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Communications of smart systems based on software-defined radio and internet of things

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Abstract: The Internet of Things (IoT) concept has many applications in smart systems, such as smart homes, smart cities, and smart healthcare systems. Many IoT-based systems have three layers: the things, the fog, and the cloud. IoT-based systems depend on a wireless telecommunication protocol to exchange data with sensors and actuators in the things layer. Bluetooth, Bluetooth Low Energy (BLE), Zigbee, and WiFi are examples of such protocols. These protocols use diverse and different transmit and receive modules that depend on a specific frequency. The challenge is to use a single, power-efficient, moderate-cost platform for the reception of wireless signals of these protocols in the fog layer and to work with the gateway's protocol for interoperability. The software-defined radio (SDR) is a reconfigurable radio frequency (RF) platform that can serve as a multi-frequency receiver. This research proposes in the fog layer an SDR platform and a gateway that receives data from this platform, reformats it into JavaScript Object Notation (JSON) to achieve interoperability, and transfers the information over HTTP(S) to online servers in the cloud layer. The developed system is moderate-cost, power-efficient, easy to set up, interoperable, and can be used for all IoT-based smart systems that follow the three-layer architecture.
Keywords: *Gateway, HTTP, IoT, Lime, SDR, Protocols, RF, SDR, Wireless.*

1. Introduction

Smart systems such as the smart home [1] smart city [2, 3] smart grid [4, 5] and smart healthcare system [6] employ the Internet of Things (IoT) [7] concept, which offers easy-to-setup and cost-effective ICT infrastructure [8]. Many IoT-based systems follow a three-layer architecture [9] :The things layer, which has sensors and actuators; the fog layer, which has a gateway where local decisions are taken; and the cloud layer, which has online servers where strategic decisions are taken. Wireless telecommunication protocols that transfer data between the things and the fog layers are short-range and low-power communication devices. These include wireless networks and protocols, mainly Bluetooth [10] Bluetooth Low Energy (BLE) [10] Zigbee [11] LoRa [12] and radio frequency identifiers (RFID) [13]. The challenge is to use a single, power-effective, moderate-cost device for the reception of wireless signals of these wireless protocols in the fog layer and to be able to work with the gateway for the IoT telecommunication protocol. The software-defined radio (SDR) [14] platform introduces the required technology as reconfigurable radio frequency (RF) modules to detect the telecommunication signals of these wireless protocols. The SDR platform is a reconfigurable system that can receive and, in some products, transmit wireless telecommunication signals of frequencies ranging from 0.1 MHz to 6000 MHz. This frequency range includes the most used wireless protocols: WiFi, Bluetooth, BLE, Zigbee, and LoRa. The SDR platform offers a unified and single cost-moderate and power-effective platform for the reception of these wireless protocols' signals. It acts as a data aggregator in the fog layer of the IoT system. Since the SDR system works in the physical layer, a

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gateway in the fog layer is proposed here to transfer the collected data over the Internet using JavaScript object notation (JSON) [15] over HTTP [16] to servers in the cloud layer. The JSON is a data format that ensures interoperability of communicating devices.

The SDR is a wireless platform consisting of two parts: the hardware and the software. Most of the SDR's operations are located in the software, where future upgrades can be executed without hardware changes.

There exist many SDR devices in the market, ranging from expensive units, like those of USRP™ [17] and HackRF [18] to inexpensive units, such as the USB-based RTL-SDR dongles [19]. Nevertheless, these dongles are used as PC-based receivers of digital video broadcasting terrestrial (DVB-T) signals; they cannot be used for sniffing WiFi, Bluetooth, BLE, and Zigbee signals. This is because their scan of RF signals is limited in the frequency range of 24 MHz to 1766 MHz. Using these dongles, we have an inexpensive solution and a good introduction to SDR theory and system design. However, it cannot transmit signals, has a limited bandwidth of 2 MHz, and has a limited frequency range that does not cover WiFi and Zigbee. The following Table 1 compares some SDR hardware platforms available in the markets and their features. The comparison is based on the tuning-frequency range in MHz, bandwidth in MHz, analog-to-digital converter (ADC) resolution in bits, transmission capability, preselect filters (indicated as RF design), minimum price in USD, the most suitable field of application, and the company or the society supporting the platform.

Table 1.
Comparison between some market-available SDR hardware platforms.

