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IoT Architecture for Enhancing Rural Societal Services in Sub-Saharan Africa

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Abstract

The potential of IoT in contributing towards sustainable economic development in Sub-Saharan Africa (SSA) through digital transformation and effective service delivery is widely accepted. However, the unreliability/unavailability of connectivity and power grid infrastructure as well as the unaffordability of the overall system hinders the implementation of a multi-layered IoT architecture for rural societal services in SSA. In this work, affordable IoT architecture that operates without reliance on broadband connectivity and power grid is developed. The architecture employs energy harvesting system and performs data processing, actuation decisions and network management locally by integrating a customized low-cost computationally capable device with the gateway. The sharing of this device among the water resource and quality management, healthcare and agriculture applications further reduces the overall system cost. The evaluation of LPWAN technologies reveals that LoRaWAN has lower cost with added benefits of adaptive data rate and largest community support while providing comparable performance and communication range with the other technologies. The relevant results of the analysis is communicated to end-users' mobile device via 2G/3G GPRS. Hence, the proposed IoT architecture enables the implementation of IoT systems for improving efficiency in three key application areas at low cost.

Keywords: IoT architecture; Connectivity technologies; Sub-Saharan Africa; Healthcare; Agriculture; Water quality and resources management

1. Introduction

According to UN, out of the 48 countries in the SSA region, 32 of them are classified as Least Developed Countries (LDCs) that are facing the most severe structural barriers to development [1]. In these countries, about 60% of the population lives in rural areas [2] and so improving efficiencies of rural services will have a larger impact in the countries' sustainable economic development. The UN member states adopted 17 Sustainable Development Goals (SDGs) in 2015, among these SDGs this work focuses on contributing towards achieving zero hunger (Goal 2), good health and well-being (Goal 3), and clean water and sanitation (Goal 6) in rural SSA. SSA region has the highest prevalence of hunger in the world, with the rate increasing from 20.7% in 2014 to 23.2% in 2017 [3]. Improving agricultural yields is one the key solutions for reducing hunger. In addition, enhancing the productivity of the agricultural sector has a considerable benefit in the economic development of the region since agriculture

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accounts for 32% of the total GDP and employs more than half of the total labor force [4]. The health index of a nation directly implicates its socioeconomic growth. However, primary healthcare coverage and access in the majority of rural areas in SSA is low, causing higher proportion of preventable deaths of newborns, children and mothers. There is also a high mortality rate in the region due to AIDS, tuberculosis, malaria and water-borne diseases. Implementing primary healthcare centers within the rural community or strengthening existing ones is among the necessary steps for reducing the mortality rate and ultimately achieve universal health coverage for the population. Water is a critical resource that is becoming scarce globally. Currently, water shortage affects more than 40% of the world's population and predicted to get worse [5]. Though World Health Organization states that access to safe drinking water is a basic human right [6], 326 million people are without access to safe water source in 2015 [7]. Providing safe drinking water and sanitation is part of the SDG, which relates with SDG 3: Good Health and Well-Being. Thus, ensuring the quality of drinking water results in reduction of water-borne diseases and the associated deaths. Efficient water resource management through prevention of leakages and pollutions help to mitigate the water shortage problem.

IoT for improving service efficiencies in various sectors, such as healthcare, agriculture, natural resource managements, infrastructures, and factories have been demonstrated [8] [9] [10]. However, such activities are few in SSA countries, especially targeting rural societal services. The implementation of IoT in agriculture, healthcare and water quality and resource management can help addressing the rural community problems in SSA, which in turn enable moving forward to the targets of UN 2030 SDGs. The main advantages of IoT in these SDGs are improving the efficiency of the relevant services with fewer resources and/or increasing impact with similar levels of existing resources. Limited connectivity and power grid infrastructure, cost and lack of skilled labor force are the major roadblocks for reaping the mentioned benefits. In this work, the potential of IoT in the mentioned three sectors, and the challenges of IoT implementation are discussed within the SSA context. Based on the findings of the discussion, resource-efficient IoT architecture is developed. The major contributions of this work are: i) evaluating the suitability of IoT connectivity technologies for rural services in SSA; and ii) Resource-efficient IoT architecture for low-cost service delivery.

