A Soft Computing Approach to Analyze Coverage and Coverage Reliability of a Wireless Network

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ABSTRACT
In wireless networks, coverage is a critical parameter that determines the efficiency of the network. Several factors affect coverage and, consequently, the overall performance of the network. Researchers have explored coverage from various perspectives, such as using different sensing range models, assessing boundary impacts, and considering sensor failures, often employing analytical approaches. Some researchers have also employed heuristic methods, though often neglecting either boundary conditions or sensor failure scenarios. However, no study has specifically explored the use of soft computing techniques to assess coverage and coverage reliability in the presence of sensor failures and boundary conditions. Coverage reliability refers to the duration during which a network maintains efficient coverage, ensuring consistent and reliable performance. In this paper, we compute Fuzzy Coverage (FC) and Fuzzy Coverage Reliability (FCR) using a Fuzzy Inference System (FIS) model under two distinct scenarios: Sensor Node (SN) failure and boundary condition. The analytical findings derived are verified using FIS model and shown to align with existing results, confirming the accuracy and applicability of the fuzzy approach. Additionally, we investigate the influence of various parameters, including the number of SNs, Sensing Range (SR), and the Sensor's Failure Rate (FR), on both FC and FCR. This analysis provides valuable insights into how these factors impact the network's coverage and coverage reliability, offering a more comprehensive understanding of network performance in real-world scenarios.

General Terms
Fuzzy Inference System, Analytical formulation, Coverage and Reliability.

Keywords
Coverage reliability, Sensor failure, Boundary condition and Fuzzy logic.

1. INTRODUCTION
In any wireless network, coverage is an essential parameter that defines how effectively an area is being monitored. In other words, we can say it directly or indirectly affects the overall performance of the network. Wireless networks are gaining interest in many applications including military, health, environmental, agriculture, industry, etc. [1] - [4]. With time, the network is expanding and the complexity of a network becomes more critical. There are a several factors influence the coverage performance such as sensor location, size of the network, environment, design, and energy constraints. In the existing literature, a huge amount of work has been done on coverage under different scenarios by adopting several connectivity based and SR based model. A connectivity-based model in wireless networks focuses on maintaining a network structure where SNs remain connected, ensuring seamless communication and data transmission [5]-[6]. Whereas SR-based models, which prioritize sensing area effectiveness, primarily evaluates the coverage of a network based on the SR of SN. It determines how well an area is monitored by the SN and how external factors impact the sensing ability. Some studies on the SR model have also considered boundary impacts [6]-[7].

To design any network, SN deployment is the key step which is done either through a deterministic approach [8] or a random approach [9]. In this paper we have considered a random deployment approach. The squared network is deployed with tiny homogenous SNs randomly. A sensor once deployed randomly can be located within or at the boundary region. Any SN lying near the boundary region covers less effective area than the SN lying at the center [10]-[13]. The author in [7] obtained analytical framework to analysis coverage with boundary conditions under fading environment. However, this analytical approach incurs significant time complexity to overcome this, many researchers have explored alternative machine learning and heuristic techniques [14] under different scenerio. In addition to boundary conditions, SN failure is another crucial parameter that cannot be overlooked. SN is an electronic device that senses and forwards data continuously. Once the information is sensed it is either kept or forwarded through a processor using a trans-receiver. This continued process of sensing, processing, and forwarding degrades the performance of SN and over a period, it may fail the entire network. In [15], relay sensor placement with a heuristic approach has been proposed that improves throughput by 5184Kbps. In [16], the Huang algorithm is discussed to balance depletion energy which improves the sensor life cycle. However, the algorithm's performance degrades for complex networks**.** SN failure is a crucial parameter that significantly impacts the coverage reliability of a network. With this in mind, this article incorporates coverage and coverage reliability analysis for both boundary conditions and sensor failure scenarios. While doing coverage analysis, many researchers utilize an analytical approach while others use a heuristic. In analytical approach the time complexity exponentially rise with number of SN deployment [17].

