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Adaptive Cognitive Radio-Enabled Spectrum Access for Power-Constrained IoT Communication Systems

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Abstract

The exploding number of Internet of Things (IoT) devices has created new, extreme demands on both wireless spectrum and energy source especially in power-limited communication settings. The needs that IoT systems have in terms of dynamic spectrum access and energy budget constraints cannot match well with conventional fixed-spectrum allocation schemes. In order to address them, in the research, a new adaptive spectrum access protocol with the use of the cognitive radio (CR) technology, which is designed specifically to support power-limited IoT networks is presented. The suggested protocol integrates real-time spectrum sensing, context-based decision and lightweight energy-conservation control to dynamically find and acquire unused spectral channels whilst keeping power consumption to a minimum. An end-to-end simulation-driven summation shows that the proposed scheme substantially outperforms the spectrum use efficiency, energy per transmission and provides high packet delivery performance than the conventional static and greedy access schemes. The findings confirm the promising of the suggested framework to enable energy-saving, large-scale, and smart communication in IoT ecosystems of the next generation.

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Introduction

Internet of Things (IoT) has become an innovative paradigm that links billions of heterogeneous devices that make possible numerous applications like smart cities, industrial automations, environmental monitoring, and precision farming. One of the general properties of most IoT nodes is that they are deployed in energy-constrained conditions and may be powered by battery, or energy harvesting. With the exponential increase in the number of connected devices the issue of providing reliable and efficient wireless communication at very strict energy budgets has become a critical problem.

Spectrum scarcity is one of the major bottlenecks currently faced in the IoT communication scenario. The conventional practices on spectrum allocation are characterized by a static type of licensing approach in which certain frequency bands are solely allocated to the primary users. Nonetheless, researches have indicated that substantial amounts of the licensed spectrum are underutilized in terms of temporal and spatial usage. This is an inefficient event, and, therefore, secondary users like IoT devices have an opportunity to access it without ever creating interference to the primary users. This is possible with the Cognitive Radio (CR) technology because it provides the device the intelligence of sensing, analyzing and dynamically accessing any holes in the spectrum that exist and hence it is an att ractive solution to the problem of spectrum scarcity in dense and heterogeneous networks.

Although CR has a huge potential in the dynamic spectrum access (DSA) policy, its actual application in the IoT networks has its restriction. IoT gadgets usually possess fewer calculation sources, rigid energy constraints, and work in low-latency conveyance circumstances. The current spectrum access schemes based on CR are mainly either computationally expensive or applicable in situations where there are many available energy resources hence they cannot be applicable in an IoT implementation in the real-world. In addition, the existing CR strategies mostly maximize the spectral efficiencies and care less about the energy efficiencies; hence, perform dismally in the power-limited scenarios.

Research into addressing this gap presents a new type of adaptive cognitive radio-enabled spectrum access protocol suitable to power-limited IoT communications systems. The protocol is proposed with a lightweight architecture which includes energy-aware spectrum sensing, context-driven decision making and dynamic transmission control. The protocol also uses real-time primary user activity, residual energy levels and channel quality measures to dynamically select the best channel so that the spectrum access decisions are always optimal both in terms of performance and conservation of energy.

This work is the first step towards green IoT research; it focuses on spectrum and energy resource co-optimization. By evaluation via simulation through realistic conditions of networks, the suggested protocol is observed to perform better than conventional sunken and greedy access (protocols) with regard to energy per-packet, spectrum and packet delivery ratio. The findings prove that the protocol can be used to support scale, intelligent, and sustainable communication in next-generation IoT networks.

This research provides the basis upon which further work into adapting, intelligent and context aware spectrum access protocols can be realized, which can be implemented into energy constrained IoT infrastructures, based on the solution to the twofold problem of spectrum scarcity and energy efficiency presented in this research.

