Fuzzy Logic and AI-Powered, SDR Relay for Secure and Efficient Cooperative Radio Communication

Srikar Bhamidipati⋆, Sainath Bitragunta⋆, Ashuthosh Bhatia†
⋆Department of Electrical and Electronics Engineering
†Department of Computer Science and Information Systems
BITS Pilani, Pilani, Rajasthan, India.
Emails: f20190377P@alumni.bits-pilani.ac.in, sainath.bitragunta@pilani.bits-pilani.ac.in, ashutosh.bhatia@pilani.bits-pilani.ac.in

***Abstract*—In this article, we develop a novel approach that leverages the capabilities of fuzzy logic and artificial intelligence (AI) to develop an intelligent, efficient cooperative RCN. Software defined radio (SDR) is flexible, scalable, and reconfigurable. Considering heterogeneous radio communication networks (RCNs), conventional relays do not perform well due to their limitations (security vulnerabilities in cooperative Internet-of-Things (IoT), inefficiencies in half-duplex relaying, etc.). We propose an AI-powered, fuzzy logic-based SDR relay to address these issues. These intelligent relays could be useful and outperform conventional relays due to their adaptability and reconfigurabilty, with added intelligence based on AI and fuzzy logic. The proposed next generation SDR relays offer significant advantages over traditional relays and have the potential to revolutionize the field of radio communication. Specifically, we analyze the decimation technique in SDR signal-to-interference plus noise ratio (SINR) resampler, Mamdani fuzzy logic controller, and use a machine learning (ML) model that uses RADIOML data set. Based on the simulation results, we show that applying fuzzy logic with an ML-enabled SDR relay could improve energy efficiency and reliability performance in advanced radio networks.**

***Index Terms*—Cooperative relays, radio access, fuzzy logic, machine learning, SDR, decimation, intelligent networks, optimization, compatibility, scalability, cloud computing.**

I. Introduction

Cooperative relay-assisted radio communication offers several benefits, namely, increased transmission range, reliability, security, and spectral efficiency, to name a few. Implementing relay as a software defined radio (SDR) brings additional advantages due to their flexibility, reconfigurability, and scalability. Recently, there has been significant interest in designing artificial intelligence (AI) enabled SDR for various applications in intelligent transportation systems, next generation wireless devices to address the integrated sensing communication and computation requirements. AI-enabled SDR relays are promising to address the challenges posed by the upcoming fifth generation (5G) technology standards, which require seamless communication between multiple heterogeneous devices, including IoT, satellite systems. The SDR technology is utilized in conjunction with relays to enable smooth communication and adapt to changing signal conditions [1]. This adaptability in the dynamic environment provides a significant advantage in areas with poor signal strength as it reduces signal interference and optimizes transmission performance.

The rapid growth of the artificial Internet of Things (AIoT) and big data enabled the use of fuzzy inference system (FIS) that involve determining the rules and membership functions. Though the task of finding suitable rules and attributes is non-trivial, the availability of large data in terms of quality and quantity use of neural networks could make the task less difficult. Adaptive neuro FIS (ANFIS) can automatically determine appropriate parameters for the membership functions, which are useful in critical decision-making. A FIS in conjunction with AI can be used in advanced radio communication networks (RCNs) such as sixth generation (6G) wireless networks.

6G radio communication networks need to be sustainable, secure, and more intelligent. The Fuzzy Logic and AI-powered SDR relay for secure and efficient signal communication is a promising solution that aims to revolutionize the traditional method of radio communication [2]. This cutting-edge technology employs a combination of advanced techniques such as fuzzy logic, artificial intelligence (AI) and SDR [3] to optimize the efficiency and security of signal transmission. Furthermore, integrating fuzzy logic and AI into the system provides a powerful mechanism to enhance the transmission process [4]. Specifically, the advanced communication technologies, with the inclusion of efficient machine learning (ML) algorithms could analyze dynamic and heterogeneous propagation environments and optimize signal transmission parameters. The acquired intelligence enables the system to adapt in real-time to changing signal conditions, thereby improving the overall performance of the system [5]. The 6G radio communication technologies should be sustainable and ensure end-to-end reliable and secure transmission of information.