Platform	Range (MHz)	BW (MHz)	ADC Resolution	Tx	RF Design	Price[1] (USD)	Typical use	Website
RTL-SDR	24-1766	2	8	X	poor	< 30	hoppy, test	rtl-sdr.com
HackRF	1-6000	20	8	√	poor	300	hoppy, test	greatscottgadgets.com
RSP 1B	0.001-2000	10	14	X	good	133	education	sdrplay.com
PlutoSDR	325-3800	20	12	√	good	195	education	analog.com
LimeSDR-USB	0.1-3800	61	12	√	very good	625	cellular	myriadrf.org
BladeRF 2.0 xA9	47-6000	61	12	√	very good	860	cellular	nuand.com
USRP B210	70-6000	61	12	√	excellent	2156	cellular	ettus.com
Crimson TNG	DC-6000	325	16	√	excellent	17000	military	pervices.com

Note: [1] Minimum prices as of April 2025.

According to RTL-SDR.com [20] choosing the suitable SDR hardware platform depends on many factors, including signal-to-noise ratio (SNR), analog-to-digital converter (ADC) resolution, bandwidth, and RF design, among other factors. In order to cover all wireless networks and protocols proposed for IoT and smart systems, the SDR product should cover all frequencies in the RF spectrum. Nevertheless, HackRF has excellent bandwidth (20 MHz) and moderate price; it has poor RF design and low-bit ADC resolution, which leads, in some cases, to an inaccurate digitization process. Although USRP™ introduces expensive products, they cover the RF spectrum, have accurate 12-bit ADC, high bandwidth, and excellent RF design. Therefore, inexpensive RTL-SDR may be used where applications of frequencies are less than 1766 MHz, and the required bandwidth is less than 2 MHz. Other platforms must be employed for applications that work on higher frequency and bandwidth. However, a reasonable compromise between cost and performance may be required in such cases.

The field of application depends on the capabilities of the platform. For example, the inexpensive RTL-SDR is suitable for hobby and testing below 1766 MHz, PlutoSDR for educational purposes, USRP™ for cellular networks, and Crimson TNG for military applications. This paper proposes the LimeSDR-USB platform for testing basic applications of smart systems integrated with the IoT protocol (JSON/HTTP) to solve interoperability issues. Therefore, a gateway incorporating the SDR software and a Java-based program is developed. The Java program extracts the payload of these protocols, formulates the data into JSON format, and transfers the formatted data over HTTP to online servers. A comparison between HTTP and HTTPS is made, and HTTPS is chosen if secured communications between the fog and cloud layers are required. The developed system is moderate-cost, power-effective, setup-easy, interoperable, and can be used for all IoT-based smart systems that follow the three-layer architecture.

2. Literature Review

This section reviews the SDR applications in smart systems, including but not limited to smart homes, smart grids, smart agriculture systems, smart cities, and smart healthcare systems.

Many home automation systems use wireless communication protocols, such as Zigbee, WiFi, Z-Wave, and Bluetooth, for telecommunications between devices in the home network. For example, authors of Gvozdenovic, et al. [21] demonstrated the performance characterization of four different Zigbee devices at the physical layer using an SDR-based testbed. Receiver sensitivity experiments showed that the devices exhibit differences of up to 2-3 dB regarding their reception capability. The research results complement previous WiFi work and illustrate the flexibility of the developed testbed to serve as a cross-protocol evaluation platform. Authors of Hito, et al. [22] designed and prototyped a device that measures Z-Wave signal strength using an Airspy SDR platform for home security installations. They used it to aid installers in placing devices and troubleshooting device connectivity. Authors of Holla and Yellampalli [23] presented a technique based on the SDR concept to convert a standard TV receiver into a smart communication hub for smart home applications.

The SDR can support the smart grid in electric grids to enhance control, reliability, protection, and automatic optimization to operate its interconnected elements effectively and efficiently. For example, authors of Mohamed, et al. [24] proposed using SDR for partial discharge detection and localization at the user end in the smart grid. Authors of Hematian, et al. [25] designed an SDR testbed to create a Long Term Evolution (LTE) network to simulate significant data traffic from enhanced smart meters (eSM) of a smart grid. The design is based on IEEE C37.118.2 [26] and IEC 61850 [27] standards to assess the transmission of large data volumes of eSM over LTE networks. The research shows the effectiveness of scheduling eSM data traffic locally within the neighborhood area network. Authors of Gomez, et al. [28] proposed using the SMS to transmit the control information from the control center to a Doubly Fed Induction Generator (DFIG) of a wind turbine, according to the Smart Grid concept. The proposed wireless network was developed in an SDR transceiver connected to an OpenBTS platform. The receiver on the turbine side was developed in a microcontroller board with a GSM card, and the DFIG controller was implemented in a Digital Signal Processor (DSP) board. The results of the tests showed that the DFIG could be controlled according to the power references, considering that they vary at low rates.

