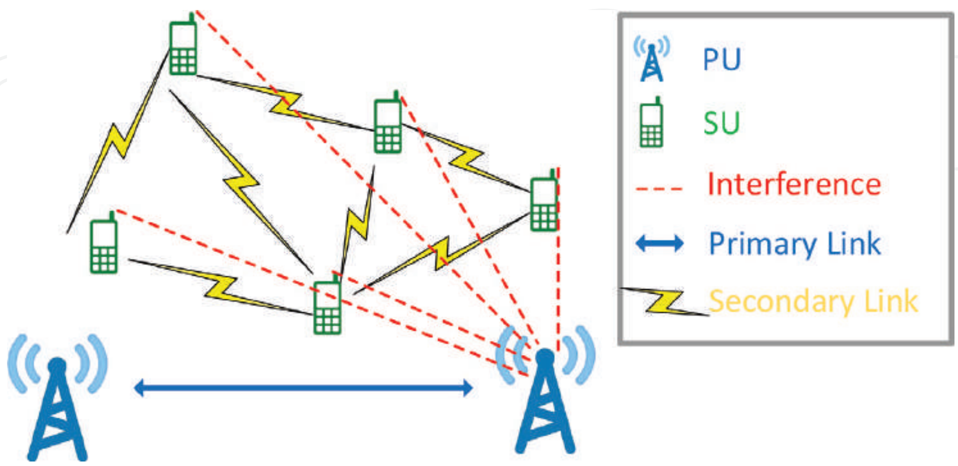


**Figure 1.** Illustration of the primary link between PU pair and interference links generated by the SUs.

| Symbol | Description |
|---|---|
| $P_1$ and $P_2$ | Transmitted powers of the PU and SU |
| $\sigma_N^2$ | Variance of the circularly symmetric additive white Gaussian noise vector |
| $R_{th}$ | Data rate threshold |
| $\alpha$ | Interference-leakage parameter |
| $M_p$ and $N_p$ | Number of transmit-and-receive antennas of PU |
| $M_s$ and $N_s$ | Number of transmit-and-receive antennas of SU |
| $K$ | Number of SU |
| $d_{j,i}$ | Distance between the *i*th transmitter and the *j*th receiver nodes |
| $\tau_{j,i}$ | Path loss exponent between the *i*th transmitter and the *j*th receiver nodes |
| $B_{j,i}$ | Channel state information exchange amount between the *i*th transmitter and the *j*th receiver nodes |

**Table 1.** The simulation symbols and their descriptions.

## 2. The impact of interference leakage on MIMO CR networks

In this study, MIMO interference alignment-based CR network with a PU and multiple SUs is considered under Rayleigh fading channel.

### 2.1. System model

In the system model as it is shown in **Figure 2**, the number of transmit-and-receive antennas of the PU is given by $M_p$ and $N_p$. The transmit antennas at each SU are given as $M_s$. The received signal, $\mathbf{y}_p$, implementing the IA technique is given as

$$\mathbf{y}_p = \mathbf{U}_p^{\mathrm{H}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \sqrt{\alpha}\sum_{i=1}^{K}\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i} + \mathbf{U}_p^{\mathrm{H}}\mathbf{n}, \tag{1}$$

where $x_p$ and $x_{s_i}$ are the transmitted signals from PU and the *i*th SU $(\text{for } i = 1, 2, \ldots, K)$, respectively. Herein, $\mathbf{H}_{pp}$ is the matrix of channel coefficients between the PU pair, and $\mathbf{H}_{ps_i}$ denotes the channel matrix between the primary receiver and the *i*th secondary transmitter. The interference leakage is modeled similar to the one in [30]. The interference-leakage parameter $\alpha$ $(0 \leq \alpha \leq 1)$ represents the status of the alignment, i.e., $\alpha = 0$ and 1 corresponds to perfect alignment and perfect misalignment cases, respectively. $\mathbf{V}$ and $\mathbf{U}$ are the precoding- and interference-suppression matrices. The superscript $(\cdot)^{\mathrm{H}}$ denotes the Hermitian operator, and $\mathbf{n}$ is the zero-mean unit variance $(\sigma_N^2 = 1)$ circularly symmetric additive white Gaussian noise (AWGN) vector.

The following conditions must be satisfied for perfect interference alignment between PU and SUs:

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$$\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i} = 0, \tag{2}$$

$$\mathrm{Rank}\left(\mathbf{U}_s^{\mathrm{H}}\mathbf{H}_{ps_i}\mathbf{V}_s\mathbf{x}_{s_i}\right) = d. \tag{3}$$

Each user transmits $d$ data streams. Using the ideal linear IA technique, (1) can be re-expressed as

$$\mathbf{y}_p = \mathbf{U}_p^{\mathrm{H}}\mathbf{H}_{pp}\mathbf{V}_p\mathbf{x}_p + \mathbf{U}_p^{\mathrm{H}}\mathbf{n}. \tag{4}$$

### 2.2. Outage probability analysis

The channel capacity and outage probability are the most important impairments which affect the quality of service (QoS) in wireless communication systems. When no CSI conditions are

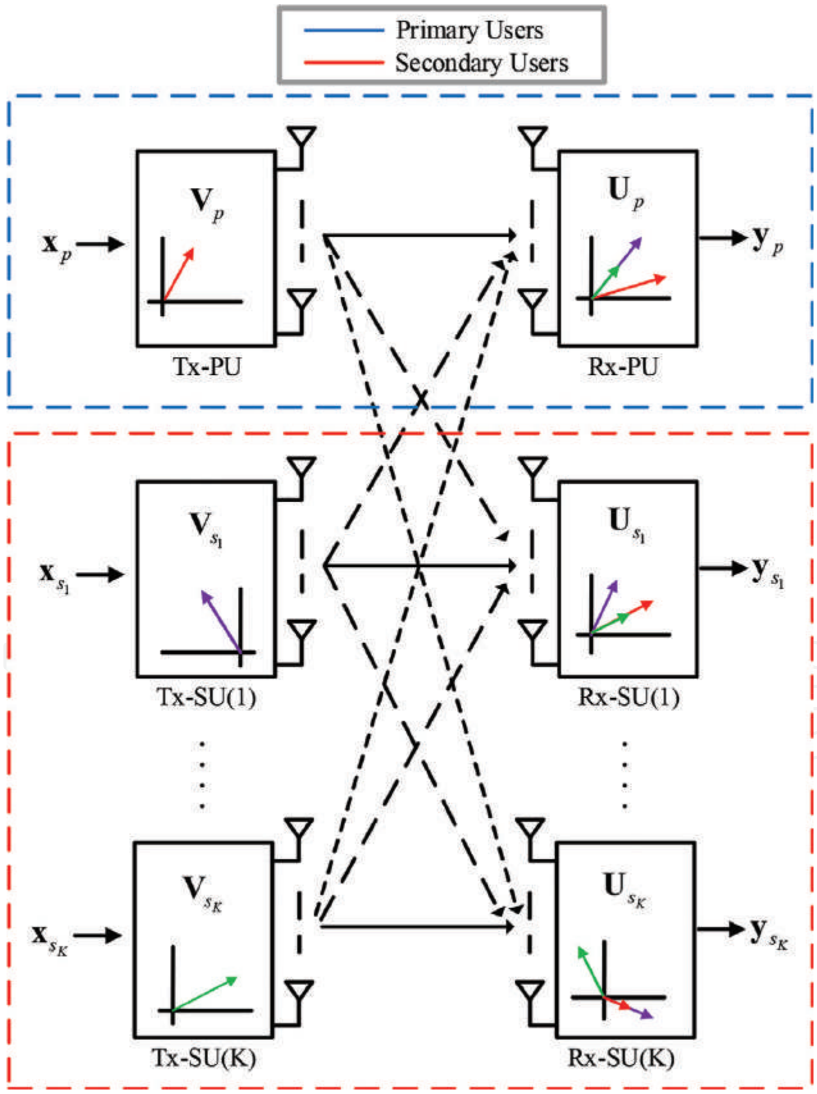


**Figure 2.** IA-based CR network with single PU and $K$ SUs sharing the spectrum.

given, MIMO channel capacity is expressed as in [31]. The channel capacity of the considered MIMO system in PU can be expressed as