II. Background, Comparisons and Comments

We first discuss conventional radio communication techniques in contemporary radio communication networks. Later, we present details on intelligent and efficient SDR relays in cooperative radio communication networks. Specifically, we focus on AI-enabled fuzzy logic-based SDR relay and discuss its features. Besides presenting the qualitative details on the ingredients, namely, the decimator, fuzzy logic controller, and ML model, we present some results that validate the proposed SDR relay capabilities.

A. Conventional Techniques for Radio Communication

Radio communication networks are primarily constrained by two major precious resources, namely, transmission power and communication spectrum. One intuitive idea in conserving these resources is multirate signal processing (MRSP) that include techniques such as decimation and compressive sensing. Two key techniques in MRSP are decimation and interpolation. Decimation is a process of reducing the sampling rate while retaining the fidelity of the signal. For instance, the data is meticulously broken down using decimation to optimize data transmission. This process reduces the amount of data that needs to be transmitted, making the transmission more efficient by reducing our bandwidth usage.

Several basic to advanced signal processing techniques are used in RCNs to improve the transmission of data [6]. Some of the widely used techniques are as follows.

- *Adaptive modulation techniques:* This technique involves changing the characteristics of the signal to transmit information. This technique helps to increase the power or bandwidth efficiency of the transmission and improve the reliability of the data transmission. Digital modulation techniques such as $M-$ary PSK and $M-$ary QAM are widely used in terrestrial and satellite communications.
- *Error control coding:* This technique involves adding redundancy strategically to the data transmitted. This redundancy helps to detect and correct errors in the data. For example, forward error correction (FEC) improves the product of reliable transmission range and data rate.
- *Spread spectrum (SS) techniques:* For example, direct sequence SS technique involves spreading the signal over a wide range of frequencies. This technique helps to reduce the probability of intercept and also increases the reliability of the transmission.
- *Antenna diversity:* This is a space diversity technique. It uses multiple antennas to transmit and receive signals. This technique helps to reduce the impact of signal fading and increases the reliability and transmission rates.

In addition to the above, radio communication networks use frequency diversity (for example, OFDM), space-time block coding, and secure coding techniques such as encryption and decryption. All these techniques help enhance quality of service (QoS) and quality of experience (QoE).

B. Role of SDR Relays in Radio Communication

Conventional radio communication techniques are limited to a specific radio communication scenario, for instance, cellular mobile, Wi-Fi, and Bluetooth, to name a few. However, integrating IoT devices with 5G, Wi-Fi, and other radios requires better flexibility and reconfigurability to achieve compatibility between heterogeneous devices. SDR is one such platform that could achieve this. We suggest employing SDR in integrated IoT-5G/B5G/6G radio communication networks. SDR-enabled network components offer features such as decimation with anti-aliasing (before decimation) and upsampling with interpolation.

The SINR resampler is a key component in the SDR relay. The key steps describing its functionalities are as follows.

Signal sampling: The SINR resampler continuously receives incoming signals from various sources. These signals are inherently variable in their SINR due to key factors: propagation distance, interference, and environmental conditions.

Signal analysis: The SINR resampler performs real-time analysis of the SINR. This analysis is typically achieved through sophisticated signal processing algorithms and ML models (for example, reinforcement learning and federated learning), leveraging the power of AI in general.

Adaptive sampling rate adjustment: Based on the SINR assessment, the SINR resampler intelligently adjusts the sampling rate of the incoming signal. When the SINR is high, and the signal is clear, the resampler can reduce the sampling rate to conserve resources. Conversely, when the SINR is low, and signal fidelity is compromised, it can increase the sampling rate to capture more data points for accurate reconstruction.

