Towards an Internet of Things Architecture for Air Quality Monitoring System in Kenya

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Abstract— The proliferation of smart objects in a communicating-actuating network creates the Internet of Things (IoT) that is made up of sensors and actuators which blend seamlessly with the environment around us collect data from the environment and allow the sharing of information across platforms. This has enabled cheaper and more scalable means of gathering, processing and presenting air quality data that is not only useful to the environmental authorities but also to the citizens. This research presents the IoT enabling technologies, architectures and how they have been used in developing air quality monitoring systems. An architectural framework based on these enabling technologies, architectures and the best practices from several cases previous cases was designed. Finally an air quality monitoring system based on this architecture was developed and tested. The research concludes that the benefits that can be realized by air quality monitoring systems based on this architecture include: sensing accuracy, large area coverage and monitoring, minimal human interaction through remote sensing and monitoring, ability to integrate these systems to the existing systems through the use of already implemented technologies that are regarded as the enablers of IoT and effective dissemination of air quality information.

Index Terms— Actuators, Air pollution, air quality monitoring, architecture, Internet of Things, sensors; wireless sensor networks.

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1. BACKGROUND

Internet of Things is a recent communication paradigm that envisions a near future, in which the objects of everyday life will be equipped with microcontrollers, transceivers for digital communication, and suitable protocol stacks that will make them able to communicate with one another and with the users, becoming an integral part of the Internet [3].

Ubiquitous sensing offers the ability to measure, infer and understand environmental indicators, from delicate ecologies and natural resources to urban environments. The proliferation of objects in a communicating-actuating network creates the IoT. Sensors and actuators blend seamlessly with the environment around us thereby enabling us obtain data from the environment such as the air quality, and the information is shared across platforms in order to develop a common operating picture [17].

IoT aims at making the Internet even more immersive and pervasive by enabling easy access and interaction with a wide variety of devices such as monitoring sensors, actuators, displays, vehicles, and so on, the IoT will foster the development of a number of applications that make use of the potentially enormous amount and variety of data generated by such objects to provide new services to citizens, companies, and public administrations [5].

Attempts have been made to monitor urban air quality, networks of fixed monitoring stations have been deployed in urban areas to provide authorities with data to define and enforce dynamically policies to reduce pollutants, for instance by issuing traffic regulation measures. However, fixed networks require careful placement of monitoring stations to be effective. Moreover, changes in urban arrangement, activities, or regulations may affect considerably the monitoring model, especially when budget constraints prevent from relocating stations or adding new ones to the network [12].

IoT has therefore made it possible to obtain air quality data through the use of air quality monitoring systems that employ IoT architectures and appropriate technologies. Such systems include: Integrated System for Regional Environmental Monitoring and Management Based on IoT[11]; Real-time Air Quality Monitoring Through Mobile Sensing in Metropolitan Areas; [9] Wireless Sensor Network Based Air Pollution Monitoring Systems [3]

This research therefore aims at taking advantage of the research that has been done by others in building air quality monitoring systems based on IoT and proposes an architecture that can be used for building an air quality monitoring system in Kenya that uses appropriate enabling technologies that are readily available and affordable.

2. Internet of Things

2.1 Definitions

Coordination and Support Action for **Global RFID-related** Activities and Standardization. **[18]** defines IoT as "A global network infrastructure, linking physical and virtual objects through the exploitation of data capture and communication capabilities. This infrastructure includes existing and evolving Internet and network developments. It will offer **specific object** identification, sensor a**nd connection capability as the** basis for development of independent federated services and applications these will be characterized by a high degree of autonomous data capture, event transfer, network connectivity and interoperability".

The IoT allows people and things to be connected anytime, anyplace, with anything and anyone, ideally using any path/network and any service.

The internet of things also employs the concepts of pervasive computing and ubiquitous computing [24]. These paradigms are enabled by large-scale embedded sensor devices.