$$C = \log_2 \det\left|\mathbf{I} + \frac{\gamma_1}{(1+\gamma_2)N_p}\mathbf{H}_{pp}\mathbf{H}_{pp}^H\right|, \tag{5}$$

where $\gamma_1 = P_1\left\|\mathbf{H}_{pp}\right\|^2/\sigma_N^2$ is the signal-to-noise ratio (SNR) of the primary link. $\gamma_2$ can be expressed as $\gamma_2 = \left(P_2/\sigma_N^2\right)\sum_{i=1}^{K}\left\|\mathbf{H}_{ps_i}\right\|^2$. Note that $\|.\|^2$ demonstrates the squared Frobenius norm of the channel matrix, $\mathbf{I}$ denotes for identity matrix, and $P_1$ and $P_2$ are the transmitted powers of the PU and SUs, respectively. If linear IA perfectly eliminates the interference between SU and PU, then SNR of the interference channel, $\gamma_2$, becomes zero. It is important to note that precoding and linear suppression vectors are assumed as $\left|\mathbf{U}_p^{\mathrm{H}}\right|^2 = \left|\mathbf{V}_p\right|^2 = \left|\mathbf{U}_{s_i}^{\mathrm{H}}\right|^2 = \left|\mathbf{V}_{s_i}\right|^2 = 1$. In the presence of interference-free communication, primary system works in the single-input and single-output (SISO) fashion [14]. Hence, the probability density function (PDF) of $\gamma_1$ can be written as $f_{\gamma_1}(\gamma) = \frac{1}{\overline{\gamma}_1}\exp\left(-\gamma/\overline{\gamma}_1\right)$, and the outage probability of the system can be obtained as

$$P_{out} = \int_0^{2^{R_{th}}-1} f_{\gamma_1}(\gamma)d\gamma, \tag{6}$$

where $R_{th}$ is the data rate threshold and $\overline{\gamma}_1 = P_1/\sigma_N^2$ denotes the average SNR of the primary system. By substituting $f_{\gamma_1}(\gamma)$ into (6), the outage probability can be obtained as

$$P_{out} = 1 - \exp\left(\frac{2^{R_{th}}-1}{\overline{\gamma}_1}\right). \tag{7}$$

In the presence of interference, the primary system works in MIMO fashion, and leakages may occur due to fast-fading Rayleigh channel. To improve the performance of the primary system, we adopt maximum ratio transmission and maximum ratio combining at the transmitter and receiver, respectively. Thereby, the end-to-end signal-to-interference-plus-noise ratio (SINR) of the primary system can be written as $\gamma_\tau = \gamma_1/(1+\gamma_2)$. In the proposed system, all channels are modeled as independent and identically distributed Chi-squared distribution, and the PDF of $\gamma_1$ can be expressed as

$$f_{\gamma_1}(\gamma) = \frac{\gamma^{M_pN_p-1}\exp\left(-\gamma/\left(\overline{\gamma}_1/M_p\right)\right)}{\left(\frac{\overline{\gamma}_1}{M_p}\right)^{M_pN_p}(M_pN_p-1)!}. \tag{8}$$

In addition, the PDF of $\gamma_2$ can be defined as

$$f_{\gamma_2}(\gamma) = \frac{\gamma^{KM_sN_p-1}\exp\left(-\gamma/\left(\alpha\overline{\gamma}_2/M_s\right)\right)}{\left(\frac{\alpha\overline{\gamma}_2}{M_s}\right)^{KM_sN_p}(KM_sN_p-1)!}, \tag{9}$$

where $\overline{\gamma}_2 = P_2/\sigma_N^2$ is the average SNR of the secondary system. Finally, the PDF of $\gamma_\tau$ can be written as

$$f_{\gamma_\tau}(\gamma) = \int_0^\infty (x+1) f_{\gamma_1}((x+1)\gamma) f_{\gamma_2}(x) dx. \tag{10}$$

By substituting (8) and (9) into (10), then with the help of [32, Eq. 3.351.3] and after few manipulations, PDF expression of $f_{\gamma_\tau}(\gamma)$ is given as

$$f_{\gamma_\tau}(\gamma) = \Delta \sum_{m=0}^{M_pN_p} \binom{M_pN_p}{m} (KM_sN_p + m - 1)! \left(\frac{\gamma M_p}{\overline{\gamma}_1} + \frac{M_s}{\alpha\overline{\gamma}_2}\right)^{-KM_sN_p+m}. \tag{11}$$

Furthermore, collecting constant terms in (11), $\Delta$ is defined by

$$\Delta = \beta\gamma^{M_pN_p-1} \exp\left(-\frac{M_p\gamma}{\overline{\gamma}_1}\right). \tag{12}$$

Hereby, $\beta$ is constituted as

$$\beta = \frac{\left(\frac{\overline{\gamma}_1}{M_p}\right)^{-M_pN_p} \left(\frac{\alpha\overline{\gamma}_2}{M_s}\right)^{-KM_sN_p}}{(M_pN_p-1)!(KM_sN_p-1)!}. \tag{13}$$

To achieve the closed-form expression of (11), binomial expression of $\left(\frac{\gamma M_p}{\overline{\gamma}_1} + \frac{M_s}{\alpha\overline{\gamma}_2}\right)^{-KM_sN_p+m}$ term must be completed. The binomial expansion of this negative exponential term is given as

$$\left(\frac{\gamma M_p}{\overline{\gamma}_1} + \frac{M_s}{\alpha\overline{\gamma}_2}\right)^{-\zeta} = \sum_{t=0}^{\infty} (-1)^t \binom{\zeta+t-1}{t} \left(\frac{\gamma M_p}{\overline{\gamma}_1}\right)^t \left(\frac{Ms}{\alpha\overline{\gamma}_2}\right)^{\zeta+t}, \tag{14}$$

where $\zeta$ is given as $\zeta = KM_sN_p + m$. Besides, the validation of (14) is restricted via $|\frac{\gamma M_p}{\overline{\gamma}_1}| < \frac{M_s}{\alpha\overline{\gamma}_2}$ condition. Under these conditions, the closed-form expression of $f_{\gamma_\tau}$ is given below:

$$f_{\gamma_\tau}(\gamma) = \Delta \sum_{m=0}^{M_pN_p} \sum_{t=0}^{\infty} (-1)^t \binom{M_pN_p}{m} (\zeta-1)! \binom{\zeta+t-1}{t} \left(\frac{\gamma M_p}{\overline{\gamma}_1}\right)^t \left(\frac{Ms}{\alpha\overline{\gamma}_2}\right)^{\zeta+t}. \tag{15}$$

Outage probability function of the proposed MIMO system with respect to $f_{\gamma_\tau}$ can be expressed as

$$P_{out} = \int_0^{2^{R_{th}}-1} f_{\gamma_\tau}(\gamma) d\gamma. \tag{16}$$

The closed-form expression for (16) can be validated with the numerical integral operation [33].

