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Design of a Bimodal Home Automation System using ESP8266 and ATMEGA328 Microcontroller

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ABSTRACT

Home automation systems are garnering increasing popularity and widespread use due to the relative ease of domestic management and comparatively high return on technology investment tied to its adoption. However, Nigeria and other emerging ICT economies are yet to fully actualize and maximize the inherent potential of these smart home technologies due to endemic challenges associated with poor infrastructure, erratic power supply and unreliable Internet connectivity. These challenges necessitate an innovative paradigmatic shift that could provide a pragmatic technological solution suitable to the context of Nigeria and other developing climes. For most smart home systems in this research context, the status quo is based on choosing whether the design would be for short- or long-range communication network. Short-range designs which are usually realized with Bluetooth technology suffer from limited range issues while poor connectivity, bandwidth and latency issues are some of the problems plaguing Wi-Fi-based long-range designs. Consequently, this research presents a hybrid adaptive architecture that combines desirable features of both short- and long-range modes. The proposed smart home system is based on using embedded systems which use mobile application to send messages to ESP8266 Wi-Fi module. Together with notifications received from the monitoring unit, these messages are parsed by Arduino's ATMEGA328 microcontroller from where instruction codes are sent for controlling the load by switching ON or OFF various relays connected to the load.

Keywords: Smart Home, Android Smartphone, Arduino UNO, Light Dependent Resistor, Passive Infrared Sensor, Information and Communications Technology (ICT).

1. INTRODUCTION

The concept of home automation started with labour-saving technologies which saw the proliferation of a number of self-automated and self-contained home appliances [1]. This later paved the way for the development of multipurpose home automation network technologies that is based on electric power transmission wiring

for monitoring, signalling and controlling of household appliances and electronic devices by simply switching ON or OFF the desired gadgets [1, 3].

Recently, industrial experts and academic researchers have demonstrated the possibility of realizing a fully automated smart home systems using Wi-Fi network and significant improvement has been achieved in this direction with the incorporation of artificial intelligence (AI) [2, 4]. For example, intelligent personal assistants like Google Assistant and Amazon Alexa are now being integrated into the design of smart homes. The driving motivation and inspiration behind this innovation is to harness the power of technology in making the home a place of maximum comfort, security and leisure [3, 6]. In addition to this, the taste, needs and demands of modern homeowners are highly sophisticated and rapidly changing. This means that engineers and technologists need to continuously keep up with this rapid pace by coming up with user-friendly innovations and novel solutions using a combination of techniques ranging from AI to embedded systems [4, 5].

Most household device manufacturers such as LG, Samsung, Philips and NEST make their devices Internet of Things (IOT) compliant in order to achieve optimum operation and seamless control in the home automation process [1, 3, 4]. The investment of these big technology firms and many emerging IT companies in smart home solutions is a convincingly clear indication of how lucrative the smart home business is. In order to buttress what has been mentioned, a research report by Statista showed that revenues generated from smart home market in the year 2017 is about 14.6 billion U.S. Dollars. Furthermore, statistics have also shown that revenues generated from the smart home industry for the last 10 years and this progressive trend is projected to continue [33].

However, Nigeria and other emerging ICT economies are yet to fully actualize and maximize the inherent potential of these smart home technologies due to endemic challenges associated with poor infrastructure, erratic power supply and unreliable Internet connectivity [34, 37]. These challenges necessitate an innovative paradigmatic shift that could provide a pragmatic technological solution suitable to the context of Nigeria and other developing climes. For most smart home systems in this research context, the status quo is based on choosing whether the design would be for short- or long-range communication network. Short-range designs which are usually realized with Bluetooth technology suffer from limited range issues while poor connectivity, bandwidth and latency issues are some of the problems plaguing Wi-Fi-based long-range designs [3, 5].

Consequently, this research presents a hybrid adaptive architecture that combines desirable features of both short- and long-range modes. The proposed smart home system is based on using embedded systems which use mobile application to send messages to ESP8266 Wi-Fi module which serve as a means of communication between the user and the Arduino. Together with notifications received from the monitoring unit, these messages are parsed by Arduino's ATMEGA328 microcontroller from where instruction codes are sent for controlling the load by switching ON or OFF various relays connected to the load. Specifically, the ATMEGA328 is used as a controller for the switching of two bulbs and speed control of a DC motor.