Smart agriculture systems employ IoT technologies and SDR platforms in their architecture. For example, authors of Fatimatou, et al. [29] proposed a smart agriculture solution for the arid regions of Chad. The environmental data collection is achieved via IoT technologies, the reception of wireless signals via the SDR platform, the transfer of data to the Internet via MQTT protocol, and the data analysis via the Fledge platform. The approach improved agricultural productivity in areas facing significant climatic challenges. Authors of Ndiaye, et al. [30] presented an approach to modernizing Guinean agriculture by integrating SDR and IoT technologies. They proposed an architecture combining a 5G network based on the USRP B210 SDR platform with environmental sensors for agricultural monitoring. Experimental results demonstrate effective temperature and humidity monitoring and stable connectivity for agricultural applications. Authors of Pedapudi, et al. [31] focus on the wireless channel characterization for agriculture applications using a simulation-based approach. Results showed that the corrected channel parameters from the developed system yield values very close to the theoretical values.

Modern cities should cope with the requirements of a smart city. For example, an intelligent transportation system employs essential technologies for road infrastructure and smart vehicles. Moreover, weather conditions are monitored, and weather information is updated frequently, which helps disaster management. The SDR can be important in achieving smart city technologies in all sectors [32]. Sensors deployed within a city could monitor traffic patterns and determine optimum traffic routing. Authors of Habibzadeh, et al. [33] conceptualized deploying some sensor nodes (called Smart Boxes) in a part of the city. The smart box acts as an emergency cell phone network in any part of the city, thereby forming an emergency sub-infrastructure. To improve scalability, researchers used an SDR platform within the box. Experiments showed that the box could serve three LTE-based cellular users and be powered by a 50-100-watt solar panel or wind turbine, confirming its feasibility as a smart city node. Authors of Mukherjee, et al. [34] designed a cloud-controlled Internet of Vehicles (IoV) based service on a laboratory scale that is focused towards Ultra Reliable Low Latency Communication (URLLC) systems, which are capable of sensing and avoiding accidents. Authors of Mahmood, et al. [35] developed a cost-efficient platform based on SDR for receiving National Oceanic and Atmosphere Administration (NOAA satellites) data in Lahore, Pakistan. These satellites are operated at approximately 137 MHz frequency and provide weather data continuously.

The healthcare sector employed the SDR to serve its wireless communications. Authors of Taha, et al. [36] assessed the efficacy of Gaussian Minimum Shift Keying (GMSK) modulation in detecting SpO2 utilizing SDR. The research emphasized the advantages of utilizing the IEEE 802.11ah standard in loT healthcare applications, such as decreased power usage, extended communication range, and enhanced dependability. The study's findings offer valuable insights into the possibilities of GMSK modulation in wireless communication systems within the healthcare business. The research paper of Suárez and Timaná [37] investigated the use of SDR to create new and innovative applications that can improve lives and prevent workers' health problems due to occupational risks. Abnormal breathing patterns can indicate respiratory or cardiovascular diseases, and early detection is crucial for fast treatment. The research paper of Saeed, et al. [38] explores RF sensing technologies, specifically radar and WiFi, for detecting human breathing patterns. Radar-based systems utilize low-power RF pulses to capture subtle chest movements associated with breathing. In contrast, SDR-based systems analyze WiFi signals to detect variations caused by human chest motion. The proposed approaches offer non-intrusive, remote-operable, and cost-effective solutions for breathing detection. The research demonstrates the potential of RF sensing technologies in healthcare, eldercare, sleep monitoring, and emergency response systems, paving the way for enhanced well-being and safety.

