Low-cost, Long-range Open IoT for Smarter Rural African Villages

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***Abstract*—Recent long-range radio technologies are promising to deploy Low Power WAN at a very low-cost for a large variety of IoT applications. However, even though, there are several issues that need to be addressed when considering deploying IoT solutions for low-income developing countries. In this article, we first explain these issues and show how they can be addressed in the context of rural sub-saharan African applications, one of them being smarter villages and farms in a small and micro deployment model. We then describe our low-cost, long-range IoT framework which takes cost of hardware and services as the main challenge to be addressed as well as flexibility, quick appropriation and customization by third parties.**

***Index Terms*—LPWAN; Low-power IoT; Low-cost IoT; rural applications; smart villages**

I. Introduction

A. *Internet of Things (IoT) in sub-Saharan Africa*

The opportunity of IoT applications in Africa is huge and Fig. 1 depicts some typical applications where real-time data collection could greatly increase quality and productivity in a number of rural applications.

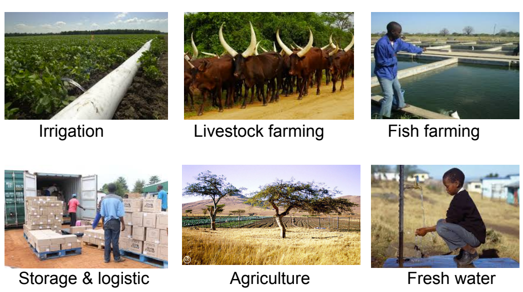

Fig. 1. Some ICT fields of opportunities in rural environments

However, when developed countries discuss about massive deployment of IoT, Africa's countries are still far from being ready to enjoy the smallest benefit of IoT: lack of infrastructure, high cost of hardware, complexity in deployment, lack of technological eco-system and background, etc [1]. In Sub-Saharan Africa about 64% of the population is living outside cities. The region will be predominantly rural for at least another generation. The majority of rural residents manage on less than few euros per day. Rural development is particularly imperative where half of the rural people are depend on the agriculture/micro and small farm business. For rural development, technologies have to support several key application sectors like water quality, agriculture, livestock farming, fish farming, etc. Therefore, when deploying IoT in the context of Sub-Saharan Africa, we believe it is necessary to target three major issues: (a) Longer range for rural access, (b) Cost of hardware and services and (c) Limit dependancy to proprietary infrastructures and provide local interaction models.

B. *IoT issues in sub-Saharan Africa*

1) Longer range for rural access: The deployment of IoT devices in rural environments is still held back by technical challenges such as short communication distances. Using the telco mobile communication infrastructure is still very expensive (e.g. GSM/GPRS, 3G/4G/LTE) and definitely not energy efficient for autonomous devices that must run on battery for months. During the last decade, low-power but short-range radio such as IEEE 802.15.4 radio have been considered by the Wireless Sensor Network (WSN) community with multi-hop routing to overcome the limited transmission range. While such short-range communications can eventually be realized in the context of developed countries smart cities infrastructures where high node density with powering facility can be achieved, it can hardly be generalized for the large majority of surveillance applications that need to be deployed in isolated or rural environments.

Deploying IoT in this context must use longer range wireless communication to decrease both the complexity and the cost of data collection. Recent so-called Low-Power Wide Area Networks (LPWAN) such as those based on Sigfox$^{\text{TM}}$ or Semtech's LoRa$^{\text{TM}}$ technology definitely provide a better connectivity answer for IoT as several kilometers can be achieved without relay nodes to reach a central gateway or base station. Fig. 2 shows a typical extreme long-range 1-hop connectivity scenario to a long-range gateway which is the single interface to Internet servers.

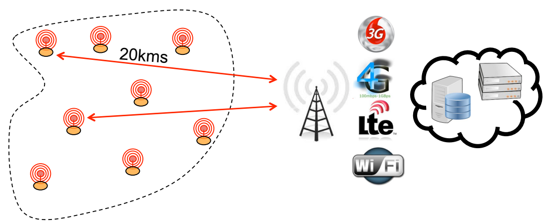

Fig. 2. Extreme long-range application

Most of long-range technologies can achieve 20km or higher range in line-of-sight (LOS) condition and about 2km in Non-LOS [2], [3]. When adding the financial cost constraint and the network availability, LoRa technology, which can be privately deployed in a given area without any service subscription, has a clear advantage over Sigfox which coverage is entirely operator-managed. Some LoRa community-based initiatives such as the one promoted by `TheThingNetwork`™ [4] may provide interesting solutions and feedbacks for dense environments such as cities but under the agriculture/micro and small farm/village environment an even more adhoc and autonomous solution need to be investigated and deployed.