The structure of the paper is as follows. In Section 2, the potential of IoT in addressing societal challenges in key rural services is discussed. Overview and comparison of IoT connectivity technologies for use in rural SSA are presented in Section 3. The major roadblocks for implementing IoT in rural SSA are explained in Section 4. The customized IoT architecture that workaround the challenges and enable implementation of IoT-based application is presented in Section 5. Finally, in Section 6 the conclusions of the work are presented.

2. IoT for selected rural societal services

Integration of IoT systems in various sectors is part of the ICT for development activities. As discussed above, water resource and quality management, healthcare and agriculture are the key sectors that need service improvement in rural SSA. In this section, the need and benefits of IoT systems in these sectors are presented.

2.1. Healthcare

Universal healthcare is among the key targets for sustainable development as the health index of a country directly impacts its socioeconomic growth [11]. Due to high population to physician ratio and resource limitations in many SSA countries, several countries have been formulating community health programs in rural areas to provide basic health and medical care close to community, which increase access and coverage of essential services. For example, in Ethiopia a community Health Extension Program (HEP) was introduced in 2003 resulting in improvements in maternal and child health and communicable diseases. Despite the success, there are challenges related to the efficiency of health extension workers and the capacity of health posts. There is a huge disparity in healthcare access and coverage between rural and urban areas. Often rural dwellers fail to seek treatment early on because of costs and long travel to the healthcare centers which are located in regional cities far away. In countries with community health program initiatives, the community health posts that are close are often under-resourced and the skills of the staff are limited. The majority of the population in SSA lives in rural areas and the mentioned challenges emphasize the importance of technological support in improving the efficiency of the community health posts. The use of IoT in healthcare has been in the forefront since the advent of IoT but the emphasis of the development has been in the context of the developed world. Integrating IoT in the community health programs contributes towards delivering quality healthcare services in resource efficient manner. The community health worker can make a better decision on the course of treatment, by using sensors for monitoring of vital signs (during the home visit by community health worker or when the locals visit the community health post for seeking treatment), and getting decision assistance from support systems. For example, in Ethiopia it has been observed that the skills of community health workers for handling maternal services were less trusted [12]. Their pre-service education did not prepare them for all the tasks under the scope of their practice [13]. Thus, the integration of IoT and decision support system help to enhance the quality of care accessibility of healthcare service to rural community.

2.2. Water resource and quality management

In rural SSA, water is often fetched from a common water point, exposing the users for microbial contamination and spread of contagious diseases, if any of the user failed to practice proper hygiene. Majority of the contagious diseases in LDC countries are waterborne, for instance diarrhea is responsible for the deaths of around 17% of children under the age of five in these countries [14]. In addition to microbial issue, drinking water quality is impacted by ground and surface water pollution, which often occurs due to substandard industrial and mining practices. The quality of water has also impact on agricultural productivity. For example, the quality of irrigation water affects soil salinity, water infiltration rate and toxicity, which in turn impacts the crop yield. Thus, it is necessary to improve the quality of water and efficiency of water usage by avoiding wastage. The use of IoT and sensor networks for water quality monitoring and efficient water resource management has been demonstrated by various researchers [15] [16].

In rural SSA, water supplies are often located at a common point in the village, which make safe transporting, storage and treatment of water within the household highly crucial to minimize the risk of contamination. With sensors embedded in the water source and household water containers, the quality of water can be monitored in real-time. This allows the local water authority to administer appropriate treatment, take actions to stop the source of contamination/pollution and educate the community on the household level treatment procedure. In case of contamination due to user's unhygienic practice, the source of cross contamination can be traced through analysis of the monitored data. The use of IoT can also improve the reliability of water service as it allows detection of water flow, level in the reservoir, leakage and/or malfunction in the infrastructure. Based on the detection, the authority can take immediate measures for optimizing the water distribution and utilization accordingly. Furthermore, with the use of level and flow sensors, an IoT can be used to monitor and alarm on flood and drought that sometimes occurs in SSA countries.

2.3. Agriculture

Despite the majority of the work force in SSA is in the agricultural sector, the productivity is low compared to the global average. SSA's capacity to ensure food security is challenged by the combined impacts of natural resources degradation, population growth, and the vulnerability of the agricultural systems to different climate change. In most rural areas, either there are no weather stations or their spatial distribution is sparse, making it difficult to gather and utilize local weather data for farming decisions. Microclimate information is more vital than before because of the prevalence of climate change and its variability in the region, which can have a severe impact in agriculture unless climate resilient solutions are integrated. The use of IoT in the agricultural sector has been proposed for several purposes, such as in irrigation management [17] [18], precision farming [8], predicting droughts [19], microclimate monitoring [20] [21], and crop disease risk evaluation [22]. These solutions showcase the potential of IoT in transforming the agriculture.

