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Communication Network Systems for White Spot Areas

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Résumé

White spot areas depict geographic locations which are not covered by mobile network operators. In Senegal, the Sylvo-pastoral hosted by Ferlo's region has a prominent role according to livestock transhumance. Nevertheless, this region is roughly covered by white spot areas. The lack of cellular network infrastructure is a pitfall for vital information dissemination for agro-pastoralists. Therefore, this paper describes the deployment and testbed performance evaluation in rural and urban environment of a LoRa-based COWShED communication architecture. By leveraging a mesh-based proof-of-concept, tangible results are obtained and thus promote several applications which overcome white spot areas limitations such as stakeholders geolocation, transhumance management, milk collection, etc.

Mots-Clés

LPWAN, experimentaion, testbed, white spot areas

I INTRODUCTION

Despite equipment efforts, mobile phones do not have connectivity in certain rural areas as well in a few urban areas. Low population density within a couple of rural areas is an economical barrier for operators. In fact, *Ferlo* region that is one of the least populated Senegalese regions is largely formed by white spot areas (geographic locations which are not covered by mobile network operators). The use of satellite communications cannot be envisaged because of their

25 low purchasing power.

26 Figure 1 illustrates 2G mobile cellular networks according to the three main Senegalese operators *Orange*, *Free* (formerly called *Tigo*), and *Expresso*. In contrast, 2 exhibit white spot areas with respect to 2G across Senegalese territory. Indeed, green areas (2) illustrate locations that are not covered by 2G mobile network around the country. For instance, according to Fig. 30 2, *Ferlo* region is located at the east-center which is mostly covered by green areas.

31 Livestock farming in Ferlo in Senegal is extensive, based on the exploitation of natural resources. Thus, the herds and their shepherds are constantly on the move in search of water and pasture(2). This pastoral mobility is a daily and seasonal adaptation, with transhumance, to the bioclimatic conditions of the environment. Ferlo is a semi-arid space where annual precipita-

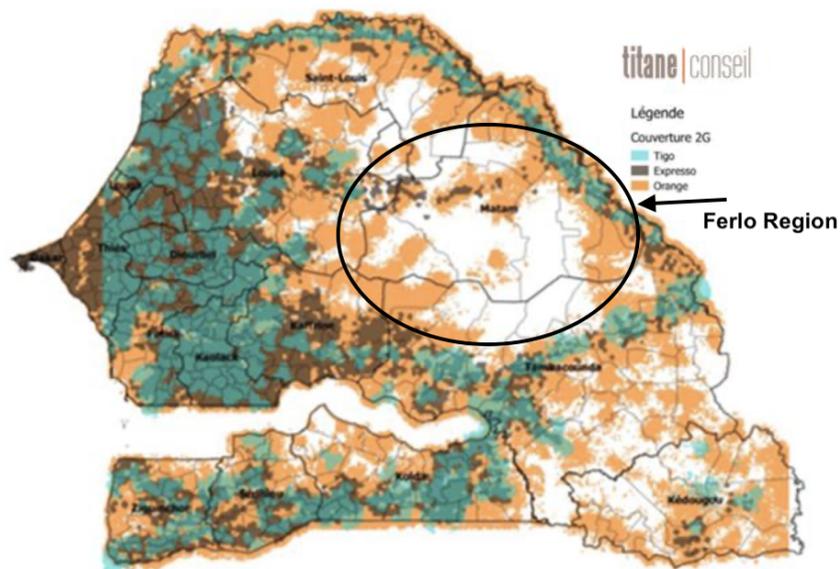


FIGURE 1 – 2G mobile networks operators coverage across Senegal in 2017
<http://www.numerique.gouv.sn/mediatheque/documentation/rapport-final-actualisation-de-la-strategie-d'accès-au-service-universel>