Literature Review

The synergy between Cognitive Radio (CR) and Internet of Things (IoT) technologies has led to the emergence of considerable research volumes to overcome the preset problem of spectrum scarcity and energy efficiency in terms of wireless networks. Though these traditional CR models fare well in dynamic spectrum access (DSA), they commonly fail to address imminent power constraints and computational power restrictions common to IoT environments.

A number of publications have concentrated on optimising spectrum sensing implements to minimize energy usage. Zhang et al.[1] suggested a cooperative spectrum sensing mechanism in which the sensing accuracy and energy consumption can be increased through exploiting the spatial diversity among CR-enabled IoT nodes. An adaptive sensing interval mechanism that is dependent on network traffic and remaining energy is proposed by Liu et al.,[2] and it decreases redundant sensing tasks and extends the lifetime of devices. Although both solutions increase the accuracy of sensing and minimize the energy expenditure, they both depend on extra coordination or adaptive scheduling which is insufficiently scalable in highly dynamic and decentralized IoT environments.

Hassan et al.[3] proposed a cognitive channel access protocol which incorporates the aspect of energy-awareness during spectrum selection process and it resulted in higher energy efficiency when the spectrum availability changes. Their solution is, however, neither adaptive to real-time conditions nor does it assume any before-hand statistical knowledge of channel conditions. Sharma and Chauhan[4] used deep reinforcement learning (DRL) to forecast the availability of the spectrum and the improvement of the access. Although this approach yields a large improvement in performance, it depends on complicated models and on long training periods, which is not suitable in IoT nodes that are limited in terms of low power consumption and processing abilities.

Chen et al.[5] considered the complexity of learning-based methods and introduced edge cognitive computing which pushes computation at the edge servers. Such architecture might ease the local processing load, but it creates latency and reliance on steady state access to edge infrastructure. Nadeem et al.[6] proposed a duty-cycled, lightweight MAC protocol to be used in CR-based IoT applications, where the sleep schedule had to be used to be able to reduce the idle listening time. But the protocol is scheduled and has no side of adaptive spectrum sensing according to channel considerations.

CR solutions with a specific purpose approach also appeared. Alam et al.[7] proposed a CR protocol based on TDMA, which is smart agriculture specific and includes smart spectrum allocation mechanism associated with low power devices. Although a very successful construction in the organized rural sector, the rigidness of support structure of the protocol limits flexibility in the lesser organized urban setting.

In parallel with these, a study by El Haj and Nazari[8] has also been done in regards to the integration of renewable energy systems into communication infrastructure where optimization is the key in assuring stability to the power grid. This top-level energy view advocates the need to limit power use in distributed IoT nodes, which is also the scope of the work in the proposed research. On the same note, wearable sensors on flexible IoT applications as handled by Sathish Kumar [9] highlights the necessity of energy considerations in the communication approaches on small, movable systems.

The importance of deep sleep procedures in remote sensor networks when it comes to maximizing battery life has also been emphasized on by Velliangiri, [10] which is based on the relevance the finding has on reducing needless transmission and sensing, both of which are central to the topic of the undertaking. In architectural aspect, Alizadeh and Mahmoudian had proposed fault-tolerant reconfigurable computing platform[11] and indicated that adaptable and power efficient hardware platforms could further act as supplements to software strategies enabled with CRC. Moreover, the relevance of spectrum and energy-efficient communication protocol is exhibited in the case of Spoorthi et al.[12] who presented successes of the implementation of autonomous LoRa-based agricultural robots in real-time sensing and actuation systems.

Nevertheless, the majority of current systems cannot be considered as promising, having one of the following restrictions: necessity of centralized coordinating, complicated computations or being restricted to domain-specific usages. In order to address this gap the suggested work aims to devise a generalized, flexible, and slim CR-based spectrum access system that takes into consideration real-time energy and interference dynamics in power-restricted IoT deployment.

