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Optimal Spectrum Utilization and Pricing Through Method of Design of Experiments in CRN: A Novel Approach

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Abstract: Cognitive Radio Networks (CRNs) play a pivotal role in addressing the spectrum scarcity Challenge by enabling secondary users (SUs) to dynamically access underutilized spectrum bands while ensuring minimal interference with primary users (PUs). In this study, we propose a novel approach that leverages Design of Experiments (DoE) principles to optimize spectrum utilization in CRNs. The research work is carried out to optimize the resources depending on the price factor and the demand in the current scenario. In such case, the demand raises from the secondary users to utilize the frequency spectrum. The primary users take a decision on the design of the experiment. The research work is carried out by designing of experiments. In this research work, Taguchi method, screen design and item factorization are implemented to determine the pricing of the spectrum for utilization by the secondary users with reference to the availability and the prices. The approach ensures efficient utilization of available spectrum resources while maintaining PU protection.

Keywords*: Design of experiments, Analysis, spectrum optimization, pricing, Taguchi method, screen design and item factorization*

1. Introduction

Design of Experiments (DoE) is a statistical methodology used to systematically plan, conduct, and analyse experiments. It helps optimize processes, improve product quality, and identify influential factors. In the context of CRNs, DoE can be applied to study various parameters affecting spectrum utilization and identify optimal settings.

CRNs face challenges related to spectrum scarcity, interference, and efficient utilization. Factors affecting spectrum utilization include:

Channel Allocation: How secondary users (SUs) are assigned channels.

- ✓ Power Control: How transmit power is regulated to minimize interference.
- ✓ Spectrum Sensing: Detecting available spectrum bands.
- ✓ Cognitive Cycle Time: How often SUs sense and adapt to changes.
- ✓ Coexistence Mechanisms: Ensuring primary user (PU) protection.
- ✓ Dynamic Spectrum Access (DSA): Efficiently accessing available spectrum.
- ✓ Quality of Service (QoS): Balancing throughput and reliability.

Applying DoE to CRNs: From the research reports, it is evident that applying DoE to CRNs is a novel approach to optimize CRN parameters. Some of the methods adopted are:

- ➢ Factorial Designs: Investigate multiple factors simultaneously.
- ➢ Response Surface Methodology (RSM): Model relationships between factors and responses (e.g., throughput, interference).
- ➢ Taguchi Methods: Optimize robustness against noise.
- ➢ Fractional Factorial Designs: Efficiently explore factor interactions.
- ➢ Central Composite Designs (CCD): Explore response surfaces near optimal points.

CRNs are intelligent wireless communication systems that dynamically adapt to their environment by re-configuring themselves based on real-time information. These networks aim to optimize spectrum utilization, especially in scenarios where spectrum resources are scarce or underutilized. CRNs classify users into two main categories: Primary Users (PUs): These are the authorized users who hold exclusive rights to specific frequency bands. Secondary Users (SUs): These users opportunistically access the spectrum when it is not being used by PUs [1].

The explosive growth of wireless technologies (such as mobile devices, IoT, and wireless services) has led to a scarcity of available spectrum. CRNs address this challenge

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by allowing SUs to utilize spectrum bands that are not actively used by PUs. Dynamic Spectrum Access enables SUs to sense and access available spectrum dynamically. SUs must avoid interfering with PUs during spectrum access.

When allocating channels to SUs, several factors come into play: Throughput: Maximizing data rates for SUs.

Interoperability: Ensuring seamless communication across different devices and networks. Resource Utilization: Efficiently using available spectrum. Secondary Market Access: Allowing SUs to access spectrum for specific purposes. While CRNs enhance spectrum utilization, interference can occur. Interference affects network performance, throughput, and reliability.

Researchers explore various aspects of CRNs including the followings. Spectrum Sensing: Detecting available spectrum bands. Channel Allocation Algorithms: Optimizing channel assignment for SUs. Power Control: Regulating transmit power to minimize interference. Coexistence Mechanisms: Ensuring PU protection. Quality of Service (QoS): Balancing performance metrics. The extensive literature analysis was carried out including [18-21], focus on spectrum optimal utilization. However, DoE application to spectrum hole utilization by secondary users opportunistically with pricing is seldom addressed. The research work presented in this paper focuses on optimizing spectrum utilization with pricing between PUs and SUs with a novel application of DoE.