Signal Reconstruction: After adjusting the sampling rate, the SINR resampler reconstructs the signal with the modified data points. This reconstructed signal is then forwarded for further processing and transmission.

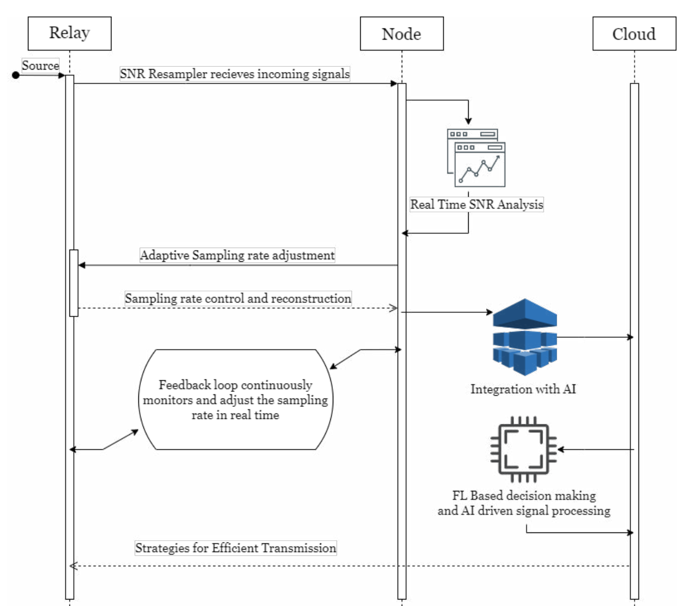

Fig. 1. The interface acting as an adaptive control component that dynamically tailors the sampling rate of incoming signals. Here, node refers to Raspberry Pi system.

A relay node is an essential component of a cooperative radio communication network. The intermediate relay nodes receive and then transmit data to destination nodes in the network, preferably with additional signal processing to improve network performance [7]. The relay node assists in extending the reliable transmission range of the network, overcoming multipath fading caused by various physical phenomena.

Unlike the conventional relays that operate in a constrained spectrum determined by the network controller, SDR relays bring several additional features that are especially useful for integrated heterogeneous networks [7]. However, several critical challenges can hinder their optimal performance. Some of these challenges are as follows.

- In the heterogeneous RCNs, security is a significant challenge due to varying scales of complexity and dynamics of channels and heterogeneous protocols in their respective protocol stacks. SDR relays must be designed with robust security features to ensure the confidentiality, integrity, and availability of sensitive data.
- Affordability of possessing new radios is another challenge. New software-centric intelligent technologies are being developed to reduce the cost of cooperative SDR relay-assisted networks. Some of these include network virtualization, cloud computing, open 5G radio access network (RAN), private 5G RAN.
- Power adaptation policies can also be integrated with cooperative conventional relay-assisted radio networks. However, in the heterogeneous network, signals experience various factors affecting the quality. Multi-physical layer (PHY) based SDR relays must be designed to adapt to changing signal conditions and optimize signal transmission parameters in such heterogeneous and hybrid (for example, RF/FSO/mmWave) networks [8].
- In the dynamically complex mobile satellite-cellular-IoT-Wi-Fi integrated networks, compatibility is another challenge, and new technologies are being developed to ensure that cooperative SDR relays are compatible with a wide range of network components and standards.
- Scalability is another key challenge in heterogeneous RCNs. Due to their programmability and adaptability, it is easy to deploy cooperative SDR relays and integrate them with new technologies such as metaverse. The SDR relays with the inclusion of knowledge-based systems designed based on AI and fuzzy logic deliver superior performance.

III. Novelty and Contribution

There do exist Cooperative SDR relay network implementations in the literature. However, the network model that we propose is novel due to the additions of fuzzy logic and ML features. The following explicitly states our work's novelty and specific contributions.