Moreover, if the objects are uniquely addressable and connected to the internet, then the information about them can flow through the same protocol that connects our computers to the internet. Since these objects can sense the environment and communicate, they have become tools for understanding complexity, and may often enable autonomic responses to challenging scenarios without human intervention. This broader principle is popularly used in IBM's Smarter Planet initiative for autonomic computing [6].

2.2 Enaling technologies

The IoT enables the participating objects link with each other and share information across among them. IoT therefore transforms these objects from being traditional i.e. being unable to communicate with others to being smart i.e. being able to link and communicate with otherobject. This is achieved through the use of underlying technologies such as ubiquitous andpervasive computing, embedded devices, communication technologies, sensor networks, Internet protocols and applications [1].

Generally, the IoT enabling technologies i.e. the building blocks can be broadly grouped into IoT elements. Understanding the IoT building blocks helps to gain a better insight into the real meaning and functionality of the IoT [1]. The six main elements needed to deliver the functionality of the IoT are discussed are described as below:

a) Identification

This involves giving the objects unique identities to ensure that they can be monitored independently and provide data uniquely. There are many techniques used in IoT to identify object and these include: EPC and ubiquitous codes (Koshizuka & Sakamura, 2010).

Providing the unique identity to the IoT objects is critical to differentiate between object ID and its address. Other addressing methods of IoT objects include IPv6 and IPv4. 6LoWPAN which can be public or private.

b) Sensing

This involves gathering data from related IoT objects within the network and sending these data to a central storage such as a data warehouse, database, or cloud. The collected data is analyzed to take specific actions based on required services. Sensing can be achieved by employing the use of The IoT sensors such as smart sensors, actuators and wearable sensing devices. IoT products such as Arduino, Raspberry PI, and BeagleBone Black are built based on these sensors in addition to built-in TCP/IP and security functionalities. They therefore connect to a central management portal to provide the required data by customers. [1].

c) Communication

Communication technologies such as RFID, NFC and UWB connect the heterogeneous participating IoT objects together to deliver specific smart services. The ideal communication among the participating objects involves the use of low power in the presence of lossy and noisy communication links. These communication technologies uses of protocols such as WiFi, Bluetooth, IEEE 802.15.4, Z-wave, and LTE-Advanced.

d) Computation

Computation is composed of processing units such, software applications and various hardware platforms. Processing units includes microcontrollers, microprocessors, SOCs, FPGA's. Hardware platforms include Arduino, FriendlyARM, Intel Galileo, Raspberry PI, Gadgeteer, BeagleBone, Cubieboard, , WiSense, Mulle, and T-Mote Sky. Software platforms provide IoT functionalities and include Operating Systems. The OS are vital since they run for the whole activation time of a device. The OS include Contiki RTOS which has been used widely in IoT scenarios, Cooja which is a Contiki simulator and allows researchers to develop, simulate and emulate IoT and WSN applications, TinyOS [10], LiteOS and Riot OS which also offers light weight OS designed for IoT environments.

e) Services

IoT services can be categorized under four classes [31] [15]: Identity-related Services, Information Aggregation Services, CollaborativeAware Services and Ubiquitous Services.

Identity-related services are the most basic and important services that are used in identifying the IoT objects.

Information Aggregation Services collect and summarize raw sensory measurements that need to be processed and reported to the IoT application.

Collaborative-Aware Services act on top of Information Aggregation Services and use the obtained data to make decision and react accordingly.

Ubiquitous Services, however, aim to provide Collaborative-Aware Services anytime they are needed to anyone who needs them anywhere.

f) Semantics

Semantic in IoT refers to the ability to extract knowledge smartly by different machines to provide the required services. Knowledge extraction includes discovering and using resources and modeling information. It also includes recognizing and analyzing data to make sense of the right decision to provide the exact service (Barnaghi, Wang, Henson, & Taylor, 2012).