### 2.3. Performance evaluation

Herein, the system performance of the MIMO CR network is studied in the presence of interference leakage for Rayleigh fading channel by comparing the analytical results with computer simulations. We assumed $P_1 = P_2 = \rho$ while $\sigma_N^2 = 1$ in the performance evaluation.

In **Figure 3**, the $P_{out}$ performance for different $R_{th}$ values is presented. We take $\alpha = -20$ dB, $M_p = 2$, $N_p = 2$, $K = 5$, and $M_s = 1$. It can be seen from **Figure** 3 that when $R_{th}$ is increased from 1 to 4 bits/channel, the $P_{out}$ performance is degraded.

In **Figure 4**, the impact of the leakage coefficient, $\alpha$, on the outage probability performance is depicted for $M_p = 2$, $N_p = 2$, $K = 1$, $M_s = 1$, and $R_{th} = 3$ bits/channel. As can be seen from the figure, when $\alpha$ is changed from $-10$ dB to $-30$ dB, the performance of the primary system is enhanced.

In **Figure 5**, $\alpha$, $M_p$, $N_p$, $M_s$, and $R_{th}$ are taken as $-20$ dB, 2, 2, 1, and 1 bits/channel, respectively. It can be observed from the figure that increasing the number of SUs decreases the outage probability performance of the primary system considerably.

In **Figure 6**, the impact of antenna diversity on the $P_{out}$ performance is investigated for $\alpha = -10$ dB, $K = 2$, and $R_{th} = 1$ dB. It is observed from the figure that, when the number of antennas at the primary transmitter and receiver increases, the system performance enhances. Besides, the receiver diversity effect on the system performance is greater than the transmitter diversity, as expected.