2) Cost of hardware and services: The maturation of the IoT market is happening in many developed countries: innovative and integrated products are available for smarter home and various monitoring applications. While the cost of such devices can appear reasonable within developed countries standards, they are definitely still too expensive for very low-income sub-saharan ones. The cost argument, along with the statement that too integrated components are difficult to repair and/or replace definitely push for a Do-It-Yourself (DIY) and ”off-the-shelves” design orientation. To be sustainable and able to reach previously mentioned rural environments, IoT initiatives in developing countries have rely on an innovative and local business models. We envision mostly medium-size companies building their own ”integrated” version of IoT for micro-small scale services. In this context, it is important to have dedicated efforts to design a viable exploitation model which may lead to the creation of small-scale innovative service companies.

The availability of low-cost, open-source hardware platforms such as Arduino is clearly an opportunity for building low-cost IoT devices from mass-market components. For instance, the Arduino Pro Mini based on an ATmega328 in its 3.3v and 8MHz version offers an excellent price/performance/consumption tradeoff. Originally designed by Sparkfun, this board can also be purchased for less than 2 euro per piece from Chinese manufacturers. It can be used to provide a platform for generic sensing IoT with LoRa long-range transmission capability. In addition to the cost argument (cost can be less than 15 euro for a fully operational long-range sensing device) such consumer-market component greatly benefits from the support of a world-wide and active community of developers.

With the gateway-centric mode of LoRA LPWAN technology, commercial LoRaWAN gateways are able to listen on several channels and LoRa settings simultaneously. They use advanced concentrators chips capable of scanning up to 8 different channels: the SX1301 concentrator is typically used instead of the SX127x chip serie which is designed for end-devices. They cost several hundredth euros with the cost of the SX1301-capable board alone to be more than a hundred euro. Here, again, the approach can be different in the context of agriculture/micro and small farm/village environment: simpler ”single connection” gateways can be built around an SX1272/76 radio module, much like an end-device would be. Using Linux-based platforms such as the Raspberry PI, which has a high price/quality/reliability tradeoff, the cost of such gateway can be less than 45 euro. Therefore, rather than providing large-scale deployment support, IoT platforms in developing countries need to focus on easy integration of low-cost ”off-the-shelves” components with simple, open programming libraries and templates for easy appropriation and customization by third-parties. By taking an adhoc approach, complex mechanisms, such as advanced radio channel access to overcome the limitations of the low-cost gateway, can even be integrated as long as they remain transparent to the final developers.

3) Limit dependancy to proprietary infrastructures and provide local interaction models: Once data are collected on the gateway, they usually have to be pushed/uploaded to some Internet/cloud servers for storage and visualization; and eventually for further processing tasks. It is important in the context of developing countries to be able to use a wide range of infrastructures and, if possible, at the lowest cost. Fortunately, along with the global IoT uptake, there is also a tremendous availability of sophisticated and public IoT clouds platforms and tools, offering an unprecedented level of diversity which contributes to limit dependency to proprietary infrastructures. Many of these platforms offer free accounts with limited features but that can already satisfy the needs of most agriculture/micro and small farm/village business models we are referring to when addressing IoT for Sub-Saharan African applications. What are the impacts on the design architecture/choices of the deployed IoT platforms? One simple design orientation for instance is to highly decouple the low-level gateway functionalities from the high-level data post-processing features, privileging high-level languages for the latter stage (e.g. Python) so that customizing data management tasks can be done in a few minutes, using standard tools, simple REST API interface and and available public clouds.

One additional important issue that need to be taken into account in the context of sub-Saharan Africa is the lack or intermittent access to the Internet. Data should also be locally stored on the gateway which can be directly used as an end computer by just attaching a keyboard and a display. This solution perfectly suits low-income countries where many parts can be found in second markets. The gateway should also be able to interact with the end-users’ smartphone through WiFi or Bluetooth to display captured data and notify users of important events without the need of Internet access as this situation can clearly happen in very remote areas.

