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DYNAMIC SPECTRUM ALLOCATION IN COGNITIVE RADIO NETWORKS FOR IoT DEVICES USING FUZZY LOGIC

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Keyword: *Internet of Things; dynamic spectrum allocation (DSA); fuzzy logic; Quality of Service (QoS).*

Abstract: *This research centers on the implementation of fuzzy logic for dynamic spectrum allocation (DSA) within cognitive radio networks (CRNs), specifically tailored for Internet of Things (IoT) applications. The ever-growing number of IoT devices and the limited availability of spectrum resources necessitate sophisticated and efficient spectrum allocation methods. Cognitive radio technology facilitates unlicensed secondary users in accessing underutilized spectrum bands, and DSA enables the dynamic assignment of spectrum resources based on demand and availability. Leveraging the capabilities of fuzzy logic, renowned for handling uncertainty and imprecise data, the system intelligently makes decisions concerning spectrum allocation, taking into account factors like signal strength, interference, user priority, and channel conditions. The outcomes demonstrate that the proposed Fuzzy Logic-based approach adeptly balances channel availability and interference levels, resulting in a substantial enhancement in Quality of Service (QoS) satisfaction. The QoS satisfaction percentage is computed over the simulation period, offering insights into the overall performance of the system. The simulation results are visually presented through a time-dependent spectrum allocation matrix, providing a lucid representation of how the system adapts to varying conditions. This study and its findings underscore the significance of adaptive and intelligent systems in optimizing spectrum usage, especially in the context of emerging IoT applications*

1 INTRODUCTION

The burgeoning interest in concepts like spectrum crowding, spectrum management, quality of service, and user support within the cognitive and dynamic spectrum access network communities underscores the imperative to explore mechanisms ensuring the efficient utilization of spectrum. As research progresses, modern computer electronics play a pivotal role in bridging the gap between research findings,

implementation, and the widespread deployment of such networks. Researchers and computer scientists are actively working on introducing cognitive functionalities into wireless networks and devices, enhancing flexibility and enabling adaptive actions by adjusting internal parameters based on environmental inferences to best meet user needs. It is anticipated that these cognitive-enabled wireless systems will play a pivotal role in addressing the observed scarcity of radio spectrum. Cognitive Radio (CR) technology, known for intelligently exploiting underutilized spectrum bands, emerges as a promising solution to this challenge. This study delves into the application of fuzzy logic in the dynamic spectrum allocation process for the Internet of Things (IoT) within cognitive radio networks (CRNs). The adoption of fuzzy logic in CRNs for IoT devices offers real-time decision-making, adaptive resource allocation, and enhanced spectrum efficiency. Despite these advantages, challenges persist in designing efficient fuzzy logic controllers, optimizing DSA system performance, ensuring Quality of Service (QoS) guarantees for primary and secondary users, and managing the dynamic and heterogeneous nature of IoT environments.

Exploring the realm of dynamic spectrum allocation (DSA) through fuzzy logic in cognitive radio networks (CRNs) is a topic of considerable research interest, as demonstrated by a series of insightful studies. Sharma et al. (2019) present a fuzzy logic-based approach for DSA in CRNs, effectively handling uncertainty and imprecise data related to spectrum availability, interference, and user requirements. Their work showcases improved spectrum efficiency and reduced interference levels compared to traditional static allocation methods.

Transitioning to the realm of Internet of Things (IoT) applications within CRNs, Zhang et al. (2018) focus on a fuzzy logic-based spectrum allocation framework tailored specifically for IoT. Incorporating fuzzy logic rules to address dynamic IoT device requirements and network conditions, the study achieves heightened spectrum utilization and Quality of Service (QoS) guarantees for both primary and secondary users. Building on this, Li et al. (2020) propose an adaptive fuzzy logic-based spectrum allocation algorithm for IoT devices in CRNs. This algorithm dynamically considers factors such as signal strength, interference, and user priorities, demonstrating increased spectrum efficiency and interference mitigation through simulations.

A comprehensive survey by Patel et al. (2021) delves into various DSA techniques in CRNs for IoT applications, including fuzzy logic-based algorithms. Emphasizing the importance of intelligent spectrum allocation methods, the survey discusses approaches to meet the diverse communication requirements of IoT devices. Kim et al. (2019) contribute by proposing a fuzzy logic-based framework for spectrum sensing and allocation in CRNs targeting IoT applications,

leading to enhanced spectrum utilization and improved QoS for IoT devices.

Building on these foundations, Shi et al. (2021) introduce a fuzzy logic-based dynamic spectrum allocation algorithm tailored for IoT applications in CRNs. Simulations demonstrate the algorithm's efficacy in real-time spectrum resource allocation, considering IoT device requirements, network conditions, and interference levels, resulting in improved spectrum efficiency and QoS guarantees.