In the literature, coverage analysis under different scenario has been used as a key parameter for evaluating the performance of wireless networks. Still, no work has been done for reliability analysis of coverage under sensor failure and boundary conditions using soft computing approach as mentioned in Table 1. This limitation motivates the development of a model that evaluates coverage and coverage reliability while incorporating both boundary conditions and SN failures through a soft computing fuzzy-based approach. The main contributions of this research are listed below:

- This paper presents FIS based soft computing approach for evaluating Fuzzy Coverage (FC) and Fuzzy Coverage Reliability (FCR), considering Sensor Node (SN) failure and boundary conditions.
- The mathematical model is developed in determining the data for FC and FCR with random distribution of SN, SR and FR and set the upper and lower bounds of input and output variables
- Once the range is established, the membership functions and rules are determined for the FIS model
- Further, the study investigates the impact of key input parameters—SN count, SR, and FR—on FC and FCR to better understand their influence on network performance.
- During analysis, it has been found, the results obtained align with the existing findings.

Here developing a mathematical model for coverage and coverage reliability evaluation under boundary condition and sensor failure scenario is a challenging task that necessitates strong mathematical skills and meticulous analysis. The data derived from the model is used to establish the upper and lower bounds for the input and output variables, which presents an additional challenge.

The rest of the work is structured in the subsequent sections: In Section 2 we have discussed the coverage evaluation. Section 3 discusses coverage reliability evaluation, Section 4 addresses the FIS model, results are investigated in section 5. Finally, the conclusion of the work is presented in Section 6.

Table 1. Comparison of proposed work with the existing research

Paper	C	CR	Boundary Condition	FR	Approach
[6]	✓	✗	✓	✗	Analytical
[7]	✓	✗	✓	✗	Analytical
[11]	✓	✓	✓	✓	Analytical
[13]	✓	✗	✗	✗	Metaheuristics
[15]	✓	✓	✓	✓	Analytical
[19]	✓	✓	✗	✗	Analytical
[20]	✓	✗	✗	✗	Machine Learning
[21]	✓	✗	✓	✗	Machine Learning
Proposed Work	✓	✓	✓	✓	FIS Model

Acronyms:

- **FC**: Fuzzy Coverage
- **FCR**: Fuzzy Coverage Reliability
- **FIS**: Fuzzy Inference System
- **SN**: Sensor Node
- **FR**: Sensor's Failure Rate
- **SR**: Sensor's Range

2. SYSTEM MODEL FOR COVERAGE EVALUATION

Coverage of a wireless network measures how efficiently a defined region is being monitored [18]. It can also be expressed as the fraction of the total area covered by sensor nodes (SN). Which is represented as in Eq. (1),

$$P_{Cov} = \frac{Total\ sensed\ area}{Total\ area\ of\ the\ region} \quad (1)$$

Where P_{Cov} is the coverage probability. A sensor senses the target at a distance x, if it lies within its sensing range r_s as is defined below in Eq. (2),

$$p_s = \begin{cases} 1 & : \quad 0 \le x \le r_s \\ 0 & : \quad else \end{cases} \quad (2)$$

Here p_s is the sensing probability of a sensor for a Boolean SR model. Coverage is a crucial performance metrics and essential to consider while designing a network. This paper, introduces a model to evaluate coverage for a square network region with the area of L^2, where L is the side of the network as shown in Fig. 1. The SN distribution is assumed to be random with uniform SR.

Once the SNs randomly deployed it may lie anywhere in the region. In the proposed model, the entire area is divided into two territories, namely the inner and border territory as shown in Fig. 1. If an SN lie near border region covers less effective area as compared to the SN lying in the inner region. Therefore, it becomes essential to consider the boundary condition. In this paper, both the inner and border regions are analyzed independently and estimate the average value for coverage [17].