Fig. 3 shows the various deployment scenarios for the Smarter Rural African Villages case. The first 2 cases depict a cellular-based and a WiFi Internet gateway scenario. The Internet connection can be either privately owned or can rely on some community-based Internet access. The last case is the fully autonomous gateway scenario where the gateway only collect data from remote devices and locally interacts with smartphones using standardized technologies such as WiFi or Bluetooth. Of course, all three scenarios can co-exist.

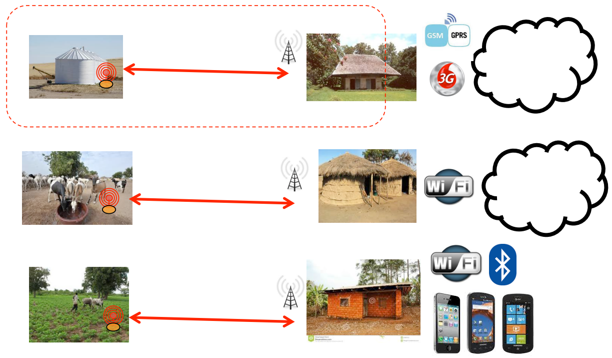

Fig. 3. Deployment scenarios in developing countries

The rest of the article is organized as follows. Section II details the long range Semtech's LoRa technology. In Section III we will present our low-cost IoT platform targeting low-income developing countries. We will detail how the design choices and architecture try to address the 3 major issues identified previously. We conclude in Section V.

II. Review of long-range transmission and low-power WAN

A. Semtech's LoRa technology

Semtech's long-range technology (called LoRa) [5], [6] belongs to the spread spectrum approaches where data can be "spreaded" in both frequencies and time to increase robustness and range by increasing the receiver's sensitivity, which can be as low as -137dBm in 868MHz band or -148dBm in the 433MHz band. Throughput and range depend on the 3 main LoRa parameters: BW, CR and SF. BW is the physical bandwidth for RF modulation (e.g. 125kHz). Larger signal bandwidth allows for higher effective data rate, thus reducing transmission time at the expense of reduced sensitivity. CR, the coding rate for forward error detection and correction. Such coding incurs a transmission overhead and the lower the coding rate, the higher the coding rate overhead ratio, e.g. with $coding\_rate = 4/(4+CR)$ the overhead ratio is 1.25 for CR=1 which is the minimum value. Finally SF, the spreading factor, which can be set from 6 to 12. The lower the SF, the higher the data rate transmission but the lower the immunity to interference thus the smaller is the range.

				time on air in second for payload size of						
LoRa mode	BW	CR	SF	5 bytes	55 bytes	105 bytes	155 Bytes	205 Bytes	255 Bytes	max thr. for 255B in bps
1	125	4/5	12	0.95846	2.59686	4.23526	5.87366	7.51206	9.15046	223
2	250	4/5	12	0.47923	1.21651	1.87187	2.52723	3.26451	3.91987	520
3	125	4/5	10	0.28058	0.69018	1.09978	1.50938	1.91898	2.32858	876
4	500	4/5	12	0.23962	0.60826	0.93594	1.26362	1.63226	1.95994	1041
5	250	4/5	10	0.14029	0.34509	0.54989	0.75469	0.95949	1.16429	1752
6	500	4/5	11	0.11981	0.30413	0.50893	0.69325	0.87757	1.06189	1921
7	250	4/5	9	0.07014	0.18278	0.29542	0.40806	0.5207	0.63334	3221
8	500	4/5	9	0.03507	0.09139	0.14771	0.20403	0.26035	0.31667	6442
9	500	4/5	8	0.01754	0.05082	0.08154	0.11482	0.14554	0.17882	11408
10	500	4/5	7	0.00877	0.02797	0.04589	0.06381	0.08301	0.10093	20212

Fig. 4. Time on air for various LoRa modes as payload size is varied

Fig. 4 shows for various combinations of BW, CR and SF the time-on-air of a LoRa transmission depending on the number of transmitted bytes. The maximum throughput is shown in the last column with a 255B payload. Modes 4 to 6 provide quite interesting trade-offs for longer range, higher data rate and immunity to interferences.

