**ON THE PERFORMANCE OF QUICKEST DETECTION SPECTRUM SENSING: THE CASE OF CUMULATIVE SUM**

**CHAPTER -1**

**ABSTRACT**

Quickest change detection (QCD) is a fundamental problem in many applications. Given a sequence of measurements that exhibits two different distributions around a certain flipping point, the goal is to detect the change in distribution around the flipping point as quickly as possible. The QCD problem appears in many practical applications, e.g., quality control, power system line outage detection, spectrum reuse, and resource allocation and scheduling. In this letter, we focus on spectrum sensing as our application since it is a critical process for proper functionality of cognitive radio networks. Relying on the cumulative sum (CUSUM), we derive the probability of detection and the probability of false alarm of CUSUM based spectrum sensing. We show the correctness of our derivations using numerical simulations.

Keywords - CUSUM detection, cognitive radio, quickest detection, spectrum sensing.

**CHAPTER-2**

**INTRODUCTION**

During the last decades, we have witnessed a great progress and an increasing need for wireless communications systems due to costumers demand of more flexible, wireless, smaller, more intelligent and practical devices explaining markets invaded by smartphones, personal digital assistant (PDAs), tablets and netbooks. All this need for flexibility and more ”mobile” devices lead to more and more needs to afford the spectral resources that shall be able to satisfy customers need for mobility. But, as wide as spectrum seems to be, all those needs and demands made it a scarce resource and highly misused. Trying to face this shortage of radio resources, telecommunication regulators and standardization organisms recommended sharing this valuable resource between the different actors in the wireless environment. The federal communications commission (FCC), for instance, defined a new policy of priorities in the wireless systems, giving some privileges to some users, called primary users (PU) and less to others, called secondary users (SU), who will use the spectrum in an opportunistic way with minimum interference to PU systems. Cognitive radio (CR) as introduced by Mitola [1], is one of those possible devices that could be deployed as SU equipment and systems in Wireless networks. As originally defined, a CR is a self aware and ”intelligent” device that can adapt itself to the Wireless environment changes. Such a device is able to detect the changes in Wireless network to which it is connected and adapt its radio parameters to the new opportunities that are detected. This constant track of the environment change is called the ”spectrum sensing” function of a cognitive radio device. Thus, spectrum sensing in CR aims in finding the holes in the PU transmission which are the best opportunities to be used by the SU. Many statistical approaches already exist. The easiest to implement and the reference detector in terms of complexity is still the energy detector (ED). Nevertheless, the ED is highly sensitive to noise and does not perform well in low signal to noise ratio (SNR). Other advanced techniques based on signals modulations and exploiting some of the transmitted signals inner properties were also developed. For instance, the detector that exploits the built-in cyclic properties on a given signal is the cyclostationary features detector (CFD). The CFD do have a great robustness to noise compared to ED but its high complexity is still a consequent draw back. Some other techniques, exploiting a wavelet approach to efficient spectrum sensing of wideband channels were also developed. Cognitive radios (CR) systems are a proposed solution to the spectrum scarcity problem found in radio frequency (RF) environment that aims to improve the overall spectrum utilization. Several studies showed (CHEN; OH, 2014) that licensed spectrum bands are often not occupied by the licensed users, thus creating the opportunity for other devices to access the unoccupied spectrum in an opportunistic way. These opportunistic devices, denoted as secondary users (SU) in the context of cognitive radios, need to be able to sense the spectrum to assess the presence or absence of licensed users, denoted as primary users (PU), either individually or cooperatively. The idea of cognitive radios was first introduced by Joseph Mitola III in 1999

but has been given a lot of attention recently due to the proposed heterogeneous nature of 5G networks .Spectrum sensing in cognitive radios still poses a challenge for high-performance

and low-energy systems due to the fact that performance is often proportional to the spectrum sensing period which, in turn, is an energy consuming task that also degrades the spectral efficiency of the secondary users (since they need to spend time and energy on a task that does not effectively result in transmitted bits). Generally speaking, cooperative spectrum sensing schemes falls into two topologies: distributed (LI; YU; HUANG, 2009) or centralized (MA; ZHAO; LI, 2008). Centralized approaches require the SUs to transmit information regarding the local spectrum sensing (e.g., the SU binary decision on spectrum occupancy for hard combination schemes) to a fusion center, which in turn combines the received data according to a given method, decides on the spectrum occupancy and retransmits the decision back to the SUs. On the other hand, distributed approaches relies on information sharing among neighboring SUs and consensus methodologies, thus eliminating the need for a fusion center. through area under the curve (AuC) metrics and receiver operating characteristic(ROC) graphics, under additive white Gaussian noise (AWGN) and Rayleigh channel models. In addition, the computational performance of each model is evaluated through standard profiling tools in order to draw a complexity tradeoff analysis. Furthermore, an analysis of training set size is conducted to reveal the effects on channel detection and training time. But, first and foremost, what do we mean by cognitive radio? Before responding to this question, it is in order that we address the meaning of the related term “cognition.” According to the Encyclopedia of Computer Science [7], we have a three-point computational view of cognition. 1) Mental states and processes intervene between input stimuli and output responses. 2) The mental states and processes are described by algorithms. 3) The mental states and processes lend themselves to scientific investigations. Moreover, we may infer from Pfeifer and Scheier [8] that the interdisciplinary study of cognition is concerned with exploring general principles of intelligence through a synthetic methodology termed learning by understanding. Putting these ideas together and bearing in mind that cognitive radio is aimed at improved utilization of the radio spectrum, we offer the following definition for cognitive radio. Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: • highly reliable communications whenever and wherever needed; • efficient utilization of the radio spectrum. Six key words stand out in this definition: awareness,1 intelligence, learning, adaptivity, reliability, and efficiency. Implementation of this far-reaching combination of capabilities is indeed feasible today, thanks to the spectacular advances in digital signal processing, networking, machine learning, computer software, and computer hardware. In addition to the cognitive capabilities just mentioned, a cognitive radio is also endowed with reconfigurability.2 This latter capability is provided by a platform known as software-defined radio, upon which a cognitive radio is built. Software-defined radio (SDR) is a practical reality today, thanks to the convergence of two key technologies: digital radio, and computer software .

A cognitive radio (CR) is a [radio](https://en.wikipedia.org/wiki/Radio) that can be programmed and configured dynamically to use the best [wireless channels](https://en.wikipedia.org/wiki/Wireless_channel) in its vicinity to avoid user interference and congestion. Such a radio automatically detects available channels in [wireless spectrum](https://en.wikipedia.org/wiki/Radio_spectrum), then accordingly changes its [transmission](https://en.wikipedia.org/wiki/Transmission_(telecommunications)) or [reception](https://en.wikipedia.org/wiki/Telecommunication) parameters to allow more concurrent [wireless communications](https://en.wikipedia.org/wiki/Wireless_communications) in a given spectrum band at one location. This process is a form of [dynamic spectrum management](https://en.wikipedia.org/wiki/Dynamic_spectrum_management). In response to the operator's commands, the cognitive engine is capable of configuring radio-system parameters. These parameters include "[waveform](https://en.wikipedia.org/wiki/Waveform), protocol, operating frequency, and networking". This functions as an autonomous unit in the communications environment, exchanging information about the environment with the networks it accesses and other cognitive radios (CRs). A CR "monitors its own performance continuously", in addition to "reading the radio's outputs"; it then uses this information to "determine the [RF](https://en.wikipedia.org/wiki/Radio_frequency) environment, channel conditions, link performance, etc.", and adjusts the "radio's settings to deliver the required quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints".

Some "smart radio" proposals combine [wireless mesh network](https://en.wikipedia.org/wiki/Wireless_mesh_network)—dynamically changing the path messages take between two given nodes using [cooperative diversity](https://en.wikipedia.org/wiki/Cooperative_diversity); cognitive radio—dynamically changing the frequency band used by messages between two consecutive nodes on the path; and [software-defined radio](https://en.wikipedia.org/wiki/Software-defined_radio)—dynamically changing the protocol used by message between two consecutive nodes

The concept of [cognitive](https://en.wikipedia.org/wiki/Cognition) radio was first proposed by Joseph Mitola III in a seminar at [KTH Royal Institute of Technology](https://en.wikipedia.org/wiki/KTH_Royal_Institute_of_Technology) in Stockholm in 1998 and published in an article by Mitola and Gerald Q. Maguire, Jr. in 1999. It was a novel approach in wireless communications, which Mitola later described as:

The point in which wireless [personal digital assistants](https://en.wikipedia.org/wiki/Personal_digital_assistant) (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.

Cognitive radio (CR) provides a solution to the inefficient use of the frequency spectrum [1–3]. This inefficiency is due to the current radio spectrum regulations which assign specific bands to particular services and grant licensed bands access to only licensed users. CR implements dynamic spectrum allocation policies by allowing unlicensed users (secondary users) to access spectrum bands licensed to primary users while avoiding interference with them [2, 3].

Cognitive radio is considered as a goal towards which a [software-defined radio](https://en.wikipedia.org/wiki/Software-defined_radio) platform should evolve: a fully reconfigurable wireless transceiver which automatically adapts its communication parameters to network and user demands.

Traditional regulatory structures have been built for an analog model and are not optimized for cognitive radio. Regulatory bodies in the world (including the [Federal Communications Commission](https://en.wikipedia.org/wiki/Federal_Communications_Commission) in the United States and [Ofcom](https://en.wikipedia.org/wiki/Ofcom) in the United Kingdom) as well as different independent measurement campaigns found that most [radio frequency](https://en.wikipedia.org/wiki/Radio_frequency) spectrum was inefficiently utilized.[[2]](https://en.wikipedia.org/wiki/Cognitive_radio#cite_note-V._Valenta_et_al.,_Survey_on_spectrum_utilization_in_Europe:_Measurements,_analyses_and_observations-2) [Cellular network](https://en.wikipedia.org/wiki/Cellular_network) bands are overloaded in most parts of the world, but other frequency bands (such as military, [amateur radio](https://en.wikipedia.org/wiki/Amateur_radio) and [paging](https://en.wikipedia.org/wiki/Paging_(telecommunications)) frequencies) are insufficiently utilized. Independent studies performed in some countries confirmed that observation, and concluded that spectrum utilization depends on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used, even when any unlicensed users would not cause noticeable interference to the assigned service. Regulatory bodies in the world have been considering whether to allow unlicensed users in licensed bands if they would not cause any interference to licensed users. These initiatives have focused cognitive-radio research on [dynamic spectrum access](https://en.wikipedia.org/wiki/Dynamic_spectrum_management).