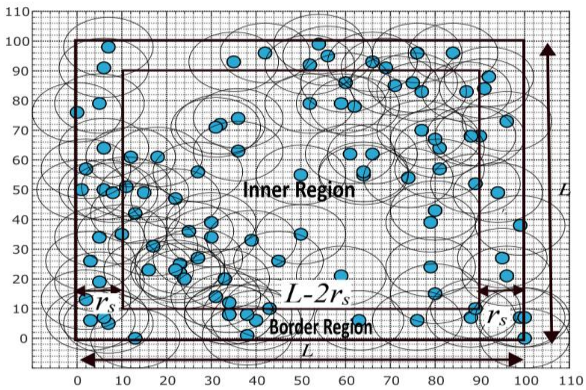

Fig. 1: Simulation in a squared network region.

Coverage Probability in Inner Region

The possibility of detecting an event of an SN lying in inner region of a square network is given as,

$$P^i_{\det} = P^i_L \cdot P^i_S \quad (3)$$

Where, $P^i_{\det}$ is the detection probability in inner region, Here, $P^i_L = A / L^2$ is the probability of an SN lying in inner region, where $A_i = (L - 2r_s)^2$ is the area of inner region and the P^i_S is sensing probability of an SN lying in inner region which is given as $P^i_S = r_s^2 / A_i$. Therefore, the event detection possibility of an SN located at inner territory can be evaluated by Eq. (3) as $P^i_{\det} = r_s^2 / L^2$

2.2. Coverage Probability in Border Region

In random distribution SN is placed indiscriminately throughout the region which may result in some SNs being placed near the border region. The SN lying near border region covers less area and affect the overall coverage. The possibility of event detection by an SN in border region of a square network is given as,

$$P^b_{\det} = P^b_L \cdot P^b_S \tag{4}$$

Here, P^b_L is the probability of an SN lie in border region that can be evaluated as,

$$P^b_L = \frac{L^2 - A_i}{L^2} \tag{5}$$

Or, $$P^b_L = \frac{L^2 - (L-2r_s)^2}{L^2} = \frac{4r_s(L-r_s)}{L^2} \tag{6}$$

P^b_S is sensing probability of an SN in border territory which is given as $P^b_S = \frac{A_{\det}}{4r_s(L-r_s)}$. Here $A_{\det}$ is area of detection by SN lying in border region. To evaluate the detection possibility of an SN lying in border territory, we first know the area of detection by the SN lying in border region. Let $A_{\det}$ be the area detected by SN lying in border region that can obtain by eliminating the area of the sector exist in outer space, *i.e.* $area(PQ)$ from overall sensed area πr_s^2 as shown in Fig 2. Further the area of sector lying outside of the region can be obtained as,

$$area(PQ) = area(POQ) - area(\Delta POQ) \tag{7}$$

$$area(PQ) = r_s^2 \cos^{-1}\left(\frac{m}{r_s}\right) - m\sqrt{r_s^2 - m^2} \tag{8}$$

Once the coverage probability evaluated independently for both of the region the approximate Coverage C_{approx} is calculated. As the SN may lie any point of the region, let s be the distance of an SN from the center of the square network and the SN can be located anywhere in the region.

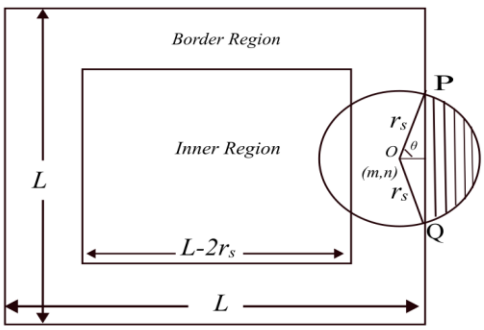

Fig. 2: SN distribution in inner and border territory

The Possibility of an event occurring at the distance t from SN is $p(s \le t) = t^2/L^2$. The probability function (pdf) for this is $2t/L^2$.