The IoT benefits from the SDR technology. Authors of Lin, et al. [39] developed a wireless IoT platform based on SDR technology. Video surveillance and temperature sensing are integrated into the platform as typical IoT applications. The developed platform demonstrated high flexibility, stability, and reliability. Therefore, the authors argue that the platform can be the basic communication infrastructure in other IoT applications. Authors of Gehron, et al. [40] introduced a novel and cost-effective IoT Chipless RFID reader for long-range applications based on SDR and enhanced blind detection technique. The proposed smart reader is connected to the cloud of Long Range Wide Area Network (LoRaWAN) devices. After tag detection, the detected tag ID is sent using LoRa at 868 MHz to the things network application server through the LoRaWAN gateway. This arrangement enables the Chipless RFID tags to be integrated with the IoT LoRaWAN networks for wireless long-range applications up to several kilometers. Authors of [41] developed an IoT gateway based on an SDR platform. The developed prototype can route data to and from IoT applications, covering WiFi, Zigbee, BLE, and LoRa wireless protocols. A graphical user interface (GUI) ensures human intervention in the system and manages all the gateway activities. The gateway uses the MQTT protocol to transfer the received data to the Internet.

However, this paper uses the LimeSDR platform in the fog layer to wirelessly communicate with the IoT protocols of the things layer. A gateway is developed based on Java to format data in JSON and transfer the formatted data to cloud servers over HTTP. A comparison between HTTP and HTTPS is made, and HTTPS is chosen where secured communications between the fog and cloud layers are required.

3. Method

The SDR presents a solution for simplifying programmability, reducing costs, ensuring scalability, and minimizing physical dimensions. The SDR hardware works in the physical layer; however, the SDR software works in the application layer. To extract the payload, namely the sensors' readings from the SDR software, an intermediate gateway is proposed in this paper, as shown in Figure 1.

The gateway includes an HTTP-based IoT client, which is written in Java. The gateway communicates with the SDR software via user datagram protocol (UDP) to receive the raw data. It transfers the extracted data via JSON/HTTP(S) to cloud servers. Interoperability is a serious issue in smart systems where various nodes transfer different data formats. Therefore, JSON solves the interoperability problem and introduces a uniform data format for all sensors that use different wireless communication protocols.

Smart systems transfer data over wireless communication networks and protocols in the RF range, and the SDR platform serves as a receiver for all these wireless communication systems. The smart fitness system transfers measurements over BLE, and the SDR platform receives this data at the edge of the fog layer. The gateway receives the data, stores it in a local database, formats it into JSON, and then retransfers it over HTTP(S) to online cloud servers. Other services use the same methodology with different wireless protocols. Smart city sectors use WiFi, smart healthcare systems use Bluetooth, smart homes use Zigbee, and smart agriculture systems use LoRa.

HTTP has various methods, including GET to retrieve web documents from the server and POST to send data to the server. This paper uses the POST method to transfer data from clients to online cloud servers. First, the gateway in the fog layer receives a datalink frame from the SDR software program. Second, the gateway retrieves the binary data, extracts each object's value, reformats the whole message in JSON, then transfers the message over HTTP (or HTTPS) to an online server, in the cloud layer.

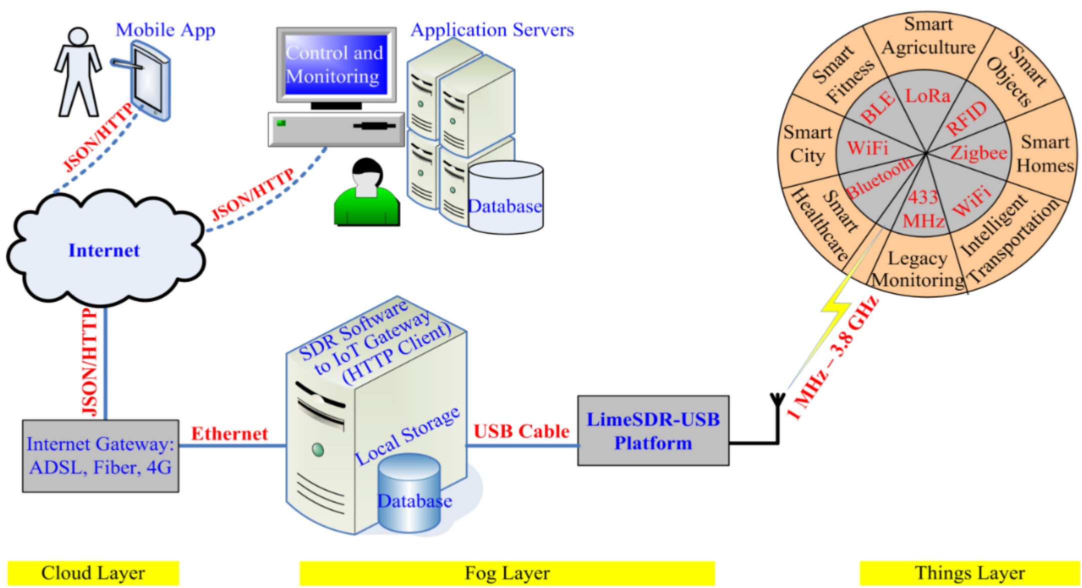

Figure 1.
SDR-based solution for wireless communications, integrated with IoT protocols, for smart systems applications.