These requirements are supported by Semantic Web technologies such as the RDF and the OWL. In 2011, the W3C adopted the EXI format as a recommendation [27]. EXI is designed to optimize XML applications for resource-constrained environments. Furthermore, it reduces bandwidth needs without affecting related resources such as battery life, code size, energy consumed for processing, and memory size.

2.3 IoT Architectures

IoT should be capable of interconnecting billions or trillions of heterogeneous objects through the Internet, so there is a critical need for a flexible layered architecture [1]. The ever increasing number of proposed architectures has not yet converged to a reference model. Meanwhile, there are some projects like IoT-A [2] which try to design a common architecture based on the analysis of the needs of researchers and the industry as shown in figure 2. From the pool of proposed models, the basic model is a 3-layer architecture [33] [30] consisting of the Application, Network, and Perception Layers.

2.3.1. Architectures based on layered models

Fig. 1 illustrates some common architectures among them is the 5-layer model (not to be confused with the TCP/IP layers) which has been used in [30] [33].An overview of the enabling technologies and the IoT elements used in all the layers of these IoT archi

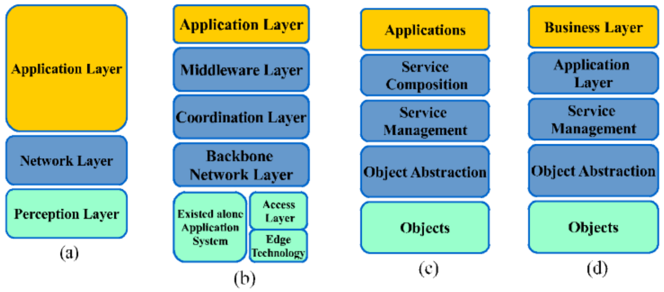


Figure 1: IoT Architectures by [30]

a) Objects Layer

This is the first layer also known as the Objects or perception layer, it represents the physical layer that has ioT sensors and actuators to perform different functionalities such as collecting and processing information from the surrounding environment. Standardized plug-and-play mechanisms need to be used by the perception layer to configure heterogeneous objects [30] [33]

b) Object Abstraction Layer

Object Abstraction transfers data produced by the Objects layer to the Service Management layer through secure channels. Data is transferred through various technologies such as RFID, 3G, GSM, UMTS, WiFi, Bluetooth Low Energy, infrared, ZigBee. Other functions such as cloud computing and data management processes are handled at this layer [30] [33]

b) Service Management Layer

Service Management or Middleware (pairing) layer pairs a service with its requester based on addresses and names. This layer enables the IoT application programmers to work with-heterogeneous objects without consideration to a specific hardware platform. Also, this layer processes received data, makes decisions, and delivers the required services over the networkwire protocols [30] [33]

c) Application Layer

The application layer provides the services requested by clients. [30] [33]

d) Business Layer

The business layer manages the overall IoT system activities and services. The responsibilities of this layer are to build a business model, graphs, flowcharts, etc. based on the received data from the Application layer. [30] [33].

Most IoT implementations follow an architecture that contains different worlds each of them with their own characteristics; Figure 2 shows an example [20]. They argue that the things world relates to micro-electromechanical systems, smart sensors, simple HMI's, and so forth, which associate in networks (Networks of Things, NoT) to ubiquitously interact with other things, the environment and/or people.

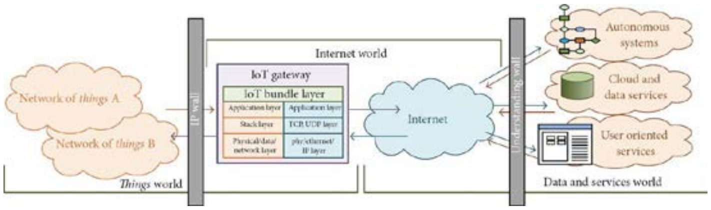


Figure 2: IoT arhitecture by (Gomez et al., 2010)

3. Case study: Integrated System for Regional Environmental Monitoring and Management Based on IoT

This research was carried out by [11]. In this study, the researchers implemented an Integrated System for Regional Environmental Monitoring and Management Based on Internet of Things. The figure below shows the architecture developed in this study.