$$C_{approx} = \frac{1}{L^2}\int_0^{L-2r_s} P^i_{\det}\frac{2t}{L^2}dt + \int_{L-2r_s}^{L} P^b_{\det}\frac{2t}{L^2}dt \tag{9}$$

3. SYSTEM MODEL FOR COVERAGE RELIABILITY EVALUTION

This paper also presents the analysis for coverage reliability for a squared network under the condition of SN failure with border effect. Coverage reliability is the parameter which determine the performance of a network or it can be defined as how long a network provide coverage efficiently. SN is an electronic component whose performance degrades with time due to several external and internal factors such as environment condition or sensor internal characteristics and over the period of time, it leads to the failure of entire network. As a result, sensor failure significantly impacts the reliability of a network. Hence, it becomes necessary to consider SN failure condition. This paper evaluates coverage reliability while considering SN failure rate (FR) of $f_r(t)$. The reliability $r(t)$ of the network is estimated as

$$r(t) = 1 - (1 - C_{approx})^{k(t)} \tag{10}$$

Here, $k(t)$ represents the remaining SNs from the original count of k SN at time t, where t is evaluated as $t = k/f_r$ and $k(t)$ as $k(t) = k - f_r \cdot t$. The mathematical formulation defined above for coverage and coverage reliability in Eq. (9) and (10) are validated using FIS model. The developed mathematical model with the system parameters with values given in Table. 2 is utilized to generate the data to set upper and lower bounds for input and output variables for FIS model. The factors with membership functions are identified that leave an impact on coverage and coverage reliability. The fuzzy decisions and membership functions are developed based on data generated through analytical model and set fuzzy rules. The term FCR is therefore used and can be defined as fuzzy coverage reliability of a wireless network which is determined using fuzzy rule membership functions. The obtained coverage reliability which is essentially a fuzzified form, hence known as Fuzzy Coverage Reliability (FCR).

Table 2: Design Parameters

Parameters	Value
Area of squared network	$L^2 = 10^4 (m^2)$; where m=meter
No. of SN	2-100
SR (r_S)	0-50 (m)
FR of SN	0-0.06 failurs/hour

4. FIS MODEL

In this section, a fuzzy inference system-based model [22]- [23] to evaluated coverage and coverage reliability for a static squared wireless network is discussed. The data is generated through the analytical formulation defined above is utilized further to evaluate FC and FCR with FIS model as shown in Fig. 3. Here we have considered three linguistic fuzzy input parameters viz. SN, SR and FR with two output variable FC and FCR as in Fig. 4. The fuzzy approach consists of three major components:

1. Fuzzification: It is the process of mapping the crisp non fuzzy input variable to the linguistic fuzzy set.
2. Fuzzy Inference Engine: It is the basic unit of fuzzy logic system. It is made up with the following functional block:
    - A rule base: It is made up with the set of rules. The rule must include the antecedents, and consequent i.e. If-Then rules.

- Fuzzy rule database: The membership mapping for the input and output parameters are established based on a database of fuzzy rules.
- Reasoning: It is the process of obtaining the results by approximating the solution with each rule mentioned in the fuzzy rule database.

3. Defuzzification: It transform the fuzzy data to crisp data.

The input parameters SN, SR and FR are mapped based on the membership functions that predict the output i.e. FC and FCR.