HTTP is the web protocol used in web browsers to transfer web pages, such as HTML documents, over the Internet. HTTPS is the encrypted version of HTTP, which is more secure than HTTP because it uses TLS encryption. HTTP is unsecured and uses TCP port 80, while HTTPS offers secured communications and uses TCP port 443. However, HTTPS is slower than HTTP and requires more computation. This paper chooses HTTPS if secured communications between the fog and cloud layers are required. The following sections provide more information about HTTP and compares HTTP with HTTPS.

4. Result

The SDR hardware receives signals from sensors via wireless communication protocols. The SDR software transfers the payload to the gateway via UDP. The gateway retrieves the binary data, extracts each object's value, reformats the whole message in JSON, then transfers the message over HTTP (or HTTPS) to an online server. The following Figure 2 shows the JSON message of a received datalink frame. The payload size of the received frame is 21 bytes; however, the JSON message size is 146 without whitespaces.


```
{
  "Module I": {
    "sensor": [
      {
        "id": "C6",
        "name": "Gas",
        "value": 100
      },
      {
        "id": "C7",
        "name": "Flame",
        "value": 67
      },
      {
        "id": "C8",
        "name": "Temperature",
        "value": 27.3
      }
    ]
  }
}
```


Figure 2.
A JSON message sent by the gateway to an online server.

A live test is conducted while the gateway receives signals from the SDR platform and transfers data over the Internet to an online HTTP server. The type of data includes text and audio from different types of sensors. While the SDR hardware receives signals from sensors in the things layer, SDR software transfers the payload to the gateway via UDP. The network history is monitored for 60 seconds using the Linux-based monitor tool. The result is shown in Figure 3, where the bandwidth

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swings between 50 and 100 kbps. In some cases, there is a noticeable silence in the transmission and reception processes, which positively influences the bandwidth and reduces it to 50 kbps. The laptop specifications used for these tests are Dell-Inspiron 3537, Intel® Core™ i5-4200U CPU at 1.6 GHz x 4, 5.85 GiB RAM, and Linux-Ubuntu operating system.

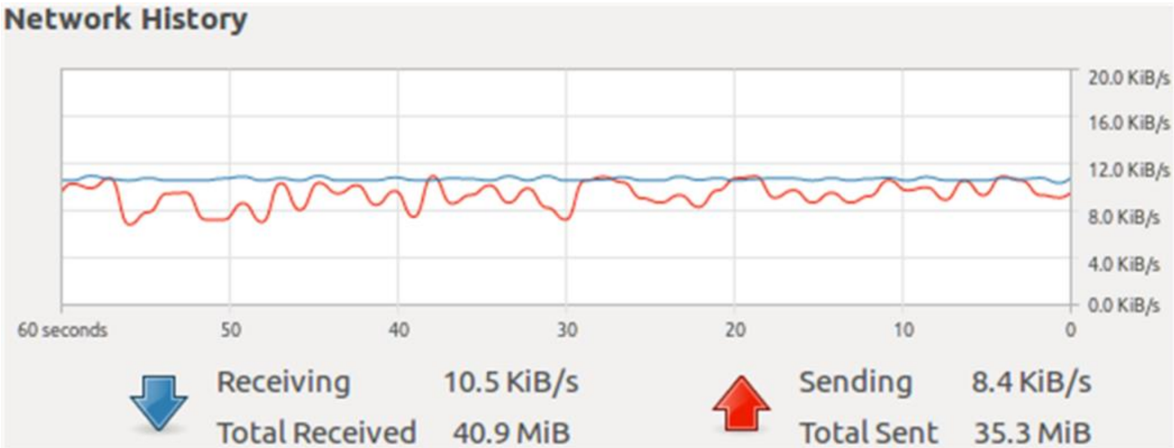

Figure 3.
Network history during 60 seconds, while the gateway is running.