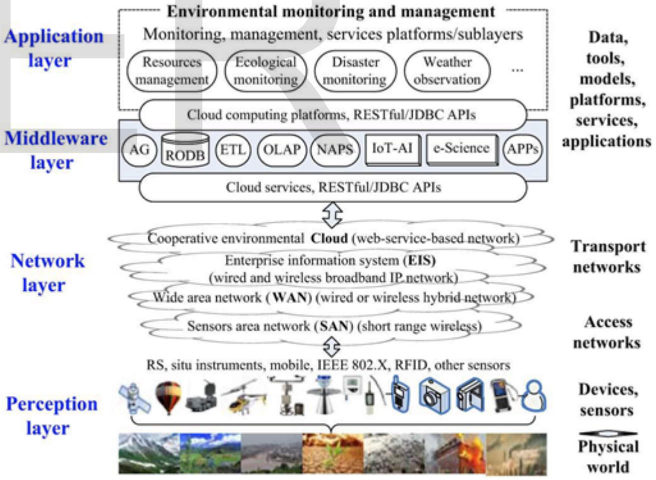


Fig 3: IoT Architecture by [11].

The prototype of this system was built on an architecture based on four layers: Perception layer; Network Layer; Middleware layer and application layer.

a. Perception Layer

This layer is mainly used for collecting data in environmental monitoring and management and includes real-time datasets, models/methods, knowledge, and others. The real-time data collection based on IoT is related to multi-sensors, including RS platforms (i.e., satellites, balloons, aircrafts, and radar), situ instruments (i.e., situ observation instruments for meteorological, hydrological, and ecological factors), mobile (i.e., 2G, 3G, and LTE), IEEE 802.X (i.e., WiFi, Bluetooth, and ZigBee), RFID, and other sensors [11].

b. Network Layer

The network layer performs basic functions of data and information transmission as well as the interconnection of systems and platforms. It mainly consists of access networks and transport networks.

Access networks are short-range wireless networks and is made up of SAN , 2G, 3G, WiFi, and ZigBee which supports the connection of things (i.e., sensors, devices, and users) in environmental monitoring and management. Transport networks consists of WAN of wired or wireless hybrid network and are usually subsystems of EIS with wired and wireless broadband IP network, and EISs could be connected to the cooperative environmental cloud with Web service-based global network [11].

c. Middleware Layer

This is the set of sub-layers for the management of data, software/tools, models and platforms, and interposed between the network layer and the application layer. In this layer, RODB is used to efficiently manage massive data generated by sensors and devices, and it is also used for storing and management of models, knowledge, and other information. [11]

d. Application Layer

The application layer consists of application support platforms, cloud computing platform, escience platforms and other platforms. This layer mainly provides the functions of storing, organizing, processing, and sharing the environment data and other information obtained from sensors, devices, and Web services.

4. PROPOSED APPROACH

The proposed system architecture in this study was based upon previous work on environmental monitoring system described in [3]. The architecture was based on the Environmental Monitoring System with Wireless Sensor Networks and IoT systems.

Modifications have been done on the original architecture for the purpose of testing this model, for example sophisticated servers have been replaced by a laptop that will be used for the experimental purpose but at the same time is expected to give accurate results as will be in the case of real server environment.

This architecture also proposes to carry out the experiment in a layered approach mainly

☐ server-end layer (server layer)

☐ Communication and data storage layer and

☐ Sensing and connectivity layer (mote layer) as implemented in [13].