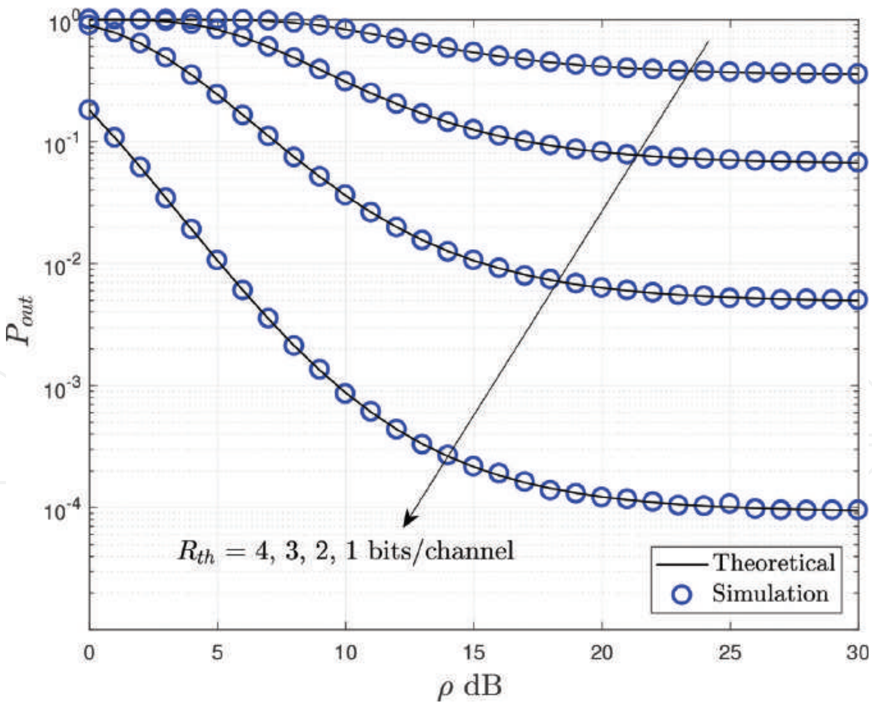


**Figure 3.** $P_{out}$ performance for different data rate threshold $R_{th}$.

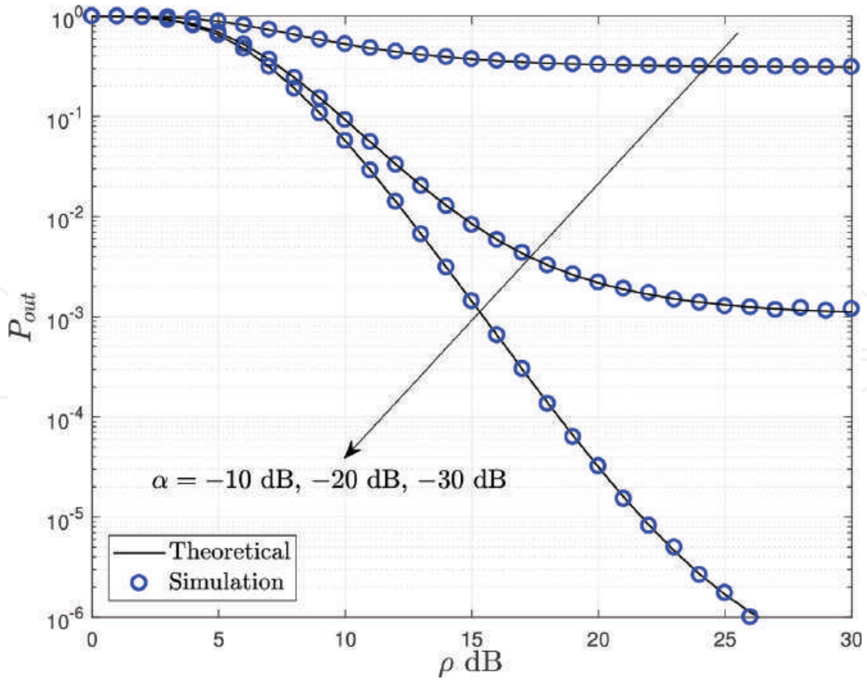


**Figure 4.** $P_{out}$ performance with varying SNR for different interference-leakage values.

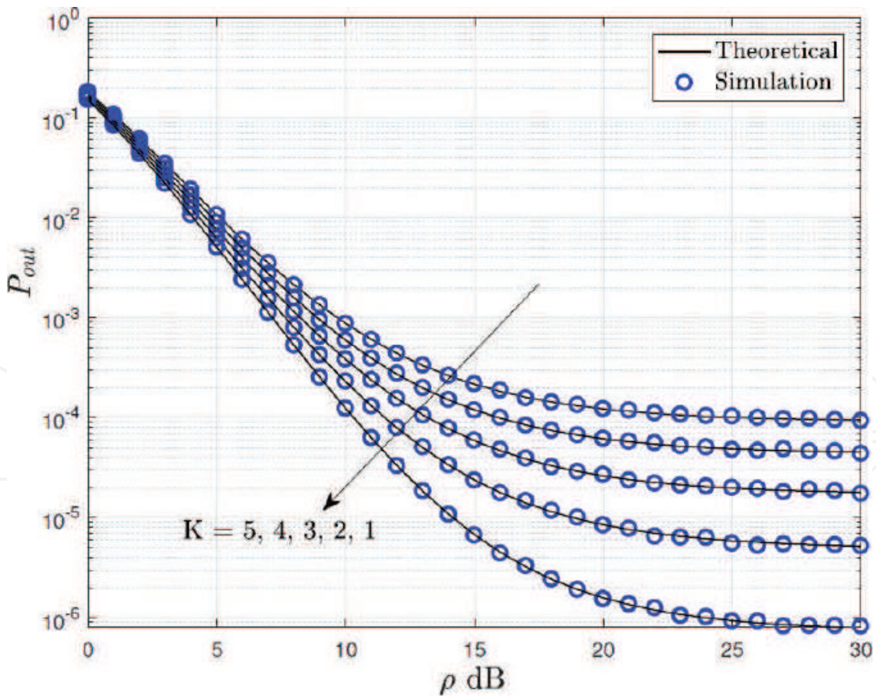


**Figure 5.** $P_{out}$ vs. SNR for different numbers of SUs.

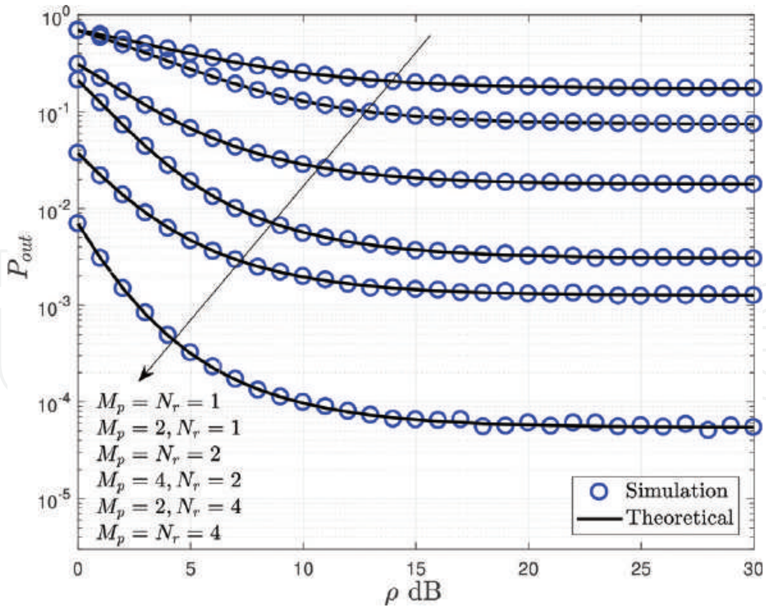


**Figure 6.** The effect of antenna diversity on the outage probability performance.

## 3. The effect of CSI quantization on interference alignment in CR networks

In this section, we investigate a cognitive two-way relaying network composed of a primary network (PN) with one pair of PU and a secondary network (SN) with two source terminals and a relay terminal ($R$).

### 3.1. System model

We consider a MIMO interference network shown in **Figure 7**, where the transmitter, $T_x$, and receiver, $R_x$, are equipped with $M_1$ and $N_1$ antennas in PN, respectively. Each PN transmitter transmits to its corresponding receiver by interfering with the SN nodes, namely, two source terminals ($S_1$ and $S_2$) and a relay terminal. That means $T_x$ transmitter sends messages to its intended receiver $R_x$, whereas it also causes interference to the unintended receivers in the SN. The SN consists of two source terminals and a relay terminal. We assume that all nodes in SN operate in an AF half-duplex mode with the help of information relaying from each source terminal to $R$ in two phases. All nodes in SN are assumed to have MIMO antennas, and there is no direct transmission between $S_1$ and $S_2$ [34–36]. We consider a scenario where the source terminals and a relay terminal are equipped with $N_{S_1}$, $N_{S_2}$, and $N_R$ antennas, respectively. In the system model based on IA for cognitive two-way relay network, the received signal at $R_x$ in PN can be written as

$$\mathbf{y}_{R_x} = \sqrt{\frac{P_{T_x}}{d_{R_x,T_x}^{\tau_{R_x,T_x}}}}\mathbf{U}_{R_x}^{H}\mathbf{H}_{R_x,T_x}\mathbf{V}_{T_x}\mathbf{s}_{T_x} + \Upsilon + \tilde{\mathbf{n}}_{R_x}, \tag{17}$$

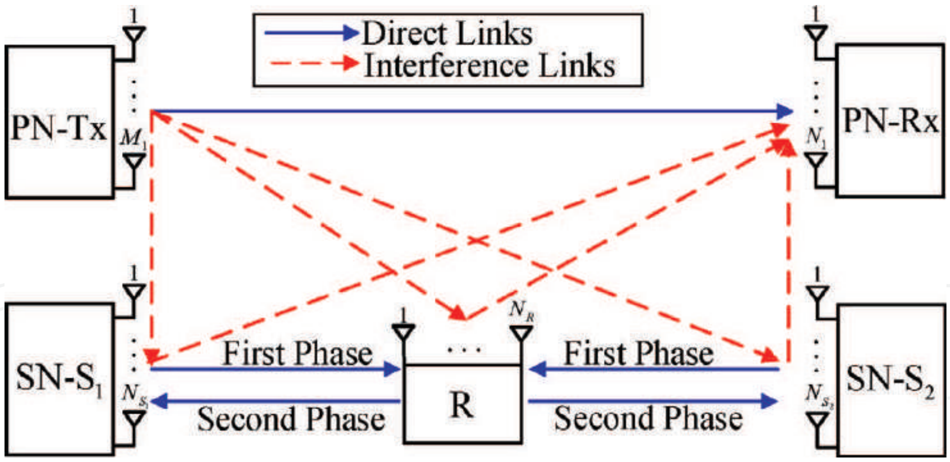


**Figure 7.** System model for interference alignment-based cognitive two-way relay network with primary network and secondary network.

where $\Upsilon$ is the interference term generated from SN to $R_x$ defined as follows:

$$\Upsilon = \begin{cases} \sqrt{\frac{P_{S_1}}{d_{R_x,S_1}^{\tau_{R_x,S_1}}}}\mathbf{U}_{R_x}^H\mathbf{H}_{R_x,S_1}\mathbf{V}_{S_1}\mathbf{s}_{S_1} + \sqrt{\frac{P_{S_2}}{d_{R_x,S_2}^{\tau_{R_x,S_2}}}}\mathbf{U}_{R_x}^H\mathbf{H}_{R_x,S_2}\mathbf{V}_{S_2}\mathbf{s}_{S_2}, & \text{first phase} \\ \sqrt{\frac{P_R}{d_{R_x,R}^{\tau_{R_x,R}}}}\mathbf{U}_{R_x}^H\mathbf{H}_{R_x,R}\mathbf{V}_R\mathbf{s}_R, & \text{second phase.} \end{cases} \tag{18}$$