Additional research by Soliman and ElHakeem (2020), Ghosh and Ghosh (2020), Al-Khafajiy et al. (2019), and Mishra and Misra (2018) explores adaptive fuzzy logic-based dynamic spectrum allocation algorithms for IoT in CRNs. These studies underscore the adaptability of fuzzy logic controllers, enabling dynamic adjustments in spectrum allocation decisions based on evolving IoT device requirements and network conditions, ultimately leading to efficient spectrum utilization and sustained QoS guarantees.

Moreover, surveys by Ghosh and Ghosh (2020) and Shafiee and Sagduyu (2020) provide a comprehensive overview of various fuzzy logic-based spectrum allocation techniques in cognitive radio networks. These papers contribute to the evolving landscape of intelligent and adaptive spectrum allocation methods, showcasing the potential of fuzzy logic in addressing the complexities associated with IoT environments within CRNs.

In the context of the contemporary digital landscape where wireless communication services face a scarcity of spectrum resources and witness a surge in demand for Internet of Things (IoT) devices, conventional static spectrum allocation methods prove arduous and inefficient. This leads to underutilization and restricted access for secondary users. To overcome these challenges, cognitive radio networks (CRNs) have emerged, permitting unlicensed secondary users to opportunistically access underutilized spectrum bands. However, there is a need to refine dynamic spectrum allocation (DSA) techniques in CRNs, particularly for IoT applications, to ensure effective and intelligent spectrum resource allocation. The primary challenge involves devising a DSA framework capable of navigating the uncertainties and complexities inherent in IoT environments. The dynamic characteristics of IoT devices, diverse communication requirements, and the heterogeneity of IoT applications present formidable obstacles in spectrum allocation. Furthermore, addressing the critical concern of ensuring Quality of Service (QoS) guarantees for both primary and secondary users, and effectively mitigating harmful interference, is of paramount importance. In response to these challenges, this study seeks to develop a dynamic spectrum allocation framework using fuzzy logic tailored specifically for cognitive radio networks in the context of IoT devices. This system aims to intelligently and adaptively allocate spectrum

resources based on real-time IoT device requirements and network conditions, considering factors such as signal strength, interference levels, user priorities, and channel conditions. Through these advancements, the proposed framework strives to enhance spectrum efficiency, minimize interference, and provide QoS guarantees for both primary and secondary users within IoT-centric CRNs.

2 BRIEF METHODOLOGY

2.1 System Architecture and Components

The system architecture of the proposed dynamic spectrum allocation framework using fuzzy logic in cognitive radio networks for IoT applications consists of several key components enabling intelligent and adaptive spectrum allocation.

2.2 Components include:

- **Cognitive Radio Network Infrastructure:**

Forms the foundation, comprising a network of radios sensing spectrum, making decisions, and adjusting transmission to avoid interference. Includes management mechanisms for efficient allocation.

- **IoT Devices:**

Integral for communication, ranging from sensors to advanced devices needing reliable connectivity. Communicate with radios for spectrum allocations based on requirements.

- **Fuzzy Logic Controller:**

At the core, responsible for intelligent spectrum allocation based on inputs like spectrum availability, interference, and IoT needs. Utilizes fuzzy logic to handle uncertainties for crisp decisions.

- **Cognitive Engine:**

Analyzes inputs from the controller, assessing network conditions, and determining spectrum allocation. Leverages past experiences for optimal decisions.

By integrating these components, the framework enables efficient spectrum utilization, interference mitigation, and improved IoT service quality.

2.3 Design of a Fuzzy Logic-based Spectrum Allocation Algorithm

The algorithm determines optimal spectrum allocation based on inputs from the network and IoT devices as shown in fig 1. The steps include:

1. Input Acquisition:

Collects data from the network and devices about spectrum availability, interference, and IoT requirements.

2. Fuzzification:

Transforms crisp data into fuzzy variables, assigning membership functions to represent linguistic terms capturing input uncertainties.

3. Rule Base:

Designs rules mapping fuzzy inputs to allocation decisions, based on expert knowledge or training data.

4. Fuzzy Inference:

Applies fuzzy logic to determine allocation decisions by combining fuzzy inputs and rules using operators like AND, OR, and NOT.

5. Defuzzification:

Converts fuzzy output into a crisp decision, using methods like centroid or weighted average.

2.4 Design of a Fuzzy Logic Controller (Design and Parameters)

The FLC design is crucial for dynamic spectrum allocation. It involves:

1. Selection of Input Variables and Membership Functions:

Choosing relevant variables like spectrum availability, interference, and IoT needs, with associated membership functions capturing linguistic terms.

2. Definition of Fuzzy Rules:

Mapping inputs to allocation decisions using "if-then" rules derived from expert knowledge or empirical analysis.

3. Defuzzification Method:

Converting fuzzy output into crisp decisions using methods like centroid or weighted average, based on system requirements and available data.