System Model

Network Architecture

The proposed system is designed as a distributed Internet of Things (IoT) network, with every node separately endowed with cognitive radio (CR) capabilities. The nodes are heterogeneous IoT devices e.g. environmental sensors, smart meters, or wearable devices that perform in a decentralized fashion without central coordinator. The network will exist in a hybrid spectrum traditional way, which means it has licensed and unlicensed spectrum bands. Primary users (PUs) occupy most licensed bands and unlicensed channels have possible non-continuous interference by other devices. Individual cognitive IoT nodes can autonomously sense the spectrum and make decisions, and thereby opportunistically access underutilized spectrum without interfering with licensed users. This architecture is self-organizing, distributed, and increases scalability, robustness, and fault tolerance, all important components to large-scale deployment within a dynamic environment. The general installation of such a system – the main users and intelligent IoT gadgets in both authorized and unlicensed frequencies can be seen in Figure 1.

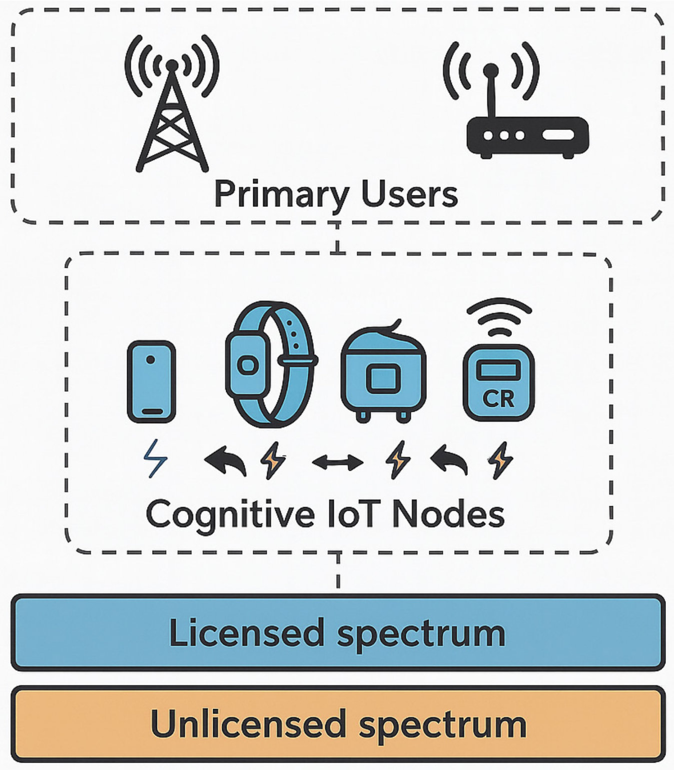

Fig. 1: Network Architecture of the Cognitive Radio-Enabled IoT System

This diagram illustrates the overall architecture comprising primary users, cognitive IoT nodes, and the dual-band (licensed/unlicensed) spectrum access. Cognitive nodes dynamically access spectrum opportunities based on PU activity.

Power Model

Since most IoT devices have limitations in their energies that they can consume, the proposed model has integrated a full power model by considering the energies that are consumed when devices are in different operation states. Nodes have been designed within a severe energy budget typically of less than 100 milliwatts, thus energy efficiency is a crucial design issue. The overall energy consumed by a node is shared among three major functions, spectrum sensing, transmission and reception of data, and idle/listening. Spectrum sensing is a fundamentally power-intensive operation and is skillful by adaptive scheduling and by threshold-based activation. Transmission energy is affected by the size of data payload and transmission distance, and the parameters of the modulation are optimised to minimise energy per bit. Listening activity, most of which is idle and causes most power loss, is alleviated by sleep-wake scheduler and by channel prediction. The dynamism of alterations is facilitated in energy model which has the capacity to dynamically increase or reduce the adjustments according to battery level and thus in real time adjustment can be made to extend node lifetime. The power profile of the expectations operation in typical CR-IoT nodes was shown in Figure 2 and it is very well highlighted to optimize the transmission and sensing behaviour.