In SSA, several farming decisions, such as pesticides, fertilizers and irrigation, are made in generic manner regardless of crop and soil specific properties, climate variability impact and spatially fine-grained soil fertility evaluations. IoT in agriculture can help to improve the productivity of agriculture in the SSA region through optimum utilization and management of relevant resources (land, water, fertilizers, and pesticides). To reap this benefit, the IoT architecture and protocols have to customized according to the specific requirements and available resources in the region. Low-cost devices and open-access technologies are necessary. The use of back-end resources, for example remote cloud and application server, has to be avoided. This is due to the lack or high cost of broadband connectivity. Lightweight and resource efficient local data processing has to be considered. The integration of such cusomized IoT system in the agriculture improves the sustainability of agriculture by enabling data-led agricultural decisions.

3. Overview and comparison of IoT connectivity technologies

A number of low-power wireless connectivity technologies for IoT have been developed in the last ten years. These technologies differ in several factors such as range of communication, complexity of the underlying protocols, network capacity (throughput & delay), power consumption and the radio spectrum band they use. IoT connectivity technologies can be classified as short- vs long-range or unlicensed vs licensed spectrum. In this section, review and comparison of low-power connectivity technologies are considered for the suggested IoT architecture and service delivery in a rural SSA community setting.

3.1. Short-range connectivity technologies

Bluetooth Low Energy (BLE) and ZigBee are the two most popular short-range connectivity technologies for IoT applications. The development of these technologies started as the connectivity options in the era of wireless sensor networks. BLE is the low power version of classical Bluetooth technology and it operates in the 2.4GHz ISM band [23]. The ZigBee alliance has developed a short-range, low-power communication standard initially for wireless sensor network applications. Zigbee builds on IEEE 802.15.4 PHY and MAC layers [24].Interested readers can follow the listed references and find the details on the technology standards and features of the technologies.

3.2. Low-Power Wide Area Network (LPWAN)

LPWAN technologies provide massive-scale wide-area connectivity for low cost, low power and low data rate device connectivity. LPWANs operating in sub-1 GHz bands complement short-range wireless communication technologies, to deliver a diversity of IoT applications [25]. The following is a list of LPWAN type of IoT connectivity technologies considered w.r.to the proposed IoT Architecture for agricultural applications.

(a) *LoRaWAN* is an open standard and operates in 433/868/915MHz frequency bands. It is based on a proprietary LoRa radio technology, which employs chirp spread spectrum (CSS) modulation with integrated forward error correction (FEC) and data rate adaptation mechanisms [25].

(b) *Sigfox* is another LPWAN technology operating in the sub-GHz band of 868/915MHz. Unlike other LPWAN technologies, it uses BPSK modulation to transmit small payload size (12 bytes) data using ultra-narrowband technology at a slow bit-rate (100 -600bps) [26].

(c) *DASH7 Alliance Protocol (D7A)*: is a wireless air interface and a system stack that operates in the sub-1GHz ISM bands (433/868/915MHz). It is targeted for extreme low power applications, such as active RFID and wireless sensor networks [27].

(d) *Weightless-p* operates in license exempt sub-GHz frequency bands, e.g, 433/470/780/868/915MHz [28].

(e) *NB-IoT* is developed by 3GPP in Cellular systems for ultra-low complexity and low throughput IoT as part of 3GPP Release 13 [29].

3.3. Comparison of LPWAN connectivity technologies

As one can understand from the list and associated references above, several connectivity technologies are available for IoT applications. The most appropriate connectivity technology for a given application depends on the application specific requirements, cost, and availability of local connectivity infrastructure and power supply. Trade-offs need to be made among several parameters such as coverage range, link reliability, flexibility, power requirements, data throughput, cost and (un)licensed spectrum. Among the features, cost, communication range, energy efficiencies, link reliability, and open source standards are the important ones for the three selected applications of rural SSA. Table 1 summarizes selected features of the mentioned technologies. Among the presented LPWAN technologies, LoRaWAN has the largest user base and deployments globally. In addition, it has the lowest deployment cost, comparable performance and similar range compared to NB-IoT and Sigfox. Based on these findings, using LoRaWAN for the applications in rural SSA is the preferred option.