The effective additive white Gaussian noise (AWGN) term with zero mean and unit variance, $\tilde{\mathbf{n}}_{R_x}$ at $R_x$ in PN, is defined by $\mathbf{U}_{R_x}^H\mathbf{n}_{R_x}$, where $\mathbf{n}_{R_x}$ is the AWGN vector with $\mathrm{E}\left[\mathbf{n}_{R_x}\mathbf{n}_{R_x}^H\right] = \sigma_{R_x}^2\mathbf{I}$ in which $\mathbf{I}$ is the unitary matrix, $\sigma_{R_x}^2$ is the noise variance, and E[.] is the expectation operator. The transmit powers at the terminals $T_x$, $S_1$, $S_2$, and $R$ are denoted by $P_i$, for $i = T_x, S_1, S_2$, and $R$, respectively. Each receive node employs the interference-suppression matrix, $\mathbf{U}_j$, (for $j = R_x, R, S_1, S_2$), while each transmit node employs a precoding matrix $\mathbf{V}_i$ [37]. The conjugate transpose of the matrix is associated with the Hermitian operator $(.)^H$ [38]. The transmit signal vector for the $i$th user is defined by $\mathbf{s}_i$. The channel between the $i$th transmitter and the $j$th receiver nodes is denoted by $\mathbf{H}_{j,i}$ for both PN and SN. The quantized CSI is passed to the transmitter by the corresponding receiver. Because of limited feedback, the transmitters have imperfect CSI causing certain performance loss. To clarify the effect of CSI quantization error on the performance of interference alignment in underlay cognitive two-way relay networks, we investigate the BER performance, instantaneous capacity, and average PEP of the considered system. Based upon the accuracy parameter, the relation between perfect CSI ($\rho_{j,i} = 0$) and imperfect CSI ($0 < \rho_{j,i} \leq 1$) can be given as

$$\mathbf{H}_{j,i} = \sqrt{1-\rho_{j,i}}\,\hat{\mathbf{H}}_{j,i} + \sqrt{\rho_{j,i}}\,\mathbf{E}_{j,i}, \tag{19}$$

where $\mathbf{H}_{j,i}$ is the real channel matrix and $\hat{\mathbf{H}}_{j,i}$ is the estimated channel matrix. The quantization error, $\mathbf{E}_{j,i}1mm$, can be expressed with the upper bound of $2^{-B_{j,i}/(M_1N_1-1)}$, where $B_{j,i}$ is the CSI exchange amount and $M_1$ and $N_1$ are the numbers of transmit-and-receive antennas, successively [21, 39]. It is assumed that both $\hat{\mathbf{H}}_{j,i}$ and $\mathbf{E}_{j,i}$ are independent of $\mathbf{H}_{j,i}$. Besides, each channel link is also modeled by two additional parameters: the distance between $i$th transmitter and the $j$th receiver nodes $d_{j,i}$ and the path loss exponent for the corresponding link, $\tau_{j,i}$, regarding for different radio environments, respectively.

In the first phase of the transmission (multiple-access phase) in SN, both $S_1$ and $S_2$ transmit their signals simultaneously to the relay terminal, $R$. Then the received signal at $R$ can be written as

$$\mathbf{y}_R = \sqrt{\frac{P_{S_1}}{d_{R,S_1}^{\tau_{R,S_1}}}}\mathbf{U}_R^H\mathbf{H}_{R,S_1}\mathbf{V}_{S_1}\mathbf{s}_{S_1} + \sqrt{\frac{P_{S_2}}{d_{R_x,S_2}^{\tau_{R_x,S_2}}}}\mathbf{U}_R^H\mathbf{H}_{R,S_2}\mathbf{V}_{S_2}\mathbf{s}_{S_2} + \sqrt{\frac{P_{T_x}}{d_{R,T_x}^{\tau_{R,T_x}}}}\mathbf{U}_R^H\mathbf{H}_{R,T_x}\mathbf{V}_{T_x}\mathbf{s}_{T_x} + \tilde{\mathbf{n}}_R, \tag{20}$$

where $\tilde{\mathbf{n}}_R = \mathbf{U}_R^H\mathbf{n}_R$ at the relay terminal in SN is expressed as zero-mean AWGN vector with $\mathrm{E}\left[\mathbf{n}_R\mathbf{n}_R^H\right] = \sigma_R^2\mathbf{I}$ in which the noise variance at the relay terminal is depicted with $\sigma_R^2$. Besides, the received signal at $S_1$ and $S_2$ terminals in SN is defined, respectively, as

$$\mathbf{y}_{S_1} = \sqrt{\frac{P_R}{d_{S_1,R}^{\tau_{S_1,R}}}}\mathbf{U}_{S_1}^H\mathbf{H}_{S_1,R}\mathbf{V}_R\mathbf{s}_R + \sqrt{\frac{P_{T_x}}{d_{S_1,T_x}^{\tau_{S_1,T_x}}}}\mathbf{U}_{S_1}^H\mathbf{H}_{S_1,T_x}\mathbf{V}_{T_x}\mathbf{s}_{T_x} + \tilde{\mathbf{n}}_{S_1}, \tag{21}$$

$$\mathbf{y}_{S_2} = \sqrt{\frac{P_R}{d_{S_2,R}^{\tau_{S_2,R}}}}\mathbf{U}_{S_2}^H\mathbf{H}_{S_2,R}\mathbf{V}_R\mathbf{s}_R + \sqrt{\frac{P_{T_x}}{d_{S_2,T_x}^{\tau_{S_2,T_x}}}}\mathbf{U}_{S_2}^H\mathbf{H}_{S_2,T_x}\mathbf{V}_{T_x}\mathbf{s}_{T_x} + \tilde{\mathbf{n}}_{S_2}. \tag{22}$$

Here, $\tilde{\mathbf{n}}_{S_1}$ and $\tilde{\mathbf{n}}_{S_2}$ are the AWGN vector with $\mathrm{E}\left[\mathbf{n}_{S_k}\mathbf{n}_{S_k}^H\right] = \sigma_{S_k}^2\mathbf{I}$, for $k = 1, 2$ and the noise variance of $\sigma_{S_k}^2$. In addition to that, in the second phase of the signal transmission (broadcast phase), $R$ broadcasts the combined signal $\mathbf{y}_R$ after multiplying with an ideal amplifying gain, $G$, which is expressed as

$$G=1\Big/\sqrt{\begin{aligned}&\frac{P_{S_1}(1-\rho_{R,S_1})}{d_{R,S_1}^{\tau_{R,S_1}}}\|\mathbf{U}_R^H\hat{\mathbf{H}}_{R,S_1}\mathbf{V}_{S_1}\|^2 + \frac{P_{S_2}(1-\rho_{R,S_2})}{d_{R,S_2}^{\tau_{R,S_2}}}\|\mathbf{U}_R^H\hat{\mathbf{H}}_{R,S_2}\mathbf{V}_{S_2}\|^2 ..\\ &.. + \frac{P_{T_x}(1-\rho_{R,T_x})}{d_{R,T_x}^{\tau_{R,T_x}}}\|\mathbf{U}_R^H\hat{\mathbf{H}}_{R,T_x}\mathbf{V}_{T_x}\|^2,\end{aligned}} \tag{23}$$

where $\mathbf{s_R} = G\mathbf{y}_R$. We assume that both $S_1$ and $S_2$ have knowledge about their own information and can remove back-propagating self-interference from the imposed signals. We also assume that all interference at the receive terminals are perfectly aligned and the following feasible conditions are satisfied for the receive nodes:

$$\mathbf{U}_j^{\mathrm{H}}\mathbf{H}_{j,i}\mathbf{V}_i\mathbf{s}_i = 0, \tag{24}$$

$$\mathrm{rank}\left(\mathbf{U}_j^{\mathrm{H}}\mathbf{H}_{j,i}\mathbf{V}_i\mathbf{s}_i\right) = f_i, \tag{25}$$

where $f_i$ is the degree of freedom and rank (.) denotes the rank operation of a matrix. By assuming that the interference is perfectly aligned by the proposed IA algorithm, and the channel matrices are constant during the transmission, we ensure that there is no interference from the unintended transmitters and guarantee that received signal achieves $f_i$ degrees of freedom [39]. The corresponding signal-to-interference-plus-noise ratio (SINR) for the links $T_x \to R_x$, $S_1 \to R$, and $R \to S_2$ can be derived by