The primary user purchases the spectrum from the authority and shares the spectrum to the SU on the basis of agreement. Since the base fees for purchasing the spectrum is relatively high, the primary users (PUs) insist to share the spectrum among the secondary users (SUs) The agreement involves the usage of the spectrum for certain duration, pricing etc. purchasing a frequency spectrum from the regulatory involves reserved price, recommended price maintenance and bidding price.

The frequency spectrum is applicable for different fields such as industry, medical and communications. Different frequency ranges are available for communication such as 800MHz,1800MHz,2100MHz, 700MHz and these frequency bands are purchased and owned by different service providers. There are certain challenges for the primary users such that they are able to continue the services. To continue the service, the PU needs to pay the maintenance fees to the government. The renewal amount is paid based on the revenue generated by the PU.

To utilize the spectrum effectively among the users, the optimization method is applied. To utilize the available resources and to maintain the service continuity, the primary users renew the license every year. Here the main factor is considered as price, wherein various frequency bands in the stated region has its own applicable price that is paid by the primary user. Fig. 1 represents the participation in the bid by the primary users. The PU quote the price, to participate in the auction. To ensure the participation in auction the bidder pays the base price to purchase the frequency band. The authorities verify the bidder details. If the bidder details are satisfied, then he participates in the auction.

Problem statement: To utilize the frequency spectrum by the secondary users by optimizing the availability of the spectrum in the regional locations with the dependent factor and to optimize the resources for effective utilization of the spectrum.

The optimization of resources depends on the availability and utilization. Different parameters are involved to optimize the available resources. Parameters are dependent on each other. The following steps are involved in optimization:

Design: Resources are allocated based on the design systems.

System: The operating environment of the domain.

Decision: The action involved on the result.

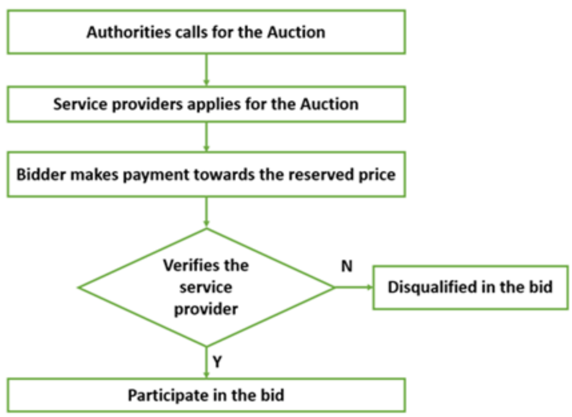

Fig.1. Participation of PU in the Bid

The service providers manage the available spectrum among the secondary users. The service for the secondary users is provided based on the verification of the users. The SU requests are handled by the cognitive system to check the availability of the spectrum of certain bands in stated region. Since all the frequency bands are not operating worldwide. The pricing for frequency spectrum is fixed by the service providers to utilize the spectrum. The utilization demand is raised by the secondary users, such that primary users need to manage the users and also the resources.

Architecture Diagram

In CRN network, both the users share the spectrum on their corresponding requirements. The Fig.2 represents the architecture for optimization of spectrum. The involves primary users and secondary users access the spectrum through different sensing techniques through which idle spectrum and the corresponding prices are included. To access the spectrum with different factors are considered to obtain the results for further decision making to utilize the spectrum.