Table 1 Comparison of selected LPWAN connectivity technologies

Connectivity technology	LoRaWAN	SigFox	Dash7	Weightless-p	NB-IoT
Rural theoretical range	20 km	40 km	2km	35 km	15 km
Network and deployment cost per base station	$ 100 - 1000	$ 4000	-	-	$15000
Max data rate (kbps)	0.3-50	0.600	200	100	200
Transmission power (dBm)	14 - 27	20	10 - 27	17	20/23
Link budget (dB)	Up to 157	163/158	Up to 140	-	154
Receiver sensitivity (dBm)	-124 to -134	-126	-97 to -110	-105 to -122	-141
Standard	LoRa alliance	SigFox	DASH7 alliance	Weightless SIG	3gpp
Topology	Star	Star	Tree, star	Star	Star
Spectrum cost	Free	Free	Free	Free	>$500 million/MHz
Frequency band (MHz)	433/868/915	868/902	433/868/915	433/868/915	LTE
Device market readiness	High	Medium	Low	Low	High

4. Challenges in implementation of rural IoT-based services

As we have seen in Section 2, IoT systems have the potential to facilitate the daily life of rural communities and contribute towards alleviating the economic burden of the poor. However, there are several challenges that need to be addressed in order to be able implement large-scale IoT-based services. In this section, some of the prominent challenges are discussed.

4.1. Lack of reliable non-intermittent power supply

In most parts of rural SSA, only about 45% of households have access to the electric grid compared to their urban counterparts with close to 94% of dwellers [30]. The electric power supply access divide varies greatly across the Sub-Saharan countries with some instances, electricity grid connections are present but there is no active electric power supply for more than half a day in a week or over weeks due to the intermittency nature of the grid power supply [30]. In such situations, sustaining reliable grid-dependent IoT connectivity technologies is not feasible, especially in remote and inaccessible rural areas. Most rural areas in SSA present viable environment for the production of renewable energy supplies and hence, IoT connectivity technologies that leverage such opportunities and are capable of running on renewable energy sources in a cost-effective manner should be designed.

4.2. Costly or non-existent broadband connectivity

In far-flung rural areas in most SSA countries, there is limited/very costly or no access to the Internet [31]. The internet penetration rate is barely at 20% in Africa, the world's lowest internet access rates [32]. This presents major barriers to the adoption of the IoT with an estimation that by 2025 Africa will have tripled internet penetration to over 50%, or around 600 million people [31]. Ericsson [33] forecasts that by 2024, around 1.9 billion people will be without reliable mobile broadband internet. A significant number of these residing in rural areas within mobile broadband coverage area but have no subscription to such a service. Thus, an IoT connectivity architecture, which is not over-reliant on internet access, should be designed to foster data storage, processing and access locally, for instance the IoT gateway acts as an end computer. Users can then attach a keyboard and a display unit directly onto the gateway to access the locally stored data. Such gateways should also flexibly interact with mobile phones of the end-users through 2G/3G GPRS or Bluetooth to notify users of the important events.

4.3. Affordable, reliable and secure IoT

The average income of a rural household in SSA is 50% less than that of their average urban household counterpart [34]. Moreover, most of the extremely poor rural dwellers rely on subsistence farming for their livelihoods with economic strain to afford the cost of IoT-based services. To provide a sustainable IoT connectivity to rural environments in developing countries, the innovative and local business models has to be considered [34] [32]. Low-cost open source hardware and software platforms, as well as connectivity technologies present alternative opportunities for affordable implementation of large-scale IoT services [35].