The first cognitive radio wireless regional area network standard, [IEEE 802.22](https://en.wikipedia.org/wiki/IEEE_802.22), was developed by IEEE 802 LAN/MAN Standard Committee (LMSC)[[3]](https://en.wikipedia.org/wiki/Cognitive_radio#cite_note-3) and published in 2011. This standard uses geolocation and spectrum sensing for spectral awareness. Geolocation combines with a [database of licensed transmitters](https://en.wikipedia.org/wiki/TV_White_Space_Database) in the area to identify available channels for use by the cognitive radio network. Spectrum sensing observes the spectrum and identifies occupied channels. IEEE 802.22 was designed to utilize the unused frequencies or fragments of time in a location. This white space is unused television channels in the geolocated areas. However, cognitive radio cannot occupy the same unused space all the time. As spectrum availability changes, the network adapts to prevent interference with licensed transmissions.[[4]](https://en.wikipedia.org/wiki/Cognitive_radio#cite_note-4)

A cognitive radio is essentially a class of software radios (SR’s) with additional capabilities

and functionalities such as environment sensing, learning, and decision-making, which enable it to reach the required dynamic performance. On software level, cognitive radio enables running of high-level application software to emulate a personal digital assistant (PDA). In order to understand the structure of a cognitive radio, we have to explore software radios and their practical version; the software-defined radios (SDR’s), since they represent the main component of a cognitive radio. The rest of this section provides a brief overview of software radios and software defined radio. A software radio (SR) is defined as a transceiver whose communication functions are realized as programs running on a suitable processor. Hence, a SR comprises all the protocol stack layers of a communication system. Based on the same hardware, adaptation of transmitter/receiver algorithms can be done on software to match different transmission standards. A wide-band antenna attached to the hardware allows its operation over different bands. A software radio is hence, highly flexible and adaptable, which meets the essence of the cognitive radio specifications. An ideal SR directly samples the antenna output and converts these samples to digital domain, and then the entire base band signal processing is done in digital domain.Software radio is rather a theoretical model, because directly digitizing the wide-band antenna output will lead to the digitization of an unnecessary huge bandwidth filled with many different

signals of no interest. This is neither technologically nor commercially desirable. A software-defined radio (SDR) is a practical version of a SR; the received signals are sampled after a suitable band selection filter to reduce sampling and digitizing complexity. The difference between a SDR and a conventional receiver lies in the reconfigurability feature in SDR, where transmission parameters can be modified via a control bus. Such a configuration is called a Parameter-controlled (PaC) SDR [6], and shown in below Figure :

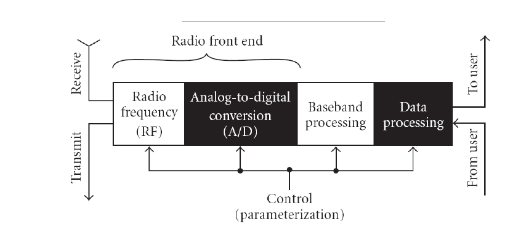


Figure : SDR/CR transceiver

Concepts and definitions introduced for Cognitive Radio technology The adoption of the cognitive radio technology as the technology for the next generation wireless networks resulted in the emergence of new concepts, new definitions and new quantities. In the following sub-sections, we discuss some of the main concepts and definitions introduced by cognitive radio technology in order to make it easier to comprehend and digest the discussions in the following sections.

1. Primary/Secondary users/networks

The presence of cognitive radio devices divides the wireless spectrum users into two types or ranks, namely, Primary (licensed) users, and Secondary (unlicensed/cognitive) users.

Consequently, two networks shall coexist; primary network, which contains all primary users with their respective licensed communication systems, and a secondary independent network that contains secondary unlicensed cognitive users. Primary users are the original incumbent users that can have legacy access to their dedicated spectrum bands unconditionally at any time or place. Secondary users are the cognitive radio users that access spectrum in an opportunistic manner. Primary users do not exhibit any cognitive behavior and their operation or design must not be affected by the presence of cognitive users. The absolute priority for spectrum access always goes to the primary user. Even if the secondary user is already transmitting over a certain channel, it must evacuate this channel immediately if a primary user was sensed to be attempting to access this channel.

2. Spectrum holes

This term was first defined as “a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user”. spectrum hole definition can expand to have many dimensions. A spectrum hole can be a band of frequencies unutilized by the primary user at a certain time, or at a certain location, or polarization, or code, or can be a combination of some or all of these. A spectrum holes were classified into three types:

1. Black spaces, which are fully occupied by primary users some of the time

2. Grey spaces, which are partially occupied by low-power interferers such as short-range

UWB devices.

3. White spaces, which are free of RF interference except for ambient noise.

The principle of a cognitive radio operation is mainly based on locating these holes and transferring data through them.

3. Spectrum pooling

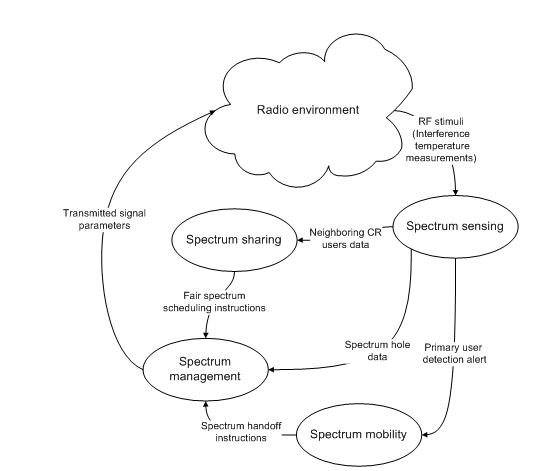
Spectrum pooling is a term that represents the coexistence of two independent radio systems;

the primary and secondary systems within the same frequency range. It enables opportunistic utilization of already licensed frequency bands by the secondary (cognitive) system. The term “spectrum pool” was first mentioned in [8]. It basically represents the idea of merging spectral ranges from different spectrum owners (military, trunked radio, etc.) into a common pool. The goal of spectrum pooling is to enhance spectral efficiency by overlaying a new radio system (cognitive radio system) on an existing one without requiring any changes to the actual licensed system.

4. Interference temperature :The interference temperature is defined to be the RF power measured at a receiving antenna per unit bandwidth [9]. The interference temperature model is proposed in [10]. It represents a new technique for measuring interference, where the contribution of a low-level communication system such as short-range UWB is assumed to be just another noise source that is included in a link budget. All of these sources are summed together to form a new noise floor as shown in Figure 3 [10]. The noise level in a given environment can be thought to be composed of three main components: 1. Natural thermal noise (KTB). 2. Unintentional man-made noise. 3. Intentional man-made noise (e.g. short-range UWB devices). Slightly increasing the noise level by allowing a small amount of intentional man-made noise can provide us with a great opportunity for low power systems to operate below this interference cap. Short-range UWB devices, for example have a very low transmission power, just one or two dB above the original noise floor, since in most wireless systems, the link budget design takes into account some link margin, therefore, the performance of these systems almost will not be affected by the presence of the UWB devices. As we can see in the figure below, the interference caused by the UWB devices is indicated by the peaks over the original noise floor, in the worst case, the new interference cap formed by the UWB devices slightly reduces the range of operation of the primary licensed system. However, this small compromise yields a huge spectrum opportunity for various systems to operate in the UWB range. Interference temperature limit (interference cap) is the fixed limit for the amount of interference that secondary users are allowed to cause to the primary users, Hence low power devices are allowed to operate as long as their transmission do not exceed the interference cap. The presence of this interference cap would assure that the licensed operation would not experience any further degradation or loss of service from new interference, and thereby provide licensed systems greater certainty regarding the maximum permissible level of interfering RF energy in the bands in which they operate. This will allow a more reliable link budget design. Two ways were proposed for reliable interference temperature estimation: 1. Using the multi-taper method [11] to estimate the power spectrum of the interference temperature due to the cumulative distribution of both internal sources of noise and external sources of RF energy. 2. Using distributed sensors that can efficiently sniff the RF environment, large number of sensors can be used to compensate for the spatial variations of interference temperature from one place to another.

Spectrum is considered a physical quantity; hence, it must be measured in units. A channel is considered the basic spectrum unit in any communication system. However, the definition of a channel varies from one respect to another. Conventionally, a channel is simply defined in the frequency dimension as a certain frequency band; this is a limited single-dimensioned definition that does not suit the cognitive radio technology as a technology for the future. A broad and comprehensive definition defines the spectrum to be partitioned into a set of orthogonal noninterfering channels [12]. This definition expands a channel to have more than one dimension such as power, location, direction of arrival (DOA), code, etc. Moreover, since a channel is basically, a part of the spectrum space, the definition of a spectrum space needs consequently to be expanded to include the multi-dimensional nature. Dynamic spectrum access in cognitive radio systems demands increased consideration of the use of time as a dimension of the signal space, since at every time instant, the channel utilization distribution changes, and consequently the distribution of spectrum holes changes. This demands very high rate of spectrum data update to avoid affecting primary user transmission. A 3D spectrum space model for modeling network resources was proposed in [15], the dimensions are time, rate and power/code, The time dimension models the time required to transfer information. The rate dimension models the data rate of the network The power/code dimension models the energy consumed for transmitting information through the network, in the case of CDMA networks, the bandwidth increase due to the multi-code transmissions is also captured in this dimension. The primary and cognitive networks both comprise heterogeneous spectrum access and utilization techniques. To guarantee successful interoperability between these networks, a universal model for a spectral unit must be specified to create a common spectral “currency” that simplifies spectrum “trading” between different communication systems. From the cognitive radio respective, a spectrum unit will help to efficiently model the multidimensional spectrum space, specify precisely the available spectrum opportunities, efficiently distribute them over CR users, and be able to evaluate the performance of both the primary and cognitive network. In, Virtual Cube concept was proposed for network performance evaluation. The Virtual Cube concept defines a unit structure based on the resource allocation techniques used in existing networks.

Cognitive tasks and functions: The extraordinary operation of a cognitive radio requires extraordinary features as well, comprising unique tasks and functions and unique challenges. In the next sub-sections, we will have an overview of the main tasks and functions required for the cognitive radio to achieve the desired expectations. 4.1. Cognitive capability & Reconfigurability. Cognitive capability refers to the ability of the radio device to achieve “awareness” of the surrounding environment by extracting useful knowledge about the surrounding radio environment in a smart and efficient manner, while exerting minimum interference to the surrounding users. This knowledge should comprise many dimensions not only frequency and time, but also space, power, interference levels, different codes, etc... Through this knowledge, the cognitive radio device can identify useful spectrum segments (spectrum holes), and use a smart algorithm to choose the best and most appropriate hole for operation. Reconfigurability enables the cognitive radio use the gained knowledge by its cognitive capability to dynamically reconfigure its transmission/receive parameters to adapt with the radio environment variations. The embedded SDR in a cognitive radio makes this task easier by enabling the cognitive radio to dynamically configure a variety of parameters such as frequency of operation, modulation and coding scheme, etc… For reconfigurability, the software-defined radio entity performs this task. For other tasks of a cognitive kind, cognitive radio assigns them to signal-processing and machine-learning procedures. 4.2. Cognitive functions The cognitive tasks mentioned in the previous section can be distributed over four main cognitive functions, namely, Spectrum sensing, spectrum management, spectrum mobility and spectrum sharing [16]. The four functions cooperation represents the cognitive cycle shown in figure 6 and discussed in the following sub-sections.