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2. RELATED STUDIES

There are a lot of research works in the area of smart home automation. Some researchers have proposed solutions in which access to and control of home appliances connected to an embedded microcontroller is achieved via Bluetooth connection [7, 8]. This class of home automation systems has the advantage of secured and low-cost design. However, the limited range of Bluetooth devices inhibits the performance of such systems by restricting the operational scope to within a short-distance neighbourhood and not for long-distance mobility. Another group of researchers proposed a user-friendly Bluetooth-based smart home architecture consisting of a cell-phone, Arduino BT board and android application [9]. This system has an alert unit together with readymade features that can fit into existing homes and it employs password protection for enhanced security and user authentication. This system also suffers from the drawback of limited operational scope due to the Bluetooth range.

Researchers have also proposed solutions based on global system for mobile (GSM) communication where a modem sends different AT commands to the microcontroller for the control of home appliances [10, 11]. The drawbacks of this system are latency resulting from network failures and lack of graphical user interface (GUI) which forces users to memorize different operational short codes. These drawbacks make this system unsuitable for telemetry, real-time monitoring and control in smart home applications. Other researchers proposed a GSM-based architecture using a modem, smartphone and PIC16F887 microcontroller for controlling electrical appliances via short message service (SMS) request [12]. The electrical appliances are wired to PIC16F887 via relays and RS232 is used for serial communication. The merit of this system is wider operational coverage and ease of getting SMS status notifications regarding home appliances on smartphones. A similar architecture was proposed by some researchers using GSM SIM900 module, LPC2148 microcontroller and Android application for controlling home appliances by displaying vital notifications on the liquid crystal display (LCD) with a wider operational scope due to the mobile network [13]. However, the system performance is affected by security and reliability issues.

In addition to this, some researchers proposed home automation architecture based on voice recognition which utilizes Arduino UNO and smartphone and relies on Bluetooth technology [14]. The inbuilt voice recognition characteristic of Android OS is employed to make control of home appliances relatively easier by simply pronouncing the desired appliance name and subsequently issuing ON or OFF commands. However, the performance of this system by the Bluetooth limited coverage. Another drawback of this system is the reduced efficiency and performance degradation in noisy environments. A smart home system using general packet radio service (GPRS) technology was proposed by some researchers [15]. This solution achieves enhanced performance by using support vector machine (SVM) for speech recognition.

Localized Wi-Fi-based smart home systems were proposed by some researchers for monitoring and controlling connected home appliances [16, 17]. For long-distance operations, the implication of this kind of localized network arrangement is

the ensuing resource bottleneck due to the traffic volume and routing complexity. Other researchers proffered similar localized solutions by using web servers to deploy applications for monitoring and controlling home appliances via the Internet [18, 19]. The drawbacks of this system are large space requirements, high installation cost; upgrade problems, scalability and compatibility issues, and prohibitive energy consumption.

Home automation solutions based on Internet of things (IoT) were proposed by some researchers [20]. The system implementation is achieved by using embedded Micro web server, smartphone, controlling devices and software application. The system architecture consists of home environment (supporting the hardware interface and monitoring unit), home gateway (supported by Arduino Ethernet shield) and remote environment (supporting Wi-Fi, 3G/4G and Android applications). This system has the advantage of controlling heating, ventilation and air conditioning (HVAC) and other energy management systems. Another similar system was proposed for controlling common household appliances via the World Wide Web (WWW) using Raspberry server and Wi-Fi connection [21]. The advantage of this system is the ability of alerting the user on time in order to prevent fire incidents.

Some researchers have proposed ZigBee-based solutions using handheld microphone, appliance controller and centralized controller running from a personal computer (PC) [22]. Differential pulse code modulation (DPCM) is utilized for data compression, Zigbee RF module is used for creating the wireless network and Microsoft application programming interface (API) is employed for speech recognition. However, the system performance is affected by speaker accent, speed and surrounding noise. In addition to this, system accuracy is limited for short distances provided there is a clear line of sight transmission. Other researchers implemented a ZigBee-based design with the overall goal of minimizing power consumption by operating in current sensor and measurement modes using a Java platform [23]. With the aid of temporal performance metrics like latency, round trip delay (RTD) and received signal strength indicator (RSSI), it was demonstrated that the system exhibits satisfactory performance.

