Developing the IoT to Support the Health Sector: A Case Study from Kikwit, DR Congo

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Abstract. Effective implementation and evaluation of development projects depends on access to accurate, complete, and timely information about the outcomes of project implementation. We explore the proposition that next-generation ICTs offer solutions for development actors operating in decentralised and extremely low-power environments to improve data collection, monitoring, and project feedback. This paper describes the potential integration of novel distributed monitoring technologies and techniques within the health sector in developing countries, and in particular the use of Internet of Things (IoT) technologies for monitoring widely distributed projects in areas with little or no infrastructure. We discuss the application of an emerging low-power wide area networking technology, LoRa, which is ideally suited to resource-limited contexts due to its low cost, low power usage, and long range. We describe our experiences in implementing a pilot project carried out in Kikwit, DR Congo to develop a LoRa-based wireless network to track the temperature of blood products, ensuring their security and viability through a decentralised, low-power, and low-cost monitoring system.

Keywords: LoRaWAN · e-Health · ICT4D · IoT for development · Smart fridge · Cold chain

1 Introduction

The Internet of Things (IoT) uses tiny, low-cost devices equipped with sensors and low-power radios to build networks that are capable of sensing and controlling the physical world. In recent years, many IoT technologies have appeared on the market, enhancing quality of life and solving nontrivial problems. These technologies have emerged mainly in developed countries due to the widespread availability of and market for consumer goods and the existence of high levels of underlying networking, electrical, and basic service infrastructure supporting these technologies. Examples of these innovations include the development of IoT applications for hyper-connected "smart city" infrastructure, agricultural monitoring and control [1], and remote sensing and data collection to support personal health care, particularly in the domain of elder care [2].

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However, IoT applications remain largely oriented toward high-income countries and consumer markets, and relatively little research has been conducted as to how emerging IoT technologies can be applied and tailored to developing country contexts. Yet, as others have argued [3,4], the IoT has the potential to benefit the development sector immensely, leveraging appropriate new technologies and techniques for monitoring widely distributed projects in areas with limited existing infrastructure. In these environments, emerging IoT technologies may hold tremendous potential to offer low-cost, low-power solutions to make service delivery and project monitoring 'smarter' (i.e. better informed through more efficient and effective monitoring).

Meaningful planning and responsible governance of development projects depends on access to accurate, complete, and timely information about the outcomes of project implementation. Key stakeholders engaged in development work often lack data about what is really happening 'on the ground', in part due to the inherent difficulties involved in Monitoring and Evaluation (M&E) in the face of large geographic distances, lack of infrastructure, and limited resources [5, pp. 71]. Quality M&E is critically important for responsive and responsible development project planning and implementation, as it provides a means to assess how precious human and material resources should be allocated, and to respond quickly to crisis situations or system failures. The lack of access to timely, reliable, and comprehensive data and feedback on project outcomes hinders the decision-making of development actors. In theory, the use of IoT technologies in this context could enable near real-time monitoring of projects, allowing stakeholders to more quickly study, refine, and optimise the execution of projects based on changing facts on the ground.

In the health sector in particular, near real-time monitoring and feedback is essential not only for saving lives but also for safeguarding essential supplies. In the past ten years, an abundance of literature has explored the emerging field of 'mHealth' and the uses of mobile technologies in the health sector in developing countries [6–9], but this has rarely been extended to explore the application of the next-generation of ICTs (such as IoT technologies) in developing countries.

To address this gap in the literature and explore the applicability of emerging IoT technologies in the health sector in development contexts, we conducted an exploratory pilot project in the Democratic Republic of Congo. This paper describes our experiences with our deployment of a LoRa Wide Area Network (LoRaWAN) for medical cold chain surveillance in an environment with unreliable electricity and a distributed health system. LoRa is a next-generation network technology that is ideally suited to resource-limited contexts due to its low cost, low power usage, and long range. This case study enabled us to test in practice the theoretical potential of IoT for real-time monitoring and feedback, to identify potential political and socio-cultural barriers to its effective local adoption, and to determine whether the economic and technological limitations of using this emerging technology in a developing country context are consistent with its application in highly developed countries.

Next we will describe the local context of our case study in the health sector in Kikwit, DR Congo, with its distributed health system and precarious access to power. The subsequent section describes the LoRa network and end devices used for monitoring blood supplies. Finally, we will offer some reflections on the lessons learned and future applications for this sort of IoT in the context of the health sector in developing countries and for development projects more broadly.