- *Ad hoc network selection in wireless systems:* A thorough examination of the existing literature reveals that the current modes of network transmission do not address the problem of network selection in the context of ML-enabled or fuzzy logic-enabled communication systems. Through this work, we propose a novel cooperative SDR relay-assisted network framework based on ML and fuzzy logic, which enables superior performance.
- *Energy efficient network design:* Energy efficiency is a critical concern for sustainable next generation radio communication networks, which should also be secure and efficient. Specifically, we focus on measuring the power consumption of the fuzzy logic and AI-powered, ML-enabled SDR relay system to analyze its performance in the context of energy awareness [9]. This integration ensures that the resulting system meets the necessary quality of service (QoS) requirements of future heterogeneous IoT-enabled wireless networks.
- *Scalability study:* For validation of the physical realization, we consider a Raspberry Pi (RPi) 4 model, which can be scaled to include multiple other avenues of network transmission lanes [10]. RPi is user-friendly and provides enough flexibility.

IV. SDR Relay-Assisted Network Model

The key idea of the proposed cooperative RCN model lies in selecting the radio transmission path via intelligent and efficient next generation SDR relay. This way it is possible to achieve the most efficient end-to-end secure and reliable transmission of data [11].

We consider the RPi model-based platform for validating our approach of using fuzzy logic and AI to enhance the performance of radio communication networks. RPi offers benefits such as computation capabilities, low cost, and scalability. The device can be used as a relay node in a transmission lane of radio communication. In heterogeneous, complex radio networks, resource management is challenging. Proper management of network resources is possible by offloading computationally intensive tasks like cloud processing [4]. Further, employing AI (specifically, efficient ML algorithms) and data analytics could help to ascertain the optimal ways of transmitting data [12]. For this purpose, we can have one of the proposed intelligent, reliable, and secure transmission methods, each explored in detail in the later sections.

A. Towards SDR−enabled intelligent network

Data transmission in plain or conventional relay-assisted cooperative radio communication networks occurs over a network infrastructure without reconfigurable and flexible features, which are not flexible for integration with IoT and related architecture. In the conventional cooperative RCN, the communication protocols involve signal reception, signal processing, and signal transmission stages appropriate for a specific bandwidth or a few choices of spectrum. In an SDR relay node, on the other hand, the signal reception stage involves receiving signals whose spectra lie in different frequency bands, namely, RF, millimeter wave (mmWave), ultra-wideband, etc.

While SDR relay brings several performance-improving features, SDR relay-assisted cooperative RCNs could offer better QoS in security-sensitive and energy-constrained applications. We present some key features of such a relay node. It is possible to implement these functionalities in SDR relays, which can be mounted on unmanned aerial vehicles (UAVs) in vehicle-to-drone (V2D) communication networks.

B. Fuzzy logic based SDR relay transmission

In this section, We further extend such an intelligent system with an additional popular logic base called fuzzy logic. An adaptive-neuro fuzzy logic-enabled network employs ML algorithms to analyze data patterns and optimize signal transmission parameters, providing significant advantages over traditional transmission methods. Thus, an SDR relay with an integrated fuzzy logic-enabled cooperative SDR relay network is promising to build and deploy secure cooperative 6G radio communication networks.

In fuzzy logic-enabled SDR relay transmission protocol, data is meticulously broken down using decimation to retain the fidelity of the signal while drastically reducing the scale of the data for efficient transmission. Fuzzy logic algorithms then analyze this data to determine the optimal transmission parameters, adaptively adjusting to changing signal conditions in real time. This results in improved transmission efficiency, reduced signal interference, and superior security and energy efficiency performance. Furthermore, fuzzy logic-enabled networks have a lower computational overhead, making them more efficient for real-time signal transmission [13].

The proposed next-generation cooperative SDR relay networks could meet the requirements of sustainable and secure 6G with a high level of security through encryption and access control. A Mamdani Controller is judicially used while implementing the Fuzzy Logic Controller.