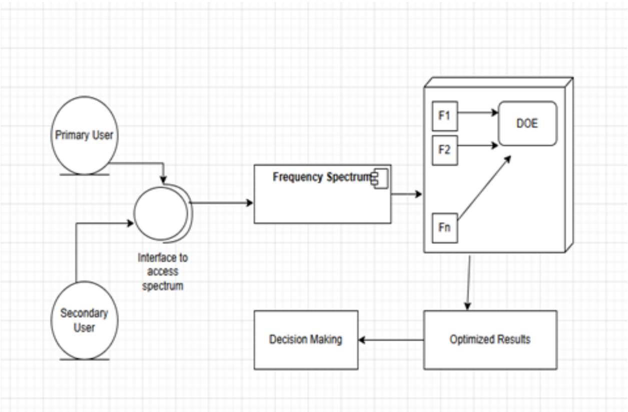

Fig. 2. Architecture of CRN for optimization

2. Conceptual Framework for Resource utilization by the secondary users

The secondary users utilize the available spectrum based on the availability of specified frequency band. The primary user identifies the secondary users by the verification process to ensure the security in the Cognitive environment. The cognitive environment consists of different users such as primary user, secondary user, authorities of the telecommunication department to monitor the process of handling and usages of frequency bandwidth. The Fig.3 represents the process of allocation of spectrum to the secondary user.

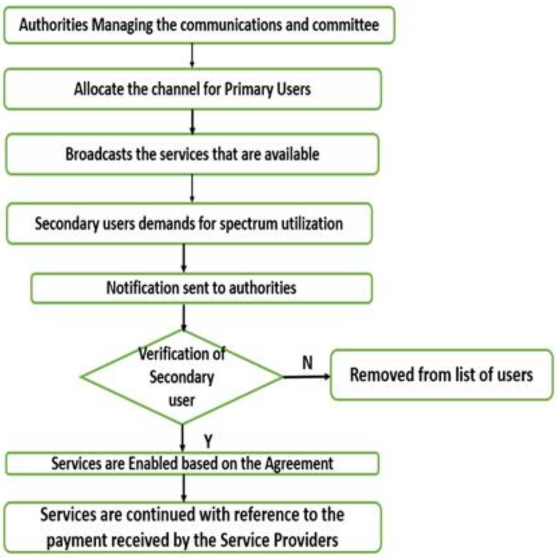

Fig.3. Allocation of spectrum to the secondary user

3. Related work

Each user tries to maximize the utility, by minimizing other’s utility of the resources. The problem was addressed with a robust optimization of cognitive radio for the primary network and secondary network [2]. There are different types of resources levelling problem wither it can be a single or multiple resources [3]. For optimization the author considers the indirect costs and liquid damages when the duration is reduced [4]. The resource allocation problem is mostly referred to the orthogonal frequency division multiple access (OFDMA) [5]. The resource allocation problem in Cognitive Radio Network is described with different approaches such as classical optimization e.g., Linear programming, studying problem structure, Heuristics, meta-heuristics, multi-objective optimization, soft computing-based etc. Each of these approaches has its own limitations such as computationally complex, time-consuming, solutions are not analysed and very complex to develop [6].

There are two different techniques to access the channel such as time division multiple access (TDMA) and carrier sense multiple access (CSMA). TDMA is adapted by the primary user whereas CSMA is adapted by the secondary user. The secondary user sends the packet when the TDMA is available on the time-slot. Some times the number of packets sent may be less or channel power may be poor due to the waste age of resources. If the TDMA is designed carefully then the resources are effectively utilized by the secondary users. The author selects the Genetic Algorithm (GA) for channel optimization. The working of GA is based on the strings, which undergoes the transformation to produce offspring. The best chromosome is selected on termination [7-8]. The tabu search finds the neighborhood and updates the current solution of the next iteration. The neighbors with the highest value are considered as the new best solution of the next iteration. If no best solution is listed, then the best solution is accepted in the process of selecting the candidate’s solution, the new solution is compared with the best solution for comparing and choosing the best solution.

The primary user dominates the access of channel. The secondary user has limited opportunity to access the channel [9]. Meta-Heuristics algorithm such as bat algorithm is a globally optimal solution which is based on the iteration optimization [10]. The new solutions are obtained through random flying near the optimal solution [11]. Hooke-Jeeves algorithm is an optimization method relevant to the initial point. The authors proposed GA for a dynamic genetic algorithm for allocating the channel in cognitive radio [12]. The hybrid system using fuzzy logic which depends on the decision support system for handling the channel switching and the GA for selecting the proper communication [13]. The partial swarm optimization (PSO) is applicable to CRNs, it is flexible for solving the spectrum allocation problem. The problem is solved under the constraints.

Different types of constraints such as Bit Error Rate (BER), total power usage, individual transfer rate is required for allocation [14].