Smart home systems with no dedicated servers and deployed with representational state transfer (RESTful) web service were proposed by some researchers [24, 25]. This network arrangement does not provide full-duplex communication and it is expensive due to the need for public Internet Protocol (IP) address allotment. As an improvement, solutions based on localized cloud-enhanced home controller (CEHC) and Google Cloud Messaging (GCM) service were proposed [26, 27, 28]. Messages are transferred in a server-client mode and extensible messaging and presence protocol (XMPP) for enabling real-time exchange of structured data between the network entities. The drawbacks of this system are security, reliability and user authorization issues coupled with the bottleneck and implementation problems associated with the extensible mark-up language (XML). Recently, an Internet-based distributed home automation system was proposed by some researchers [29]. The combination of Windows, Apache, MySQL and PHP (WAMP) was used to realize full-duplex and persistent connection and JavaScript object notation (JSON) data serialization. Hypertext mark-up language (HTML5) was utilized for flexible and intuitive GUI mobile and web applications. The key advantage of this system is the reduction of computing complexity and elimination of public IP address allotment costs.

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Researchers are using EnOcean as an emerging energy harvesting technological solution for home automation systems [30, 31, 32]. The system architecture is built using automation controller, Linux-based Duckbill 2 thumb drive, router, TCM310 transceiver and Internet-enabled connection devices. The advantage of using this technology is the ability to leverage on its energy efficiency and easy installation features.

3. DESIGN METHODOLOGY

The block diagram of the proposed bimodal home automation system is as illustrated in Figure 1. The microcontroller board is connected to two light bulbs via a relay switching circuit, the 5V DC brushless motor is connected by means of a motor switching circuit and the Wi-Fi module is connected through the UART ports of the board. The relay switching circuit consists of a transistor, diode, resistor configuration connected to the coil terminals of the 5V relay. The microcontroller controls the bulbs by sending ON/OFF control signals to the relay via the switching circuit. The DC motor is also connected to a PWM pin of the microcontroller via a motor switching circuit. The motor switching circuit consists of an IRF540N MOSFET, resistors and a diode across the motor. The Wi-Fi module selected was the ESP8266-01 which was connected to the microcontroller through serial communication method.