Spectrum sensing :On the startup of a cognitive radio device operation, the first task to be done is to get acquainted to the surrounding radio atmosphere by identifying the available spectrum opportunities for transmission. Such opportunities are available in the form of spectrum holes. The wireless communication spectrum has many dimensions, a communication channel (or spectrum hole) can be defined not just by frequency and bandwidth; a channel can be defined over space (spatial diversity), code (CDMA systems), polarization (polarization diversity) or direction of arrival DOA (multiple antenna systems). Hence, spectrum sensing is not confined to opportunities in just time or frequency domain, it extends also to many other domains. Consequently, cognitive spectrum sensing requires fast and efficient techniques for locating spectrum holes. The sensing technique should be smart enough to identify different communication technologies in the surrounding medium, and be able to expand its scanning dimensions to cover the code domain also. Mainly, the spectrum sensing techniques can be classified with respect to weather sensing data is exchanged between users or not as cooperative and non-cooperative techniques. Classification according to the detection techniques typically covers transmitter detection or interference based detection. Receiver detection, despite being more likely to be accurate, is impractical. A brief discussion of these sensing techniques is done below. Another classification [17] classifies spectrum sensing into two categories, namely, power-based sensing, and waveform based sensing, but this classification does not cover all sensing aspects.

A. Non-Cooperative & Cooperative detection For non-cooperative detection, each CR device detects primary user signals independently through their local observations. In most cases, a CR network is physically separated from the primary network so there is no interaction between them, but still the CR device records their presence. This may lead to inaccurate sensing data. At the same time, some primary devices might be inside the CR’s range but due to shadowing, the CR device cannot detect them. Cooperative detection presents one possible solution that can add more accuracy to the detection process. Sensing information is exchanged between CR devices to assure maximum accuracy. Cooperative detection refers to spectrum sensing methods where information from multiple CR users is incorporated for primary user detection. An example of such information for MB-OFDM-based systems is the binary allocation vector [18]. In this vector, each bit represents one OFDM sub-carrier, if a bit has a value of one, this means that the corresponding sub-carrier is occupied, if it has the value of ‘0’, this means the sub-carrier is vacant and available for cognitive access. By applying a logical OR the collected vectors from different CR devices, maximum protection for Primary users with respect to interference can be obtained. Cooperative detection can be implemented either in a centralized or in a distributed manner .In the centralized method [19], it is assumed that there is a common base station capable of both receiving and sending with which all CR devices communicate. Each CR device individually detects local primary users, if found, it informs other CR devices through the base station. Distributed solutions [20] require exchange of observations among CR users through an assigned common control channel (CCC).

THE increasing demand of spectrum slots is a result of the exponential growth of wireless networks. On the other hand, this growth is facing the classical spectrum scarcity problem. Statistical analysis of spectrum usage presented in [1] shows that the spectrum is underutilized. Therefore, interest in cognitive radio (and multi-tier priority access [2]) networks has also grown accordingly. In cognitive radio networks, spectrum slots are allocated to users in a dynamic fashion. At first, the spectrum slot is assigned to its owner, also known as primary user (PU). Users with less priority, also known as secondary users (SU) are allowed to access this designated spectrum slot whenever its owner is not exploiting it. After spectrum sensing stage, the CR device now has information about the available spectrum holes that would be spread over different frequency bands or timeslots or locations or codes, etc. Each hole has its own unique characteristics such as frequency, bandwidth, noise level, etc... Spectrum management protocol has to analyze data given about spectrum from the sensing stage, and then decide which band to choose according to the QoS requirements. This requires a cross-layer co-operation between spectrum sensing (Physical layer) and upper layers which will do the analysis and decision. The analysis and decision tasks are discussed briefly below. More details about the cross layer performance for spectrum management are discussed in section 5.4. A. Spectrum analysis Detected spectrum holes in the spectrum sensing stage need to be characterized in order to extract the characterization parameters of each hole that define their eligibility to handle a certain application. Examples of such parameters include operating frequency, bandwidth, path loss, interference level, delay spread, channel error rate and holding time. Holding time is defined as the expected time duration that the CR user can occupy a licensed band before being interrupted. It is a critical CR-related parameter, which directly affects the quality of service. Holding time can be estimated through observations of the primary users’ transmission behavior over each channel. Channel capacity, which can be derived from the parameters explained above, is one of the most important factors for spectrum characterization; spectrum decision mainly depends on it as a decision parameter. Interference temperature model also can be exploited for capacity estimation. B. Spectrum decision Each application running on a CR device requires a certain QoS, which in turn sets some minimum requirements for the desired operating channel. For example, applications such as real- time video transfer demand a high quality of service, large bandwidth, very small delay and a large holding time in order to guarantee a satisfactory video quality. In other words, we need a high quality channel. On the other hand, non real-time applications such as file transfer do not impose very tight constraints on channel quality. The spectrum decision protocol must first be able to define the minimum acceptable parameters for each application, and then compare them to the available choices generated by the spectrum analysis. The decision algorithm must be able to decide which channel best fits the requirement.

Spectrum mobility (spectrum handoff) As discussed before, cognitive radio operation is mainly about exploiting unused licensed spectrum segments in an opportunistic manner. This must be done without affecting the primary users’ operation. If this was not 100% guaranteed, primary users would not allow cognitive users to share their spectrum. Therefore, As soon as a primary user starts transmission over a channel occupied by a secondary user, the secondary user must immediately evacuate the channel in a smart and efficient manner that would not cause any harm to the integrity of the primary user transmission. Such a function is called “spectrum mobility” or “spectrum handoff”. A spectrum mobility protocol must also guarantee the secondary user a smooth transition in terms of the associated latency, since as the secondary user transits from one channel with certain parameters to another channel with different parameters; this required a very fast adaptation to the new parameters like operating frequency, modulation scheme and the adequate associated source/channel coding. This requires cooperation between all layers in network stack to quickly adapt to the new operation parameters and provide transparency to the transition latency.. Useful information about this latency can help to improve mobility performance if provided by the spectrum sensing protocol, where it can give an estimation of the transition process duration in advance; this can help the upper layers minimize performance degradation during transition.

Spectrum sharing A wide range of spectrum opportunities is open for CR users to access; this besides being an advantage, imposes a challenge to the CR technology, since access should be organized between CR users in a fair manner. Spectrum sharing is the function concerned with this subject; it is similar to the medium access control (MAC) protocol used in most networking systems. However, due to the dynamic nature of the CR network and the presence of two ranks of users (primary and secondary users), Spectrum sharing protocol must exploit smarter and more advanced algorithms to guarantee peaceful co-existence with primary users and fair spectrum sharing between secondary users. Efforts done on designing spectrum sharing protocols took two main directions: 1. Game theory, exploiting Nash equilibria or no-regret learning algorithms [28, 7]. More details are explained. 2. Information theory, mainly through exploiting Iterative water-filling algorithm [29] which was developed originally for dynamic spectrum management in digital subscriber lines [30]. Both approaches were well discussed and evaluated in [7], mentioning their advantages and disadvantages. Cognitive radio system architecture A cognitive radio network will operate in a unique environment, the spectrum of its operation contains licensed and unlicensed bands, and licensed bands are allocated to different systems with various communication technologies. Operation in such a heterogeneous atmosphere requires a unique network architecture that can adapt quickly, coexist peacefully and operate efficiently in such environment

CR network elements :The spectrum will witness the coexistence of two major networks, the primary network, and the secondary (CR) network. The primary network represents the already existing licensed network infrastructure. It has the legitimate right to access its own dedicated band at any time without any interruption or interference from any intruder. The primary network elements comprising primary users and primary base stations do not exhibit any cognitive behavior. Their coexistence with the secondary network elements should not disturb their operation or require them to add any additional functions or design modifications. However, the primary base-station may be requested to have both legacy and CR protocols for the primary network access of CR users [16]. On the other hand, the secondary (CR) network, that does not have any legitimate rights for using any spectrum bands, attempts to access the temporarily unused spectrum segments in an opportunistic manner that does not affect the primary network operation. CR network can be either an infrastructure-based network or an ad-hoc-based network. Because of the opportunistic nature of the CR network operation, the CR network elements comprise elements with more complicated functionalities than those of the primary network. In [31], a CR network architecture called DIMSUM-Net was proposed. It consists of four elements: base stations, clients, a Radio Access Network Manager (RANMAN) that obtains spectrum leases, and a per-domain spectrum broker that controls spectrum access and plays a role in sharing spectrum resources among different CR networks. 5.2. CR network access CR users can communicate with each other either in a multi-hop manner or through the CR base-station. Thus, in CR networks, there are three different access types [16]: 1. CR network access: CR users can access their own CR base-station both on licensed and unlicensed spectrum bands. 2. CR-ad hoc access: CR users can communicate with other CR users through ad hoc connection on both licensed and unlicensed spectrum bands. 3. Primary network access: The CR users can also access the primary base-station through the licensed band [16]

**CHAPTER-3**

**LITERATURE REVIEW**

**[1] S. Haykin:** Cognitive radio is viewed as a novel approach for improving the utilization of a precious natural resource: the radio electromagnetic spectrum. The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind: • highly reliable communication whenever and wherever needed; • efficient utilization of the radio spectrum. Following the discussion of interference temperature as a new metric for the quantification and management of interference, the paper addresses three fundamental cognitive tasks. 1) Radio-scene analysis. 2) Channel-state estimation and predictive modeling. 3) Transmit-power control and dynamic spectrum management.

**Summary:**

Learned about the Cognitive radio and three fundamental cognitive tasks.