Table 3: Range for Input/Output Parameter

Input Parameter	Range	Small	Medium	Large
SN	0-100	0-30	20-80	80-100
SR	0-50	0-20	10-30	25-50
FR	0-0.06	0-0.02	0.016-0.0457	0-0.6
FC	0-100	0-40	10-90	80-100
FCR	0-1	0-0.5	0.1-0.9	0.7-1

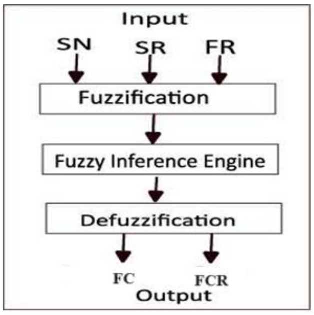

Fig. 3: FIS Model

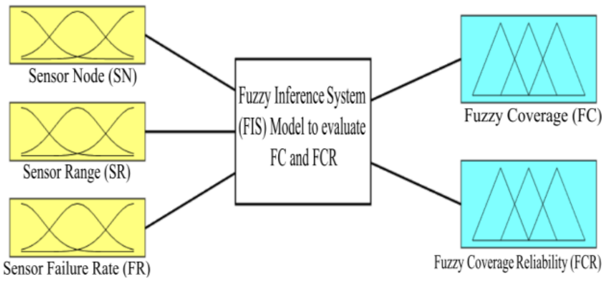

Fig. 4: Fuzzy model for coverage and coverage reliability

The variables for input output parameters are defined in three fuzzy set. The all-linguistic input variable of fuzzy set is mapped using Gaussian and outputs with triangular function to achieve an efficient solution. The crisp value of aggregate fuzzy set for FC and FCR are estimated using Mamdani FIS as follows,

$$P = \frac{\int y * \mu_w * dy}{\int \mu_w * dy} \tag{3}$$

Table 4: Membership Curve for Input/Output Parameter

Membership function for Input Parameter		
SN (μ_{SN})	**SR (μ_{SR})**	**FR (μ_{FR})**
$\begin{cases} \frac{30-x}{30} & 0\le x\le 30 \\ \frac{x-20}{30} & 20\le x\le 50 \\ \frac{80-x}{30} & 50\le x\le 80 \\ \frac{x-70}{30} & 70\le x\le 100 \end{cases}$	$\begin{cases} \frac{20-x}{20} & 0\le x\le 20 \\ \frac{x-10}{10} & 10\le x\le 20 \\ \frac{30-x}{10} & 20\le x\le 30 \\ \frac{50-x}{25} & 25\le x\le 50 \end{cases}$	$\begin{cases} \frac{0.01-x}{0.01} & 0\le x\le 0.01 \\ \frac{x-0.005}{0.015} & 0.005\le x\le 0.02 \\ \frac{0.035-x}{0.015} & 0.02\le x\le 0.035 \\ \frac{x-0.03}{0.03} & 0.03\le x\le 0.09 \end{cases}$
Membership function for Output Variable Parameter		
FC (μ_{FC})	**FCR (μ_{FCR})**	
$\begin{cases} \frac{40-x}{0.01} & 0\le x\le 40 \\ \frac{x-10}{40} & 10\le x\le 50 \\ \frac{90-x}{40} & 50\le x\le 90 \\ \frac{x-80}{20} & 80\le x\le 100 \end{cases}$	$\begin{cases} \frac{0.5-x}{0.5} & 0\le x\le 0.5 \\ \frac{x-0.1}{0.4} & 0.1\le x\le 0.5 \\ \frac{0.9-x}{0.4} & 0.5\le x\le 0.9 \\ \frac{x-0.7}{0.3} & 0.7\le x\le 1 \end{cases}$	

Here, μ_w is the aggregate output function and y is the all existence fuzzy output. The Table 3. is representing the range for the input/output variable. The membership functions for these variables are defined and governed by 36 fuzzy rules using the 'and/or' operators. These rules are illustrated in the fuzzy rule editor shown in Fig. 5. The Table 4 displays the mapped parameters derived from the membership function.

5. FINDINGS AND ANALYSIS

In this section, the results obtained for coverage and coverage reliability using FIS and analytical framework in MATLAB R2024a has been discussed. The consequence analysis on the performance metrics using several factors including the SN quantity, SR and FR has been discussed. The model is developed for a squared region with the side of L in a range of 100m. The results obtained from analytical framework is validated with the results generated through FIS model. It has been observed the obtained results is to be consistent with existing research. The paper presents data obtained through mathematical simulation, which is subsequently utilized to define the range of the fuzzy set as in Table 3. The membership function is defined for each region as shown in Table 4. Fuzzy rule is established as in Fig. 5 to obtain the desired results.