$$\gamma_{T_x \to R_x} = \frac{\frac{P_{T_x}\left(1-\rho_{R_x, T_x}\right)}{d_{R_x, T_x}^{\tau_{R_x, T_x}}} \|\mathbf{U}_{R_x}^H \hat{\mathbf{H}}_{R_x, T_x} \mathbf{V}_{T_x}\|^2}{\Psi + \sigma_{\tilde{n}_{R_x}}{}^2}, \tag{26}$$

$$\gamma_{S_1 \to R} = \frac{\frac{P_{S_1}\left(1-\rho_{R, S_1}\right)}{d_{R, S_1}^{\tau_{R, S_1}}} \|\mathbf{U}_R^H \hat{\mathbf{H}}_{R, S_1} \mathbf{V}_{S_1} \mathbf{s}_{S_1}\|^2}{\frac{P_{T_x}\rho_{R, T_x}}{d_{R, T_x}^{\tau_{R, T_x}}} \|\mathbf{U}_R^H \mathbf{E}_{R, T_x} \mathbf{V}_{T_x}\|^2 + \sigma_{\tilde{n}_R}^2}, \tag{27}$$

$$\gamma_{R \to S_2} = \frac{\frac{P_R\left(1-\rho_{S_2, R}\right)}{d_{S_2, R}^{\tau_{S_2, R}}} \|\mathbf{U}_{S_2}^H \hat{\mathbf{H}}_{S_2, R} \mathbf{V}_R \mathbf{s}_R\|^2}{\frac{P_{T_x}\rho_{S_2, T_x}}{d_{S_2, T_x}^{\tau_{S_2, T_x}}} \|\mathbf{U}_{S_2}^H \mathbf{E}_{S_2, T_x} \mathbf{V}_{T_x}\|^2 + \sigma_{\tilde{n}_{S_2}}^2}, \tag{28}$$

$$\Psi = \begin{cases} \frac{P_{S_1}\rho_{R_x, S_1}}{d_{R_x, S_1}^{\tau_{R_x, S_1}}} \|\mathbf{U}_{R_x}^H \mathbf{E}_{R_x, S_1} \mathbf{V}_{S_1}\|^2 + \frac{P_{S_2}\rho_{R_x, S_2}}{d_{R_x, S_2}^{\tau_{R_x, S_2}}} \|\mathbf{U}_{R_x}^H \mathbf{E}_{R_x, S_2} \mathbf{V}_{S_2}\|^2, & \text{first phase} \\ \frac{P_R\rho_{R_x, R}}{d_{R_x, R}^{\tau_{R_x, R}}} \|\mathbf{U}_{R_x}^H \mathbf{E}_{R_x, R} \mathbf{V}_R\|^2, & \text{second phase} \end{cases} \tag{29}$$

where $\mathbf{E}_{j,i}$ is the quantization error and $\|.\|$ is the Euclidean norm. In here, $\gamma_{S_2 \to R}$ and $\gamma_{R \to S_1}$ can be found by changing the subscript $S_1$ with $S_2$ of (27) and $S_2$ with $S_1$ of (28). Assuming the channels are reciprocal over SN direct links, thus the channel gains for $S_1 \to R$ and $R \to S_1$ and $S_2 \to R$ and $R \to S_2$ links are identical, respectively.

### 3.2. Performance analysis

This section starts by the instantaneous capacity analysis of the proposed system with interference alignment in underlay cognitive two-way relay networks with CSI quantization. We then study the BER and average PEP performance.

The capacity is expressed as the expected value of the mutual information between the transmitting terminal and receiving one. In light of this fact, we consider the method developed in [29]; the instantaneous capacity in PN can be expressed as

$$C_{R_x} = \log_2\left(1 + \gamma_{T_x \to R_x}\right), \tag{30}$$

where $\gamma_{T_x \to R_x}$ is the instantaneous SINR for the corresponding link of $T_x \to R_x$. On the other hand, end-to-end capacity for the SN, based on the least strong link over two-hop transmission, is denoted as follows:

$$C_R = \frac{1}{2}\log_2\left(1+\min\left(\gamma_{S_1\to R}, \gamma_{R\to S_2}\right)\right) + \frac{1}{2}\log_2\left(1+\min\left(\gamma_{S_2\to R}, \gamma_{R\to S_1}\right)\right). \tag{31}$$

$\gamma_{S_1\to R}$ and $\gamma_{R\to S_2}$ are the instantaneous SINR for the $S_1 \to R$ and $R \to S_2$ links, respectively.

Average BER for binary phase shift keying (BPSK) modulation can be expressed as

$$\mathrm{BER}_j = Q\left(\sqrt{\gamma_j}\right) \tag{32}$$

where $Q(x)$ is the Gaussian Q-function and defined by $Q(x) = \left(1/\sqrt{2\pi}\right)\int_x^\infty e^{-t^2/2}dt$ [37].

Average pairwise error probability ($\overline{\mathrm{PEP}}$) can be computed as averaging the Gaussian Q-function over Rayleigh fading statistics [40], $f_{\gamma_{T_x\to R_x}}(\gamma) = \left(e^{-\gamma/\overline{\gamma}_{T_x\to R_x}}\right)/\overline{\gamma}_{T_x\to R_x}1mm$, where $\overline{\gamma}_{T_x\to R_x} = P_{T_x}\left(1-\rho_{R_x,T_x}\right)/d_{R_x,T_x}^{\tau_{R_x,T_x}}\sigma^2_{\tilde{n}_{R_x}}$

$$\overline{\mathrm{PEP}} = \int_0^\infty Q\left(\sqrt{\gamma_{T_x\to R_x}}\right)f_{\gamma_{T_x\to R_x}}(\gamma)d\gamma. \tag{33}$$

Finally, this integral can be evaluated with the help of Mathematica and average PEP under Rayleigh fading channel can be derived in a closed form as follows:

$$\overline{\mathrm{PEP}} = \frac{1}{2}\left(1-\sqrt{\frac{\overline{\gamma}_{T_x\to R_x}}{2+\overline{\gamma}_{T_x\to R_x}}}\right). \tag{34}$$

### 3.3. Numerical results

In this section the numerical results are provided with various scenarios to evaluate the performance analysis for IA in underlay cognitive two-way relay networks with CSI quantization. BER performance for direct transmission links of the proposed system is illustrated in **Figure 8** over Rayleigh distribution for different amounts of CSI exchange with varying SNR. For convenience, we set $d_{j,i} = 3\ m$ and $\tau = 2.7$, and 3×3 MIMO configuration is studied in this figure. Because of the number of interfering links, the quantization error for the $T_x \to R_x$ transmission is greater than the other links ($S_1 \rightleftarrows R \rightleftarrows S_2$). Even if the analyzed BER performance of the SN seems better than the PN, it should not be forgotten that SN operates in half-duplex mode. Performance loss in BER due to imperfect CSI ($B_{j,i} = 4$, for instance) becomes larger as SNR increases compared to the perfect CSI (for $B_{j,i} = \infty$) case.

In **Figure 9**, the average PEP versus SNR is plotted for $d_{j,i} = 3\ m$ and $\tau = 2.7$ over Rayleigh fading channel in PN. It can be noticed from the figure that as SNR increases, average PEP decreases, as expected. To reach the perfect CSI case, we take $B_{j,i} = \infty$, and the average PEP performance noticeably enhances. We also consider the case of imperfect CSI ($B_{j,i} = 4$) for the comparison purposes in the same figure.