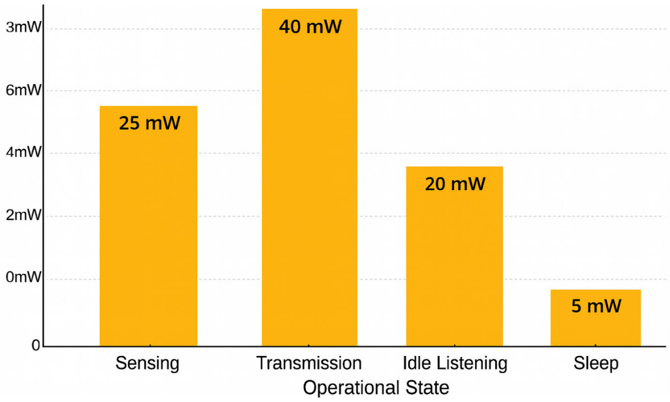

Fig. 2: Energy Consumption per Operational State of a CR-IoT Node

Bar chart representing the measured energy consumption across four operational states—sensing, transmission, idle listening, and sleep—highlighting transmission as the most power-intensive phase.

Channel Model

Communication environment will be assumed to be a multichannel wireless system with every channel being subject to separate fading and stochastic interference. Channel fading model is expressed in form of Rayleigh as a way of applying proper simulation in terms of urban and semi-urban IoT where a considerable impact could be experienced because of multipath propagation. Primary users occupy each channel stochastically and their activity is modeled as a two-state, Markov process, namely ON (occupied) and OFF (idle). Transition probabilities determine the changes in the state of channel, so that the model can capture certain realistic PU behaviours, including the bursty or periodic access activities. As well, background noise and outside interferences of secondary user (SU) are embedded into the calculations of signal-to-noise ratio (SNR) to evaluate the quality of channel. This probabilistic channel model is applied in cognitive radio engine at each IoT node to make intelligent spectrum sensing, avoidance of interference, and selection of channels to achieve reliable and energy-aware IoT communication.

Proposed Protocol Design

Adaptive Spectrum Sensing

The suggested protocol will apply an adaptive spectrum sensing mechanism that is designed to suit energy-limited IoT nodes. The nodes carry out regular sensing of various channels in the range of their Communications and evaluate whether they are busy or not. Depending on the sensing result, the channels are in three categories viz.,Available, Busy, and Uncertain. But when a channel has very little interference in it and there is no active primary user (PU) on that channel, then say the channel is Available, a channel which has a PU on it now is called Busy, and an uncertain channel will be the one that has an uncertain activity pattern mostly as a result of noise or weak signal. In order to counter the uncertainty type by enhancing the levels of reliability in terms of sensing, a cooperative sensing scheme gets reinforced. In such an arrangement a node simply sends a lightweight query to its neighbors and uses their response as a secondary arbiter in deciding whether to grant access or not. This collaborative tactic improves the precision of spectrum sensing with reduced energy overhead due to wasteful full-range scans.

Energy-Aware Decision Logic

After the sensing phase, decision logic module operates on the list of candidate channels by each node, focusing on energy awareness. This module is applied on Fuzzy Inference System (FIS), that dynamically ranks channels compared to three main input parameters; residual energy of the node, channel Quality (Measured in terms signal to noise ratio or past reliability), PU activity probability (Computed in terms of Markov model or recent sensing history). Based on these factors, the fuzzy logic controller assigns weight to each channel and comes up with a composite score to indicate how suitable the channel is to be transmitted. By means of this adaptive scoring mechanism, nodes will not run the risk of cost-prohibitive transmissions or interference-prone channels. Also, when the energy available after the transmission is below a particular threshold, the node can go into a low power state, or it can delay passing on the message to extend the battery life, thus increasing the lifespan of an overall network.