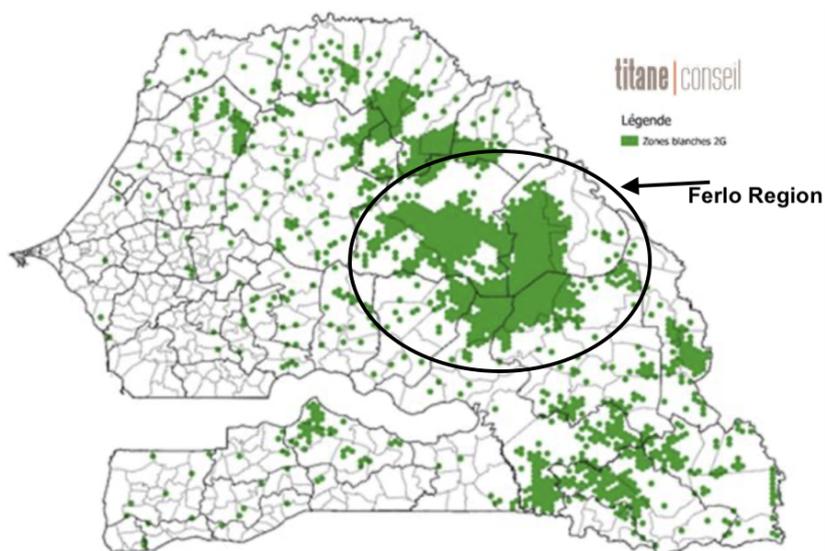


FIGURE 2 – 2G white spot areas within Senegal in 2017

tion is between 300 and 600mm ranges of water(3) (4). The low rainfall in this pastoral area directly influences the hydrological capacities, flora and fauna. It also reduces the possibility of agricultural development of the land. For instance, *SPAIF* project (5) was launched in order to manage livestock transhumance. Nevertheless, breeders within these white spots have at no time possibility to use their mobile phone in real time to communicate or transmit useful information such as water point status, situation in boreholes and pasture, epizootic diseases (local and neighbouring countries), cattle rustling along transhumance transit roads.

Therefore, *COWShED* (COmmunication within White Spots for brEeDers) aims at collecting various information and disseminate that into the network(environmental, pastoral activity, animal health, organization and management of pastoral lands, and agriculture). The technical solution for our architecture system is based on technologies for challenged networking scenarios such as Opportunistic Networking, Internet-of-Things and Device-to-Device communication using Low Power Wide Area Networks. In fact, the interest of IoT industry towards the Low Power Wide Area Networks (LPWANs) is consequently increasing. Therefore, by 2024, the IoT industry is expected to generate a revenue of 4.3 trillion dollars (6) (7). Most LPWA networks operate in unlicensed *ISM* bands at 169, 433, 868/915MHz, and 2.4GHz depending on the region of operation(8). One of the most pronounced LPWAN candidate is LoRa. It has a long battery life and is low cost. Coverage is also one of its most critical performance metric). A couple of works have shown the possibility to use *LoRa* technology as a communication system. Indeed, the physical and data link layer performance of *LoRa* (8) (9) have been evaluated by field tests and simulations in (10) (11) (12).

In this paper, we built an end-to-end communication system between smart phones via relay boxes that exchange information (text and audio) through *LoRa* transmission protocol. Therefore, a Linear regression model for path loss estimation is proposed for both urban and rural areas by means of empirical tests according to the Received Signal Strength Indicator (*RSSI*). Furthermore, we consider different use cases and scenarios that enable better management of resources and decision making in relation to milk collection and emergency management.

The remainder of the paper is organized as follows. Section II describes our LoRa-based communication architecture. Section III depicts our experimental test and the Linear regression model. Section IV describes services added to the device. Finally, Section V concludes our work.

II LORA-BASED COWSHED REQUIREMENTS AND ARCHITECTURE

In undeserved areas, satellite communications are very expensive for rural populations. In order to choose the best communication system, we have to take into account some critical metrics to make a comparison between the existing Long Range solutions. Coverage, power consumption and cost are one of the most important metrics. In fact, Ferlo's villages are very far one from another and lot of them have no electricity. Therefore, our device should not consume a lot of energy and should be low-cost. We assume that a LPWAN device is the best solution because it has a better coverage and consume less energy than Bluetooth and WI-FI. We chose LoRa which is one of the most used and reliable technology for large coverage with respect to LPWAN (9).

Due to LoRa low data rate (50kbps maximum), the data transmitted in the network is majorly based on text messages. For the users that aren't literate, we added the possibility of sending voice messages. However, we should limit the duration of the voice message because it increase the size of the message and by the same time increases the sending time due to our low data rate.