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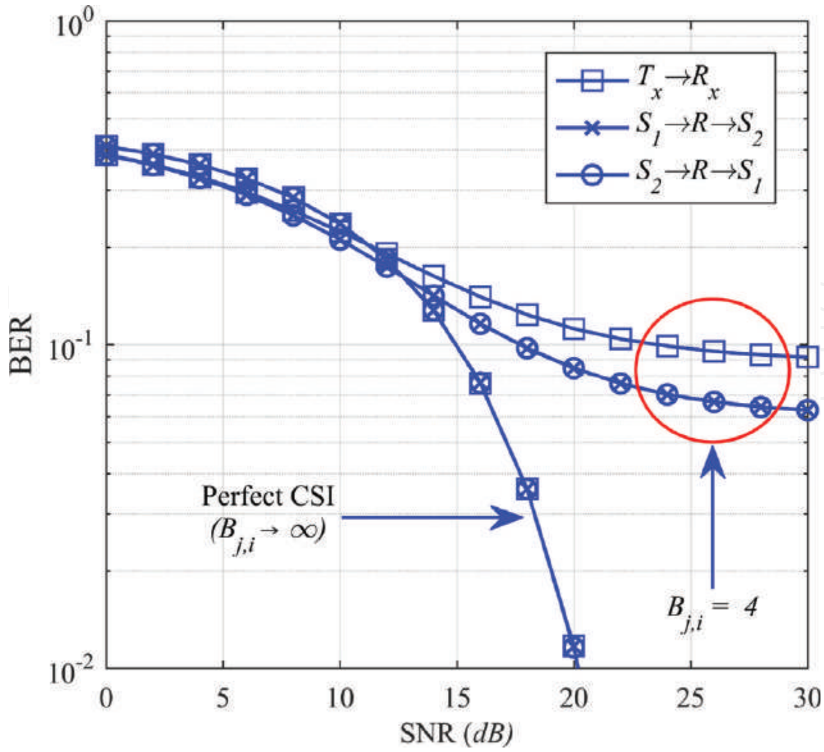


**Figure 8.** BER performance for different amounts of CSI exchange with varying SNR.

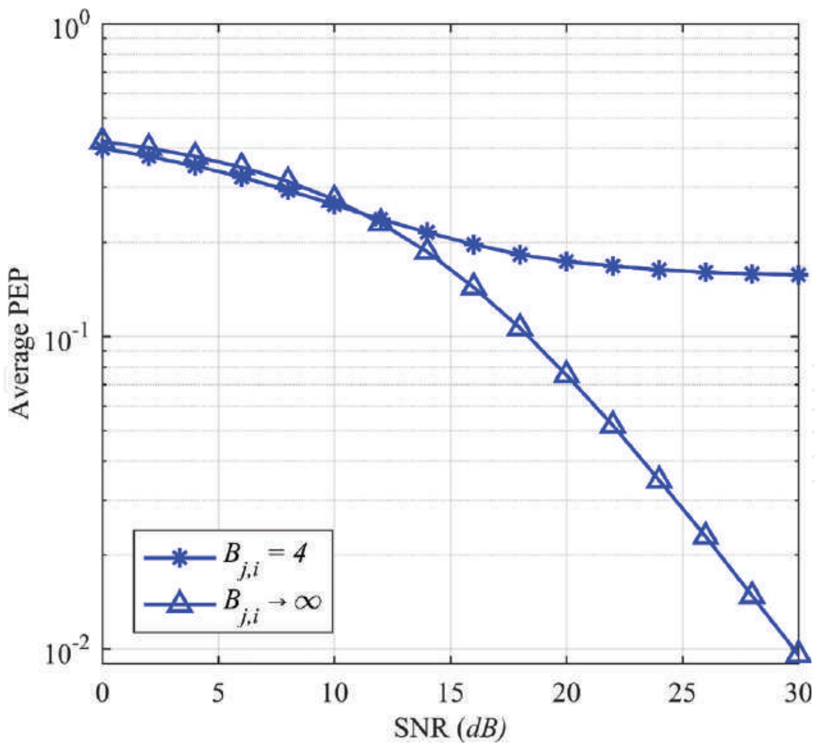


**Figure 9.** Average PEP performance for different amounts of CSI exchange with varying SNR over Rayleigh fading channel in primary network.

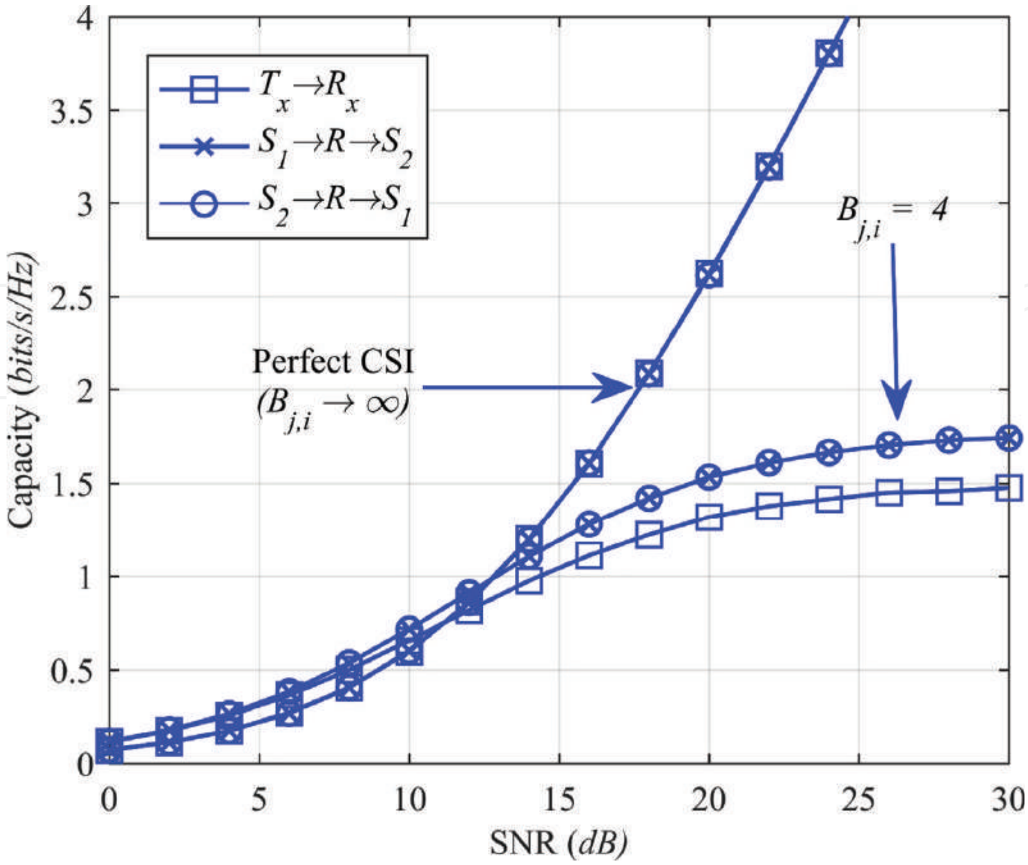


**Figure 10.** Capacity vs. SNR of the primary network and secondary network nodes under different CSI scenarios.

**Figure 10** examines the capacity analysis with perfect and imperfect CSI for different direct links in PN and SN. The results clearly show that, examining the capacity with perfect CSI, performance improvement becomes larger as the SNR increases.