In this paper, the simulations are performed independently for both analytical and FIS framework to evaluate the performance and outcomes of both approaches, allowing for a comparative analysis of their effectiveness in modeling.

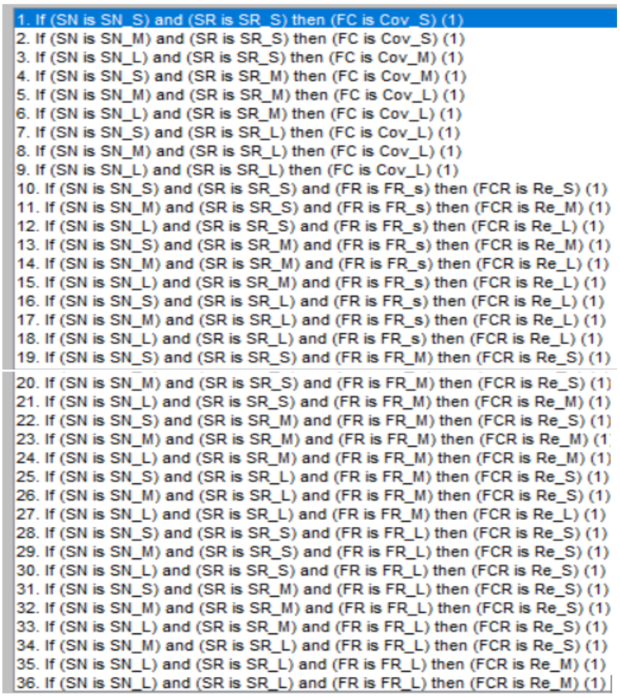

Fig. 5: Fuzzy rule editor

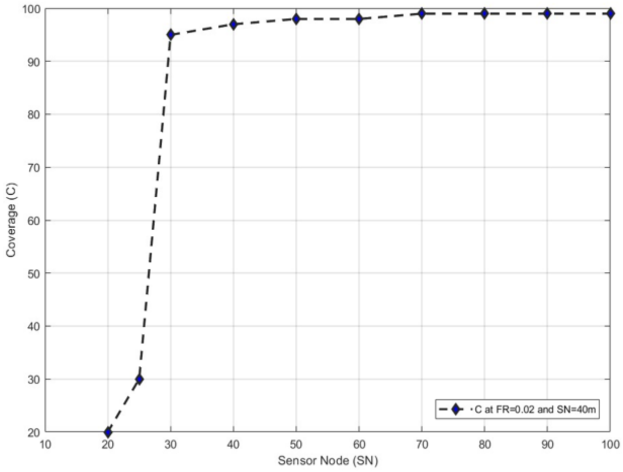

Fig. 6: Coverage (C) w.r.t. SN using mathematical framework

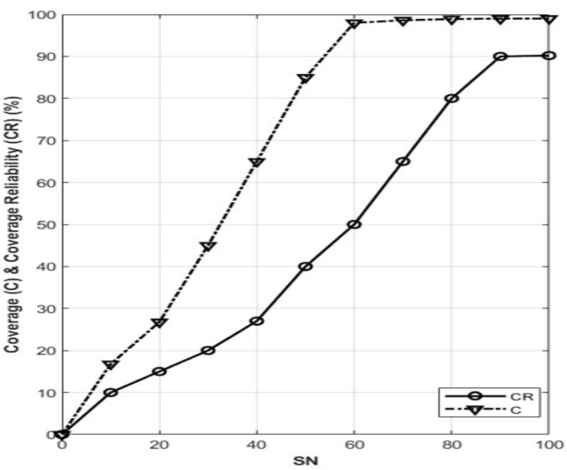

Fig. 7: C and CR w.r.t. SN using mathematical simulation

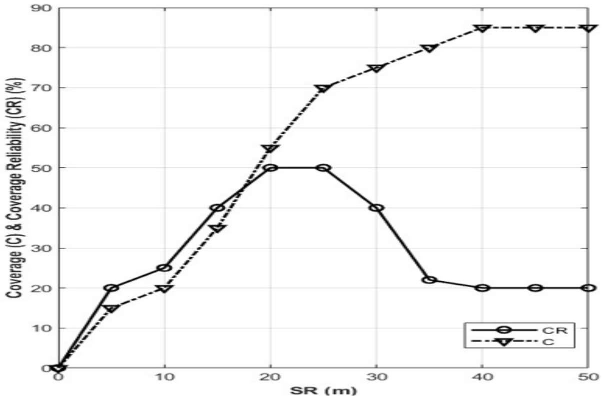

Fig. 8: 2D plot for C and CR w.r.t. SR using mathematical simulation

5.2. Results generated through FIS model

This section presents the results generated by the FIS model, which show a strong similarity to the outcomes produced by the mathematical framework. Fig. 9 and Fig. 10 illustrate the results obtained through the FIS model for FC and FCR with respect to SN, while Fig. 11 and Fig. 12 demonstrate the variations in FC and FCR with respect to SR. In addition to SN and SR, an analysis of the failure rate (FR) has also been conducted, revealing its lower impact on FC. Similarly, as the SN's failure rate (FR) increases, the FCR shows a decreasing trend. as in Fig.13. Through analysis, it has been observed the coverage FC is increasing with SN and SR, and giving the negative impact with FR. It has been observed the FCR beyond the SN range of 60 raise up to 0.889 as represented in Fig. 10. The rise of SN count, FC and FCR both increases. It is also observed that the value of FCR falls between 0.7 and 0.885 when we kept the SN count above 80 and SR between 40 and 50, while keeping FR fixed at 0.02. Similarly, it has been observed an SR below the range of 20m reduces the FC as in Fig.11, however the FCR rises between the SR range of 15m to 20 m and reduces beyond 40m due to overlapping as in Fig.12. The FCR with the same range of SR of 20m found < 0.6 or near 60%. The analysis also shows the detrimental impact of FR on FC and FCR as illustrate in Fig. 13. The surface view for FC and FCR are also obtained with the reference input 0.03 as shown in Fig. 14, Fig. 15 and Fig. 16.