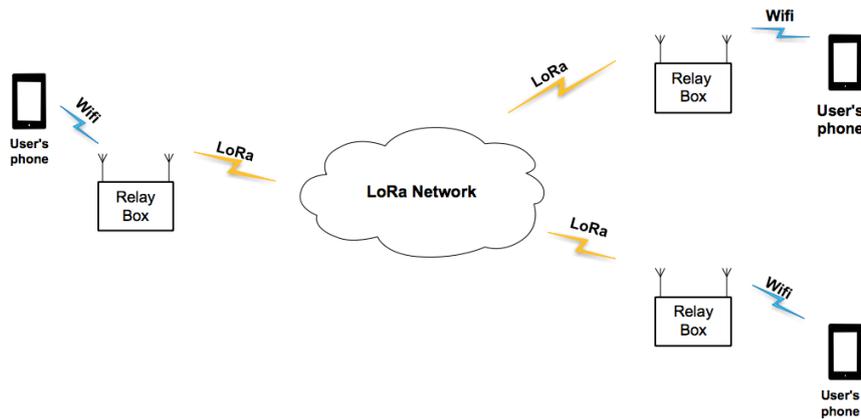


FIGURE 3 – LoRa-based COWShED communication architecture

80 Therefore, we built an end-to-end communication system between smart phones via relay boxes
 81 that exchange information (text and audio) through *LoRa* transmission protocol. Fig. 3 shows
 82 the designed communication architecture between users.

83 A communication between a given mobile box (smart phone) and a relay box (based on *Dragino*
 84 *LG01 – P*) is done by *WiFi* based on *IEEE802.11n* (14). We consider a *LG01 – P* box which
 85 contains a *400MHz* CPU that hosts *openwrt* with *16MB* flash and *8MB* of storage memory,
 86 a *LoRa* chip (*SX1276*) transmitter, and an *arduino Yun* card. We build a mobile application in
 87 which we can connect to a web server installed in the relay box and send/receive data through
 88 *WiFi*. A *MySQL* server is installed in the box to save both data sent from the mobile appli-
 89 cation and data coming from the network. Then we made a *Shell* script that takes data from the
 90 database and send it to an *arduinoYuncard*. The *arduino* Card reads the data by running Linux
 91 process with the *Bridge library's Process class*. Once the data is in the *arduino* card, we send it
 92 through *LoRa* to the destination node. According to *LoRa* configuration, we had :

- 93 — spreading factor : 12 (4096 chips)
- 94 — channel size : 125khz
- 95 — Power transmission : 14dBm
- 96 — coding rate : 4/5

97 It is worth noticing that *LoRa* uses the 868MHz ISM Band in Senegal which is a free band.
 98 Communications are then free of charge for the users. The prototype is as depicted in Fig.
 99 4 where the communication, between both previous components, is based on *IEEE802.11n*
 100 (*WiFi*).

101 We also made a Bluetooth-based communication prototype which is formed by two compo-
 102 nents. The first one is illustrated in Fig. 5 and formed by : (i) a Long Range transmitter (*LoRa*
 103 chip *Sx1272*) card which acts as relay and can either broadcast received information from bree-
 104 der's smart phone towards next hops or transmits received information from neighborhood to
 105 breeder's smart phone ; (ii) an *arduinoUno* card which acts as processing unit ; (iii) a Blue-
 106 tooth Low Energy (*BLE*) card which either transmits received information from *LoRa* card to
 107 smart phone, or from smart phone to *LoRa* transmitter. It should be noted that the considered
 108 smart phone is our second component. Indeed, both components communicate through their
 109 Bluetooth interfaces. In so doing, a mobile application is deployed within each smart phone
 110 and enables to send information (message text or emoticon) from breeder's smart phone to our
 111 gateway (Fig. 5).