2 Project Context

Many sectors in DR Congo are currently confronted by insufficient capacity for effective and timely data collection and monitoring. Conflict and political instability have compounded the challenges of serving a population distributed over a vast geographic area with limited infrastructure [5]. Decentralised mechanisms for data collection and M&E are critically important in this context. This is particularly true for the health sector, due to the extensive reliance on donor funding and the distributed nature of both state health structures and donor-led health interventions [10].

Our pilot project is based in Kikwit, DR Congo, a representative example of a low-infrastructure environment. Kikwit is a secondary town in the interior of the country, located 525 km southeast of the capital, Kinshasa. The town was the site of a serious Ebola outbreak in 1995, which spurred an influx of biomedical technologies and expertise [11]. However, the town of about 1.2 million inhabitants spread throughout an area of 92 km^2 remains cut off from the electricity grid. The primary form of energy supply in Kikwit is thus provided by petrol-powered generators or solar panels. Although there have been some donor-supported initiatives to partially electrify critical locations (such as the general hospital) with more sophisticated solar systems, the vast majority of health centres do not have a regular electricity supply (a best-case scenario usually involves a generator running at most a few hours per day).

The state health infrastructure in DR Congo is decentralised, with a large number of provincial and district health offices involved in the distribution of essential medicines, vaccines, and blood products. The cold chain extends only to the district level, as community health facilities usually lack access to any electricity, and GSM coverage—although improving—is still lacking in many rural areas. The distances between health centres and the extremely degraded state of the roads compound the challenge of delivering essential medical supplies. The ability to monitor the integrity of the cold chain is vitally important for supply safety, as is the ability to coordinate supply levels and stock movements.

The second author conducted fourteen months of anthropological fieldwork in the health sector in Kikwit (since January 2015), which has revealed significant challenges associated with data collection, the urgent need for monitoring of projects, and the desire for new technologies to ease the strain on over-burdened and under-resourced organizations and individuals. In particular, local health institutions lack reliable, systematic, and cost-effective monitoring for medical supplies cooled by these often sporadic power sources. For example, the current approach to monitoring medical cold storage is time- and labour-intensive, based upon manual twice-daily temperature measurements with no electronic records. Furthermore, when temperature-controlled medical supplies such as blood, vaccines, and insulin leave the central office, their status is no longer monitored, introducing scope for unsafe use.

This location is thus an ideal site for the our LoRa case study because it features a large, decentralised population and health infrastructure without any reliable power source. Health facilities face serious challenges in ensuring the medical cold chain, and M&E is crippled by constant barriers to electricity and communication. Moreover, given the paramount importance of foreign donors in supporting both state and private health institutions in the region, local partners have a strong desire for improved monitoring capacity and any means of producing more reliable measurements and evaluation of project results and successes (in order to help secure future funding and support from these donors).

We conducted our initial pilot in collaboration with the Provincial Centre for Blood Transfusion (*Centre Provincial de Transfusion Sanguine*, or CPTS), the local body responsible for coordinating the collection, testing, and storage of blood and blood products. CPTS is centrally located in the Plateau neighbourhood of Kikwit, but it oversees and coordinates transfusion-related activities throughout the Bandundu region (a large territory encompassing 52 health zones across the former Bandundu province, now comprising the provinces of Kwilu, Kwango, and Mai-Ndombe). CPTS relies heavily on a network of fridges and cooler boxes (for the transportation and storage of blood products) and has expressed an interest in the monitoring capacities that IoT technologies could provide (e.g. to verify fridge temperature or stock levels of different blood types, or potentially even to identify individual donors by code or RFID tag). They are usually able to keep their blood stored at safe temperatures in a solar-powered fridge, the temperature of which is monitored manually and recorded twice daily. However, this system can on occasion break down, for example due to the large amount of dust in the air during the dry season, reducing the efficiency of the solar panels. From the CPTS central office, they distribute blood to smaller health zones where and when it is needed. When blood is distributed to the surrounding health centres, however, no temperature monitoring is carried out.