Electromagnetic transmissions in the sub-GHz band of Semtech's LoRa technology falls into the Short Range Devices (SRD) category. For instance, in Europe & Sub-Saharan Africa, electromagnetic transmissions in the EU 863-870MHz ISM Band used by Semtech's LoRa technology falls into the Short Range Devices (SRD) category. The ETSI EN300-220-1 document [7] specifies various requirements for SRD devices, especially those on radio activity. Basically, transmitters are constrained to 1% duty-cycle (i.e. 36s/hour) in the general case. This duty cycle limit applies to the total transmission time, even if the transmitter can change to another channel. In most cases, however, the 36s duty-cycle is largely enough to satisfy communication needs of deployed applications. It is possible to provide QoS by implementing radio activity time sharing but these issues are beyond the scope of this paper.

B. LoRa LPWAN network deployment and architecture

As indicated previously, the deployment of a LoRa LPWAN can be realized in an adhoc manner (privately owned) or can rely on an operator. Although direct communications between devices are possible, most of applications using sensors for surveillance follow the gateway-centric approach with mainly uplink traffic patterns. In the typical architecture for public large-scale LPWAN, data captured by end-devices are sent to a gateway which will push data to well identified network servers, see Fig. 5. Then application servers managed by end-users could retrieve data from the network server. If encryption is used for confidentiality, the application server can be the place where data could be decrypted and presented to end-users. This architecture can be greatly simplified for small, ad-hoc deployment scenarios such as described in Fig. 3 where the gateway can directly push data to some end-user managed servers or public IoT-specific cloud platforms if properly configured.

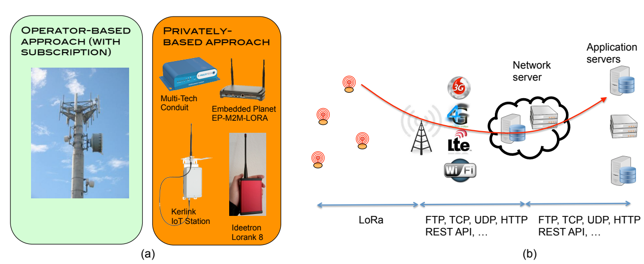

Fig. 5. (a) gateway-centric deployment; (b) typical LPWAN architecture

III. Low-cost LoRa IoT platforms

A. Single-connection low-cost LoRa gateway

The implementation of the full LoRaWAN specification [8] requires gateways to be able to listen on several channels and LoRa settings simultaneously. In the context developing countries, it is more important to keep both the cost and the complexity low and to target small to medium size deployment scenario for various specific use cases instead of the large-scale, multi-purpose deployment scenarios defined by LoRaWAN. Note that our approach can deploy more than 1 gateway to serve several channel settings if needed. This solution presents the advantage of being more optimal in terms to cost as incremental deployment can be realized and also offer a higher level of redundancy which should be taken into account in developing countries. We believe this statement remains true even for recent LoRa community-based deployment initiatives such as the one conducted by `TheThingNetwork`™ [4] where the deployment still targets large-scale, public and multi-purpose networks.

Our LoRa gateway [9] could be qualified as "single connection" as it is built around an SX1272/76, much like an end-device would be. Our low-cost gateway is based on a Raspberry PI (1B/1B+/2B/3B) which is both a low-cost (less than 30 euro) and a reliable embedded Linux platform. There are many SX1272/76 radio modules available and we currently tested with 4: the Libelium SX1272 LoRa, the HopeRF RFM92W/95W, the Modtronix inAir9/9B and the NiceRF SX1276. Most SPI LoRa modules are actually supported without modifications as reported by many users. In all cases, only a minimum soldering work is necessary to connect the required SPI pins of the radio to the corresponding pins on the Raspberry pin header as depicted in Figure 6. The total cost of the gateway can be less than 45 euro.