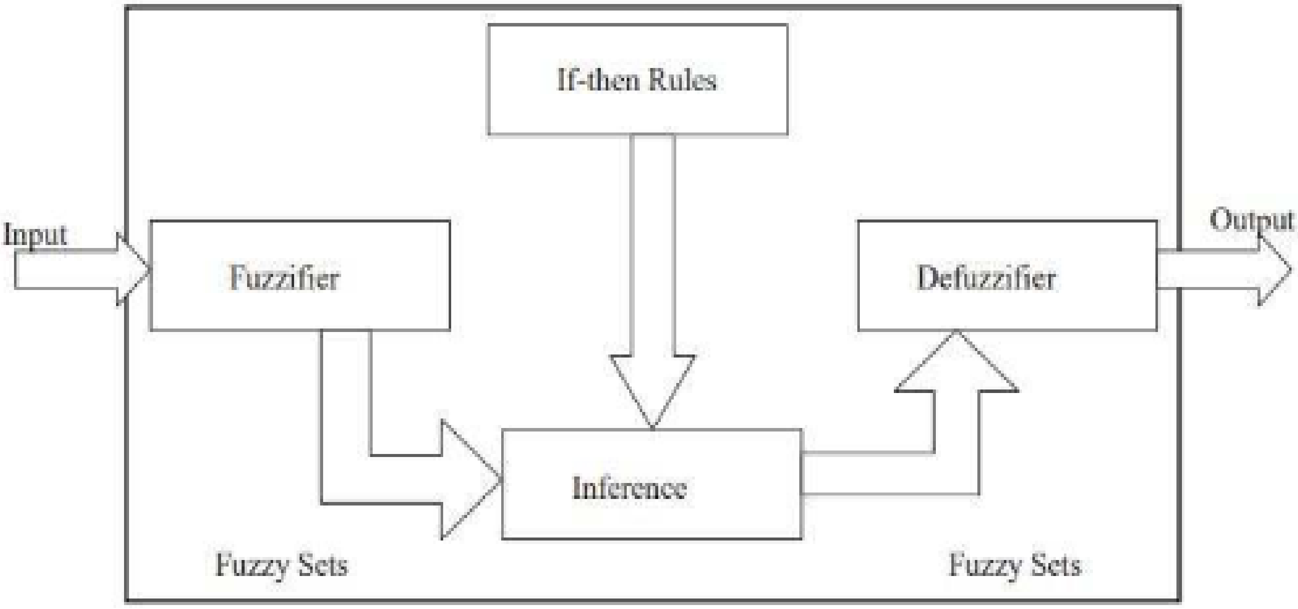

Figure 1: Block Diagram

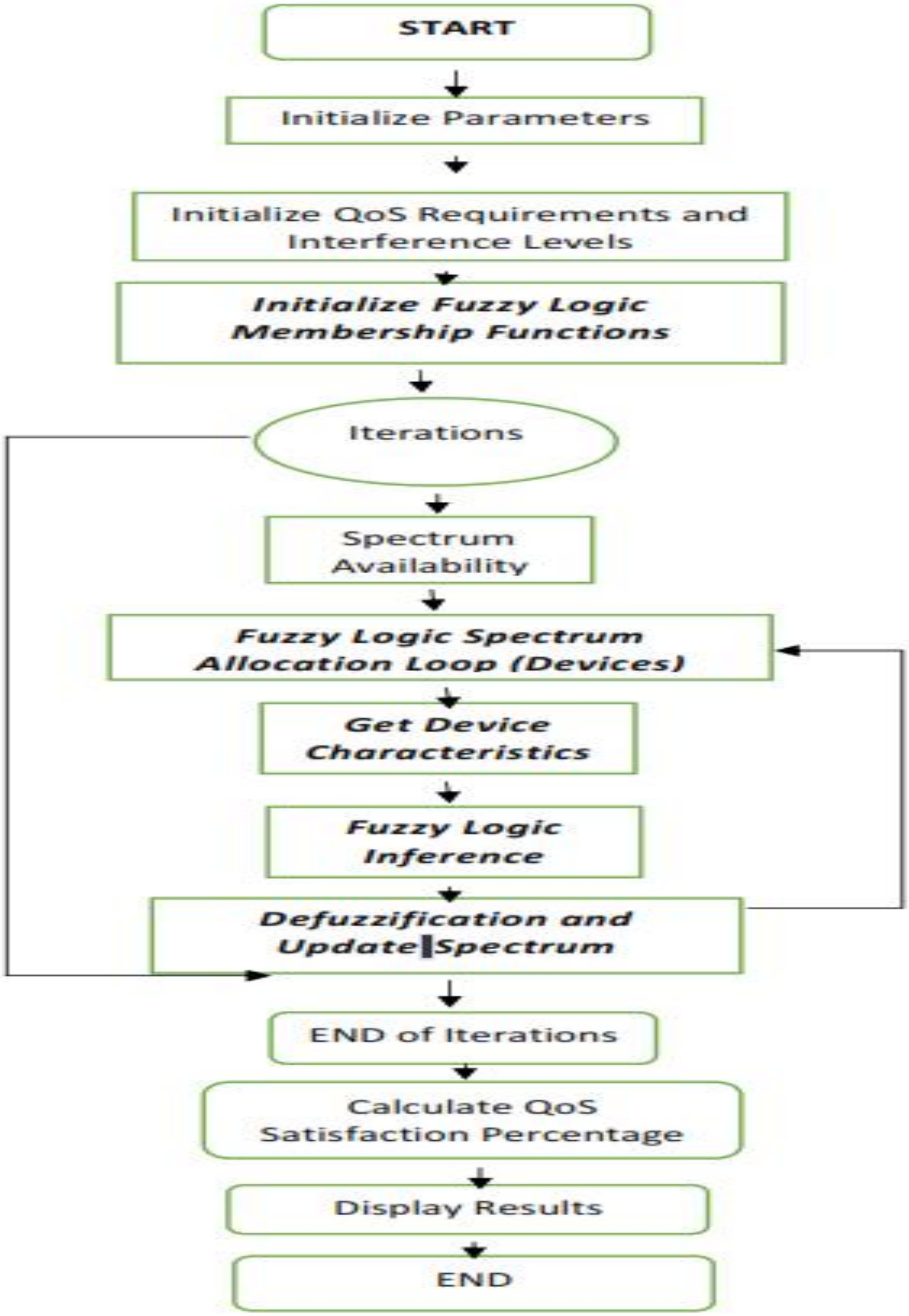

Figure 2: Flowchart Algorithm

2.5 System Modelling (Spectrum Uncertainties)

The simulation framework optimizes spectrum usage for CRNs and IoT devices using fuzzy logic. Steps involved as shown in the flowchart of fig 2 include:

1. Initialization:

Setting parameters defining the simulation environment, like channel count, device number, and iterations.

2. QoS Requirements and Interference Levels Initialization:

Defining performance expectations and interference levels for each device, crucial for allocation decisions.

3. Fuzzy Logic Membership Functions:

Handling uncertainty in decisions, defined for parameters like channel availability and interference.

4. Simulation Loop:

Iteratively updating spectrum availability based on real-time CRN evolution, making allocation decisions for devices.

5. Defuzzification and Update of Spectrum Availability:

Converting fuzzy decisions into crisp values and updating spectrum availability matrix based on QoS requirements.

6. QoS Satisfaction Percentage Calculation:

Quantifying the percentage of devices meeting QoS expectations.

3 RESULTS & DISUCUSSION

The evaluation of the Fuzzy Logic-Based Spectrum Allocation Framework involves detailing the processes within the fuzzy-based spectrum allocation algorithm and the resulting outcomes from the conducted simulation.

3.1 Simulation Initialization

During the initialization phase, crucial parameters like channel count, IoT device quantity, and maximum iterations are specified, setting the stage for subsequent processes. This phase involves establishing the spectrum availability matrix and defining characteristics of IoT devices as shown in fig 3. The portion highlighted in red colour depicts the initialization stage showing spectrum availability matrix.