Although the initial pilot encompasses only the surveillance of temperature for blood products, we envisage this quite easily being extended to the monitoring of other aspects of the medical cold chain in Kikwit and the surrounding region, particularly for the transportation of vaccines and other temperature-sensitive medications. The central office of the health district, for example, has a critical need for monitoring the temperature of fridges for vaccines and other medications, and could benefit greatly from systematic monitoring technology (both in terms of efficiency and the security of ensuring cold chain integrity).

3 Project Implementation

In this section, we will describe our experience of rolling out a communication network and monitoring system suitable for development projects in DR Congo, and offer a technical description of the technology we have implemented.

3.1 Choice of Technology

The limited existing infrastructure and unreliable electricity access that characterised the local context, as described above, necessitated the use of networking infrastructure with the following key features:

- Low cost: network and devices should have low manufacturing costs and should not depend on a cellular connection so as to eliminate recurring network fees.
- Long range: given the wide geographic distribution of the local health system (as is the case for many sectors in developing countries), hardware should have an inherently long range and should support software for extensible mesh networking, enabling sequences of wireless devices to form arbitrarily large mesh networks.
- Low power: since power infrastructure is unreliable or absent and projects are often too widely distributed for manual battery changes as a feasible solution, operational power requirements should be very low and capable of running on locally available alternative solutions such as solar systems.

With these general goals in mind, we evaluated a number of emerging technologies that would enable the realisation of a robust wireless network serving the community in Kikwit. Numerous competing technologies have emerged on the market that realise Low Power Wide Area Networks (LPWANs) that do not depend on cellular network coverage. The most notable of these are the SigFox [12] and LoRa [1] radio technologies, both of which are already being employed to support IoT applications in Europe and North America. The two technologies differ significantly in their marketing models: SigFox requires users to subscribe to licensed network providers, whereas LoRa enables users to establish their own private network infrastructure. In the DR Congo, there is currently no established SigFox infrastructure [12] and the authors are not aware of any current plans to establish one in the near future. It is thus also likely that until SigFox networks are established in the developing world, it will remain an unsuitable technology to support such applications.

In contrast to SigFox, the LoRa radio technology enables users to establish their own network infrastructure using any one of the numerous gateways or concentrators available on the market at low prices (ranging from €100 to €1200). Such gateways offer an effective range of over 15 km and offer end device battery lives of more than 10 years with messages sent daily. Furthermore, the range of the network can be arbitrarily extended by building a 'mesh' of networks wherein each node serves as a router, as described below. This technology thus fulfills our three essential criteria (low cost, long range, low power) outlined above.

These features make the LoRa radio technology ideally suited to widely distributed monitoring where there is little or no existing infrastructure.

3.2 Gateway Infrastructure

For our pilot implementation, we installed LoRa-based network infrastructure at the CPTS office in Kikwit, as shown in Fig. 1. This was an ideal location to place the networking infrastructure as it covered a large majority of the most important health facilities in Kikwit (marked with a cross symbol) and enables the monitoring of all of the frequently used schools and churches where the CPTS carries out blood collection drives.

We installed a Multitech® Conduit MTCDT-H5 gateway [13] equipped with a LoRa mCard to provide the base station at the CPTS offices. This was equipped with a Taoglas® 5dBi antenna [14] mounted on the antenna pole of the building at approximately 5 m above the ground level.

To enable the gateway to operate continuously without the need to draw on the sporadic energy sources available at the CPTS offices, we also installed an independent solar system. The continuous power consumption of the gateway was found to be approximately 15 W, and we established that we could reliably power the gateway using a 150 W (peak) solar panel together with a 100 Ah battery.

3.3 Sensing Devices

The sensing element of the solution attains low power and long range operation via the combination of the LoRa radio technology with the μPnP platform. μPnP provides zero-configuration customisation of wireless sensor nodes with diverse sensors at 10 million times lower power than USB and a cost overhead of just 1 cent per sensor. A technical description of the μPnP system is available in [15]. The devices themselves use Microchip's RN2483 LoRa radio module, which is connected to a μPnP board, allowing up to 3 sensors to be connected. A detailed technical description of the final solution can be found in [16].

(a) (b)

Fig. 1. LoRa deployment in Kikwit: (a) Range testing area; (b) LoRa gateway and fridge sensor devices

For this pilot, we have chosen this particular architecture based on pre-existing tools in order to enable rapid development and deployment, as well as flexibility for future expansion and experimentation (i.e. the ability to add new sensors and other custom devices).