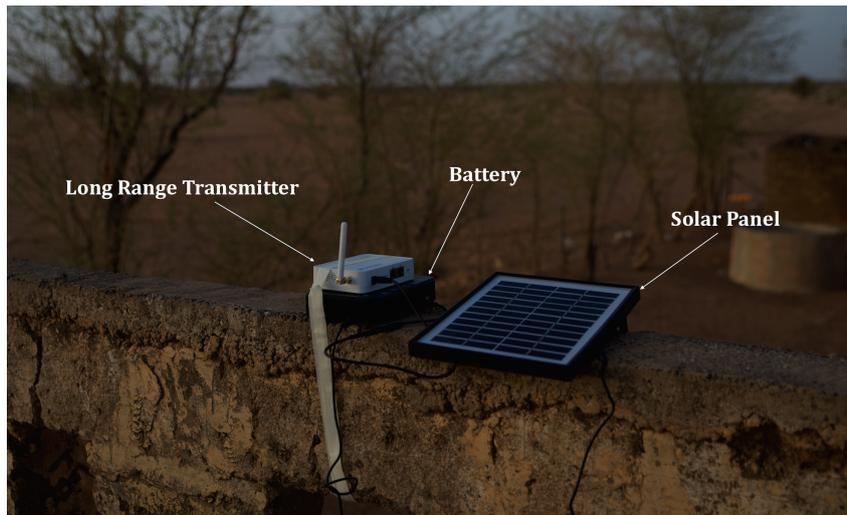


FIGURE 4 – WiFi-based communication prototype

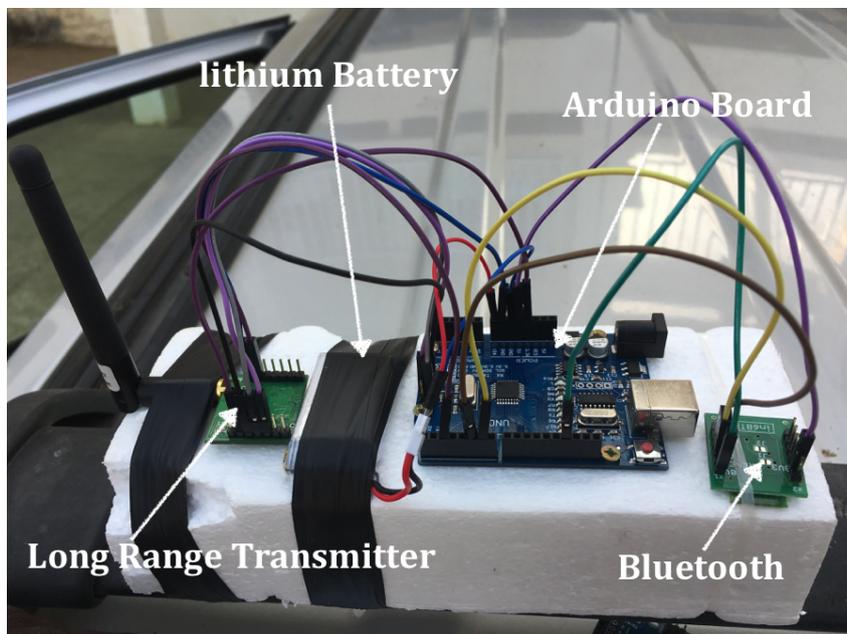


FIGURE 5 – Bluetooth-based communication prototype

112 Fig. 6 illustrates a communication scenario with respect to COWShED architecture. By leverag-
 113 ing LoRa transmission between two relay boxes, it depicts an end-to-end communication bet-
 114 ween two mobile boxes (smart phone) using bluetooth or WiFi. The store and forward concept
 115 is due to the large distance that separate different users of the network, and the lack of central
 116 equipment to interconnect all the users. In fact, this network has to be seen as a Delay tolerant
 117 network with an ad hoc architecture. We assume that it is a sparse and intermittently connected
 118 mobile adhoc network where reliable communication and end-to-end connectivity is not always
 119 available for message transmission

120 Furthermore, *Ferlo* is an area in Senegal where solar irradiation is very important. Sunshine
 121 duration ranges from 7 to 12 hours by day overall the year (17). Therefore, to ensure power
 122 supply, we use solar power systems with replaceable batteries of $7.4V$ and $5200mA$ which have
 123 8 hours of autonomy with our device. The battery is recharged by a $4W$ solar panel.