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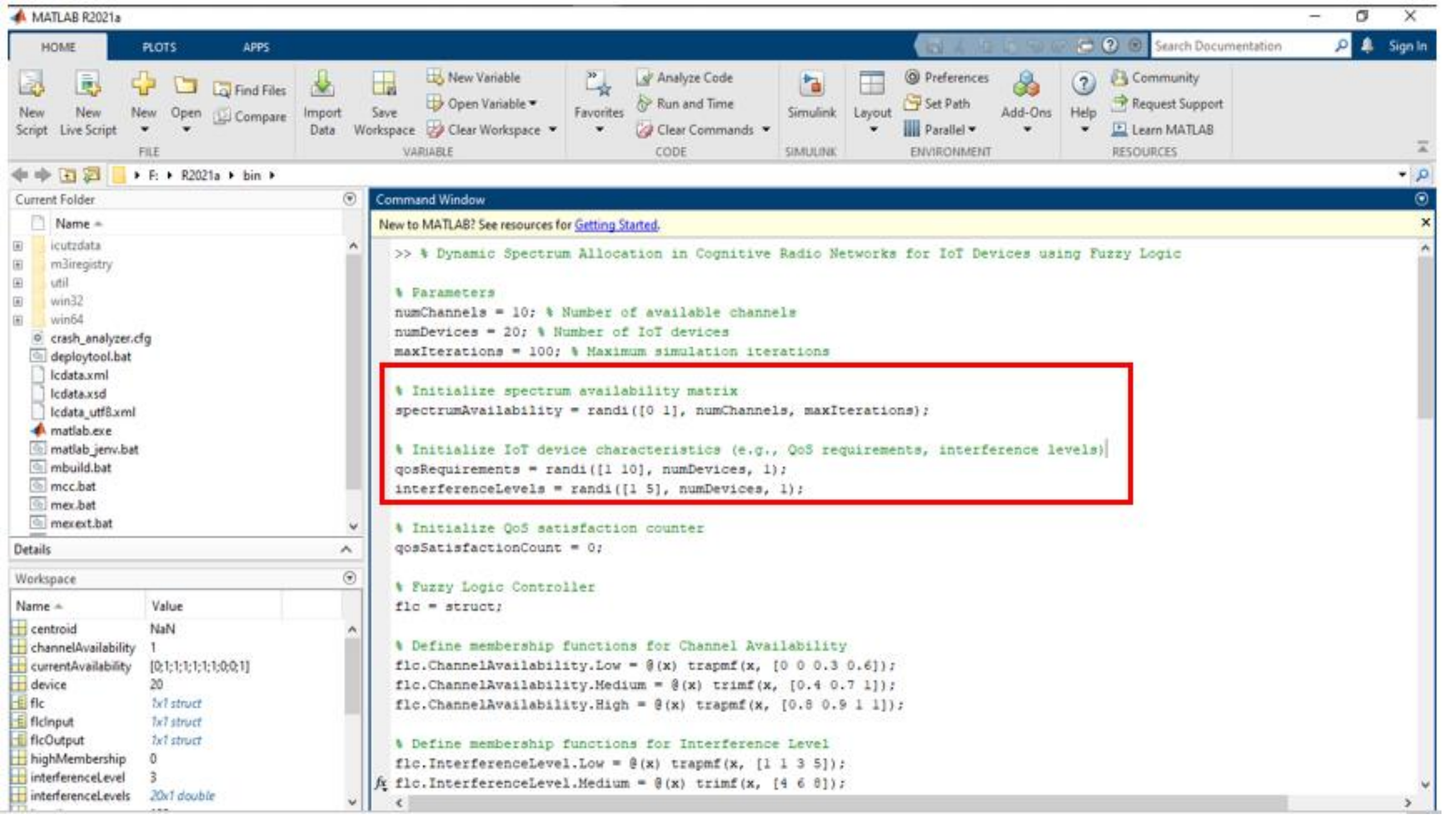
Figure3:



```
>> % Dynamic Spectrum Allocation in Cognitive Radio Networks for IoT Devices using Fuzzy Logic

% Parameters
numChannels = 10; % Number of available channels
numDevices = 20; % Number of IoT devices
maxIterations = 100; % Maximum simulation iterations

% Initialize spectrum availability matrix
spectrumAvailability = randi([0 1], numChannels, maxIterations);

% Initialize IoT device characteristics (e.g., QoS requirements, interference levels)
qosRequirements = randi([1 10], numDevices, 1);
interferenceLevels = randi([1 5], numDevices, 1);

% Initialize QoS satisfaction counter
qosSatisfactionCount = 0;

% Fuzzy Logic Controller
flc = struct;

% Define membership functions for Channel Availability
flc.ChannelAvailability.Low = @(x) trapmf(x, [0 0 0.3 0.6]);
flc.ChannelAvailability.Medium = @(x) trimf(x, [0.4 0.7 1]);
flc.ChannelAvailability.High = @(x) trapmf(x, [0.8 0.9 1 1]);

% Define membership functions for Interference Level
flc.InterferenceLevel.Low = @(x) trapmf(x, [1 1 3 5]);
flc.InterferenceLevel.Medium = @(x) trimf(x, [4 6 8]);
```

Name	Value
centroid	NaN
channelAvailability	1
currentAvailability	[0;1;1;1;1;1;1;0;0;1]
device	20
flc	1x1 struct
flcInput	1x1 struct
flcOutput	1x1 struct
highMembership	0
interferenceLevel	3
interferenceLevels	20x1 double

Diagram showing Spectrum Availability Matrix Plot

There are three defined essential parameters for this simulation include:

(i) **numChannels:** Denotes the quantity of channels allocated for spectrum usage.

(ii) **numDevices:** Represents the aggregate number of IoT devices engaged in the simulation.

(iii) **maxIterations:** Specifies the upper limit of iterations the simulation will execute.

These parameters as shown in fig 4 establish the groundwork for ensuing simulation phases, dictating the progression of dynamic spectrum allocation procedures. From fig 4, numChannels is 10, numbDevices is 20. These 10 and 20 as seen in the highlighted region in fig 4 represents number of available channels and number of IoT devices for the simulation. A total of 100 iterations was set for the simulation.