3.4 Network Topology

Our pilot project initially concentrated on the implementation of a network based on a star topology (i.e. having centralised concentrators in the network), due to the small scale and relatively concentrated project sites involved in the initial pilot. However, one of the key benefits of the technology we have selected is the ability to flexibly expand the network as the project develops. Hence, this topology can be modified in the future to have either a star-of-stars or a mesh-based topology in order to expand the coverage as far as possible.

Mesh networking allows for the building of arbitrarily long-range networks by expanding the role of a low-power wireless device from a simple transmitter to a combined transmitter and router. All wireless devices then establish multi-hop routes to the gateway and therefore do not need to be within direct range (i.e. being in range of any of their peers is sufficient). This approach enables coverage over greater distances, without modification to the hardware. Our approach builds on classical approaches to low-power mesh networking such as Low Power Listening [17] and time synchronisation [18], though these must be adapted to the hardware platform developed.

3.5 Temperature Monitoring System

Our initial pilot concentrated on developing a robust automated temperature monitoring system for the fridges used by CPTS. We deployed two small dual 12V DC/220V AC-powered fridges, which enabled flexible operation either from solar panels or from the 12 V power outlet of a vehicle, and additionally by AC power when connected to a generator. One of the two fridges also featured the ability to freeze ice packs, extending the cooling capacity of the fridges during offsite blood collection drives at various locations in the community. We equipped these 'smart' fridges with our monitoring devices (sensors and a battery-powered LoRa end device) already integrated inside. We designed these 'LoRa MediFridges' to be completely independent units, with the flexibility to be used either onsite at the CPTS central office or on the road as mobile fridges for blood collection or distribution.

However, our objective was also to introduce a robust monitoring system to be used with the existing cooling infrastructure already in place. Hence, we additionally integrated our temperature-sensing devices into the existing solar-powered fridges already installed at the CPTS offices. Because the generator is used only sporadically to power computers or laboratory equipment for testing as needed, the blood, blood products, and testing reagents are regularly stored in the solar fridge. Unfortunately, the system is prone to temperature fluctuations and hence close monitoring of this fridge is essential. Our sensing device was initially installed as a supportive monitoring system alongside the manual system, but the aim is that it can replace manual temperature measurements, reducing workload for CPTS staff and increasing the reliability of their monitoring system.

Based on consultation with the staff of the CPTS, we configured these devices to generate a sensor reading every 15 min. This interval was chosen to balance reactionary potential with battery life (i.e. sufficient frequency of measurement to enable timely intervention, but infrequent enough to ensure a battery life in the order of years [16]). These readings included information about the internal and external temperature (i.e. both inside the fridge and the ambient air temperature), and the humidity. Following initial deployment, we realised the need to monitor the solar system in order to predict the expected operational duration of the fridges. The flexible plug-and-play nature of μPnP [15] enabled us to quickly adapt the configuration to additionally include measurements of the voltage of the solar system, so as to be able to monitor the total energy input and consumption.

This sensor data is transmitted to the central gateway, where it is stored and a local web page is generated automatically. This web page is accessible via a WiFi network run by the gateway, and enables the CPTS staff to access and evaluate this data. If the temperature of one of the fridges rises above the optimal temperature range of 1 °C to 6 °C, the staff are able to intervene quickly to ensure the safe storage of the blood and blood products by either transferring them to another fridge operating at a safe temperature, using the generator or 12 V system to cool a mobile fridge as a temporary solution, or transferring the products to another fridge in Kikwit (such as at the general hospital) for safekeeping. For our own research purposes, we also transfer this data over a GSM modem to a central database in Belgium, where we also provide a web-based interface to access the data remotely (i.e. off-site locations and beyond the range of the local WiFi network). An example of the temperature trace from the solar-powered fridge is shown in Fig. 2. However, it is important to note that the local web interface does not depend on any external GSM network or internet connection to function, and the staff can access the information locally regardless of whether the data is transmitted to the remote database.