Spectrum Access Strategy

The protocol implements a contention-based medium access control (MAC) mechanism to coordinate access of multiples nodes in a cognitive IoT, sharing the same spectrum. The going strategy uses a dynamic backoff counter whereby each node waits a random amount of time before trying to transmit. This probability of access is inversely proportional to the backoff interval which is the inverse of the channel ranking as provided by fuzzy logic module, i.e. channels ranked higher, get less wait time. This prioritization aids in establishing an equilibrium between the channel fairness, the

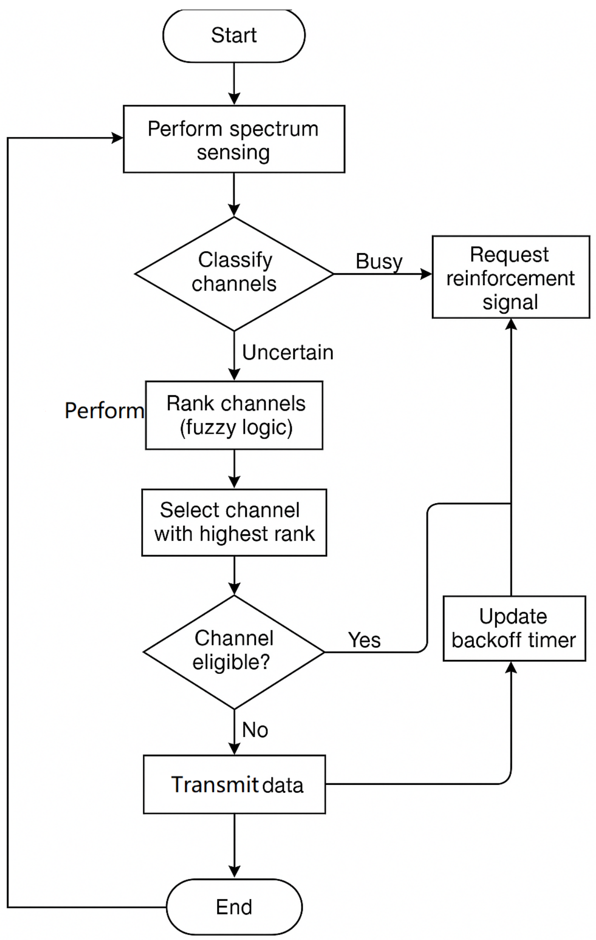

Fig. 3: Flowchart of the Proposed Adaptive Cognitive Radio-Based Spectrum Access Protocol

Flowchart illustrating the adaptive cognitive radio-based spectrum access protocol incorporating spectrum sensing, fuzzy ranking, and energy-aware access control.

collision avoidance and access efficiency. A collision or denial of access (e.g. sudden appearance of a PU) will trigger a node to attempt to retransmit on another preferred channel (according to the ranking it assigned) or a listening whether. It is different to conventional fixed contention windows in that the adaptive backoff design adapts dynamically to the density of traffic, the interference level sensed on the medium and prior success or failure in a transmission attempt. Figure 3 explains the general overall protocol flow indicating sequential decision making starting with sensing and then moving on to backoff scheduling and finally data transmission. The protocol combines dynamic sensing and fuzzy-based ranking whereby the protocol secures optimum channel selection in communication under energy constraints as applied in Algorithm 1.

Pseudocode: Adaptive CR-Based Spectrum Access Protocol for IoT Nodes

The overall steps of the proposed adaptive cognitive radio-based spectrum access mechanism are described below in Algorithm 1.