**[2]** **B. U. Kazi and G. A. Wainer:**

The next generation wireless cellular network is aimed to address the demands of users and emerging use cases set by industries and academia for beyond 2020. Hence, The next generation 5G networks need to achieve very high data rates, ultra-high reliability, extremely low latency, energy efficiency and fully connected coverage. To meet these demands, ultra-dense networks (UDN) or ultra-dense heterogeneous networks (UDHetNet), millimeter wave (mmWave) and multicell cooperation such as coordinated multipoint (CoMP) are the three leading technology enablers. In this paper, we have made an extensive survey of the current literature on 5G wireless communication focusing on UDN, mmWave and CoMP cooperation. We first discuss the architecture and key technology enablers to achieve the goals of the 5G system. Subsequently, we make an in-depth survey of underlying novel ultra-dense heterogeneous networks, mmWave and multicell cooperation. Moreover, we summarize and compare some of the current achievements and research findings for UDHetNet, mmWave and CoMP. Finally, we discuss the major research challenges and open issues in this active area of research .

**Summary:**

Studied about UDHetNet, mmWave and CoMP, major research challenges and open issues in this active area of research .

**[3]** **Y. Ye, Y. Li, G. Lu, and F. Zhou, :**

Spectrum Sensing (SS) plays an essential role in Cognitive Radio (CR) networks to diagnose the availability of frequency resources. In this paper, we aim to provide an in-depth survey on the most recent advances in SS for CR. We start by explaining the Half-Duplex and Full-Duplex paradigms, while focusing on the operating modes in the Full-Duplex. A thorough discussion of Full-Duplex operation modes from collision and throughput points of view is presented. Then, we discuss the use of learning techniques in enhancing the SS performance considering both local and cooperative sensing scenarios. In addition, recent SS applications for CR-based Internet of Things and Wireless Sensors Networks are presented. Furthermore, we survey the latest achievements in Spectrum Sensing as a Service, where the Internet of Things or the Wireless Sensor Networks may play an essential role in providing the CR network with the SS data. We also discuss the utilisation of CR for the 5th Generation and Beyond and its possible role in frequency allocation. With the advancement of telecommunication technologies, additional features should be ensured by SS such as the ability to explore different available channels and free space for transmission. As such, we highlight important future research axes and challenging points in SS for CR based on the current and emerging techniques in wireless communications.

**Summary:**

Studied the utilisation of CR for the 5th Generation and Beyond and its possible role in frequency allocation. With the advancement of telecommunication technologies, additional features should be ensured by SS

**[4] N. A. El-Alfi, H. M. Abdel-Atty, and M. A. Mohamed:**

Spectrum scarcity is a challenging problem in wireless communications: high data rates are needed to support 5G new technologies. However, the spectrum is underutilized. To address this problem, cognitive radio (CR) is proposed to exploit the underutilized spectrum. The main requirement for the future CR networks is wideband spectrum sensing, which provides secondary users with the available frequency bands across a wide frequency range. Secondary users should fill these bands without causing interference to licensed users. Thus, new waveforms are proposed for the 5G physical layer. Generalized frequency division multiplexing (GFDM) is considered to be a contender for the 5G new physical layer. The GFDM is a block-based waveform that is suitable for fragmented spectrum scenarios and is designed to overcome the drawbacks of orthogonal frequency-division multiplexing (OFDM) used in 4G. The GFDM is the perfect candidate for 5G and CR technologies. Considering the cyclostationarity properties of modulated signals, we propose an optimized recovery method for the GFDM signals in the wideband regime. By exploiting the signal sparsity, we can recover the spectral correlation function (SCF) of the GFDM from digital samples of the GFDM taken at a sub-Nyquist rate to reduce the sampling time. Furthermore, a generalized likelihood ratio test is applied to the recovered function to detect multiple signal sources and identify the spectrum occupancy. The numerical results show that our method achieves a high probability of detection at a low signal-to-noise ratio (SNR) with robustness in terms of rate reduction in wireless networks.

**Summary:**

Studied about the cyclostationarity properties of modulated signals, optimized recovery method for the GFDM signals in the wideband regime.S

**[5] L H. V. Poor and O. Hadjiliadis:**

The problem of detecting abrupt changes in the behavior of an observed signal or time series arises in a variety of fields, including climate modeling, finance, image analysis, and security. Quickest detection refers to real-time detection of such changes as quickly as possible after they occur. Using the framework of optimal stopping theory, this book describes the fundamentals underpinning the field, providing the background necessary to design, analyze, and understand quickest detection algorithms. For the first time the authors bring together results that were previously scattered across disparate disciplines, and provide a unified treatment of several different approaches to the quickest detection problem. This book is essential reading for anyone who wants to understand the basic statistical procedures for change detection from a fundamental viewpoint, and for those interested in theoretical questions of change detection. It is ideal for graduate students and researchers in engineering, statistics, economics, and finance..

**Summary:**

Learned about Quickest detection and a unified treatment of several different approaches to the quickest detection problem.

**CHAPTER-4**

**EXISTING METHOD**

Spectrum sensing can be achieved through different techniques including Matched filter detection and cyclostationary detection .On the other hand, signal detection based on probabilistic models, i.e general-likelihood-ratio test (GLRT) exploits the distributions of the received signal under the two hypotheses (occupied or vacant spectrum slot)

**Matched filter detection:**

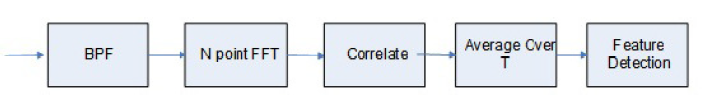
The first thing that would come to our mind when thinking of a technique for spectrum sensing is to detect active transmission channels between primary transmitters and receivers. Downlink channel detection is usually more efficient to detect, since the transmitter is most probably a base station hence, downlink signals are stronger and easier to detect. While uplink signals from primary users are usually weak due to the limited battery power capability. In practice, however, it is hard to use downlink channel detection for spectrum sensing purposes, since it is too difficult to determine which primary users are inside the scanning range, since simply we can detect a channel but the primary device is out of the CR communication range, so this might result in exaggerated sensing data. This leaves us with the only possible solution, which is the detection of the weak transmitted signals from primary users. This solution, although it needs more receiver sensitivity, can give us a better idea about the spectrum utilization in the surrounding area, and hence be able to locate and characterize the available spectrum holes. Detection of such transmission can be done most simply by detecting radiated energy over the band of interest, or by using a matched filter, but these techniques, despite being simple have many drawbacks, another technique was proposed, namely, cyclostationary feature detection [22], which outperforms the first two techniques. The three techniques are discussed in the following sub-sections.In Stationary Gaussian noise channel, usually, a matched filter gives optimum detection results and a maximum SNR, provided that information about the shape of the transmitted signal is available.



The matched filter is that it requires less time to achieve high processing gain due to coherency. Can distinguish between primary user signals and other CR user’s signal. This allows the CR device to have deeper knowledge of the surrounding radio environment and helps in taking better spectrum sharing decisions.

Since most wireless network systems have pilot, preambles, synchronization words or spreading codes, these can be used for the coherent detection. Pilot detection In mostly all current communication system, a deterministic pilot signal is transmitted for synchronization and channel acquisition. The power of the pilot tone is typically 1-10% of the total transmitted power. This makes transmitter detection based on pilot signal detection a very attractive technique. The benefit of pilot signals, if they are perfectly known to cognitive radio sensor, is that it can be processed coherently using a matched filter, hence achieve a maximal SNR as explained before. In most primary communication systems, a sine wave tone is used as a pilot signal .However, for packet-based systems, a short preamble packet containing a high autocorrelation pseudo-noise sequence is used as a pilot. If a cognitive radio sensor knows the packet structure of the system, then it can perform coherent processing of a preamble through a set of matched filter correlators.

**Cyclostationary feature detection**: In cyclostationary feature detection ,modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. These modulated signals are characterized as cyclostationary since their mean and autocorrelation exhibit periodicity. These features are detected by analyzing a spectral correlation function .It differentiates the noise energy from modulated signal energy, since noise is wide sense stationary signal that does not exhibit periodicity signal and had no spectral correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity.



A scheme that combines spectral analysis with pattern recognition based on neural networks was proposed .Distinct features of the received signal are extracted using cyclic spectral analysis, The neural network, then, classifies signals into different modulation types By combining these techniques a more efficient and reliable classifier can be developed where a significant amount of processing is performed offline.

Since the current radio environment is highly dynamic, especially in multiple access bands, therefore, spectrum-sensing data must be updated frequently. Scanning the spectrum for detection is slow, and it is not a smart approach for spectrum sensing, a cognitive radio is inherently a smart device; hence, a smarter approach for sensing is required.

**General Likelihood Ratio Test:**

Spectrum sensing based on GLRT has been presented in which different tests are obtained under different parameter assumptions, i.e., unknown noise variance and/or signal covariance matrix. In the sequel, the GLRT is reviewed in its general form, and it will be employed for the detection of OFDM signals . If any of the two hypotheses describing a binary hypothesis testing problem involves some unknown parameters, the hypothesis is called a composite hypothesis [24]. For a composite hypothesis, one approach is to perform the maximum likelihood estimation (MLE) of the unknown parameters. The estimated parameters are then used in the likelihood ratio test as if they are correct values. The result is then called the generalized likelihood ratio test (GLRT) [24]. This approach enables the cognitive radio receiver to incorporate the uncertainties in calculating the test statistics. Spectrum sensing based on GLRT was presented in [25] for single antenna CR user and in [32,33] for multi-antenna CR receiver. The decision tests have been obtained under different number of unknown parameters, e.g., noise variance and/or signal covariance matrix. For the general case when both noise variance and signal covariance matrix are unknown, exploiting the GLRT algorithm gives the arithmetic to-geometric mean (AGM) method . Denote the eigenvalues of the sample covariance matrix .  The AGM test statistic is given as



where λ = (λ1, . . . , λL). If some information such as noise variance or the rank of signal covariance matrix is available, this additional information can be incorporated into the test statistics to give a modified test statistics as a function of the eigenvalues .

In practical scenarios, it is difficult to know the likelihood functions exactly. For instance, we may not know the noise power σ2ηση2 and/or source signal covariance RsRs. Hypothesis testing in the presence of uncertain parameters is known as “composite” hypothesis testing. In classic detection theory, there are two main approaches to tackle this problem: the Bayesian method and the generalized likelihood ratio test (GLRT).

In the Bayesian method [[16](https://link.springer.com/chapter/10.1007/978-981-15-0776-2_3#CR16)], the objective is to evaluate the likelihood functions needed in the LRT through marginalization, i.e.

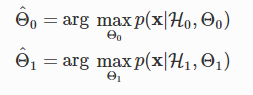


where Θ0 represents all the unknowns when H0H0 is true. Note that the integration operation in above equation should be replaced with a summation if the elements in  if the elements in Θ0 are drawn from a discrete sample space. Critically, we have to assign a prior distribution  p(Θ0|H0) to the unknown parameters. In other words, we need to treat these unknowns as random variables, and use their known distributions to express our belief in their values. Similarly p(x|H1) can be defined. The main drawbacks of the Bayesian approach are listed as follows: 1.The marginalization operation in the above equation is often not tractable except for very simple cases;

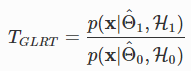
 2.The choice of prior distributions affects the detection performance dramatically and thus it is not a trivial task to choose them.