Upon the above analysis, the developed gateway, which acts as a bridge between the SDR and the cloud-based servers via HTTP, shows outstanding performance results.

5. Discussion

The IoT system in this paper is designed based on the three-layer model of the IoT architecture proposed in Din, et al. [9] which consists of a things layer, a fog layer, and a cloud layer. This paperwork adds an interface layer to the architecture that deals with the GUI and user interactions.

The things layer contains sensors, actuators, LEDs, and switches, among other things. It collects raw data from things via wireless communication networks such as WiFi, Bluetooth, and Zigbee.

The fog layer is an intermediate layer between the cloud and the things layers. When the fog layer receives sensor data, it decides whether to process it locally or transfer it to the cloud layer. The fog layer inherits the cloud functions and brings data processing and storage near the things layer to increase the speed of data processing and analysis. Therefore, it comprises various software and hardware components that form a local ecosystem for the IoT system. In this paper, an SDR platform receives the signals of WiFi, Bluetooth, BLE, Zigbee, and RFID, among other wireless protocols. These protocols hold raw data from sensors in the things layer. The SDR platform is located at the edge of the fog layer. Hence, the SDR presents a solution for simplifying programmability and ensuring scalability.

The cloud layer is responsible for strategic actions. In general, insensitive data received from things is transferred from the fog layer to the cloud layer. The cloud layer processes, analyses, routes, and manages data received from sensors of the things layer, and results are stored on online cloud servers. The cloud layer allows online access and management of analyzed and stored data. This paper uses HTTP(S) to telecommunicate data between the fog and the cloud layers.

Authors of Fatimatou, et al. [29] proposed a smart agriculture solution to improve agricultural productivity in areas facing significant climatic challenges in Chad. They employed IoT technologies to collect data from sensors. They used an SDR platform to receive wireless signals of these protocols. Then, they used the MQTT protocol to transfer data to the Internet. Authors of Gavrilă, et al. [41] developed an IoT gateway based on an SDR platform, which could telecommunicate data with WiFi, Zigbee, BLE, and LoRa wireless protocols. The gateway uses the MQTT protocol to transfer the received data to the Internet.

However, the IoT system in this paper is designed based on the three-layer model of the IoT architecture, as mentioned. This paperwork adds an interface layer to the architecture that deals with the GUI and user interactions. Moreover, HTTP(S) is proposed here for telecommunications between the fog and cloud layers. The HTTP(S) is a browser-friendly protocol and hence does not require a translator, like WebSockets, which is required for the MQTT. The MQTT is a broker-based telecommunication protocol that uses the subscribe-and-publish model. The MQTT suits practical scenarios with multiple communication parties (publishers and subscribers). However, in this paper, two telecommunicating parties exist: the gateway in the fog layer and the server in the cloud layer. This is why HTTP(S) is proposed for this scenario.

Table 2 demonstrates the main differences between HTTP and HTTPS. While HTTP does not offer secured communications, HTTPS encrypts data via TLS and offers ciphered data transfer.

Table 2.
Comparison between HTTP and HTTPS.

Property	HTTP	HTTPS
Security	Un secured	Secured
Encryption	Not available	via TLS
Data transfer	Plain text	Ciphered
URL	http://	https://
TCP port	80	443
Latency	Lower than HTTPS	Higher than HTTP
Computational time	Lower than HTTPS	Higher than HTTP

The comparison shows that HTTPS offers secured communications but higher latency and computation.

6. Conclusion

This paper addresses some challenges of IoT-based smart systems, such as interoperability, programmability, and scalability, via an SDR platform. Such architecture provides a reconfigurable platform that minimizes costs and physical dimensions and provides the flexibility and modularity required for developing prototypes and telecommunication systems.

The SDR hardware receives wireless signals of communication protocols and transfers the payload to the SDR software. A gateway developed in Java receives the payload via UDP from the SDR software. It then reformats the data in JSON to ensure interoperability and transfers the formatted data to online servers via HTTP(S).

A comparison between HTTP and HTTPS is conducted, and HTTPS is chosen if secured communications between the fog and cloud layers are required. However, HTTPS consumes higher latency and computation.

The proposed system has many advantages, including easy setup, moderate cost, and interoperability. It can be used for IoT-based smart systems that follow the three-layer architecture.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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