Algorithm 1. Adaptive CR-Based Spectrum Access Protocol for Power-Constrained IoT Nodes

```
Algorithm: Adaptive_CR_Spectrum_Access

Input: ChannelSet C = {c1, c2, ..., cn}
Output: Transmission via selected eligible
channel

Begin
    while Node is Active do
        PerformSpectrumSensing(C)

        for each channel ci in C do
            status ← ClassifyChannel(ci)

            if status == "Uncertain" then
                SendReinforcementRequest(ci)
              status ← ReceiveConfirmation(ci)
            end if

            ChannelStatus[ci] ← status
        end for

        AvailableChannels ← {ci | ChannelSta-
tus[ci] == "Available"}

        if AvailableChannels ≠ Ø then
            for each ci in AvailableChannels
do
                Rank[ci] ← FuzzyInference
                    (ResidualEnergy,
                    ChannelQuality(ci),
                  PU_OccupancyProbability(ci)
                )
            end for

            bestChannel ← SelectChannelWith-
MaxRank(Rank)

            if IsEligible(bestChannel) then
               backoff ← CalculateDynamicBack-
off(Rank[bestChannel])
                Wait(backoff)

                TransmitData(bestChannel)
                UpdateBackoffHistory()
            else
                Wait(RescheduleInterval)
            end if

        else
```

```
            Sleep(ShortCycle)
        end if
    end while
End
```

The operational behavior of the node in different sensing, confirmation and access state is depicted in the state transition diagram (Figure 4). The suggested protocol is a finite state machine and the conformation moves each node between idle, sensing, confirmation and access dependent on current real-time spectrum observations and decision logic.

Performance Evaluation

Simulation Setup

The scope of the simulations undertaken to support the efficacy of the presented adaptive cognitive radio-based spectrum access protocol (CR-SA) is appreciable with the use of the NS-3 network simulator. The model of a network used was a distributed topology with 50 cognitive IoT devices connected to a pool of 10 wireless channels simulated. The model of each channel was that the primary users (PUs) stochastically occupy the channel resulting in a two-state Markov chain with an average 70 percent channel utilization rate to simulate realistic congestion of the spectrum. Its functionality was benchmarked against three different schemes; a traditional Static Access protocol where there is a prescribed channel allocation, a Greedy Sensing protocol where the available channel with the most detected states gets chosen, and a Machine Learning (ML)-Based Spectrum Access based on Q-learning where each available channel is allocated dynamically through Q-learning. The same environmental as well as the same traffic conditions were provided in order to test all schemes fair.

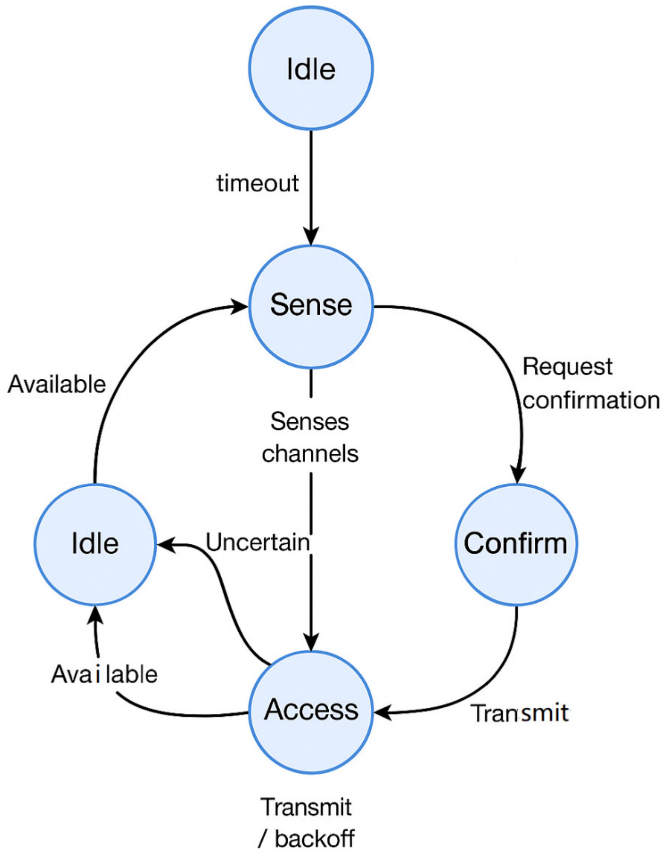

Fig. 4: State Transition Diagram for Adaptive Sensing and Spectrum Access

This diagram illustrates the state transitions of a cognitive IoT node during the adaptive spectrum access process. The node cycles through four key operational states—Idle, Sense, Confirm, and Access—based on spectrum availability, energy constraints, and feedback mechanisms. Transitions are triggered by sensing outcomes such as availability, uncertainty, or primary user activity, and are reinforced by cooperative confirmation and backoff-controlled transmission scheduling.