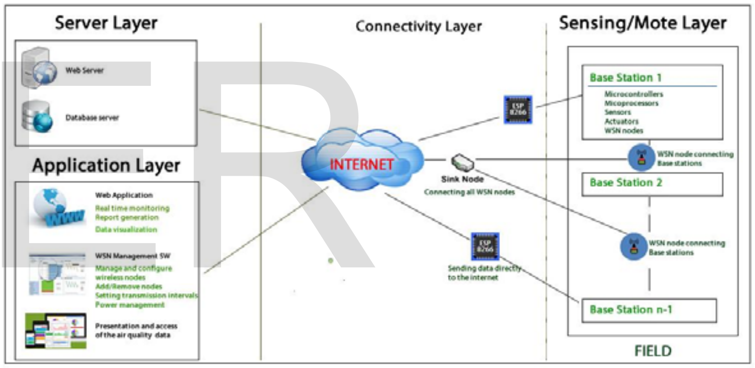


Fig 4: Proposed IoT architecture for implementing the air quality monitoring system in Nairobi County

The system based on this architecture consists of Nodes/Mote layer that is composed of objects for collecting environmental data and are equipped with different kinds of sensors, placed on structures such as street light poles, buildings, billboards and sends data to a central location via WSN that is connected to the Internet through a gateway unit.

This air quality monitoring system shall make it possible to collect air pollution parameters such as CO level, Methane, NOx, SOx, LPG, CNG, Carbon Monoxide and Alcohol. An overview of the types and roles of the devices involved in the system is given below:

a. Sensing and connectivity layer

This is the layer where the IoT wireless sensor nodes assembled into a base station will be placed. The base stations will be mounted on different structures such as street light poles that are geographically distributed within and out of the city.

The nodes in these base stations will then be uniquely be identified and mapped to provide accurate context information of the node. The nodes are will be powered by though connection to the power source of the lighting used in the different objects they are mounted in such as the power for the billboards, street lights and the CCTV cameras.

b. Communication layer and data storage

This is the layer that will ensure the transmission of data from the notes to the central storage as well as ensure that the data processed from the server end layer reaches the intended audience. In order to allow low-power transmission of data from the nodes to the server, constrained link layer technology such as 6LoWPAN will be used.

The nodes will also be assigned with unique IPv6 addresses and each node will be individually accessible from anywhere in the Internet by means of IPv6/6LoWPAN. Nodes collectively deliver their data to a sink node, which represents the single point of contact for the external nodes.

Alternatively, each node will publish its own features and data by running a CoAP server. In either case, a gateway is required to bridge the 6LoWPAN cloud to the Internet and perform all the transcoding described in the previous section.

c. Database server

The database server will be used for collecting the data that needs to be monitored in time by communicating with the HTTP-CoAP proxy server, which in turn takes care of retrieving the required data from the proper source. The data stored in the database are accessible through traditional web programming technologies. The information can either be visualized in the form of a web site, or exported in any open data format using dynamic web programming languages.

d. Server-end layer

This is the layer where a server will be used to host databases and the data from Arduino IDE as well as the contents of the sensor readings. In order to allow the data to be accessed to the public, a public IP address will be used to allow for remote access.

4.1 Designing the Air Quality Architectural Model

After studying several architectural models used for designing IoT enabled air quality monitoring systems, a three-layer architectural model by [13] was seen as suitable and was therefore adopted for this research.

Figure 12 shows a schematic view of system architecture consisting of three layers namely, mote, server and application layers.

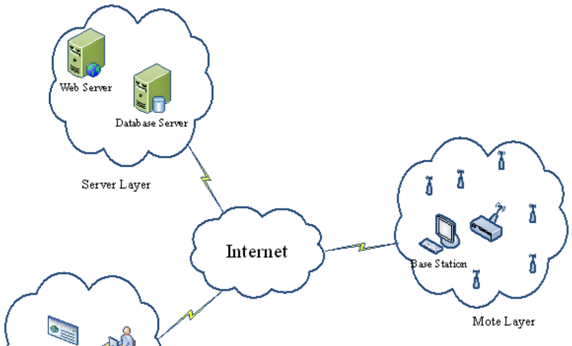


Figure 5: System architecture adopted from [25]

Mote layer:

This is the layer that consists of wireless sensor nodes and a Base Station. The base station is a package of nodes. Each node has one or more sensors plugged into the bread board and Arduino board as well as a transmitter, a power supply and microcontroller.