In wireless communication systems, multiple obstacles such as vegetation, terrain irregularity and buildings along the path of the signal propagation attenuate the transmission power. The attenuation of the signal transmission power reduces the communication range and consequently degradation of the network coverage as well as link reliability. Rural areas in SSA are characterized typically by clustered settlements, which are far apart with vast open areas of different terrains in between (UN, 2014). Accurate path-loss estimation is critical in designing reliable networks as every time the distance is doubled, only a fourth of the signal power is received, degrading the SNR at the end receiver. Commonly available long-range IoT connectivity technologies achieve at least 15 km in line of sight (LOS) conditions but fail to attain 2 km in non-line of sight (NLOS) conditions [36]. Hence, the design of an IoT connectivity architecture that takes into account the specific terrain and settlement scenarios of rural SSA is critical for realizing reliable IoT applications. Most parts of the rural areas in SSA are remote and not easily accessible, which may create difficulty in ensuring the maintainability and security of the IoT devices. To tackle such issues, involving the locals as active stakeholder from the beginning of the project and hosting the key devices (e.g., gateways, local data processing devices) at socio-economical facilities such as schools, clinics and government administrative posts are necessary.

5. Proposed IoT architecture

The three or more layered IoT architectures that involve broadband connectivity, cloud services and remote servers are unaffordable and in some areas even impossible to implement due to the inaccessibility of connectivity infrastructure. To achieve wide-spread implementation of IoT system in the three key application areas (water resource and quality management, healthcare, and agriculture) of rural SSA, resource and cost efficient IoT architecture has to be developed. In this regard, we developed an architecture that does not need costly broadband connectivity as well as cloud and remote server resources. This is achieved by performing data processing, and network management processes (e.g., device activations/update, security configuration and network control) in locally deployed powerful enough computing device. The use of resource efficient data processing algorithm and the sharing of the computing device by the three applications further reduces the initial network deployment as well as maintenance costs. In addition, the architecture along with its protocols facilitates incorporation of energy harvesting system and efficient energy usage for uninterrupted availability of the IoT network. The protocols also enables reliable link connectivity despite attenuations and multipath effects. All these allow to fulfill application specific requirements within the rural SSA resource context that ultimately ensure low-cost service delivery to the rural end users. The proposed architecture is illustrated in Figure 1. The three applications share data processing and controlling component by each of them running in own container in the computing device. The specific requirements of each application and their network configurations are briefly discussed in the below paragraphs.

In case of healthcare, the IoT system is targeted for strengthening the efficiency and reliability of services provided by community health posts. The workers in the community health posts have limited knowledge and practical skills in diagnosis and devising treatment plans. The health posts are also often under resourced in diagnostic equipment due to high costs. The health post workers can monitor relevant vital signs of the patient at the health post or during their home visits using low-cost biosensors and wearables. The monitored bio-data are communicated to the gateway using LoRaWAN and recommendation on the treatment plan after the analysis of the data is communicated to the health post worker in her/his end-device. The recommendation and bio-data are further communicated to the regional healthcare center/hospitals, this is especially important in case of severe ailments and/or further follow-ups by well-training healthcare professionals. This chain of communication requires implementation of star of star LoRaWAN network topology with acknowledgement mode for ensuring correct reception of messages.