A spectrum allocation scheme is dynamic-time varying based on chaotic binary particle swarm optimization. The chaotic map improved algorithm for optimizing the initial population and the optimal positions for all the particles in each generation [15]. The ant colony optimization algorithm with graph-cut modelling for sensing the spectrum and intelligently deciding the spectrum availability [16]. The Bee swarm behaviour solves the optimization problem in cognitive radio network [17].

4. Proposed Methodologies for Frequency Utilization

The frequency spectrum is reused based on the availability from the primary user and demand by the secondary users. To maximize the utilization with minimum resources, the available spectrum needs to be optimized by considering several factors. In order to re-allocate or reuse the spectrum design of experiments is applied for optimizing the resources. The experiments are designed into three classifications such as Taguchi method, Item Analysis and screen design. Each of these design experiments contributes its own way for identifying the utilization of spectrum within the available frequency range. The design of experiments works on the basis of number of factors considered, level of factors and difficulty.

4.1 Taguchi method

Taguchi methods is a robust design experiment. This method is applicable for design process. The Taguchi method involves the orthogonal arrays to organize the parameters that are affecting the experiment process and the level of experiment at which it varies. The collected data is used to determine the factor which affect the quality with minimum requirements and resources. The Taguchi method involves the data representation in orthogonal array format which with various levels of experimentation. This method involves statistical approach to determine and re-allot the unused spectrum to the secondary users. This approach enhances to usage of spectrum through managing the quality of services. In this experiment, different frequencies and the corresponding prices are considered to determine the utilization of spectrum by the primary users. The system impacts based on financial factor. The secondary user makes the decision to utilize the available spectrum in a dedicated range of frequency with the pricing that are imposed on the channel.

4.2 Item Analysis

Item analysis is a process that identifies the effectiveness of the item. The item analysis is distinguished into two categories such as item difficulty and item discrimination.

Item difficulty: The item difficulty in a test is a measure of the sample which takes a test and answers them correctly. The value takes between 0 and 1. High values indicates that item is easy and low values indicates that item is difficult.

Item discrimination: It distinguishes between the skills. Discrimination index is the principal measure of discrimination. Further the values are classified into high skill and low skill. The top half represents the high skill and the bottom half represents the low skill. The discrimination index values fall between -1 to +1. The values close to +1 indicates the performance is good. The values close to 0 indicates poor performance and the value close to -1 indicates that consists of worst and incorrect who performs best.

The experiment for CRN using item analysis depends on the number of frequency spectrum available, price of spectrum usage by secondary users, purchase price by primary user, identification of idle spectrum in a stipulated time. In item analysis, frequencies and the corresponding costs are considered as items. The frequency is allocated to SU based on the status of availability, price value. The SU pays rental for spectrum utilization. The item difficulty is a vital in designing the experiment which enhances fair and effective allocation of spectrum to the secondary users. This enables the correlation of price for the users. The individual frequencies are analysed based on the pricing.

4.3 Screening Design

Screening design is one of design experiment for industries. In screening design certain factors are considered to narrow down the long list of factors. It takes fewer runs than other design of experiments. The screening designs uses the factors to indicate robustness during testing. The screening design are used in two different types: i) fractional factorial and Plackett-Burman. These methods are feasible for interactions among the factors.

i)Fractional Factorial Design: In screening design, the resources are considered as factors to allocate the frequency to the SU based on price.

ii)Placket-Burman design constructs are applied to identify the dependent variable and independent variable by reducing the number of levels of experimentation. The frequencies of different ranges used for communication are indicated as orthogonal matrices with their individual prices of various service providers or states that frequency band is allocated. The number of runs for the experiments leads to the interactions among the factors that are considered.

5. Results and Interpretation

5.1 Taguchi Method Result

The Taguchi method design and implementation process consists of different factors and number of runs based on the factors. The design summary for Taguchi method is described as array with number of runs, factors and the number of columns. Based on the factors and runs SN ratios are analysed with the graphical representation.

The comparison between F1 and F2 indicates that the standard error is too small than the T-value to declare the significance. The resulting p-value is greater than common levels indicating the coefficient differs from zero. The spectrum utilization is 48.22% from Taguchi method. The Fig.4 represents the graphical analysis between the frequency set F2, F1 and the price set P1, P2.