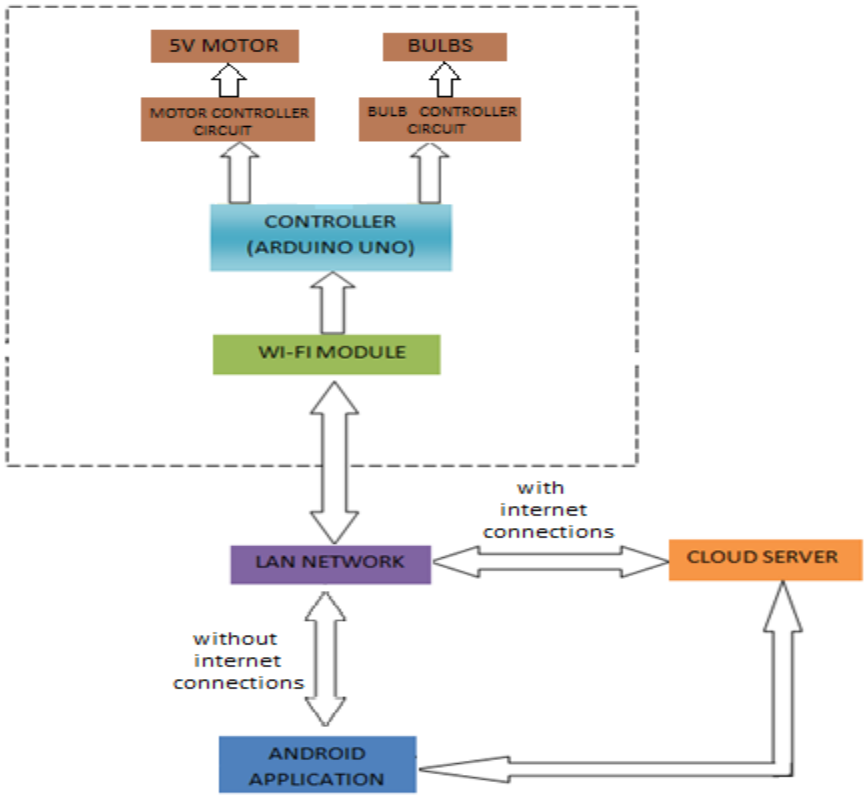

Figure 1: Block Diagram of Proposed Bimodal Home Automation System

The major focus of this research is configuring the Wi-Fi module in order for it to operate in two different modes: online (or long-range) and offline (or short-range) modes. The online mode allows long-distance communication between the user and the household devices in which Internet connection is used. In this research, the user uses an Android application to change states of the devices on a Cloud server. The Wi-Fi module periodically requests for data from the Cloud and uses the most up-to-date data to make changes. Internet connection is required for the Wi-Fi module to make requests to the Cloud and this is simply realized by using the home Wi-Fi hotspot. The offline mode does not require internet service and is particularly useful when the user is in a short distance with respect to the range of the home Wi-Fi hotspot. It must be mentioned that range varies depending on the type of Wi-Fi hotspot service used. The ESP8266 acts as a webserver in this mode, responding to various HTTP requests from the user via an Android app. For most smart home systems in this research context, system designers either use the online mode via a Website or a Cloud server which requires Internet connection or the offline mode with Bluetooth, local Wi-Fi network and other similar connections. Some designers have proposed a hybrid of the modes by implementing an Internet-Bluetooth framework or Internet-ZigBee approach. The contribution of this research is that this adaptive hybrid mode is achieved using only one device and a single mode of communication. This makes the design methodology of this research very cost-effective and easily implementable, especially for developing ICT economies where adequate project funding and access to design materials are major causes of concern. It must also be emphasized that the ESP8266-01 employed in this research is a very cheap and easily programmable Wi-Fi module that can function in this hybrid mode with comparatively less computational complexity.

4. HARDWARE IMPLEMENTATION

The hardware parts employed in this research were implemented in modular segments. These modules are subsequently explained in numbered point form.

1. The power supply unit consisting of 9V 2A step down transformer, bridge rectifier to convert AC to DC power, filter capacitor of 470µF connected in parallel for smoothing the DC voltage from bridge rectifier, LM7809 regulator to regulate 9V DC to power the Arduino. In order to provide coil voltage to the relays and power the 5V DC motor, 9V is converted to 5V and regulated via LM7805 regulator. A dedicated power supply channel is also used to supply 3.3V for ESP8266-01 consisting of 5V tap, LM317 regulator biased with 220Ω resistor and potentiometer, and two 0.1µF capacitors for smoothening.
2. The ESP8266 Wi-Fi module and Arduino are connected correctly according to instructions with reset and programming pushbuttons for ESP8266 Wi-Fi module and allowance is created for FTDI chip for programming ESP8266 Wi-Fi module.
3. Relay driver circuit for switching ON and OFF relays at appropriate times consists of two 5V taps from the PSU for energizing the relay coil. BC548 transistors are used as switches based on the command from Arduino while 1N4001 diodes are used to prevent fly-back voltage or counter EMF damages to Arduino from relay. There are also voltage taps from 230V mains to the common of relay and one of the device terminals (bulb).