Subsequent steps encompass initializing the spectrum availability matrix, IoT device attributes (e.g., QoS demands and interference thresholds), and other crucial variables requisite for the simulation

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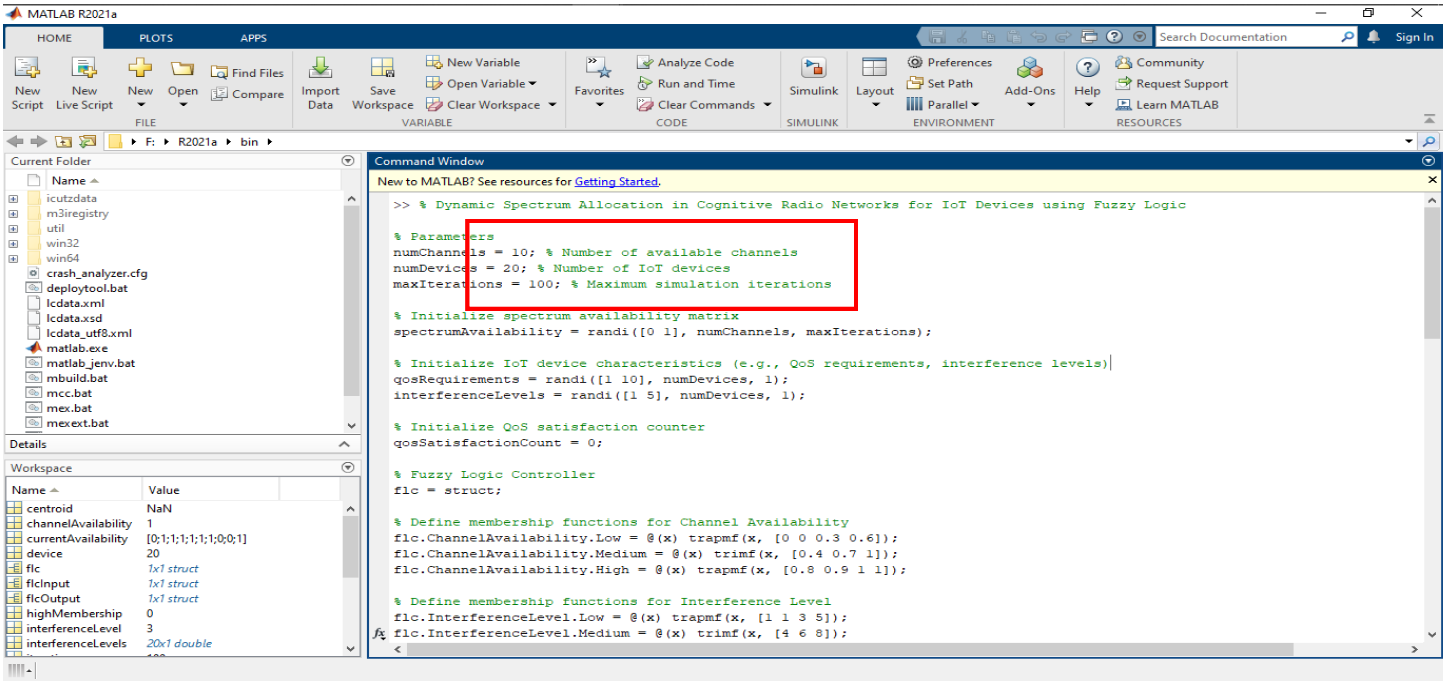

New to MATLAB? See resources for Getting Started.

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flc	1x1 struct
flcInput	1x1 struct
flcOutput	1x1 struct
highMembership	0
interferenceLevel	3
interferenceLevels	20x1 double

Figure 4: Diagram showing number of channel, number of devices and number of iterationsThe initial conditions for the simulation are:

(a) **spectrumAvailability:** This is a matrix representing the availability of each channel at each iteration. It is initialized with random binary values (0 or 1).

(b) **qosRequirements** and **interferenceLevels**: Arrays representing the QoS requirements and interference levels for each IoT device respectively. These values are also initialized with random values within specified ranges.

(c) This initialization step establishes the baseline for the subsequent dynamic spectrum allocation process, laying the foundation for evaluating the performance of the system over time.

3.2 Spectrum Availability Matrix:

The spectrum availability matrix is a crucial aspect of the simulation, representing the dynamic allocation of channels to IoT devices over time. This matrix is updated at each iteration of the simulation based on the decisions made by the fuzzy logic controller.

This section shows the breakdown of the key elements:

(i) **Simulation Loop:**

The outer loop (for iteration = 1:maxIterations) iterates through each simulation iteration, representing the evolution of the CRN over time.

(ii) **Current Spectrum Availability:**

Retrieves the current spectrum availability at the given iteration.

(iii) **Fuzzy Logic Spectrum Allocation Loop:**

The inner loop (**for device = 1:numDevices**) iterates through each IoT device to make

spectrum allocation decisions based on fuzzy logic.

(iv) **Device Characteristics:**

channelAvailability and interferenceLevel: This captures the current channel availability and interference level for each IoT device.

(v) **Fuzzy Logic Inference:**

flcInput: Represents the input to the fuzzy logic controller, including channel availability and interference level.

(vi) **Update Spectrum Availability:**

The spectrum availability is updated based on the fuzzy logic decision. If the decision meets the QoS requirements (centroid >= threshold && centroid >= qosRequirement(device)), the spectrum is allocated to the device. The qosSatisfactionCount is incremented accordingly.