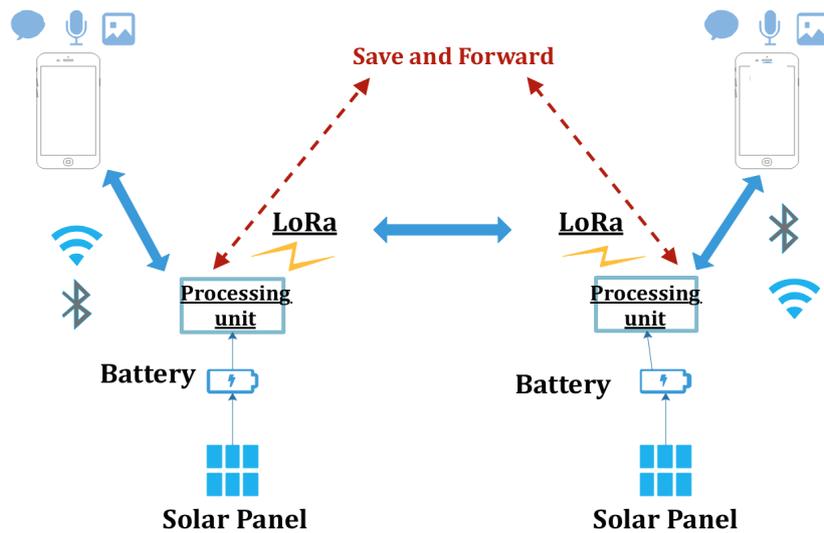


FIGURE 6 – COWShED communication Architecture



FIGURE 7 – Breeder in communication through COWShED architecture

124 For instance, Fig. 7 shows a herder wearing a bag containing our *LG01* box which is powered
 125 by a solar panel. The whole system is embedded in bag designed by us.

126 Table 1 illustrates a brief comparison between both designed prototypes. It is worth noticing that
 127 Bluetooth-based communication prototype is useful for text messages service, warning system
 128 or other IoT applications that do not require to transfer big amount of data with LPWANs. In

TABLE 1 – Performance evaluation of prototype-based on Bluetooth and WiFi

Device	Range	Bit rate	energy consumption	Storage
Bluetooth Based	-	-	+	-
WiFi based	+	+	-	+

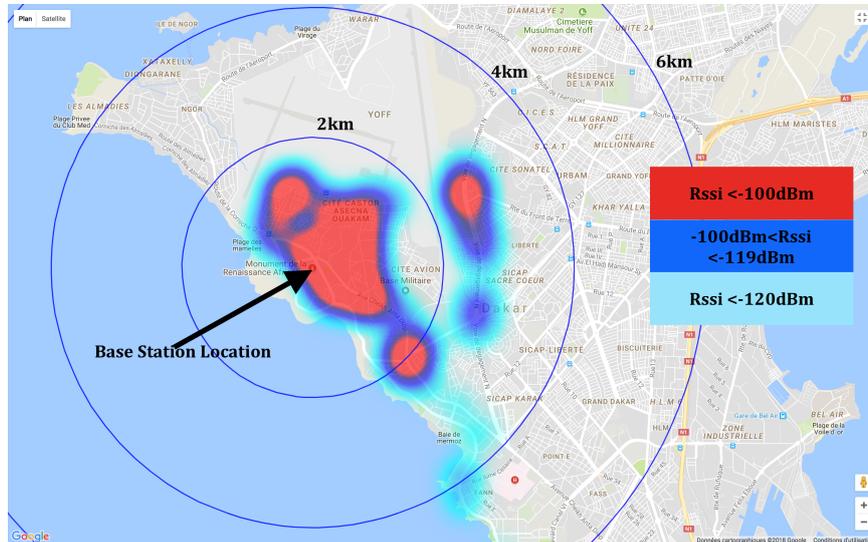


FIGURE 8 – Received *RSSI* from a Base Station located within urban area

129 contrast, WiFi-based communication prototype is more relevant when we consider a store-and-
 130 forward transmission scheme. In case of voice messages or pictures, it will be more suitable.
 131

132 III TESTBED MANAGEMENT AND LINEAR REGRESSION MODEL

133 3.1 Urban and rural testbed deployment

134 In order to evaluate transmission devices reliability, we perform extensive tests by considering
 135 urban and rural areas. The measurements were done in “*Dakar*” (14.754048, -17.489429) pe-
 136 ninsula (urban area) and “*Namarel*” (16.040129,-14.750423) village located in Ferlo region
 137 (rural area). We deployed an architecture made of two components that communicate via LoRa.
 138 A fixed base station sends data at regular intervals to a mobile station. The base station is made
 139 of an *ArduinoUNO* card, a LoRa Shield (14) and a computer. The mobile station is formed
 140 by an *ArduinoUNO* card, a *Dragino* LoRa Shield (14), a *GPS* Shield module and a com-
 141 puter. The communication between the computer and the *Arduino* board is carried out via a
 142 serial port. The collected data from the serial port are stored in a local database hosted by the
 143 computer. The required duty cycle of 1% (15), (16) in *EU* organization for the 868MHz *ISM*
 144 band is not currently applied in Senegal. Therefore, our base station is able to send data with
 145 respect to a fixed interval time.