C. Additional remarks on AL-enabled FL SDR relay

Cooperative SDR relay-assisted radio communication networks with AI integrated FIS could outperform their conventional counterparts in terms of QoS. This superior performance is because fuzzy logic-based or adaptive neuro-fuzzy logic algorithms could enhance the decision-making ability of the relay nodes, which could optimize the end-to-end performance. Automated Fuzzy logic-based algorithms can efficiently handle the imprecision and uncertainty associated with received signals, making the transmission process more reliable and efficient. In such a network, the transmission process involves encryption techniques to maintain security [14].

However, these additions could increase the complexity of the SDR relay node. Novel green computing approaches could be employed to compute complex algorithms via multi-access edge computing (MEC). This way, the implementation complexity of such modern cooperative SDR networks can be reduced with decentralized computing. However, this requires communication between these computing servers to the intelligent SDR relay that decides whether to forward the information to the destination node or stop forwarding data to conserve precious network resources.

V. Filtering and Decimation in SDR relay

We now describe the decimation algorithm's role and its significance. Decimation serves a pivotal role in the SDR relay, contributing to the overall functionality of the cooperative RCN. Some salient features are as follows.

Resource optimization and balanced network performance : Decimation strategically reduces the processing burden by selectively discarding samples from the incoming signal. This key signal processing operation optimizes resource utilization and bandwidth, aligning with the key objective of cost-effective and efficient radio communication.

Signal quality enhancement: By acting as a filter, Decimation enhances signal quality by removing high-frequency noise and interference. Removing unwanted samples ensures reliable and secure signal transmission, a critical ingredient of the SDR relay we proposed in this work.

Adaptive rate Sampling: Decimation, in collaboration with the SINR Resampler, adapts the signal's sampling rate based on real-time diverse SINRs in dynamic fading channels. This adaptive rate sampling optimizes resource allocation while maintaining signal integrity.

Compatibility and integration: By adapting the signal to meet downstream process requirements, Decimation ensures system compatibility, preventing bottlenecks and fostering a cohesive operation.

VI. Simulation results and interpretations

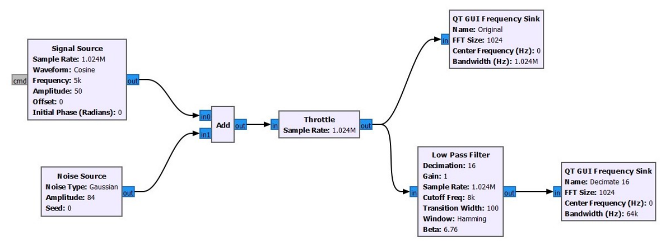

Fig. 2. Block diagram for decimation of signals in the RTL-SDR platform [15].

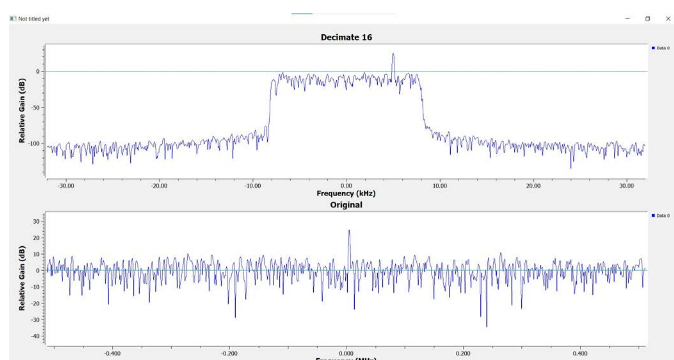

Fig. 3. A representative result on filtering and decimation.