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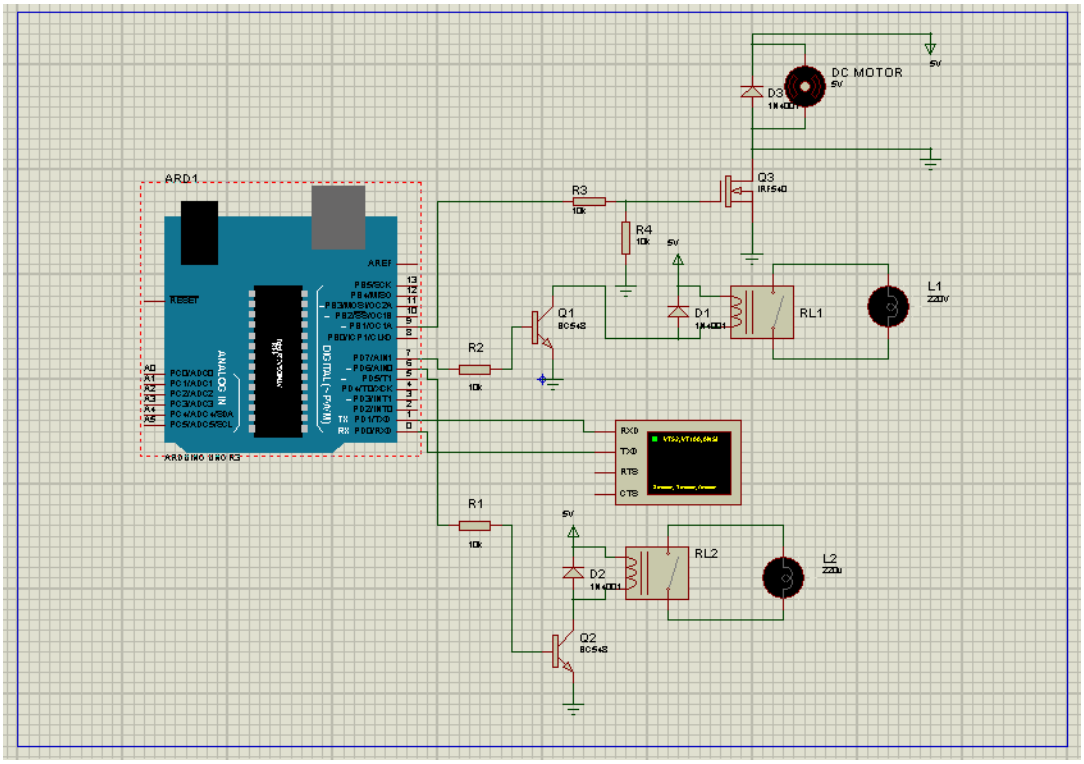

Figure 2: Schematic of Proposed Bimodal Home Automation System.

Based on the hardware schematic depicted in Figure 2, two relays, motor, relay switching circuit and motor switching circuit represent the appliances being controlled coupled with their drivers.

4.1 HARDWARE MODULES

Arduino UNO's ATMEGA328 microcontroller board is employed which has 14 digital I/O pins (of which 6 can be used as PWM outputs), 6 analog inputs and 16 MHz external crystal oscillator. Since most 8-bit AVR boards run on instructions per second, Arduino runs about 16 MIPS while the UNO board contains all units for proper operation of the microcontroller. These functional units include voltage regulator (for providing 5V and 3.3V derived from a 6-20V external power supply through a power jack), reset button, on-board programmer interfaced via USB and other important units. ATMEGA328P has 32 KB of flash memory for code storage, 2 KB of SRAM and 1 KB of EEPROM. These features and facilities enable Arduino to interconnect with computer, another microcontroller, sensors, drivers, actuators as well as other communication devices such as Wi-Fi shields and Bluetooth modules. In this research, ESP8266 is for communication while Arduino acts mainly as actuator to switch state of bulbs and speed of DC motor.

Furthermore, ESP8266 is used to provide Wi-Fi networking solution for the mobile platform design by embedding Wi-Fi capabilities into the home automation system. On-board processing and storage capabilities of ESP8266 are leveraged upon in order to allow it to be integrated with sensors and application specific devices through GPIOs. Wireless Internet access is added to the design through

UART interface. Additional features like adaptive radio biasing, fast duty cycle switching, spur cancellation, radio co-existence and interference mitigation were also harnessed in this research. ESP8266 was used as a cheap Wi-Fi adapter in this research with the ability to adaptively change modes.

Relay driver module is used for signal construction from the digital circuit which will be pre-amplified through FETs or BJTs as Darlington arrays. In this research, 5V output digital pin is connected to base of BC548 NPN BJT to drive 5V relay supporting up to 10A electrical load. Transistor base current, IB, of 0.5 mA is sufficient to drive the transistor fully into saturation as it can be obtained through base resistance, RB of:

$$R_B = \frac{V_{BE}}{I_B}$$

With base-emitter voltage, V_{BE} = 5V and base current I_B = 0.5 mA, then:

$$R_B = \frac{5\ v}{0.5\ mA} = 10\ k\Omega$$

Therefore, 10 kΩ is used to limit current to the transistors in relay modules. The resistor is used to bias the transistor and this biasing voltage is in fact the triggerring voltage which is received from source. Diode, Dp helps in preventing reverse current fom passing through the transistor. This reverse current may cause permanent damage to the transistor. Transistor Qs, resistor Rb and diode connected across the relay circuit make up the switching circuit as contained in the hardware schematic of Figure 2.