To make the LRT applicable, we may estimate the unknown parameters first and then use the estimated parameters in the LRT. Known estimation techniques could be used for this purpose. However, there is one major difference from the conventional estimation problem where we know that signal is present, while in the case of spectrum sensing we are not sure whether there is source signal or not (the first priority here is the detection of signal presence). At different hypothesis, H0H0 or H1H1, the unknown parameters are also different.

The GLRT is one efficient method to resolve the above problem, which has been used in many applications, e.g., radar and sonar signal processing. For this method, the maximum likelihood estimation of the unknown parameters under H0H0 and H1H1 are first obtained as



where Θ0 and Θ1 are the set of unknown parameters under H0 and H1, respectively. Then, the GLRT statistic is formed as



Finally, the GLRT decides H1 if  TGLRT(x)>γ, where γ is a threshold, and H0 otherwise.

It is not guaranteed that the GLRT is optimal or closes to the optimum when the sample size goes to infinity. Since the unknown parameters in Θ0and Θ1 are highly dependent on the noise and signal statistical models, the estimations of them could be vulnerable to the modeling errors.

The key advantage of the GLRT approach is that by concentrating on a certain portion of the observation, one can exploit structural properties of the covariance matrix to improve its estimation in the GLRT. The decision statistic is then obtained as a function of the signal observations. This is presented in detail in [31] and an OFDM-based CR system., robust spectrum sensing algorithms which rely on important features in the received signal, such as multipath structure, cyclic prefix or receive diversity can be developed for efficient spectrum sensing. Moreover, utilizing multiple CRs in a collaborative manner can further improve the sensing performance. In the next section, the motivation, benefits and methods of implementing a cooperative cognitive radio network are presented. A very popular form of hypothesis test is the likelihood ratio test, which is a generalization of the optimal test for simple null and alternative hypotheses that was developed by Neyman and Pearson.

Likelihood ratio tests are useful to test a composite null hypothesis against a composite alternative hypothesis. Suppose that the null hypothesis specifies that θ (may be a vector) lies in a particular set of possible values, say Θ0, i.e. H0 : θ Є Θ0; the alternative hypothesis specifies that Θ lies in another set of possible values Θa, which does not overlap Θ0, i.e. Ha : θ Є Θa. Let Θ = Θ0 ∪ Θa. Either or both of the hypotheses H0 and Ha can be compositional.

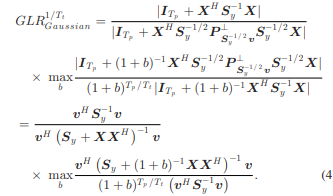
Let be the maximum (actually the supremum) of the likelihood function for all θ Є Θ0. That is, = maxθ Є Θ0 L(θ). represents the best explanation for the observed data for all θ Є Θ0. Similarly, =  represents the best explanation for the observed data for all . If  then a best explanation for the observed data can be found inside Θ0 and we should not reject the null hypothesis H0 : θ Є Θ0. However, if then the best explanation for the observed data could be found inside Θa, and we should consider rejecting H0 in favour of Ha. A likelihood ratio test is based on the ratio .

Define the likelihood ratio statistic by

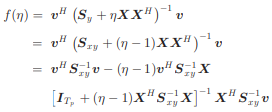


A likelihood ratio test of employs Λ as a test statistic, and the rejection region is determined by Λ ≤ k. Clearly, 0 ≤ Λ ≤ 1. A value of Λ close to zero indicates that the likelihood of the sample is much smaller under H0 than it is under Ha, therefore the data suggest favouring Ha over H0. The actually value of k is chosen so that α achieves the desired value.

Proposition 1: Suppose Ts ≥ M. The GLR for the composite hypothesis testing problem in (3) is given by



A few remarks are in order from the expression in (4): The GLR is a product of two terms, the first of which is recognized as Kelly’s test statistic, i.e., the GLR for deterministic amplitudes αtp . The second term (which is always lower than one) is a corrective term due to the fact that now αtp are considered as Gaussian distributed random variables. Note that b corresponds to the signal to-noise ratio and is proportional to P, see Appendix A. The numerator of the second term measures the gain of the filter  towards the target. When the latter is absent or very weak, X contains noise only, and the filter is more efficient when (1 + b)−1 grows close to 1, or equivalently when b goes to 0: in this case, the estimated target power will be small. In contrast, if X contains a strong target,  will tend to eliminate it if (1 + b)−1 is too large: in such a case, the estimated b should be large. Since the above GLR involves the same quantities as Kelly’s GLR, it follows that is has a constant false alarm rate with respect to R, i.e., its distribution under H0 is independent of R. The new detector requires solving the optimization problem .In order to solve it efficiently, let us define  Then, if the determinant form is employed, one can make use of the fact that  where are the eigenvalues of M, to efficiently compute the function to be maximized with respect to η. Likewise, if the second form of the detector is used, one can notice that



which can be used, e.g., to compute efficiently f(η) over a grid of values of η and solve the optimization problem.

The previous GLR is usually referred to as a one-step GLRT as it is computed from both X and Y and maximization of the likelihood function is carried out with respect to all unknown parameters, namely P and R here. Similarly to what was proposed in [7], we now investigate two-step approaches where R is first assumed to be known, and the GLRT is derived based on X only. Then, an estimate of R, based on Y only, is substituted for R. This is the principle of the adaptive matched filter (AMF) of [7]. As was illustrated in the literature, AMF yields some loss compared to Kelly but it is not that significant, at least for Ts large enough and in the matched case where the assumed target signature coincides with the actual one. However, in the mismatched case, i.e., when v differs from the actual target signature, AMF lacks sensitivity, i.e., it still provides a good probability of detection even for non negligible mismatches. In order to overcome this drawback, a common approach consists in injecting a fictitious signal under H0 , “orthogonal” to v, so that the detector is less inclined to decide in favor of H1 in the case of signature mismatch, We adopt the same philosophy here and consider the following detection problem



where the vector u can be either zero (similarly to AMF), orthogonal to v, i.e., u ⊥ v or orthogonal to v in the whitened space.

**GLRT for a simple null hypothesis:**

Let {f(x|θ) : θ Є Ω} be a parameteric model, and let θ0 Є Ω be a particular parameter value. For testing



the generalized likelihood ratio test (GLRT) rejects for small values of the test statistic



where lik(θ) is the likelihood function. (In the case of IID samples  

The numerator is the value of the likelihood at θ0, and the denominator is the value of the likelihood at the MLE ˆθ. The level-α GLRT rejects H0 when Λ ≤ c, where (as usual) c is chosen so that PH0 [Λ ≤ c] equals (or approximately equals) α. Note that the GLRT differs from the likelihood ratio test discussed previously in the context of the Neyman-Pearson lemma, where the denominator was instead given by lik(θ1) for a simple alternative θ = θ1. The alternative H1 above is not simple, and the GLRT replaces the denominator with the maximum value of the likelihood over all values of θ.

GLRT for testing a sub-model: More generally, let Ω0  Ω be a subset of the parameter space Ω, corresponding to a lower dimensional sub-model. For testing



the generalized likelihood ratio statistic is defined as



In other words, Λ is the ratio of the values of the likelihood function evaluated at the MLE in the sub-model and at the MLE in the full-model. For large n, under any

  Λ is approximately distributed as  where k is the difference in dimensionality between Ω0 and Ω, and an approximate level-α test rejects H0 when 

**DISADVANTAGES:**

1.One critical problem in detection theory is the quickest change detection (QCD) problem. The objective of QCD is to detect the change point in a series of collected samples or measurements as quickly as possible, i.e., finding the point at which the distribution of the received samples changes.

2. In Cyclostationary Feature Detection, Computationally complex and requires significantly long observation time.

3. In Matched filter detection, It requires a priori knowledge of the primary user signal such as the modulation type and order, the pulse shape, and the packet format. Hence, if this information is not accurate, then the matched filter performs poorly.

4. Matched filter based detection is complex to implement in CRs.

**CHAPTER-5**

**PROPOSED METHOD**

A framework for sequential detection for cognitive radio networks is presented as follows:

In the sequential change-point detection problem, one observes samples sequentially. Initially, the samples are drawn from a certain distribution. At an unknown time, the distribution changes. Once this occurs, one needs to raise an alarm as quickly as possible, hence to minimize the delay (rigorous definitions will be given in the sequel) between the time when the change occurs and the time when the alarm is raised. The sequential change point detection problem is different from but has a close relationship with the classic sequential testing problem. In the classic sequential testing problem developed by Wald [5], the objective is to distinguish between two hypotheses from a sequence of statistically homogeneous random samples. All the samples are drawn from the same distribution, it is only the identity of this distribution that is in question. In the scenario considered in change point detection, the random observations are not homogenous, and one should raise an alarm as soon as an inhomogeneity occurs. On the other hand, the sequential change-point detection problem can be modelled and solved as sequences of classical open-ended sequential testing problems [3]. In the cognitive radio setup, the onset of activity of a primary user at an unknown time will change the distribution of the received signal of cognitive users. Hence, the change detection framework is well suited for this problem. After the submission of this work, we got to know [6], which also considers the application of change point detection in cognitive radio. The model considered in [6] is In [14] the authors derived an approximate closed-form expression for the distribution of the detection delay for quickest detection. A joint design based on observation scheduling policy and stopping time that minimizes the detection delay for quickest detection is presented in [11]. Furthermore, the authors in [11] extended their study to the multi-channel sensing case. In this letter, motivated by the great need to find closed-form expressions for false-alarm and detection probabilities for the above-mentioned critical applications, we revisit the problem in [7] and provide closed-form expressions for the false-alarm and detection probabilities under finite sensing interval. To the best of the authors knowledge, closed-form expressions for these probabilities in the considered problem do not exist in literature. In fact, it was stated in [14] that exact analysis for this problem is intractable. The sought expressions are important in practical systems since the number of collected samples is finite and any quality-of-service optimization will require the knowledge of both detection and false-alarm probabilities. We give those probabilities in closed-form and verify all our findings through numerical evaluations.

Change detection is a fundamental problem arising in many fields of engineering, in finance, in the natural and social sciences, and even in the humanities. This book is concerned with the problem of change detection within a specific context. In particular, the framework considered here is one in which changes are manifested in the statistical behavior of quantitative observations, so that the problem treated is that of statistical change detection. Moreover, we are interested in the on-line problem of quickest detection, in which the objective is to detect changes in real time as quickly as possible after they occur. And, finally, our focus is on formulating such problems in such a way that optimal procedures can be sought and found using the tools of stochastic analysis.