**Figure 11** demonstrates the effects of $B_{j,i}$ and $d_{j,i}$ parameters on the BER performance for the SN with varying SNR when $\tau = 2.7$ and 3×3 MIMO scheme is used. The results clearly show that for a fixed SNR value, the performance of the considered system increases with the decrease of the $d_{j,i}$. It can be seen from the same figure that the increase on the amount of CSI exchange $B_{j,i}$ positively affects the BER performance.

**Figure 12** shows the capacity performance of PU in the underlay cognitive two-way relay network over Rayleigh fading channel with varying path loss exponent, $\tau$. The results show a performance improvement while the value of $\tau$ decreases. In this plot, $B_{j,i} = 8$, $d_{j,i} = 3\ m$, and the 3×3 MIMO scheme are considered. Depending on the environmental conditions for mobile communications, typical $\tau$ values, ranging from 1.6 to 5, are used to plot this figure. First, for the line of sight in a building, the environment is considered with the $\tau$ values of 1.6 and 1.8. Second, capacity is computed for the free-space environment with $\tau = 2$. Then, the capacity performance is presented with $\tau$ values of 2.7 and 3.3 for urban area cellular radio environment. Finally, the shadowed urban cellular radio environment is associated with two different $\tau$ values of 3 and 5 to analyze the capacity performance with varying SNR [41].

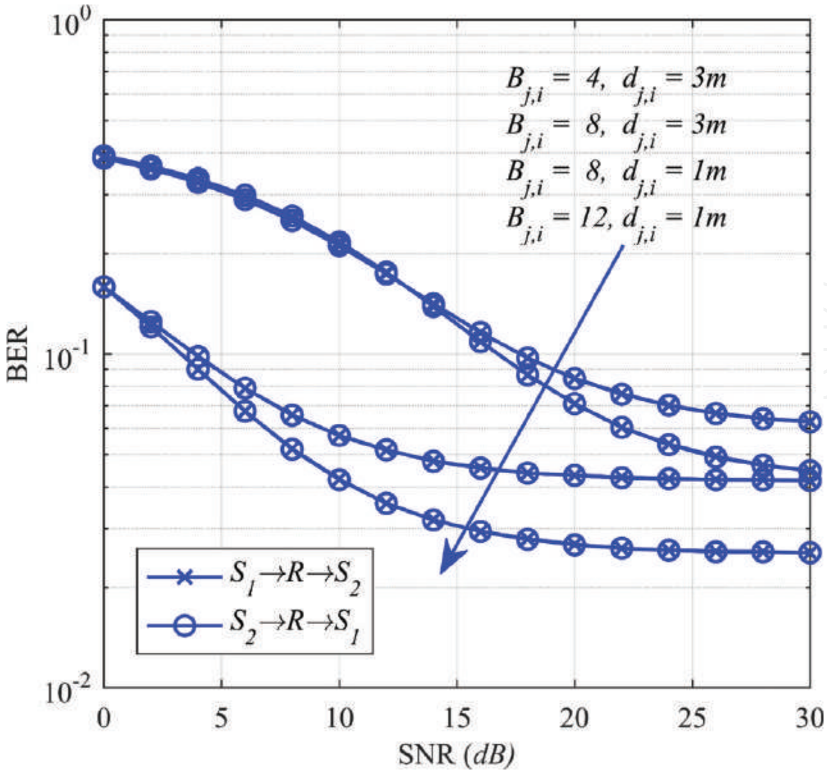


**Figure 11.** BER performance for different amounts of CSI exchange and distances with varying SNR over Rayleigh fading channel for secondary network.

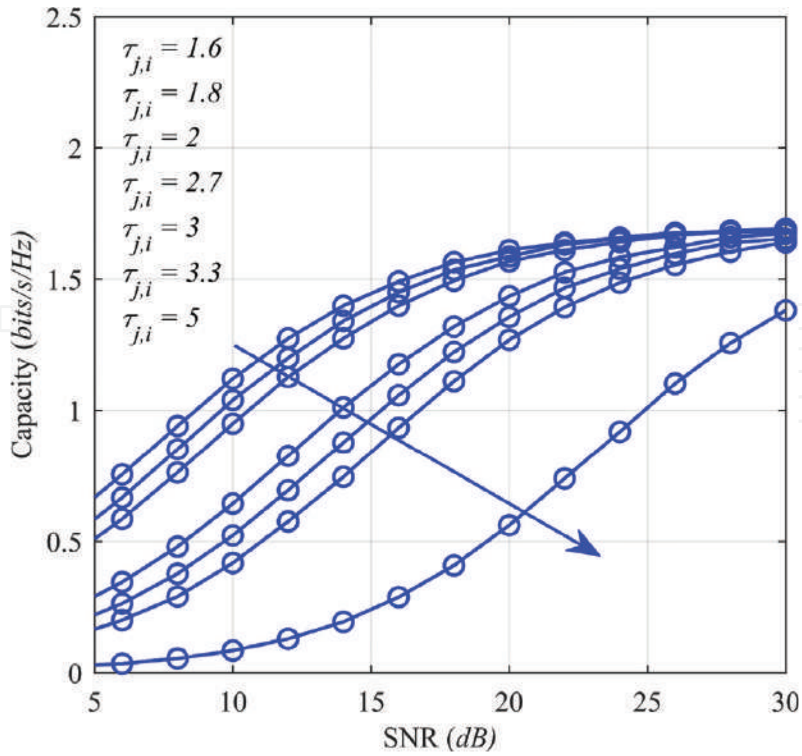


**Figure 12.** Capacity changes with SNR for the environmental conditions having different path loss exponents.

## 4. Conclusion

In this chapter, the system performance of linear interference alignment on the MIMO CR network is investigated under interference leakage. To quantify the performance of the primary system under a certain level of interference leakage, the closed-form outage probability expression is derived for Rayleigh fading channel. In all analyses, the theoretical results closely match with the simulations which confirm the accuracy of the derived expressions.

In the second part of this work, considering a practical issue, we investigate the performance of interference alignment in underlay cognitive radio network with CSI quantization error over general MIMO interference channel. Amplify-and-forward scheme for two-way relay network under Rayleigh fading is considered. The impact of the CSI exchange amount, the distance between the *i*th transmitter and the *j*th receiver nodes, and the path loss exponent on the BER performance, system capacity, and average PEP for the proposed system model are analyzed. We provide the exact closed-form expression for the average PEP in primary network over Rayleigh distribution, while IA algorithm perfectly eliminates the interference. The present performance analysis can be extended to the multiple secondary user pairs, and this approach will be another subject of our future work.

It would be interesting to study on various scenarios, including single-hop, multi-hop, and multi-way networks in future work to analyze the system performance over the recently developed interference alignment algorithms for next-generation 5G wireless communication systems.

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## Author details

Arif Basgumus[1], Mustafa Namdar[1], Hakan Alakoca[2], Eylem Erdogan[3] and
Lutfiye Durak-Ata[2]*

*Address all correspondence to: lutfiye@ieee.org

1 Department of Electrical and Electronics Engineering, Dumlupinar University, Turkey

2 Informatics Institute, Applied Informatics Department, Istanbul Technical University, Turkey

3 Department of Electrical and Electronics Engineering, Istanbul Medeniyet University, Turkey

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