BC548 switches ON and OFF as it moves from saturation to cutoff. Motor driving circuit was realized using IRF540 N-channel MOSFET, 2 resistors and flyback diode. The method used is commonly known as PWM control of DC motors where digital means are used for getting analog results by creating a square wave. This ON-OFF pattern is dynamically simulated for voltages to ON (5V) and OFF (0V) by changing the portion of time the signal spends in ON state compared to the time the signal spends in OFF state [6]. PWM signal is applied to gate of N-channel and adjusted for controlling speed of DC motor.

5 SOFTWARE DESIGN

The software design consists of programming Wi-Fi module and Arduino, setting up of Cloud server and developing Android application. A significant portion of this research was done through Wi-Fi module which was programmed to respond to various situations. These operational conditions are subsequently listed with brief explanations.

1. If user is in range of home LAN network and wants to control various household devices or get information regarding various conditions in the house without using Internet connection (or as a result of lack of or poor connectivity).
2. If user is not in range of the home LAN network but still wants to have access to the house using Internet connection.

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3. If user is inside the house and within the range of home LAN network and wants to control devices or get information regarding various conditions in the house using Internet connection.

An ESP8266-based code was written to handle all the aforementioned scenarios. This program configures ESP8266 by allowing it to connect to the desired LAN after which the following checks are performed:

1. Can cloud server be accessed? If no, lack of (or poor) Internet connection is assumed. Therefore, local area mode is used. If Cloud server can be accessed, Internet connection is present. Keep performing "Check 1" once every one minute when in local area mode. Check for Internet connection takes about a second.
2. If Internet connection is present, check for value of "test" on Cloud server. If test = 1, Android application (or user) wants to use local area mode although user has Internet connection. Therefore, ESP8266-01 is configured as local area mode. If test = 2, Android application wants to use Cloud server mode. Perform "Check 2" every 30 seconds if there is Internet connection. If there is no Internet connection, do not perform this check. Check takes about a second.
3. If during Cloud server mode, ESP8266-01 cannot access Cloud server for any reason, revert back to local area mode and give notice of error to user.

An android application was designed to handle both local area and Cloud server modes. If local area mode is selected, the android phone which is on the same Wi-Fi network as ESP8266 sends HTTP GET requests to ESP8266. ESP8266 is configured as a Webserver in local area mode to respond to different types of GET requests. For example, if 192.168.63.34/ON1 is sent to ESP8266 then ESP8266 sends message ON1 to Arduino while 192.168.63.34/OFF1 means OFF1 is sent to Arduino. If Cloud server mode is selected, the android phone sends HTTP POST request to the private channel on ThingSpeak whenever the user wants to change the state of a device. ESP8266 then checks this channel for any new posted state. The states received from ThingSpeak channel are then sent to Arduino.

5.1 ANDROID APPLICATION

The android application was created using MIT's Appinventor 2 in order to achieve an easy frontend and backend application design. Frontend of the mobile application provides GUI for monitoring and controlling user's equipment through design tab of MIT's Appinventor. The design process involves dragging and dropping various components needed for the application to function (such as buttons, labels) from palette to viewer as well as changing component properties such as colour, shape size and spacing using Properties tab. Apart from Designer tab, Blocks Editor forms the second central work window of Appinventor development environment. The Blocks Editor is where individual components of the application are brought to life and assigned specific tasks which form the overall functionality of the mobile application (backend).

The android application performs two functions: a screen that takes care of sending HTTP POST requests (e.g., https://api.thingspeak.com/update?api_key=WK9UQG4R89XTQZXZ&field1=0) to

ThingSpeak and another screen that handles sending HTTP GET requests in local area mode (e.g., http://192.168.43.34/ON2).