The nodes are distributed over an area of interest and are placed uniquely to be able to collect data from different areas. They are also carefully placed to ensure that the distance between the nodes does not exceed the maximum RF communication range. Energy optimized routing has also been used to optimize the communication of the nodes. [13]

Server layer:

This is the layer that stores all the sensor data. The data from the nodes in each base station are sent to the server via an internet. The data can also be manually transferred to the server in case of a connection failure through the use of USB cables. The server is therefore able to obtain and process data from the base stations, populate the WSN data and send the data to the application layer for visualization. [13]

Application layer:

This is the layer that is used for accessing the air quality data once it is processed and visualized. The application layer also allows the administrators of the system to have remote access to WSN data using web browsers. This provides the administrators with a powerful tool to visualize realtime WSN data and compare data from various nodes. In addition, the application layer allows the administrators to access the base st tions remotely and be able to modify sensor nodes' configurations. [13]

4.2. Designing the air quality monitoring system

The overview of the system is described in figure 6. All environmental sensors act as input and connected to a microcontroller i.e. an Arduino Uno R3.

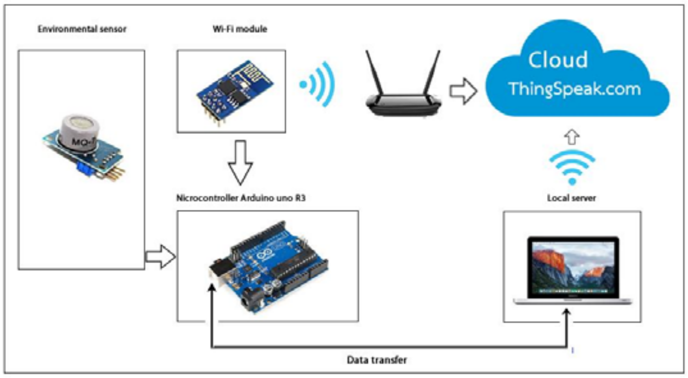


Figure 6: System Overview

The sensors are organized in a breadboard. The other tools used include a Wi-Fi module to connect to Wi-Fi to enable the data from the nodes to be sent to the web-server. The output of this system is visualized data that is sent to cloud and can be accessed by electronic devices such as laptops, mobile phones and other hand-held devices.

a. Electrical component

Electrical component of this prototype consists of seven gas sensors such as MQ 2, MQ 7 carbon monoxide sensor, a Wi-Fi module ESP8266, resistors, Linear regulator and LED's. The sensors are connected to the microcontroller i.e. Arduino Uno R3 via an expansion board (bread board).

By using the breadboard, all sensors and other nodes will get power identically and the voltage to these nodes will be 5V. However, it is not recommended to directly connect ESP8266 with Arduino because Arduino speaks in 5V and may result damaged in both sides. Therefore, 3.3 V linear regulators are used to decrease the power from Arduino. The schematic circuit is shown in figure 14. Figure 14 also shows how the gas sensors are connected to the microcontroller.