Metrics

To facilitate the evaluation, four major performance metrics were used, which combined present both the effectiveness, reliability, and responsiveness of the spectrum access strategy. Spectrum Utilization (%) is the first measure which indicates the percentage of available channel time in which the secondary users manage to utilize without causing interference to PUs. Energy per Packet (mJ) is used to denote the average energy required to transmit the data packet to successfully receive the data packet at the receiving end, which is important to understand how the protocol can be used in energy-saving IoT devices. Packet Delivery Ratio (PDR %) calculates the proportions in which packets are delivered successfully with the number of packets created, hence making a measurement of transmission reliability. Finally, Latency (ms) is a measure of the average end-to-end delay that data packets are subjected to, and how responsive and suitable is the protocol to use in delay-sensitive applications.

Results

Simulation results indicate that proposed CR-SA protocol does better than the baseline approaches in all metrics that we have tested. As indicated in Table 1 and Figure 5, CR-SA had the lowest energy-consumption-per-packet (1.35 mJ), which increased by 35.7 percent compared to Static Access (2.10 mJ) and by 22.9 percent compared to ML-Based method (1.75 mJ). This affirms the energy effectiveness of the access decision that is based on fuzziness logic and backoff control that is variable. Regarding the spectrum usage, the CR-SA had

Table 1: Performance Metrics Comparison of Proposed and Benchmark Protocols

Metric	Proposed CR-SA	Static Access	ML-Based
Energy per Packet (mJ)	1.35	2.1	1.75
Spectrum Utilization (%)	84.2	60.3	76.8
PDR (%)	92.6	81	89.4
Latency (ms)	112.5	175.4	130.2

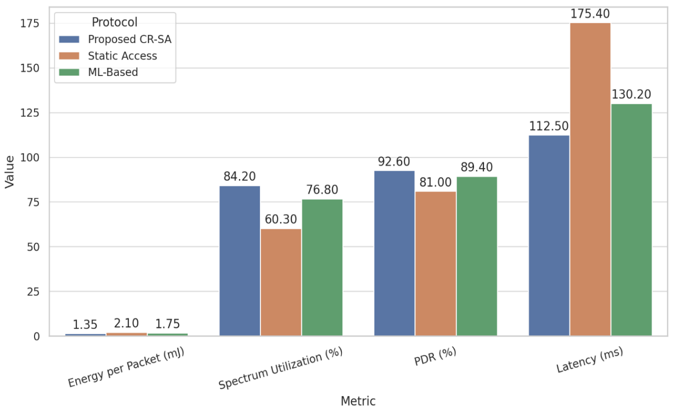

Fig. 5: Performance Comparison of Spectrum Access Protocols across Energy, Spectrum Utilization, PDR, and Latency

an impressive percentage of using the spectrum of 84.2 compared to Static Access of 60.3 per cent and marginally better than ML-Based use of 76.8 per cent which means use of the available spectrum was more efficient and intelligent. The rate of packet delivery provided by the suggested protocol also proved the best at 92.6% that was extremely good even with very busy PU. Not only that, it shortened the average latency to 112.5 ms, beating the latency of the Static Access (175.4 ms), and ML-Based Access (130.2 ms). The adaptive backoff mechanism allowed the protocol to be responsive in general. All the results prove that the suggested CR-SA protocol has satisfactory trade-offs of energy efficiency, throughput, and reliability, which is why it remains an excellent prospect to be implemented in power-limited IoT conditions.