We now present the simulation results we obtained. Firstly, we present the result of decimation, where the bandwidth needed to transmit the signal has now significantly been reduced. Fig. 2 and Fig. 3 show the decimation algorithm and its associated result, respectively. Further, we also observed that the latency is lowered. By observing the frequency response of the signal data, it can also be noted that the SINR of the signal has also been improved over a factor of $\sim$ eight times. However, exact improvement depends on the decimation rate and filtering techniques employed for a specific application. This simple result that we presented enabled us ample processing power to scale up on the RPi model. Unlike conventional cooperative relays, SDR-based relays are highly flexible and reconfigurable, enabling their use in 5G-IoT and beyond 5G-IoT (B5G-IoT) networks. Setting an appropriate decimation factor as needed by the application is possible with additional features such as fuzzy logic, which is computationally less complex.

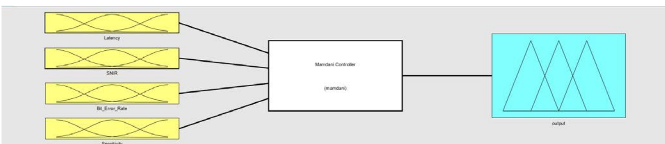

Fig. 4. An illustration of Mamdani fuzzy logic controller.

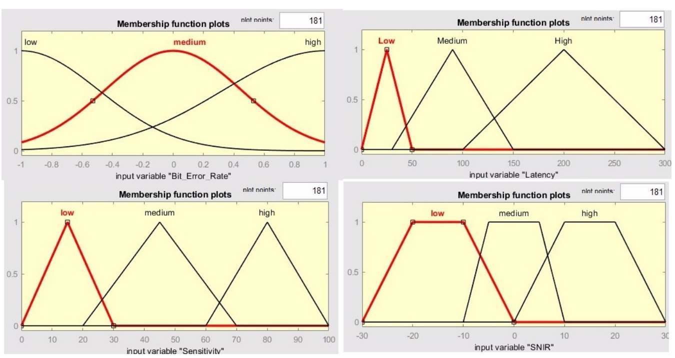

Fig. 5. Input membership functions of the Mamdani fuzzy logic controller.

Fuzzy logic controller: To validate the proposed system of fuzzy logic-based SDR, we consider the Mamdani-type fuzzy logic controller (FLC) as illustrated in Fig. 4. It is a popular type of fuzzy controller that works based on linguistic variables and rules to make decisions based on uncertain or ambiguous input data. With the recent developments in semantic communications, this approach is useful for 6G and beyond communications. Mamdani-type FLC is often preferred over other types of fuzzy controllers because it provides a transparent and intuitive way to model complex systems and enables the incorporation of knowledge base useful for intelligent and efficient decision-making.

The controller consists of three primary components: the fuzzification module, the rule base, and the defuzzification module [16]. The fuzzification module converts crisp input data into fuzzy sets, which are then used in the rule base to determine the appropriate output. The rule base contains a set of rules that define the relationship between the input and output variables. Finally, the defuzzification module converts the fuzzy output into a crisp output value. Fig. 5 depicts the input membership functions of the Mamdani Controller. The surface plots of fuzzy outputs in Fig. 6.