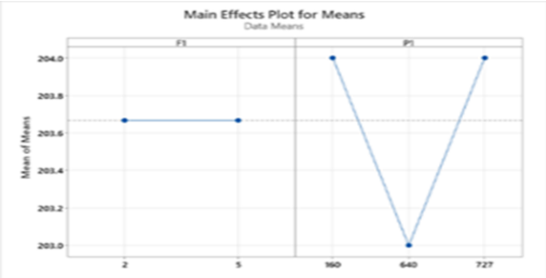

Fig. 4. Frequency utilization analysis

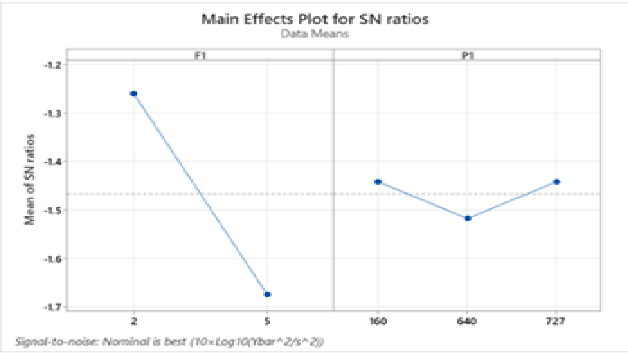

Fig. 5. SN Ratio

The Fig.5 represents signal-to-noise ratio wherein nominal is considered as best, resulting in reduction of price with the minimal frequency usage. The residual plot examines that the goodness of fit in least square and the assumption with the pricing for the corresponding is met. The Fig.6 represents the data point which measures the SN ratios with the available set of frequencies, which PUs can share allocated spectrum to the secondary users.

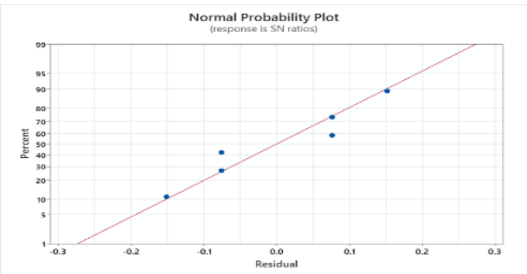

Fig.6. Residual with response to SN ratio

Inference from the experiment shows the comparison between F2 and F3 indicates that the standard error is too small than the T-value to declare the significance. The resulting p-value is greater than common levels indicating the coefficient differs from zero. The estimated model Coefficients for SN ratios is 44.82%.