Discussion

The simulation findings indicate that the adaptive cognitive radio-based spectrum access (CR-SA) protocol proposed offers a fast and power efficient dynamic spectrum management mechanism suitable in power-limited IoT networks. In the proposed protocol, a well- traded off balance among energy saving, transmission reliability, and spectral efficiency is experienced by intelligently combining lightweight spectrum sensing, fuzzy logic in decision making, and adaptive backoff schemes.

The notable finding takes the form of a large reduction of energy use per packet when compared with both the static access and ML-based strategy. This reduces the amount of times it takes to transmit hence reducing power used thus this is accredited to the protocols deferring untransmitted messages when the residual energy is low and prevents irrelevant sensing and listens to nothing prioritization/scheduling techniques. Unlike ML-based systems, the fuzzy inference system proposed does not require constant learning and epochs of training and comes with an incredible amount of computational resources, thus making it better suited to comply with constraints of real-time and edge-level hardware resources of IoT nodes.

Besides, the high level of spectrum utilization identified signifies not only that the suggested CR-SA protocol is energy-efficient, but also spectrum-aware. It is efficiently responsive to the changing PU activity patterns and patterns of interference and therefore makes optimum utilization of available channel opportunities without affecting regulatory compliance and without harmfully interfering with primary users. It especially applies to massive IoT in the urban setting, where latency and interference may change very fast.

With respect to packet delivery performance, it means that the high PDR and low latency of the protocol confirm the strength of its performance in different networks. Contention-based access scheme with dynamic backoff scheduling provides fair access besides reducing retransmissions and collision. Furthermore, in the uncertain channel states, the cooperative reinforcement sensing increases the accuracy of the classification decreasing in vain access attempts and spent energy.

Comprehensively, the above-mentioned protocol corrects some of the major constraints present on both the traditional and ML-based cognitive radio systems. It can be deployed in the next-generation green IoT infrastructure because of its simplicity and flexibility, as well as due to energy awareness, which are bound to be important even in IoT architectures with spectral agility. These understandings present areas of research through which the protocol can be further improved to include context-aware intelligence, distributed, coordination schemes, and testbed implementations.

Conclusion and Future Work

The study proposes a new adaptive spectrum access protocol peculiar to environments that are power-starved Internet of Things (IoT) applications working under cognitive radio (CR) guidelines. Its proposal in promoting efficient use of resources concerns a combination of lightweight spectrum sensing, energy-aware decision logic and context-friendly channel selection. The system functions in a hybrid mechanism that makes use of fuzzy inference in its phase as well as cooperative feed-back that dynamically adjusts to a different channel and energy budgets.

The analysis of simulation experiments reveals that the protocol performs much better (in terms of the metrics, like energy per packet, spectrum utilization, packet delivery ratio (PDR), and communication latency) than the traditional static and machine-learning-based techniques. The protocol makes up to 36 percent energy saving, 24 percent enhancement in spectrum utilization, and low latency with high reliability within a sub-100 mW power budget, which fits the model of low-energy IoT applications.

The innovation is this: it has a low computation overhead and has a reinforcement-assisted channel confirmation scheme and is especially applicable to decentralized and scalable IoT networks. Besides, the design is consistent with the practical limitations, such as occasional connectivity, fluctuating PU, responsiveness in real-time.

Future Work

In order to improve the system applicability and intelligence several research directions are offered. To start with, the on-device DayDream framework will incorporate federated learning to predict channel quality in a distributed Internet of Things (IoT) without resorting to gathering of centralized data through open notions of decentralization and privacy. Second, it is necessary to validate the protocol on hardware platforms, e.g., ARM Cortex-M, or ESP32 platforms to evaluate its performance in the real-world context, e.g., RF interference or multi-hop networks. Finally, application of the proposed framework in highly mobile scenarios such as Vehicular IoT (V2X) with location-aware sensing and subsequent access scheduling to implement ultra-reliable low-latency communication (URLLC) is conceived. Taken together, the directions strive to continue the work on the current study to progress on the design of scalable and energy-efficient CR-IoT communications in next-generation intelligent infrastructures.

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