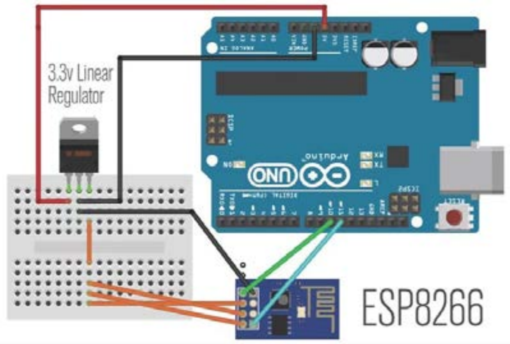


Figure 7: Electrical System

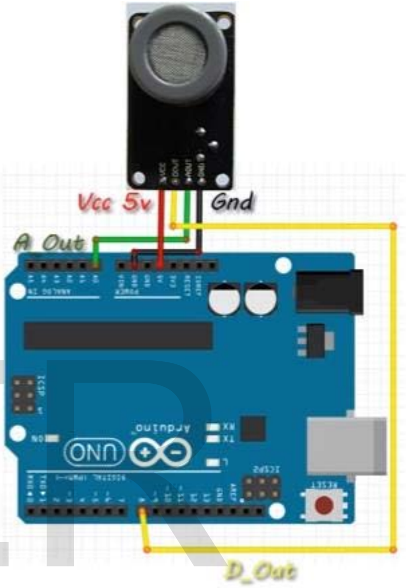


Figure 8: Sensor connection to Arduino

b. Software component

The softwares used in this system are mainly for communication between the nodes and the servers for data processing, visualization and data access. There are two communication methods that can be used in this research.

The first is the use of Serial0 for direct communication between Arduino and PC and the second method is the use of Serial1 for communication between Arduino and ESP8266 Wi-Fi module to transfer data to the server via web-server. In this research, thinspeak.com webserver was used for prototype purpose. Here are many open source systems that are readily available and can be developed to allow the nodes to send the sensor data directly to web-servers.

Another important function of this section is the ability to view the data from the sensors either before or after it has been processed into information. The data can be viewed locally in a computer when the node is connected using a USB cable via Serial0 to the computer and the readings are viewed from the serial monitor of the Arduino IDE.

The data can also be viewed via a web server through the use of an IDE programme code that enables the data to be read form the node and sent to the web-server using the ESP8266

Wi-Fi module. In this case, the baud-rate of the module must be set e.g. at 115200 for Serial1 Serial0 can be set in any baud-rate. After baud-rate is set, the connection to Wi-Fi router must be set.

The Wi-Fi connection allows data transmission from the Arduino node directly to webservers using standard HTTP protocol. The communication between Arduino and ESP8266 can be tested using AT command. When the module is ready and connected to Wi-Fi, it will read all sensors data from analog input of Arduino. The data collected in Arduino must be converted to string hence it can be used to update data value on the web.

d. Application layer

In this prototype design, a web application is used to access the air quality data. The website used is www.thingspeak.com. In this website, an account and a cha nel is created to get API key that is used for updating values from the nodes in visual form such as the use of graphs and charts.

Communication between the board module and ThingSpeak is initiated by the use of AT command. It is important to note that the API's generated in thingspeak.com can be used in other interfaces such as mobile apps through the use of iframes.

Apart from sending the data to a free IoT webserver such as thingspeak.com, the same data can also be sent to local database and webserver within the Local Area Network. The major difference is the IP address used, process of data acquisition and http request packet construction are remain the same.

5. SIMULATION RESULTS

a) Sensor readings in location A

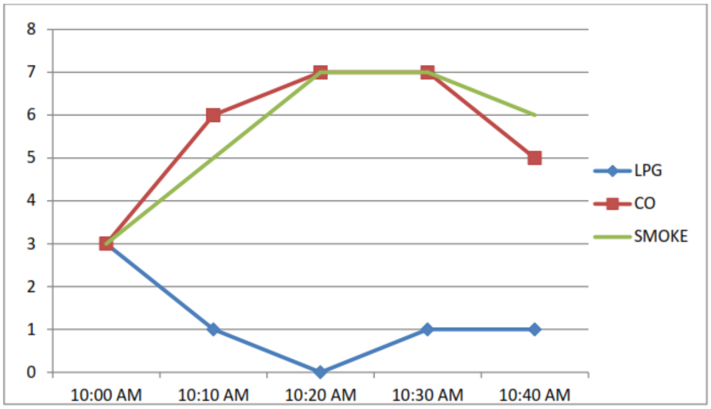
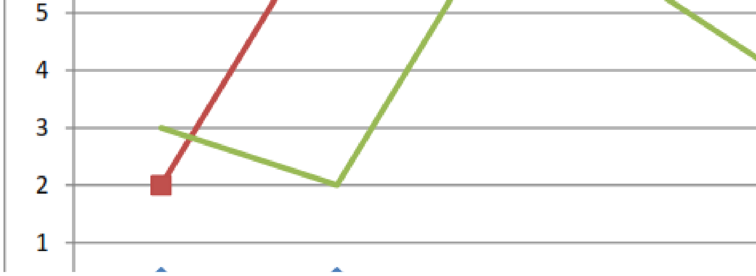