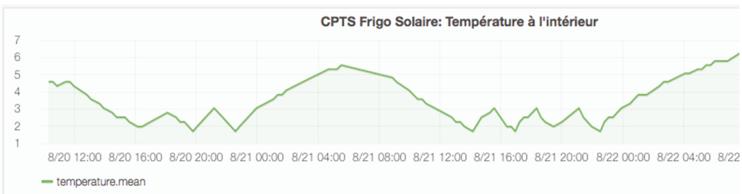

Fig. 2. Trace of daily temperature profile from solar-powered fridge

3.6 Limitations and Lessons Learned

Our experiences in implementing this pilot project revealed that there are several limitations to these technologies. With limited networking experience and informatics literacy, transferring sufficient knowledge and skills so that local actors can continue to use, apply, and extend the project outcomes after the completion of the pilot remains a challenge. This is particularly true given that we are collaborating with health professionals with no background in computer science, rather than specialists in this field. One potential solution is to incorporate a collaboration with local universities and incorporate training on networking and emerging IoT technologies and their local applications as part of informatics courses. This speaks to the need to foster local IoT innovation and experimentation [19] rather than merely transplanting solutions developed in Northern countries or other disparate contexts.

Moreover, our range test results in Kikwit indicate that the effective range of μPnP-WAN devices is not consistent with the coverage radius of the LoRa gateway [16]. This is attributed to interferences in the operational environment, and we expect that deploying the gateway in locations with higher altitude might alleviate this problem. However, it is not always practical to find such high-altitude locations, so other techniques to improve the range and reliability of the ad-hoc LoRa networks should be investigated. The redundancy offered by a mesh network, as described above, is also expected to improve reliability by providing multiple paths between the gateway and each LoRa device.

A final limitation relates to the scalability of network infrastructure installed in this environment. Although it has been shown that LoRa wide area networks scale well in urban areas to support thousands of devices per gateway [20,21], the local political and economic context may hinder scalability. Even in rural areas, solutions like ours may readily integrate into particular projects or coordinated NGO programmes, but integration into weak and under-resourced state health infrastructures is more challenging. Hence, widespread deployments at national or regional levels may be slow or difficult without external (i.e. donor) support.

4 Conclusion and Future Work

This paper has described how emerging IoT technologies may be applied to facilitate the meaningful planning and responsible governance of development projects by providing accurate, complete, and timely information about the outcomes of project implementation. We have described the ways in which emerging technologies like LoRa are ideally suited to data collection and monitoring in decentralised and low-power environments, and our experiences applying this technology in the health sector in DR Congo.

In implementing our experimental pilot project in Kikwit, we have confirmed that IoT technologies like the LoRaWAN can indeed function in resource-limited contexts and areas with very little existing infrastructure. Although the project is in its infancy with preliminary results only, the technology shows sufficient potential to warrant further investigation and experimentation. Since there are few others using this technology in similar settings, the field of study would benefit greatly from further applied research projects on how to effectively integrate the IoT into development contexts.

While the scope of this research project to date has been limited to collaboration with the CPTS and monitoring the temperature of blood and blood products, the scope for expansion of this project is immense and the potential applications of similar technologies and systems are many. The most immediate and simplest opportunity for expansion is to extend our temperature monitoring system to other health-related institutions in the Kikwit area, such as the general hospital and the central office of the health zone. This would extend the scope of the cold chain monitoring beyond the domain of blood transfusion to include the surveillance of vaccines and life-saving medications that require refrigeration.

As described above, our research group is working on a mesh protocol for gaining ground and extending the reach of our LoRa network in Congo. As the size and range of the network expands, real-time monitoring of portable coolers (i.e. insulated boxes filled with cold packs and medical supplies) could for the first time extend the medical cold chain to rural health facilities. Scalability on this level would take time, resources, and coordination, but seems technically quite feasible.

Moreover, given the fact that GSM coverage in rural areas remains limited and unreliable, there is a second-order effect to be gained from rolling out a mesh network by creating new lines of communication between the smaller health centres and the central health offices. Once such a network is available, the possibilities of offering more than just temperature monitoring start to be realised. For example, one critical problem faced by the health sector is the logistics of provisioning all the local health centres with essential medicines. Given the poor state of the roads and long transport times, many deaths are caused by the inability to monitor and anticipate stock levels in the remote health centres and distribute medicines before they are needed (rather than merely responding to stock shortages).

The potential to automate the monitoring of stock and facilitate communication with a central distribution point is just one example of how the integration of novel distributed monitoring technologies and techniques could make a significant impact within developing countries. Given the vast selection of different sensors on the market, there are many possibilities to look beyond health and apply this type of IoT-based monitoring solution to other sectors and development projects (such as water quality or agricultural monitoring).

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