We consider an SU operating in frame basis [15], as depicted in Fig.

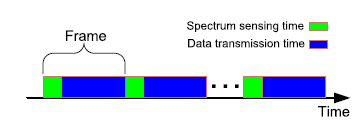


Figure: Periodic spectrum sensing.

The time is partitioned into frames of equal length. Each frame consists of a spectrum sensing phase and data transmission phase. In case the decision during the spectrum sensing phase is declared to be existence of the PU’s signal, the SU remains silent during the data transmission phase since the frame belongs to the PU. Otherwise, the SU starts to exploit the data transmission phase to transmit and receive its own data.When spectrum sensing phase starts, the SU begins to collect samples, with N denoting the maximum number of collected samples during the spectrum sensing phase. If the PU is not occupying this spectrum slot,  where,  is a zero-mean white Gaussian noise with variance . If the PU is occupying the frequency band, the received signal at the SU is  where is the product of the channel coefficient, h, and the PU signal, The signal  is assumed to be an independent and identically distributed (i.i.d.) Gaussian signalwith zero mean and variance P [7], [14]–[16]. When the Pu signal is presentdenotes a Gaussian distribution with mean · and variance \*.Otherwise, .

The spectrum sensing operation has two cases: A) Detection of the entrance of the PU’s signal; or B) Detection of exiting of the PU user, i.e., empty spectrum frame. In the first case, the two detection hypotheses are defined as



where is the time instant at which the PU enters the spectrum and N is the total number of samples collected during the sensing time duration at each frame. When = 1, this indicates that the PU is already occupying the spectrum when the SU started its sensing time within the frame. Typically, the decision statistic is compared to a threshold to decide on the occupancy status of the spectrum. If the decision raises a flag at sample Ns, where Ns >=, the detection delay is Nd = Ns − However if the flag is raised when Ns < , this indicates a false-alarm event with Nf = Ef0 [Ns] as the mean time to false alarm. In sequential detection, the objective is to minimize Nd and maximize Nf . We are interested in evaluating the performance of the CUSUM technique, i.e., calculating the probability of detection and probability of false alarm when a flag is raised. In the second case, the two detection hypotheses are defined.



When = 1, this indicates that the PU has already exited the spectrum when the SU began its spectrum sensing operation.

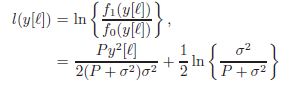
\*If a primary user stops transmission, then a secondary user should detect this event quickly, in order to be able to start its own transmission quickly. A small detection delay will allow secondary users to take short transmission opportunities. On the other hand, if the primary user starts transmission, the cognitive user should detect this event as quickly as possible, in order to vacate the band for the primary user. A small detection delay will allow the design of a spectrum reuse scheme that has minimal impact on the licensed users. Of course, the desire to reduce the detection delay should be balanced with a certain false alarm constraint. Our goal is to establish a statistical framework to analyze detection delay subject to certain false alarm constraints, and more importantly to design a scheme that can minimize the delay.

**QCD BASED ON CUSUM:**

The utilization of CUSUM for spectrum sensing under the assumption of full knowledge of distributions of the signal under the two hypotheses is a common practice in literature [7], [14]. This assumption provides a performance upper bound benchmark for the case when the variance of the signal under H1 is unknown. In this letter, we investigate in details the first case, i.e., when the spectrum status changes from vacant to occupied. For the other case, same flow of steps can be used to detect the change of status of the spectrum from occupied to vacant; hence, we only point out the change in formulation to save space and make the discussion concrete. Next, we present necessary background review on CUSUM algorithm before we proceed to present our performance analysis work.

CUSUM Algorithm Background:

CUSUM algorithm is based on LRT [6]. When the spectrum slot is vacant, the collected samples by the SU follow a certain distribution, say distribution F0, with density function f0. Ditto, as the PU starts using the frequency band, the distribution changes to F1 with density f1. In this case, the detection of the entrance of the PU’s signal is a sequential change detection problem where the received samples are processed sequentially and the decision statistic is calculated after each sample. The decision on the occupancy status of the spectrum is also made sequentially. To this end, the loglikelihood ratio is calculated for each sample sequentially through:



where [is the density function value at sample .The Kullback-Leibler divergence of f0 from f1exhibits a negative drift before the entrance of PU signal and positive drift otherwise [6] and the decision statistic for the CUSUM test can be applied recursively using [7]:

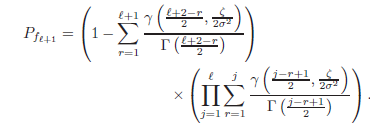


B. Performance Analysis of CUSUM Algorithm

Using CUSUM algorithm, after the spectrum status changes, as the number of collected samples increases, the probability of detection increases and, eventually, can reach its maximum value, i.e., 1. However, within the paradigm of periodic sensing, depicted in Fig. 1, the total number of collected samples is bounded by the periodic sensing time. To this end, when applying CUSUM algorithm in cognitive radio applications where the size of the detection window is fixed, i.e., finite number of collected samples is used, the receiver operating characteristics (ROC), determined by the probability of false alarm and the probability of detection, are key performance metrics related to deciding on the status of the spectrum.

In Proposition 1, we derive closed-form expressions for the detection and false-alarm probabilities of the decision statistic of the CUSUM test, . The distribution of the received signal under the two hypotheses is the same mentioned above

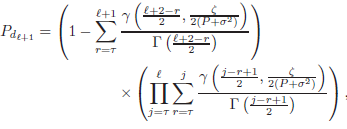
Proposition 1: The false-alarm probability for the sample, is given by



The total false-alarm probability is given by



In addition, the detection probability is given by:



Where  is the threshold, c1 =,is the lower incomplete gamma function, and Γ(·) is the gamma function. The total detection probability is given by



Proof: The proof of Proposition 1 is provided in Appendix. Using our closed-form expressions and for a desired Pf or Pd under finite sensing time, the decision statistic is compared to the threshold , which can be calculated according to the desired performance metric.

PROOF FOR PROPOSITION 1

To derive closed-form expression for the probability of false alarm and the probability of detection, we need to define the probability distribution of the decision statistic defined in decision statistic for the CUSUM test .Hence, Our starting point in the derivation is in decision statistic for the CUSUM test, which is defined using a max operation. Therefore, let us first consider two random variables (RVs) V1 and V2, the probability distribution function of their maximum, U = max[V1, V2], FU(u), can be given by



To this end and noting that 1 in (6) is the maximum of a RV and zero, and defining this RV as , therefore by substituting in equation for the probability distribution of at a threshold , we have



Here, we always have the threshold  > 0, hence equation is now



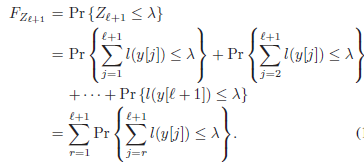
Note that the probability that a RV U lies in an interval [u1, u2], where u1 < u2, can be given by

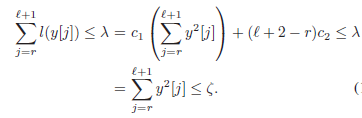


Using previous equation to substitute for the first term in present equation and noting that  now becomes

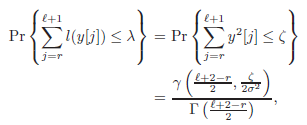


where represents the probability distribution of The quantity represents the likelihood ratios summation up to the sample with the possibility that each g will be reset to zero at any sample inside the   samples. It is noteworthy that, combinations or positions of each zero incident do not have an impact on the results, only position of the last occurring zero matters. Hence, has possibilities. For example, if the output of the maximization with zero process resulted in no zero,  If a zero occurred at the first sample  and so on. We have

Note that



where  and c2 =  Recalling that the collected samples are Gaussian RVs, the samples  are Chi-square RVs. Hence  is a Chi-square RV with  degrees of freedom since it is a summation of Chi-square RVs. Consequently



where denotes the lower incomplete gamma function and Γ(·) is the gamma function. This leads to



The probability of false alarm for the  sample where  is given by:

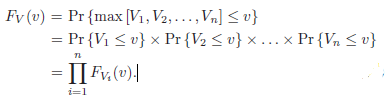


Note that the joint distribution of two independent random variables V1 and V2 can be given by



Moreover, the distribution of the RV V = max [V1, V2, . . . , Vn], where V1 and V2 to Vn are independent

RVs, is given by



The probability of detection for the sample where is given by



It must be noted that are correlated RVs, nevertheless,we assume independence as an approximation to makethe closed-form expressions derivations feasible. Due tothe recursive nature of ’s, deriving a closed-formexpression with dependence assumption might be infeasible,as also stated.

**CHAPTER-6**

**ADVANTAGES AND APPLICATIONS**

**Advantages:**

1.The QCD(Quickest Change Detection ) problem is solved by using CUSUM Algorithm

2.The proposed QCD BASED ON CUSUM,requires less observation time and less in complexity .

3.No priori knowledge of the primary user signal such as the modulation type and order, the pulse shape, and the packet format is required .

4. Proposed QCD BASED ON CUSUM performs better when compared to other spectrum sensing techniques.

5.unlike Matched filter based detection is complex to implement in CRs,the proposed method is implemented in CR.

**Applications:**

1.Spectrumsensing ,

2.Resource allocation and scheduling .

3.Powersystem line outage detection

4.Bioinformatics

5. Quality control.

**CHAPTER-7**

**MATLAB**

**7.1 INTRODUCTION TO MATLAB**

**What Is MATLAB?**

MATLAB is an elite dialect for specialized registering. It incorporates calculation, representation, and programming in an easy to-utilize condition wherein issues and preparations are communicated in herbal numerical documentation. Run of the mill utilizes comprise

• Math and calculation

• Algorithm advancement

• Data obtaining

• Modeling, re-enactment, and prototyping

• Data examination, investigation, and representation

• Scientific and designing illustrations

• Application advancement, including graphical UI building

MATLAB is an intuitive framework whose important statistics aspect is an show off that does not require dimensioning. This allows you to tackle several specialized processing issues, particularly those with framework and vector info, in a small quantity of the time it'd take to compose a program in a scalar non intuitive dialect, as an instance, C or FORTRAN.

The call MATLAB stays for grid studies facility. MATLAB changed into first of all composed to present easy access to framework programming created by way of the LINPACK and EISPACK ventures. Today, MATLAB motors fuse the LAPACK and BLAS libraries, inserting the cutting side in programming for network calculation.

MATLAB has advanced over a time of years with contribution from several customers. In university situations, it's far the usual academic apparatus for early on and propelled guides in mathematics, designing, and science. In enterprise, MATLAB is the tool of choice for excessive-profitability studies, advancement, and exam.