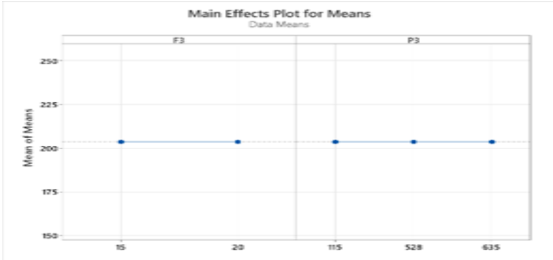

Fig.7. Plot means for F3 and P3

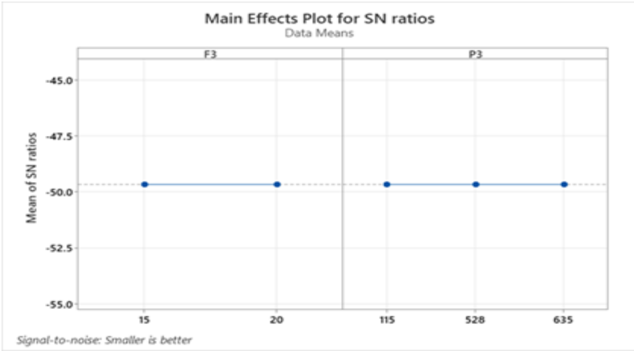

Fig.8. Signal to noise ratio

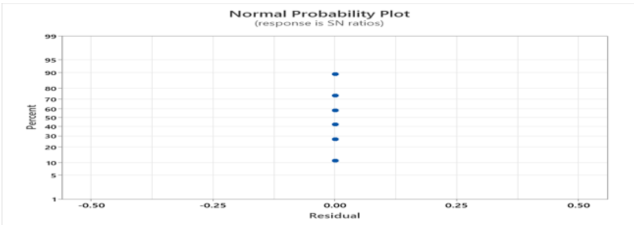

Fig.9. Residual plot

5.2 Results and Interpretation of Item Analysis

Item Analysis is carried out based on PU_Price, Rental_price, SU, Status. The correlation of price matrix indicates negative for the rental analysis for the spectrum utilization. The covariance matrix between the rental price for the secondary users is negative indicating the unavailability or non-allocation of spectrum. The Cronbach's alpha value is -0.9 hence it indicates that the item needs to be considered in opposite directions or the assumptions are not valid.

The item analysis is carried out based on the nested ANOVA method which includes degrees of freedom. The variance is 30% which indicates the frequency and price that varies from the actual data difference which is allocated.

Fig.10. Matrix plot of Price

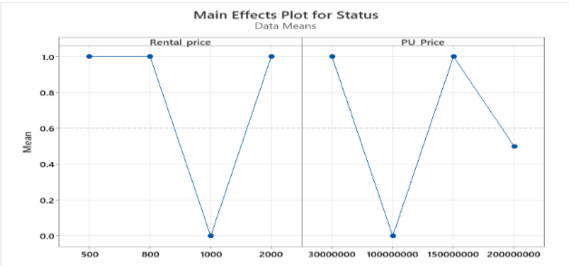

Fig.11. Status plot for Allocation

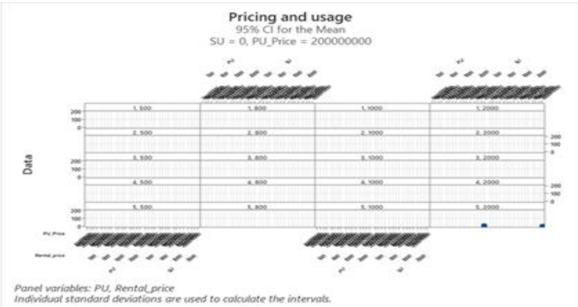

Fig.12. Interval plot

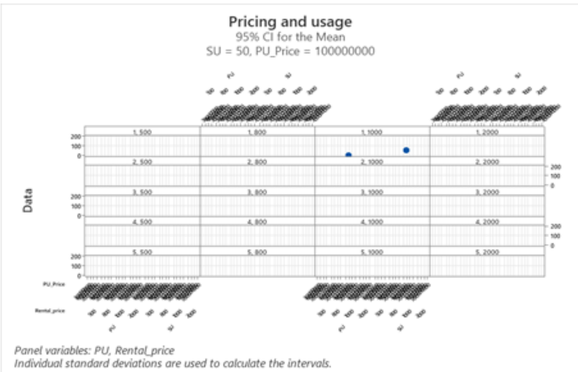

Fig.13. pricing and usage

5.3 Results and interpretation of Screening Design Experiment

The screen design involves different runs of experiment carried through the factors. The factors are assumed as frequency and price. The screen design experiment is implemented using Plackett-Burman design. The R-sq value is 58.28% variation with the significant model. The residual plots are randomly distributed on the both sides.