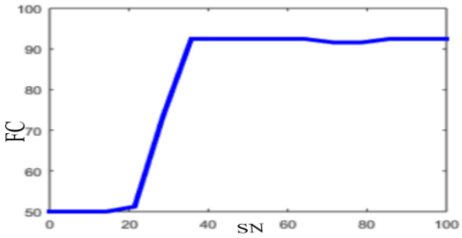

Fig. 9: 2D plot for FC analysis w.r.t. SN

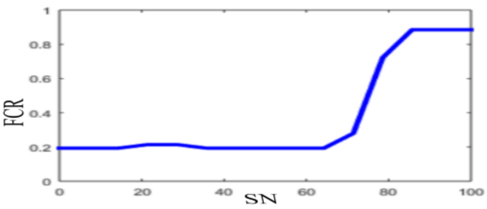

Fig. 10: 2D plot for FCR analysis w.r.t. SN

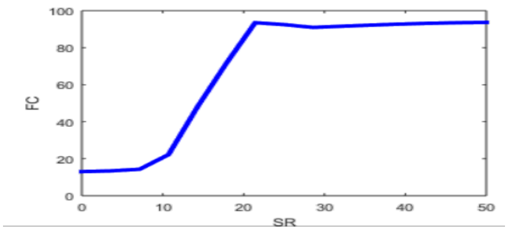

Fig. 11: 2D plot for FC analysis w.r.t. SR

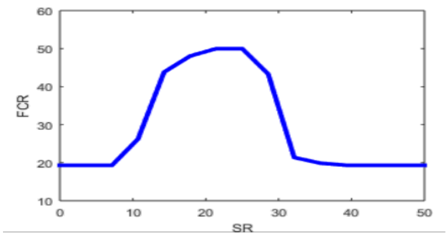

Fig. 12: 2D plot for FCR analysis w.r.t. SR

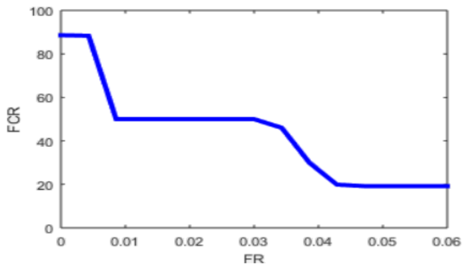

Fig. 13: 2D plot for FCR w.r.t. FR

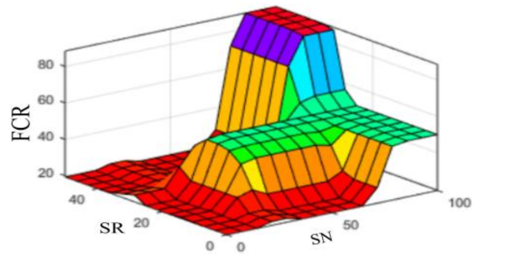

Fig. 14: Surface view for FCR w,r,t. SN and SR

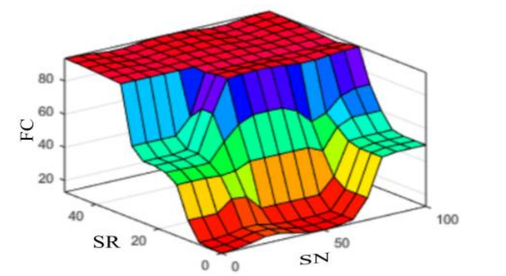

Fig. 15: Surface view for FC w.r.t. SN and SR

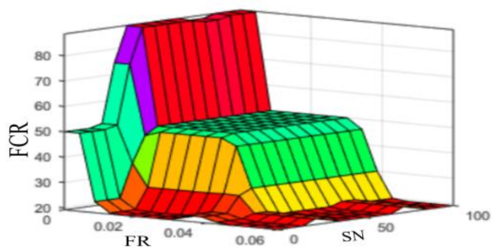

Fig. 16: Surface view for FCR w.r.t. SN and FR

6. CONCLUSION

This paper proposes FIS based model aimed at evaluating the FC and FCR of a wireless squared network. The model incorporates three key linguistic input variables: SN, SR, and FR, each defined within a fuzzy set and categorized into three distinct ranges. Additionally, the model takes into account the failure of the SN and boundary conditions to provide a more precise estimation of FC and FCR, enhancing predictions of network performance under different scenarios. The lifetime of SNs is assumed to range from 0.1 to 0.6, directly impacting FC and FCR predictions. SNs are randomly and uniformly distributed across the network, simplifying the model and ensuring homogeneous node characteristics. The study finds that FCR decreases as FR increases. Increasing SNs beyond 70 out of 100 improves FC, while SR positively impacts FC when it exceeds 30 meters, but degrades beyond 50 meters due to coverage overlap and interference.

A separate analysis was conducted for developed mathematical framework under same scenario and the results obtained from this framework follow the same trends as generated by the FIS model. This study also incorporate SN failure and boundary conditions, provides more accurate predictions and handles uncertainties in real-world environments. This fuzzy approach allows for better handling of uncertainties in real-world environments, where precise measurements are often difficult to obtain. The framework has been validated through existing work. The study suggests further extending the model to explore different sensing range models and sensor failure distributions for a deeper understanding of network performance and reliability under varying conditions.

7. ACKNOWLEDGMENTS

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