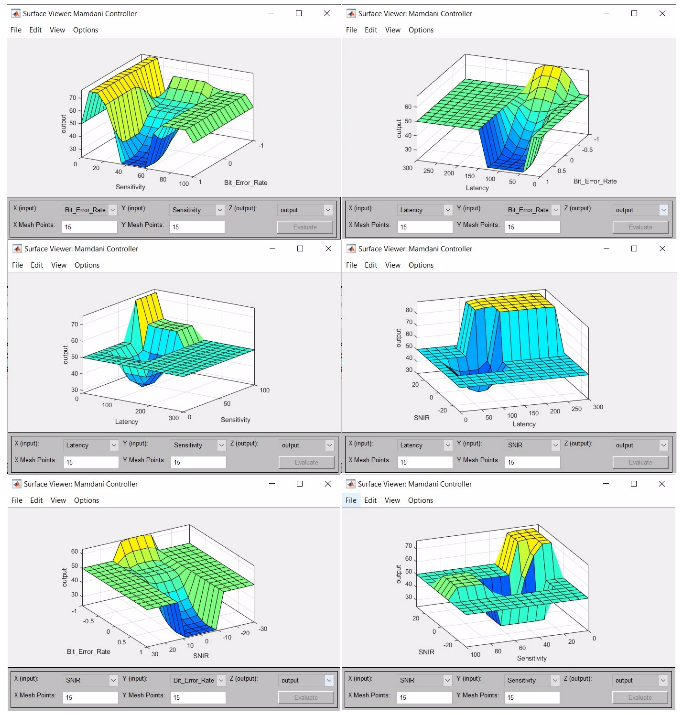

Fig. 6. Surface plots of the fuzzy outputs.

We use the RADIOML $2018.01A$ dataset to train the ML model, a key ingredient of the SDR relay system. The following tables present some of the numerical results we obtained. We present the statistics for three key performance measures: latency, bit error rate, and SINR.

TABLE I
STATISTICS FROM SIMULATIONS OF THE PLAIN TRANSMISSION MODEL USING CLOUD COMPUTING.

Performance measure	Measured value
Latency (ms)	17
Bit Error Rate	2.5×10^{-4}
SINR (dB)	13

TABLE II
STATISTICS FROM SIMULATIONS OF A FUZZY LOGIC BASED TRANSMISSION MODEL USING CLOUD COMPUTING.

Performance measure	Measured value
Latency (ms)	19
Bit Error Rate	1.1×10^{-4}
SINR (dB)	24

In the tables, we presented the numerical results obtained on various performance measures: latency, bit rate error, and SINR. We observe that conventional transmission achieves the lowest end-to-end latency, higher bit rate error, and a low SINR. Furthermore, we observe that using fuzzy logic-based and AI-powered SDR achieves superior performance results.

VII. Concluding Remarks and Future Research

We proposed a novel, intelligent, and secure next generation radio communication framework that integrates fuzzy logic and AI-powered SDR relay systems. We analyzed and showed that such smart RCNs are promising for highly secure and efficient signal communication [17]. The proposed SDR relay node could serve as an intelligent and efficient repeater between the source and destination, optimizing the transmission process by adapting to changing signal conditions and minimizing signal interference [18].

Future research in this field could focus on further improving the reliability and security of these systems [19], as well as exploring their potential for use in emerging technologies such as the Internet of Things (IoT) and 5G networks [20]. With the emergence of quantum computing, the scope of processing power will increase exponentially [10].

FIS to ANFIS for next generation SDRs: It is assumed that the fuzzy logic algorithms utilized in the FIS are developed and implemented based on rigorous mathematical principles and logical reasoning. This assumption is valid and supported by extensive research and development in fuzzy logic-based systems, which provide a reliable framework for handling imprecise and uncertain data [14]. Extension to adaptive neuro-fuzzy logic algorithms could enhance the overall AI-powered 6G network's QoS and QoE.

SDR relay node to spectrum sharing nodes: Note that the SDR relay can be equipped with efficient hybrid PHY hardware and integrated with RPi 4 model. The choice is justified by the proven computation capabilities and versatility of RPi in various scientific and engineering applications [21]. The SDR relay node acts as a vital intermediary between the source and destination, optimizing the transmission process by adapting to dynamic propagation conditions and minimizing interference [22]. Further research could be towards employing spectrum sharing relay nodes (cognitive radio relay) and investigating the overall performance.

As technological advancements continue, we explore novel and innovative ways such as quantum key distribution (QKD), integrated sensing, computing, and communication to improve next generation radio communication networks [23]. Integrating fuzzy logic and AI-powered SDR relays with the 5G-IoT networks is a promising step towards achieving sustainable 6G networks [24]. Further research and development in this field will undoubtedly lead to breakthroughs and advancements in sustainable, secure, intelligent signal communication.

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