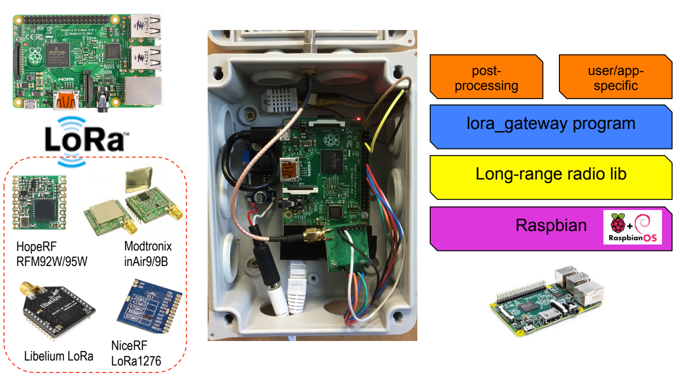

Fig. 6. Low cost gateway from off-the-shelves components

Together with the "off-the-shelves" component approach, the software stack is completely open-source: (a) the Raspberry runs a regular Raspian distribution, (b) our long range communication library is based on the SX1272 library written initially by Libelium and (c) the `lora_gateway` program is kept as simple as possible. We improved the original SX1272 library in various ways to provide enhanced radio channel access (CSMA-like with SIFS/DIFS) and support for both SX1272 and SX1276 chips.

We tested the gateway in various conditions for several months with a DHT22 sensor to monitor the temperature and humidity level inside the case. Our tests show that the low-cost gateway can be deployed in out-door conditions with the appropriate casing. Although the gateway should be powered, its consumption is about 350mA when using an RPI 1B+.

B. Post-processing and link with IoT cloud platforms

After compiling the `lora_gateway` program, the most simple way to start the gateway is in standalone mode as shown is figure 7a. All packets received by the gateway is sent to the standard Unix-stdout stream.

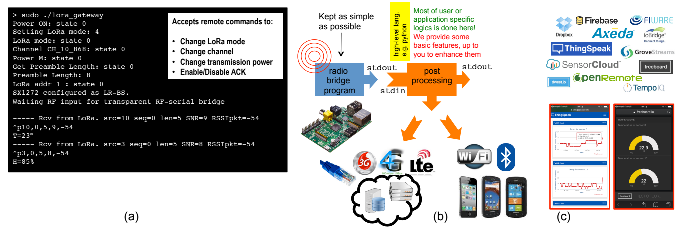

Fig. 7. Post-processing data from the gateway

Advanced data post-processing tasks are performed after the gateway stage by using Unix redirection of gateway's outputs as shown by the orange "post-processing" block in Fig. 7b. We promote the usage of high-level language such as `Python` to implement all the data post-processing tasks such as access to IoT cloud platforms and even advanced features such as AES encryption/decryption. Our gateway is distributed with a `Python` template that explains and shows how to upload data on various publicly available IoT cloud platforms. Examples include `Dropbox`™, `Firebase`™, `ThingSpeak`™, `freeboard`™, `SensorCloud`™, `GrooveStream`™ & `FiWare`™, as illustrated in Fig. 7c, and most of them use simple REST API interface.

This architecture clearly decouples the low-level gateway functionalities from the high-level post-processing features. By using high-level languages for post-processing, running and customizing data management tasks can be done in a few minutes. One of the main objectives of IoT in Africa being technology transfer to local developer communities, we believe the whole architecture and software stack are both robust and simple for either "out-of-the-box" utilization or quick appropriation&customization by third parties. For instance, a small farm can deploy in minutes the sensors and the gateway using a free account with `ThingSpeak` platform to visualize captured data in real-time.

C. Gateway running without Internet access

Received data can be locally stored on the gateway and can be accessed and viewed by using the gateway as an end computer by just attaching a keyboard and a display. The gateway can also interact with the end-users' smartphone through WiFi or Bluetooth as depicted previously in Fig. 7b. WiFi or Bluetooth dongles for Raspberry can be found at really low-cost and the smartphone can be used to display captured data and notify users of important events without the need of Internet access as this situation can clearly happen in very remote areas.

Fig. 8 shows our low-cost gateway running a `MongoDB`™ noSQL database and a web server with `PHP/jQuery` to display received data in graphs. An

Android application using Bluetooth connectivity has also been developed to demonstrate these local interaction models.

Fig. 8. Fully autonomous LoRa gateway

D. Low-cost LoRa end-devices

Arduino boards are well-known in the microcontroller user community for their low-cost and simple-to-program features. These are clearly important issues to take into account in the context of developing countries, with the additional fact that due to their success, they can be acquired and purchased quite easily world-wide. There are various board types that can be used depending on the application and the deployment constraints. The Arduino Pro Mini, which comes in a small form factor and is available in a 3.3v and 8MHz version for lower power consumption, appears to be the development board of choice for providing a generic platform for sensing and long-range transmission, see Fig. 9.