MATLAB highlights a collection of more utility-specific arrangements known as tool booths. Important to most clients of MATLAB, device kits permit you to learnandapply particular innovation. Tool compartments are exhaustive accumulations of MATLAB capacities (M-records) that reach out the MATLAB condition to take care of precise training of problems. Territories in which tool stash are reachable include flag coping with, manipulate frameworks, neural structures, fluffy reason, wavelets, pastime, and severa others.

**The MATLAB System:**

The MATLAB system consists of five main parts.

**Development Environment:**

 This is the set of tools and centres that help you operate MATLAB features and files. Many of that gear are graphical person interfaces. It includes the MATLAB desktop and Command Window, a command history, an editor and debugger, and browsers for viewing assist, the workspace, files, and the hunt direction.

**The MATLAB Mathematical Function:**

This is a great collection of computational algorithms ranging from standard capabilities like sum, sine, cosine, and complex arithmetic, to extra sophisticated features like matrix inverse, matrix eigen values, Bessel functions, and speedy Fourier transforms.

**The MATLAB Language:**

This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both "programming in the small" to rapidly create quick and dirty throw-away programs, and "programming in the large" to create complete large and complex application programs.

**Graphics:**

MATLAB has considerable centres for displaying vectors and matrices as graphs, as well as annotating and printing those graphs. It consists of high-stage functions for 2-dimensional and 3-dimensional records visualization, photograph processing, animation, and presentation graphics. It also consists of low-stage capabilities that will let you absolutely customise the appearance of graphics as well as to construct complete graphical person interfaces for your MATLAB programs.

**The MATLAB Application Program Interface (API):**

This is a library that allows you to put in writing C and Fortran applications that have interaction with MATLAB. It consists of facilities for calling workouts from MATLAB (dynamic linking), calling MATLAB as a computational engine, and for studying and writing MAT-documents.

**7.2 MATLAB WORKING ENVIRONMENT:**

## MATLAB DESKTOP:

Matlab Desktop is the principle Matlab application window. The desktop consists of five sub windows, the summon window, the workspace program, the existing catalog window, the order records window, and at the least one figure home windows, which can be proven simply while the consumer suggests a sensible.

The order window is the area the customer sorts MATLAB orders and expressions at the initiate (>>) and wherein the yield of these fees is shown. MATLAB characterizes the workspace because the association of factors that the customer makes in a work session. The workspace software demonstrates these elements and some statistics approximately them. Double tapping on a variable within the workspace application dispatches the Array Editor, which may be applied to get data and salary instances modify sure homes of the variable.

The present Directory tab over the workspace tab demonstrates the substance of the existing registry, whose way is seemed within the present index window. 1For case, within the windows running framework the manner may be as consistent with the subsequent: C:MATLABWork, demonstrating that registry "paintings" is a subdirectory of the primary catalog "MATLAB", which is delivered in pressure C. Tapping on the bolt inside the present index window demonstrates a rundown of as of past due utilized approaches. Tapping at the seize to one aspect of the window enables the client to exchange the existing catalog.

MATLAB utilizes an inquiry way to discover M-data and different MATLAB related documents, which might be sort out in catalogs within the PC file framework. Any file keep strolling in MATLAB must dwell inside the ebb and go with the flow registry or in an index that is on are trying to find manner. Of direction, the statistics supplied with MATLAB and math works device kits are included into the inquiry way. The least stressful method to look which indexes are at the inquiry manner. The handiest method to peer which catalogs are soon the quest way, or to encompass or regulate an inquiry manner, is to pick set manner from the File menu the computer, and after that utilization the set way exchange container. It is exquisite exercise to add any typically utilized catalogs to the pursuit way to hold a strategic distance from again and again having the exchange the existing index.

The Command History Window contains a record of the orders a client has entered in the charge window, including both present and past MATLAB sessions. Already entered MATLAB orders can be chosen and re-executed from the charge history window by right

tapping on a summon or arrangement of orders. This activity dispatches a menu from which to choose different choices notwithstanding executing the orders. This is helpful to choose different choices notwithstanding executing the summons. This is a valuable component while trying different things with different orders in a work session

**Using the MATLAB Editor to create M-Files:**

The MATLAB manager is both a word processor unique for making M-statistics and a graphical MATLAB debugger. The proofreader can display up in a window without everybody else, or it could be a sub window in the laptop. M-facts are intended by means of the expansion .M, as in pixelup.M. The MATLAB editorial manager window has various draw down menus for errands, for instance, sparing, seeing, and troubleshooting documents. Since it plays out a few basic checks and furthermore utilizes shading to separate between exclusive additives of code, this content device is suggested as the equipment of selection for composing and changing M-capacities. To open the proofreader, sort regulate at the incite opens the M-report filename.M in a supervisor window, organized for altering. As referred to before, the record has to be inside the momentum catalog, or in an index within the pursuit manner.

**Getting Help:**

The important technique to get help on line is to utilize the MATLAB assist application, opened as a exclusive window both via tapping at the query mark image at the computing device toolbar, or by using writing help program on the provoke within the order window. The help Browser is an internet application coordinated into the MATLAB computing device that shows a Hypertext Markup Language (HTML) statistics. The Help Browser contains of two sheets, the assistance pilot sheet, used to find out data, and the show sheet, used to look the statistics. Clear as crystal tabs aside from pilot sheet are applied to play out a pursuit. Second, within the motion pictures taken via transferring camera setup, the state of affairs becomes extra complex because the heritage may additionally exchange by using shifting shot, we cannot tune item motion exactly inside the sum of distinction map. Therefore, in this situation, the purpose is executed through reusing the previous seam and applying it to the cutting-edge body. In order to discover the seams, we use the preceding seam from previous body to look the modern-day seam in contemporary frame. our method is using a seam computed in frame1 (in crimson) to go looking a comparable seam in frame2. For the pixels close by the area of previous seam, we decide how a lot the selected pixel might vary from the pixel of preceding seam. We use difference of the 2 pixels as the degree of temporal coherence. If the distinction value of first seam pixel is over the threshold, we can keep to go looking the next seam pixel on three feasible pixels (in yellow, blue and brown) in subsequent row, until we discover 5 consecutive pixels that also exceed the threshold.

When we can't search the matching seam, we recalculate the energy for a new seam. We assume a seam 𝑆l-1 has been calculated inside the previous body, and a seam must be calculated for the contemporary frame. For preserving the temporal coherence, we want to make a new seam close to the previous seam with the identical index. We use the distinction among preceding seam and all pixels at the current body as the measure

Thus we upload temporal coherence price Tc(i,j) to the strength map earlier than calculating a seam 𝑆L. The price Tc is zero while the body pixels have the equal fee as previous seam pixels. Using our temporal coherence price, we will calculate the seam which has least electricity and is more close to the preceding seam in previous frame. Consequently, we will decrease the jittery artifacts inside the films.

**COMMUNICATION:**

Communications System Toolbox™ offers algorithms and gear for the layout, simulation, and analysis of communications systems. These capabilities are furnished as MATLAB ® features, MATLAB System gadgets™, and Simulink ® blocks. The machine toolbox includes algorithms for source coding, channel coding, interleaving, modulation, equalization, synchronization, and channel modeling. Tools are supplied for bit blunders charge evaluation, producing eye and constellation diagrams, and visualizing channel characteristics. The machine toolbox additionally provides adaptive algorithms that allow you to version dynamic communications structures that use OFDM, OFDMA, and MIMO techniques. Algorithms support fixed-point facts arithmetic and C or HDL code era.

**Key Features**

▪ Algorithms for designing the physical layer of communications systems, which includes supply coding, channel coding, interleaving, modulation, channel fashions, MIMO, equalization, and synchronization

▪ GPU-enabled System objects for computationally intensive algorithms together with Turbo, LDPC, and Viterbi decoders

▪ Interactive visualization equipment, consisting of eye diagrams, constellations, and channel scattering capabilities

▪ Graphical tool for evaluating the simulated bit mistakes rate of a machine with analytical outcomes

▪ Channel models, consisting of AWGN, Multipath Rayleigh Fading, Rician Fading, MIMO Multipath Fading, and

LTE MIMO Multipath Fading

▪ Basic RF impairments, along with nonlinearity, section noise, thermal noise, and section and frequency offsets

▪ Algorithms available as MATLAB features, MATLAB System objects, and Simulink blocks

▪ Support for fixed-point modeling and C and HDL code technology

**System Design, Characterization, and Visualization:**

The layout and simulation of a communications gadget requires analyzing its reaction to the noise and interference inherent in real-world environments, reading its behavior the usage of graphical and quantitative manner, and determining whether the resulting overall performance meets requirements of acceptability. Communications System Toolbox implements a selection of obligations for communications machine layout and simulation. Many of the functions, System objects™, and blocks inside the device toolbox perform computations associated with a specific thing of a communications gadget, consisting of a demodulator or equalizer. Other talents are designed for visualization or evaluation.

**System Characterization**

The system toolbox offers several standard methods for quantitatively characterizing system performance:

▪ Bit error rate (BER) computations

▪ Adjacent channel power ratio (ACPR) measurements

▪ Error vector magnitude (EVM) measurements

▪ Modulation error ratio (MER) measurements

Because BER computations are fundamental to the characterization of any communications system, the system toolbox provides the following tools and capabilities for configuring BER test scenarios and accelerating BER simulations:

**BER tool**— A graphical user interface that enables you to analyze BER performance of communications systems. You can analyze performance via a simulation-based, semi analytic, or theoretical approach.

**Error Rate Test Console** — A MATLAB object that runs simulations for communications systems to measure error rate performance. It supports user-specified test points and generation of parametric performance plots and surfaces. Accelerated performance can be realized when running on a multi core computing platform.

**Multi core and GPU acceleration** — A capability provided by Parallel Computing Toolbox™ that enables you to accelerate simulation performance using multi core and GPU hardware within your computer.

**Distributed computing and cloud computing support** — Capabilities provided by Parallel Computing Toolbox and MATLAB Distributed Computing Server™ that enable you to leverage the computing power of your server farms and the Amazon EC2 Web service. Performance Visualization. The system toolbox provides the following capabilities for visualizing system performance:

**Channel visualization tool** — For visualizing the characteristics of a fading channel

**Eye diagrams and signal constellation scatter plots** — for a qualitative, visual understanding of system behavior that enables you to make initial design decisions

**Signal trajectory plots** — for a continuous picture of the signal’s trajectory between decision points

**BER plots** — for visualizing quantitative BER performance of a design candidate, parameterized by metrics such as SNR and fixed-point word size

**Analog and Digital Modulation**

Analog and digital modulation strategies encode the facts circulation into a sign this is appropriate for transmission. Communications System Toolbox presents some of modulation and corresponding demodulation abilities. These talents are available as MATLAB features and gadgets, MATLAB System Modulation sorts provided by the toolbox are:

**Analog,** including AM, FM, PM, SSB, and DSBSC

**Digital,** including FSK, PSK, BPSK, DPSK, OQPSK, MSK, PAM, QAM, and TCM



**Source and Channel Coding**

Communications System Toolbox affords source and channel coding talents that can help you develop and compare communications architectures fast, enabling you to discover what-if eventualities and avoid the need to create coding competencies from scratch.