Figure 9: Air quality data in location A

The data obtained in this location shows that in this area, there was minimal level of carbon dioxide. However, due to the fact that there is a smoking zone, when the sensor was moved to this point, the readings of CO and smoke were seen to rise rapidly.



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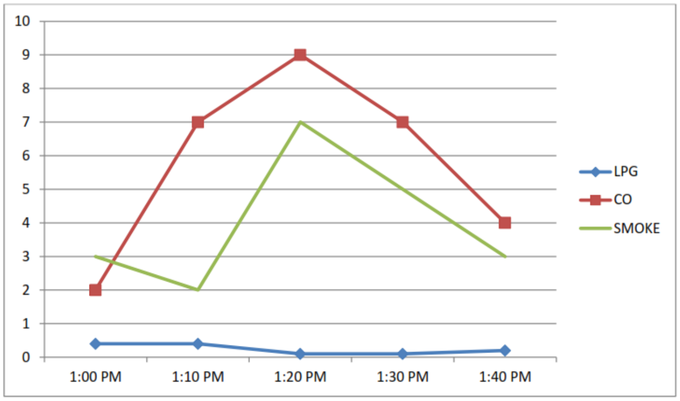
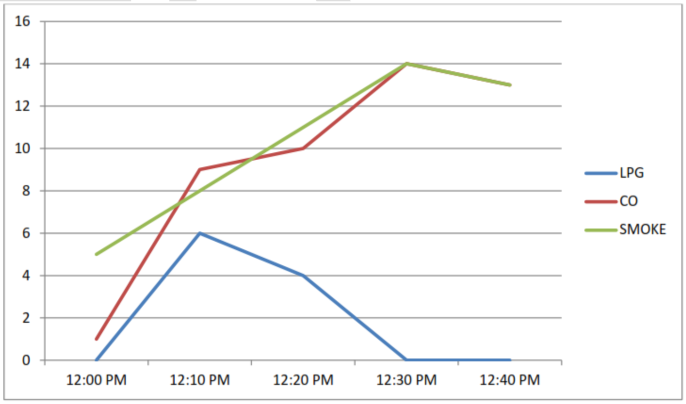


Figure 10: Air quality data in location B

The readings show that the levels of CO are much more than the previous readings in location A. However the levels might not have been high due to the fact that there was less activity in this area as the cars are parked long term with little movement of cars coming in and going out. The sensor also captured an increasing level of CO when the sensor was moved closer to a vehicle that was just parked.

c) Sensor readings in location C

Sensor data was also taken from another location (a main car park area) at midday and the results is shown in figure 11:



he results show that there was a significant change in the CO levels as well as smoke levels. This can be attributed to the fact that this being the main car park area, there is a lot of activities in terms of vehicles coming and leaving. The CO levels are therefore high as there are more fumes from the exhaust of the cars.

6. CONCLUSION

In conclusion, the study established that the possible solutions to improve current challenges of air quality monitoring by environmental authorities can be done through the adoption of IoT system in the air quality monitoring practices in Kenya.

The air quality monitoring systems based on IoT will improve efficiency of air quality monitoring as the systems are scalable, low-cost, provide sensing accuracy, can be integrated to other ICT systems and can obtain air quality data with a wide coverage with minimal or no human interaction.

The air quality monitoring systems based on IoT will also make it possible to timely disseminate air quality data to all the citizens and the environmental authorities to appropriate actions.

The environmental authorities should therefore create more labs for testing the technologies that make up the internet of things as this can be vital in building systems that can readily be used for air quality.

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