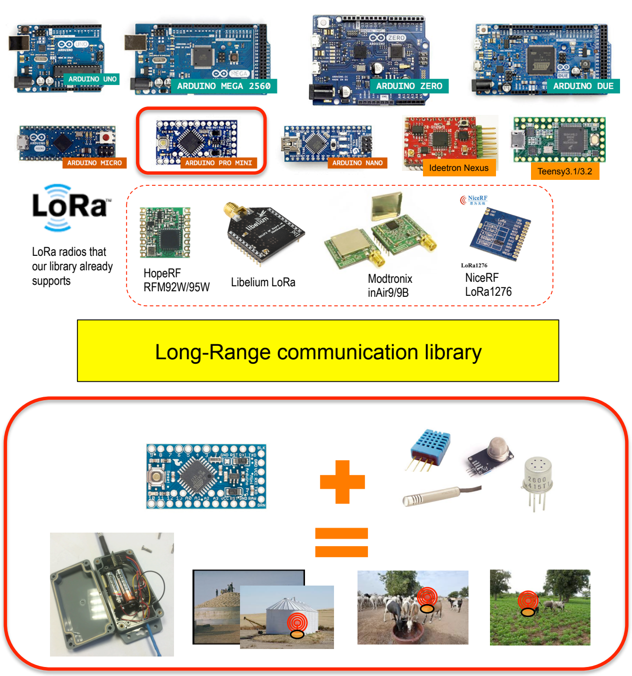

Fig. 9. Low-cost LoRa end-device for customization

Arduino Pro Mini clones can be purchased for less than 2 euro a piece from Chinese manufacturers with very acceptable quality and reliability level. Similar to the low-cost gateway, all programming libraries are open-source and we provide templates for quick and easy new behaviour customization and physical sensor integration for most of the Arduino board types as shown in Fig. 9.

For very low-power applications, deep-sleep mode are available in the example template to run an Arduino Pro Mini with 4 AA regular batteries. For instance, with a duty-cycle of 1 sample every hour, the board can run for almost a year, consuming about 146μA in deep sleep mode and 93mA when active and sending, which represents about 2s of activity time. Our tests conducted continuously during the last 5 months show that the low-cost Pro Mini clones are very reliable.

IV. Integrating advanced functionalities

The framework we propose, even if targeted for low-cost, off-the-shelves component design and "out-of-the-box" operation (see Fig. 10), leaves room for more research-oriented tasks as it actually provides a flexible framework for adding and testing new advanced features that are lacking in current LPWAN.

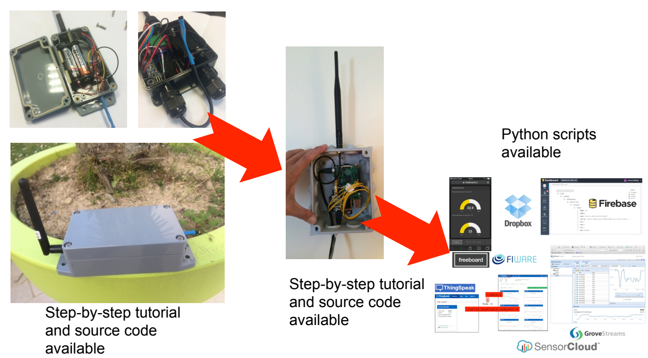

Fig. 10. "out-of-the-box" low-cost IoT platform

For instance, while the LoRaWAN specifications may ease the deployment of LoRa networks by proposing some mitigation mechanisms to allow for several LoRa networks to coexist, it still remains a simple ALOHA system with additional tight radio activity time constraints without quality of service concerns. We briefly describe below 2 issues of long-range networks that are currently studied: improved channel access and activity time sharing for quality of service.

1) Improved channel access: A CSMA-like mechanism with SIFS/DIFS has been implemented using the Channel Activity Detection (CAD) functionality of the LoRa chip and can further be customized. A DIFS is defined as 3 SIFS. Prior to packet transmission a DIFS period free of activity should be observed. If "extended IFS" is activated then an additional number of CAD followed by a DIFS is required. If RSSI checking is activated then the RSSI should be below -90dB for the packet to be transmitted. These features are summarized in Fig. 11.