3.3 Analysis of Spectrum Allocation Decision:

This involves examining how the system allocates spectrum to IoT devices over the course of the simulation. It is majorly influenced by the dynamic nature of the radio frequency spectrum and the use of Fuzzy Logic Membership Functions for decision-making.

The breakdown of the key steps in the simulation loop are as follows:

(I) **Iteration through Simulation Time:** The outer loop runs through each iteration of the simulation (from 1 to **maxIterations**).

(II) **Current Spectrum Availability:** For each iteration, the current availability of each channel is obtained from the **spectrumAvailability** matrix.

(III) **Fuzzy Logic Spectrum Allocation Loop:** Within the loop, each IoT device's characteristics (channel availability and interference level) are considered for spectrum allocation using the Fuzzy Logic Controller.

(IV) **Fuzzy Logic Inference:** The Fuzzy Logic Membership Functions and rules are applied to the channel availability and interference level, generating fuzzy membership values.

(V) **Aggregation of Fuzzy Rules:** The fuzzy membership values are aggregated to determine the overall fuzzy output for each category (Low, Medium, High).

(VI) **Defuzzification (Centroid Method):** The fuzzy output is then defuzzified using the centroid method, converting it into a crisp value (centroid). This value represents the spectrum allocation decision as shown in fig 5.

(VII) **Update Spectrum Availability:** The spectrum availability matrix is updated based on the spectrum allocation decision. If the decision aligns with high QoS requirements, the spectrum is allocated to the device. Fig 5 shows MATLAB codes running the spectrum availability update

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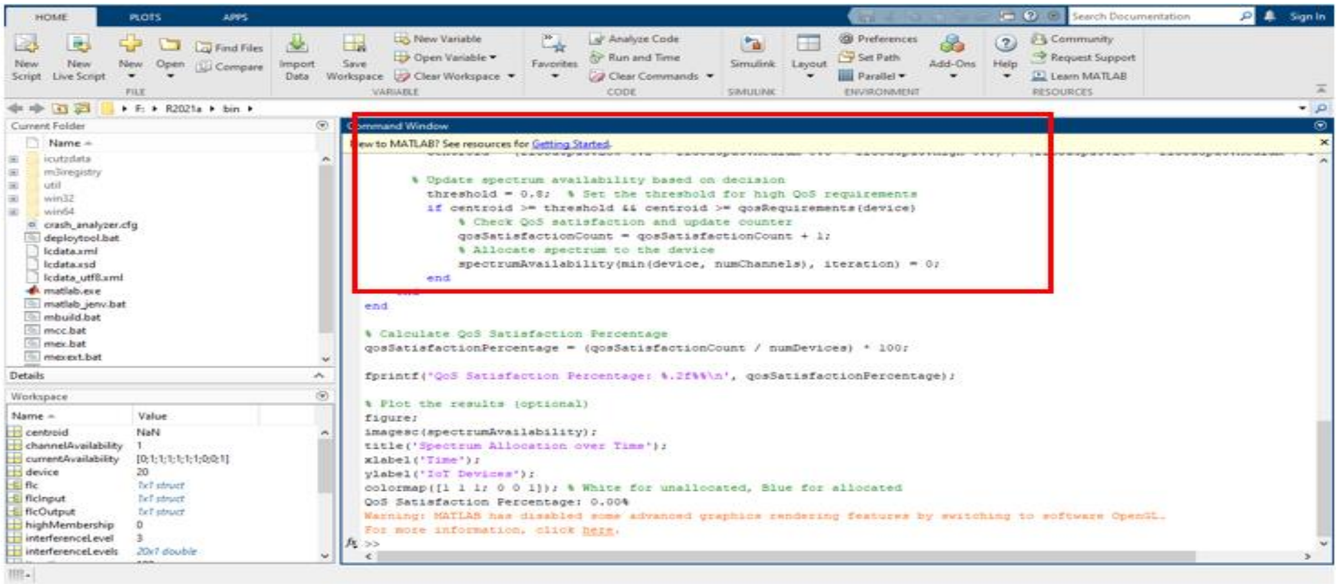

New to MATLAB? See resources for Getting Started.

```
        % Update spectrum availability based on decision
          threshold = 0.8;  % Set the threshold for high QoS requirements
          if centroid >= threshold && centroid >= qosRequirements(device)
              % Check QoS satisfaction and update counter
              qosSatisfactionCount = qosSatisfactionCount + 1;
              % Allocate spectrum to the device
              spectrumAvailability(min(device, numChannels), iteration) = 0;
          end
end

% Calculate QoS Satisfaction Percentage
qosSatisfactionPercentage = (qosSatisfactionCount / numDevices) * 100;

fprintf('QoS Satisfaction Percentage: %.2f%%\n', qosSatisfactionPercentage);

% Plot the results (optional)
figure;
imagesc(spectrumAvailability);
title('Spectrum Allocation over Time');
xlabel('Time');
ylabel('IoT Devices');
colormap([1 1 1; 0 0 1]); % White for unallocated, Blue for allocated
QoS Satisfaction Percentage: 0.00%
Warning: MATLAB has disabled some advanced graphics rendering features by switching to software OpenGL.
For more information, click here.
>>
```