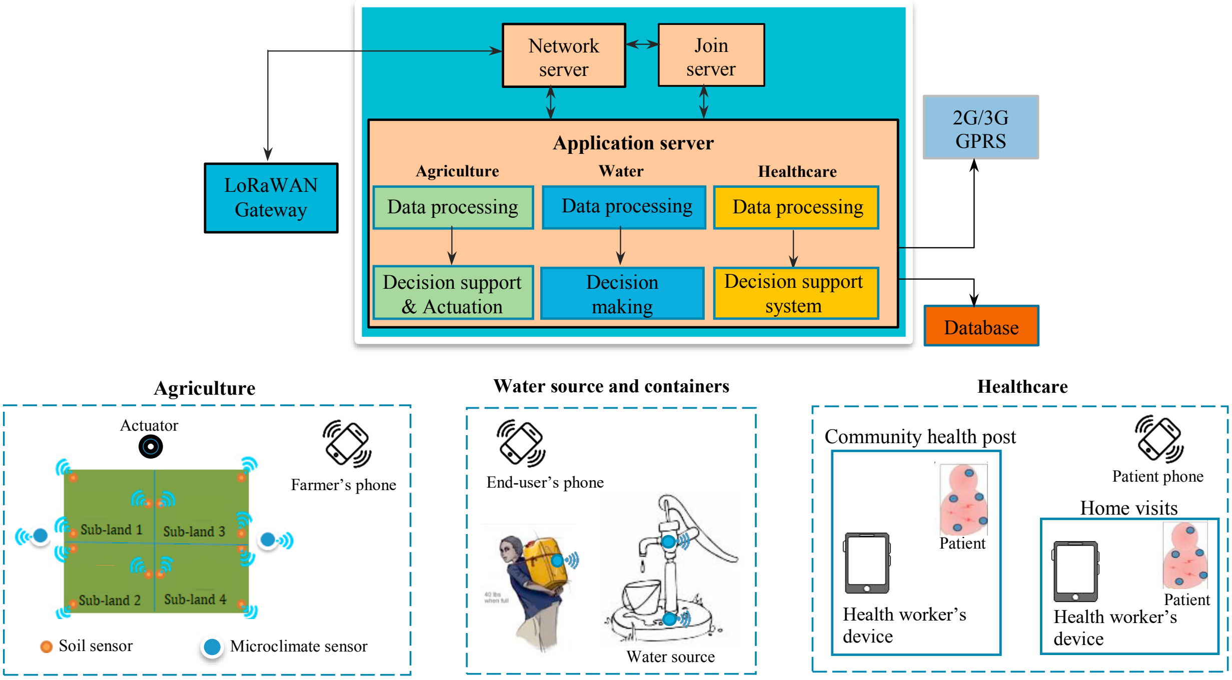

Figure 1 Proposed IoT architecture for key application areas of rural SSA.

The IoT system for water resource and quality management focuses on i) preventing water wastage due to leakages and infrastructure malfunctions at the common water point, 2) ensuring access to safe drinking water, and 3) providing early warning on the onset of water-borne diseases in the community along with traces of possible cross contamination. Water quality and infrastructure health monitoring sensors that are deployed at the common water source point communicates their sensed data to the gateway through LoRaWAN. The water quality monitoring sensors that are embedded in the water fetching container of the households involve mobility. For tracing any contacts in case of cross contamination suspicion as well as provide instant quality metrics to the mobile phone of the household, BLE transceiver besides LoRaWAN is integrated in the water contrainer. The list of contacts along with the quality parameters are communicated to the gateway using LoRaWAN. The analysis of water quality, infrastructure health and contact tracing are performed at the data processing component. Warnings and recommendations on the safety of the water is delivered to the mobile phones of the households as 2G/3G GPRS. Periodical water quality analysis reports are communicated to regional water body authority and healthcare centers to help formulation of long-term sustainable solutions.

The IoT system in agriculture assists the smallholder farmers to improve crop yields by monitoring relevant soil, climate and water parameters and providing recommendations on farming decisions (e.g. fertilizers amount/type, irrigation timing/amount, timing for collection of crops). Sensors are deployed in the farmlands to monitor various parameters, such as soil moisture, pH, fertility, and microclimate. In case of irrigated farms, sensor needs to be deployed in the water source and infrastructure to monitor water level and flow. As farmlands can be large and far from the gateway with integrated data processing, the use of star of star LoRaWAN topology may be required in some of the cases. The data processing component needs to integrate farmers' indigenous and agricultural expert knowledge as well as soil and crop characteristics as inputs to the data analysis subsystem.

The implementation of the IoT system should be based on open source and low cost development boards. It is required that the implemented protocols facilitate establishment of robust links and fulfillment of applications quality of service requirements. Security of the communication, stored data and the devices has to be guaranteed. Laws, regulations and policies on data access and handling has to be formulated, this is critical especially in the case of healthcare application.

6. Conclusions

Affordable and resource-efficient IoT architecture for improving service efficiencies in water resource and quality management, healthcare, and agriculture in rural SSA was developed. The architecture has addressed the issue of unavailability/costly broadband connectivity by enabling the application and network related processes to be performed at local computational device, which is integrated with the gateway, instead of in remote cloud and servers. The implementation of energy scavenging system in the architecture was proposed to tackle the problem of power grid unavailability and/or their unreliable service. Based on the results of LPWAN technologies evaluation, the use of LoRaWAN was decided since it has lower deployment costs and no subscription or license fees. In addition, specific requirements of the three application areas and other relevant contexts of rural SSA were taken into account in the architecture. With the mentioned customizations, the proposed IoT architecture has the potential to transform the life of rural dwellers and contribute towards sustainable development of SSA countries. The developed architecture will be implemented and pilot tested for the three application areas in rural Ethiopia in our future work.

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