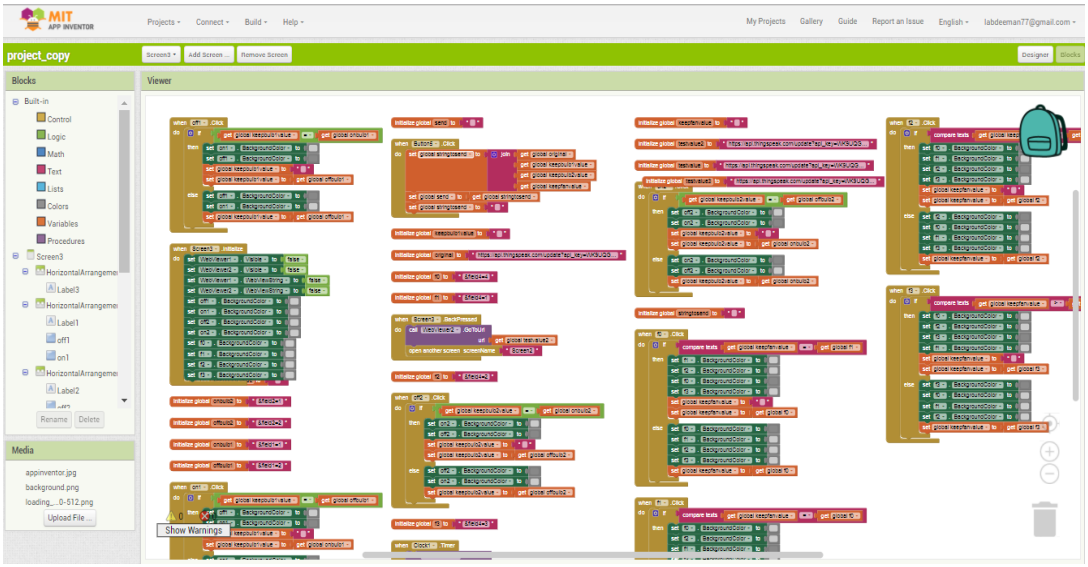

Figure 3: Appinventor interface for developing android apps

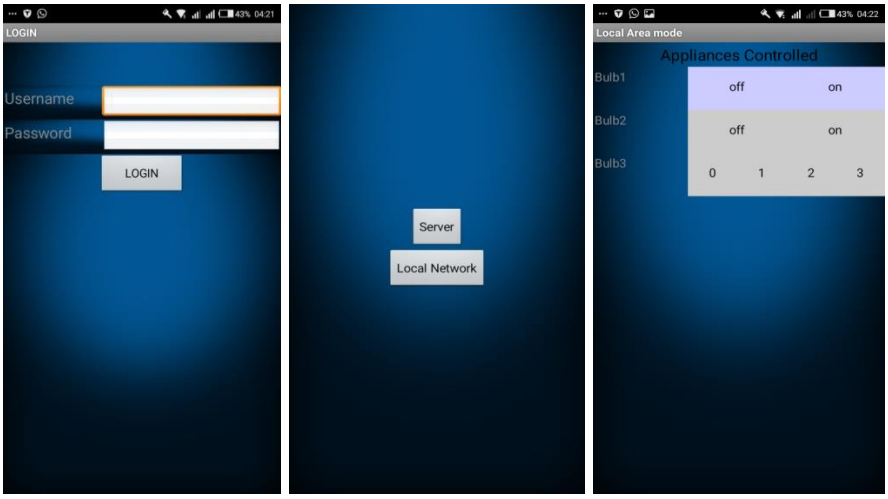

Figure 4: Screenshots of Android app

6. CONCLUSION

This research proposes and implements a bimodal home automation architecture which has the advantage of low cost and flexible control using Android-based smartphone. The proposed solution relies on a single Wi-Fi module for performing multiple forms of communication between the remote user and the household appliances. The ESP8266 acts as a server in one mode and it then switches to a client in another mode. The Arduino UNO mainly acts as an interpreter of instructions/commands and a hub for controlling multiple devices (around 18 independent controls for the UNO). Smartphone with inbuilt support for Wi-Fi is

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used to access and control the devices at home. When Wi-Fi connection is not available, mobile cellular networks such as 3G or 4G can be used to access the system. The system also uses Google speech recognition engine thus eliminating the need for an external voice recognition module. Future research works include incorporating SMS and call alerts, performing automatic controls with various sensors and adoption of private Cloud server for commercialization of the system.

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