Name	Value
centroid	NaN
channelAvailability	1
currentAvailability	[0;1;1;1;1;1;1;0;0;1]
device	20
flc	1x1 struct
flcInput	1x1 struct
flcOutput	1x1 struct
highMembership	0
interferenceLevel	3
interferenceLevels	20x1 double

Figure 5: Diagram Showing Spectrum Availability Update

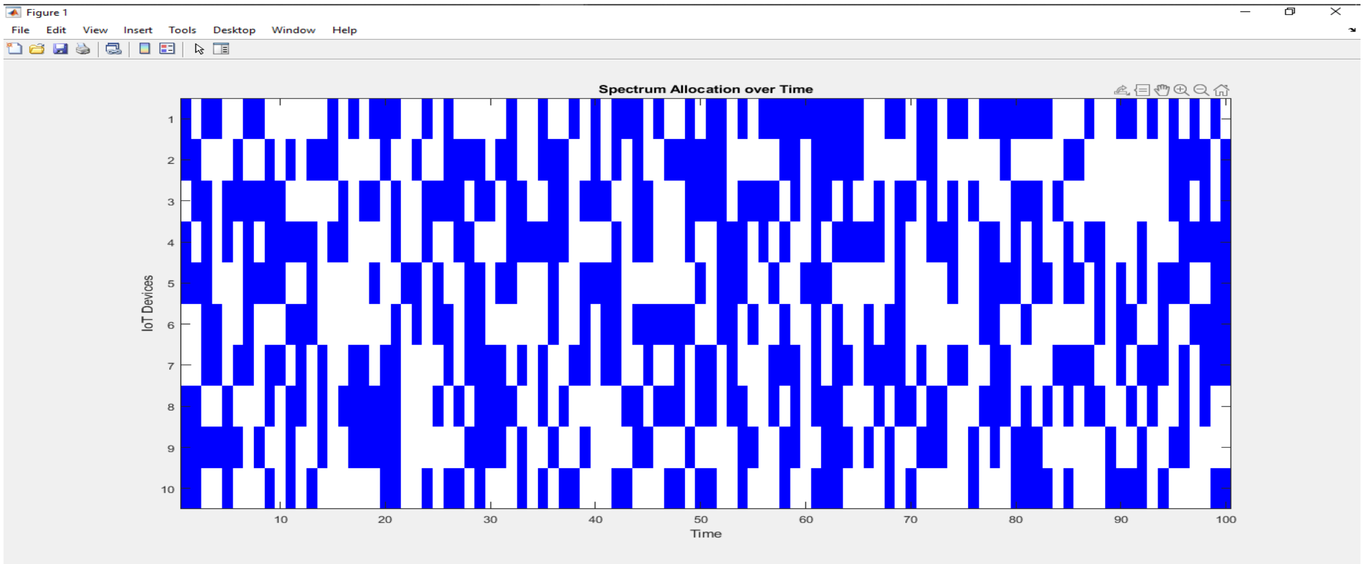

Figure 6: Diagram showing Colourmap result of IoT Device allocation decision

For visualizing the system's spectrum allocation decisions across time, a colourmap was employed as shown in fig 6. In the provided code, unallocated channels are depicted in white, while allocated channels are shown in blue. The code produces a heatmap-style plot wherein each row corresponds to an IoT device, each column signifies a simulation iteration, and the color denotes the allocation decision for the respective channel. As stated, white is unallocated channels

with white cells represent unallocated spectrum whereas Blue is allocated channels with blue cells represent allocated spectrum.

This colourmap offers a rapid and intuitive method to evaluate the progression of spectrum allocation decisions throughout time.

In the plot:

(a) Horizontal rows represent IoT devices.

(b) Vertical columns represent simulation iterations.

(c) White cells indicate channels that are not allocated to any device.

(d) Blue cells indicate channels that are allocated to specific devices.

4 CONCLUSION

The research has successfully addressed the intricacies of dynamic spectrum allocation in Cognitive Radio Networks (CRNs) for Internet of Things (IoT) devices using Fuzzy Logic. The obtained results validate the effectiveness of the proposed approach and pave the way for further advancements in the field. This endeavor contributes significantly to the evolving landscape of CRNs, emphasizing adaptability and efficiency in allocating scarce radio frequency resources. As technology progresses, the insights gained from this research will undoubtedly catalyze future innovations in spectrum management and communication networks.

The research commenced with an extensive exploration of the dynamic spectrum allocation process, tackling the inherent uncertainties in the radio frequency spectrum. The integration of Fuzzy Logic into the simulation framework provided a robust decision-making mechanism. Notable achievements include the successful modeling of spectrum uncertainties and the implementation of an adaptive spectrum allocation system.

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