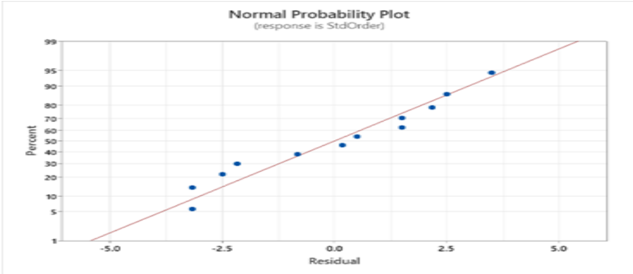

Fig.14. Standard order of plot

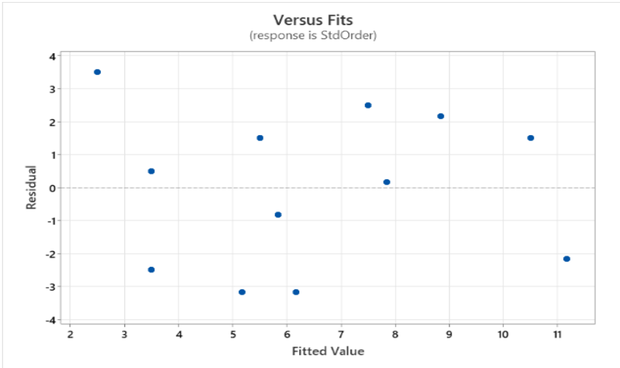

Fig.15. Residual plot of screen design

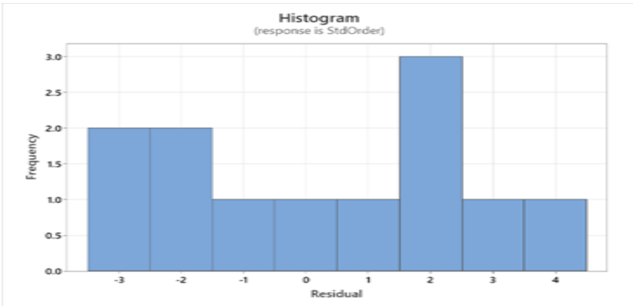

Fig.16. Hist plot for frequency vs price with residual

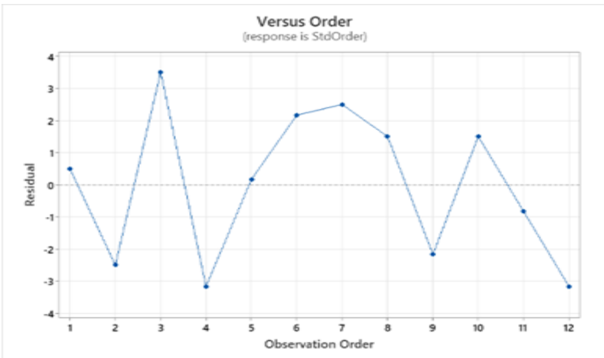

Fig.17. Observation order for allocation

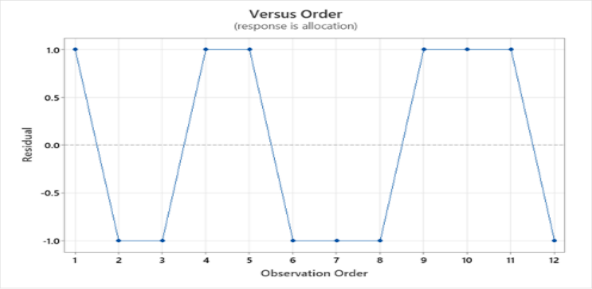

Fig.18. Observation order

6. Conclusion

In this research work an extensive design method is applied for spectrum utilization by the secondary users. The experiment is carried out to indicate the various dependent and independent factors which leads to the allocation of the spectrum to the secondary users. In this work, three design techniques are used to optimize the allocation of the spectrum by the primary users considering the rental price as one of the factors. The Taguchi method resulted in good-fit when considered with normal is best and for smaller is best, it resulted in smaller distribution to fit. In Item analysis, the alpha value is negative and doesn't fit the values. The screen design varies from positive to negative. The Taguchi method with normal is best suits good for allocation of spectrum.

The research work explores an innovative approach to spectrum utilization by secondary users. The study investigates various factors—both dependent and independent—that influence spectrum allocation decisions. Specifically, the focus is on optimizing spectrum allocation by primary users, with rental price as a critical consideration.

Key Contributions: The research work proved once again the power of Taguchi Method and its application as a robust optimization technique, to enhance spectrum allocation. By considering different scenarios (normal is best and smaller is best), the work achieved a better fit for distribution.

Novelty in Item Analysis: Our findings reveal that the alpha value (a measure of reliability) is negative, indicating a departure from conventional assumptions. This unexpected result challenges existing paradigms and contributes to the field.

Screen Design Implications: The shift from positive to negative screen design further underscores the uniqueness of our approach. We discuss how this design variation impacts spectrum allocation outcomes.

Overall, the work sheds light on effective spectrum management strategies, emphasizing the role of rental pricing and innovative methodologies. By combining theoretical insights with practical implications, the work contributes to advancing spectrum utilization in CRN.

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