**Source Coding**

Source coding, also referred to as quantization or signal formatting, is a manner of processing facts a good way to lessen redundancy or prepare it for later processing. The system toolbox offers a diffusion of styles of algorithms for imposing source coding and interpreting, inclusive of:

▪ Quantizing

▪ Companding (*µ*-law and A-law)

▪ Differential pulse code modulation (DPCM)

▪ Huffman coding

▪ Arithmetic coding

**Channel Coding**

▪ orthogonal area-time block code (OSTBC) (encoder and decoder for MIMO channels)

▪ Turbo encoder and decoder examples

The gadget toolbox offers application functions for developing your personal channel coding. You can create generator polynomials and coefficients and syndrome deciphering tables, in addition to product parity-take a look at and generator matrices.

The system toolbox additionally presents block and convolutional interleaving and deinters leaving functions to reduce facts errors as a result of burst mistakes in a conversation machine:

**Block,** including General block interleaver, algebraic interleaver, helical scan interleaver, matrix interleaver, and random interleaver.

**Convolutional,** including General multiplexed interleaver, convolutional interleaver, and helical interleaver

**Channel Modeling and RF Impairments**

Channel Modeling

Communications System Toolbox provides algorithms and tools for modeling noise, fading, interference, and different distortions which might be commonly found in communications channels. The system toolbox supports the subsequent styles of channels:

▪ Additive white Gaussian noise (AWGN)

▪ Multiple-enter multiple-output (MIMO) fading

▪ Single-enter single-output (SISO), Rayleigh, and Rician fading

▪ Binary symmetric

A MATLAB channel object provides a concise, configurable implementation of channel models, enabling you to

specify parameters such as:

▪ Path delays

▪ Average path gains

▪ Maximum Doppler shifts

▪ K-Factor for Rician fading channels

▪ Doppler spectrum parameters

For MIMO systems, the MATLAB MIMO channel object expands these parameters to also include:

▪ Number of transmit antennas (up to 8)

▪ Number of receive antennas (up to 8)

▪ Transmit correlation matrix

▪ Receive correlation matrix

To combat the effects noise and channel corruption, the system toolbox provides block and convolutional coding and decoding techniques to implement error detection and correction. For simple error detection with no inherent correction, a cyclic redundancy check capability is also available. Channel coding capabilities provided by the system toolbox include:

▪ BCH encoder and decoder

▪ Reed-Solomon encoder and decoder

▪ LDPC encoder and decoder

▪ Convolutional encoder and Viterbi decoder

****

**RF Impairments**

To model the effects of a non-ideal RF front end, you can introduce the following impairments into your communications system, enabling you to explore and characterize performance with real-world effects:

▪ Memory less nonlinearity

▪ Phase and frequency offset

▪ Phase noise

▪ Thermal noise

You can include more complex RF impairments and RF circuit models in your design using SimRF™.

****

**Equalization and Synchronization**

Communications System Toolbox lets you discover equalization and synchronization strategies. These techniques are usually adaptive in nature and tough to design and symbolize. The machine toolbox affords algorithms and tools that will let you swiftly select the proper approach on your communications machine. Equalization To compare one-of-a-kind techniques to equalization, the device toolbox offers you with adaptive algorithms which include:

▪ LMS

▪ Normalized LMS

▪ Variable step LMS

▪ Signed LMS

▪ MLSE (Viterbi)

▪ RLS

▪ CMA

These adaptive equalizers are available as nonlinear decision feedback equalizer (DFE) implementations and as

Linear (symbol or fractionally spaced) equalizer implementations.

**Synchronization**

The device toolbox provides algorithms for each service segment synchronization and timing phase synchronization. For timing section synchronization, the machine toolbox presents a MATLAB Timing Phase Synchronizer object that offers the following implementation techniques:

▪ Early-late gate timing method

▪ Gardner’s method

▪ Fourth-order nonlinearity method

**Stream Processing in MATLAB and Simulink**

Most verbal exchange structures cope with streaming and frame-primarily based statistics using a aggregate of temporal processing and simultaneous multi frequency and multichannel processing. This form of streaming multidimensional processing can be visible in superior communication architectures consisting of OFDM and MIMO. Communications System Toolbox enables the simulation of advanced communications structures via helping move processing and frame-based simulation in MATLAB and Simulink. In MATLAB, circulate processing is enabled by way of System items™, which use MATLAB objects to symbolize time-based and facts-driven algorithms, sources, and sinks. System objects implicitly manipulate many information of flow processing, including information indexing, buffering, and management of set of rules state. You can mix System gadgets with fashionable MATLAB functions and operators. Most System items have a corresponding Simulink block with the identical abilities. Simulink handles circulation processing implicitly with the aid of coping with the float of information thru the blocks that make up a Simulink model. Simulink is an interactive graphical environment for modeling and simulating dynamic systems that uses hierarchical diagrams to symbolize a machine version. It includes a library of widespread-reason, predefined blocks to represent algorithms, resources, sinks, and device hierarchy.

**Implementing a Communications System**

Fixed-Point Modeling Many communications systems use hardware that requires a fixed-point representation of your design.

Communications System Toolbox supports fixed-point modeling in all relevant blocks and System objects™ with tools that help you configure fixed-point attributes.

Fixed-point support in the system toolbox includes:

▪ Word sizes from 1 to 128 bits

▪ Arbitrary binary-point placement

▪ Overflow handling methods (wrap or saturation)

▪ Rounding methods: ceiling, convergent, floor, nearest, round, simplest, and zero

Fixed-Point Tool in Simulink Fixed Point™ facilitates the conversion of floating-point data types to fixed point. For configuration of fixed-point properties, the tool tracks overflows and maxima and minima.

**Code Generation**

Once you've got advanced your set of rules or communications device, you can robotically generate C code from it for verification, rapid prototyping, and implementation. Most System gadgets, functions, and blocks in Communications System Toolbox can generate ANSI/ISO C code the use of MATLAB Coder™, Simulink Coder™, or Embedded Coder™. A subset of System gadgets and Simulink blocks also can generate HDL code. To leverage present highbrow belongings, you can choose optimizations for specific processor architectures and integrate legacy C code with the generated code.

You can also generate C code for both floating-point and fixed-point data types.

DSP Proto typing DSPs are used in communication system implementation for verification, rapid prototyping, or final hardware implementation. Using the processor-in-the-loop (PIL) simulation capability found in Embedded Coder, you can verify generated source code and compiled code by running your algorithm’s implementation code on a target processor. FPGA Prototyping

FPGAs are used in communication systems for implementing high-speed signal processing algorithms. Using the FPGA-in-the-loop (FIL) capability found in HDL Verifier™, you can test RTL code in real hardware for any existing HDL code, either manually written or automatically generated HDL code.

**CHAPTER -8**

**HARDWARE & SOFTWARE REQUIREMENTS:**

**Software:**

• Matlab R2018a.

**Hardware:**

**Operating Systems:**

• Windows 10

• Windows 7 Service Pack 1

• Windows Server 2019

• Windows Server 2016

**Processors:**

Minimum: Any Intel or AMD x86-64 processor

Recommended: Any Intel or AMD x86-64 processor with four logical cores and AVX2 instruction set support

**Disk:**

Minimum: 2.9 GB of HDD space for MATLAB only, 5-8 GB for a typical installation

Recommended: An SSD is recommended a full installation of all Math Works products may take up to 29 GB of disk space

**RAM:**

Minimum: 4 GB

Recommended: 8

**CHAPTER-9**

**RESULTS**

We provide simulation results for the detection of the entrance of the PU signal. We compare the numerical calculations for Pf and Pd with our derived analytical approximations presented in the above Equations. We plot total probability of detection at various samples after the entrance of the PU signal, i.e., Pd vs Pf for different signal to noise ratio (SNR) values.

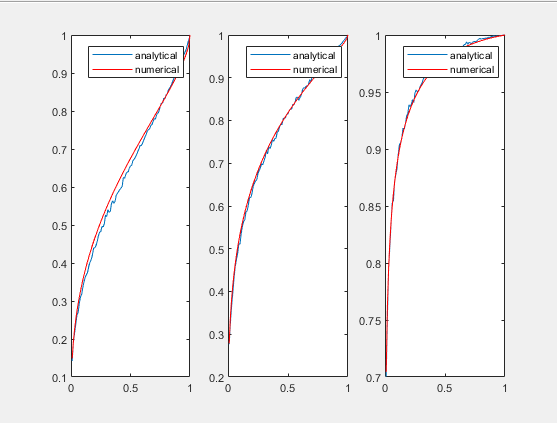
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Figure:ROC curves for numerical and analytical simulations for SNR = -10 dB.

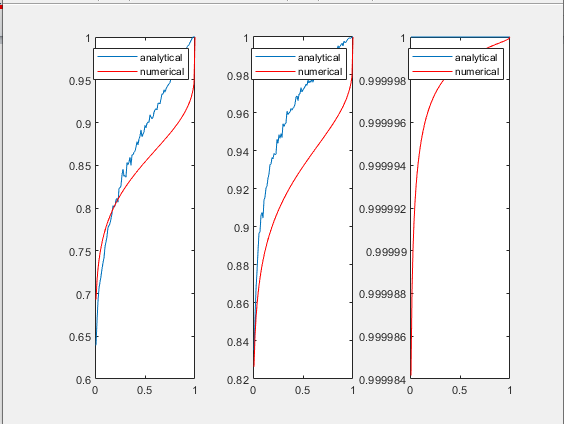
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Figure:ROC curves for numerical and analytical simulations for SNR = 3 dB.

**CHAPTER-10**

**CONCLUSION**

We derived closed-form expressions for the probability of false alarm and probability of detection for QCD-CUSUM sequential test. Spectrum sensing is used as an application of CUSUM test with detecting the entrance of PU signal as the example. Through simulation comparison between analytical and numerical results, we showed that our derived expressions provide a very close approximation. The provided results can be used in all applications that require channel sensing and will simplify the optimization formulation procedures to achieve better performance for various applications.

**CHAPTER-11**

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