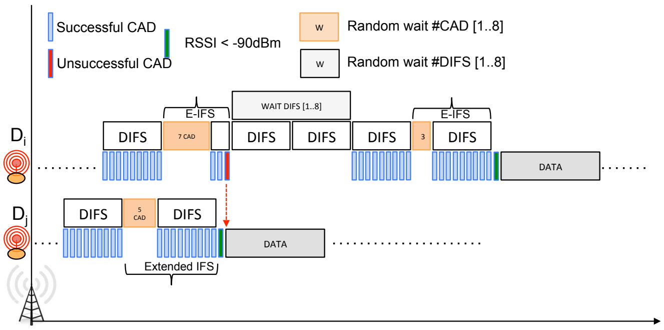

Fig. 11. CSMA-like mechanism for increased robustness

By running a background periodic source of LoRa packets, we observed that the improved channel access succeeds in reducing packet collisions. The current framework is used to study the impact of channel access methods in a medium-size LoRa deployment when varying timer values due to the long time-on-air of long-range technologies.

2) Activity time sharing.: We also propose and implement an exploratory activity time sharing mechanism for a pool of devices managed by a single organization. We propose to overcome the tight 36s/hour radio activity of a device by considering all the sensor's individual activity time in a shared/global manner. The approach we propose will allow a device that "exceptionally" needs to go beyond the activity time limitation to borrow some from other devices. A global view of the global activity time, G_{AT}, allowed per 1 hour cycle will be maintained at the gateway so that each device knows the potential activity time that it can use in a 1-hour cycle. Fig. 12 shows how the deployed long-range devices D_i sharing their activity time initially register (REG packet) with the gateway by indicating their local Remaining Activity Time l^i_{RAT0}, i.e. 36s. The gateway stores all l^i_{RAT0} in a table, computes G_{AT} and broadcasts (INIT packet) both n (the number of devices) and G_{AT}. This feature is currently tested for providing better surveillance service guarantees.

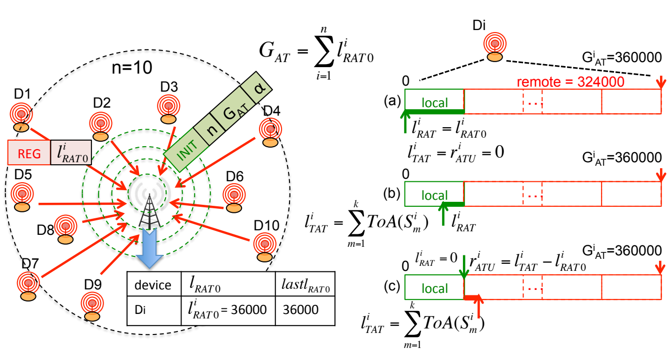

Fig. 12. Exploratory activity time sharing mechanism

V. Conclusions

In this paper we presented several important issues that need to be addressed when considering deploying IoT solutions for low-income developing countries: (a) Longer range for rural access, (b) Cost of hardware and services and (c) Limit dependancy to proprietary infrastructures and provide local interaction models. We described our low-cost and open IoT platforms for rural African application that addressed these issues. Targeted for small to medium size deployment scenarios the platform also privileges quick appropriation and customization by third parties. The whole framework is currently intensively tested for deployment in the context of the H2020 WAZIUP project with real test-beds in cities, villages and farms to be set up.

WAZIUP is a collaborative research project using cutting edge technological research applications on IoT, related big data management and advanced analytic issues in sub-Saharan Africa. The project brings liaison with the whole IoT European Research Cluster (IERC) and leading research and development organizations in Africa. The project is driven by a consortium of 5 EU partners and of 7 partners from 4 sub-Saharan African countries. It has support from multiple African stakeholders and public bodies with the aim of defining new innovation space to advance the African Rural Economy. Central to WAZIUP's concerns is the inclusion of developer communities (e.g., Coders4africa) and innovation hubs (e.g. CTIC, iSpace) who have experience to train, adapt, validate and disseminate results. WAZIUP's technical partners will develop methodologies, tools, software libraries and "recipes" for building low-cost IoT and data analysis platforms. Quick appropriation and easy customization by third parties is ensured by tightly involving end-users communities in the loop, namely rural African communities of selected pilots, and by frequent training and hackaton sessions organized in the sub-Saharan Africa region.

Acknowledgments

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