146 Since *Dakar* peninsula hosts more than 3 million people and lots of buildings having at least
 147 four floors, we planned to place 4 base stations to be able to cover the whole city. For this
 148 reason, we considered the following sites within *Dakar* as radio beacon :

- 149 — The top of “Phares des Mammelles” that ranges up to 126m.
- 150 — The esplanade of “Monument de la Renaissance” which measures 100m.
- 151 — The “Virage”, our lowest point with roughly 20m of height.

TABLE 2 – Urban area performance evaluation

Range (km)	Number of transmitted packets	Number of received packets	Packet Error Rate
0-2 km	2501	2176	13%
2-4 km	2560	2199	15%
4-6 km	2300	1620	31%
6-8 km	2110	633	70%
Total	9471	6628	30%

152 — The highest building in Dakar “Building Kebe” with 75.36m of height.

153 On the other hand, *Namarel* is in a semi desert area where the overall environment across
 154 several kilometers has the same trend as shown in Fig. 9. During our visit, we found large areas
 155 of land which own few trees as well a couple of neighboring villages. We placed a base station
 156 on the roof of the *Namarel* headquarters as depicted in Fig. 4. Furthermore, a device is placed
 157 on a pickup in motion. It is worth noticing that the pickup has criss-crossed around the village
 158 in order to evaluate transmission range.

159 During our performance evaluation, 10.000 packets were sent according to the urban area with
 160 a maximum transmission range of 10 km. In contrast, according to rural use case scenario, 3017
 161 packet were sent with a maximum transmission range of 16 km. Indeed, in rural area we have
 162 a better line of sight which enables efficient transmission. Fig. 8 shows received *RSSI* from a
 163 Base Station located within an urban area. Table 2 and Table 3 show evaluation performance of
 164 Packet Error Rate (*PER*) as a function of covered distance in urban and rural areas respectively.
 165 We found that packet error rate ratio increases a bit when the range goes up. Furthermore, by
 166 taking into account a fixed transmission distance, the *PER* obtained in urban area is upper than
 167 one estimated in rural area. As example, for transmission range up to 4km, we obtained 0%
 168 *PER* (respectively 13%) for rural area (respectively urban area).

169 3.2 Linear Regression model

170 According to received packets, we aim to make a channel attenuation model for each base
 171 station. The obtained models enable to estimate path loss by using LoRa Technology. Our model
 172 can be divided into two parts.

— For every received packet with the mobile station in motion we saved the Received Signal



FIGURE 9 – Namarel testbed overview

TABLE 3 – Rural area performance evaluation

Range (km)	Number of transmitted packets	Number of received packets	Packet Error Rate
0-4 km	757	757	0%
4-8 km	807	793	1.7%
8-12 km	803	760	5.3%
12-16 km	650	601	7.5%
Total	3017	2911	4%

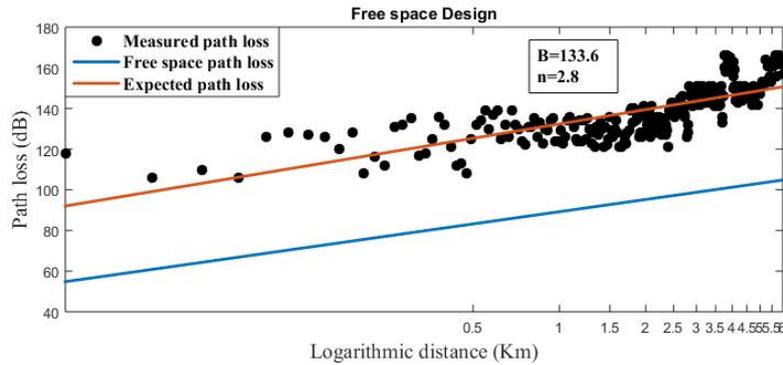


FIGURE 10 – Path Loss for an urban base station.

Strength Indicator (*RSSI*) (20) and the Signal-to-Noise-Ratio (*SNR*). We used it to calculate the Path Loss (*PL*) with the following link budget.

$$PL = |RSSI| + SNR + Ptx + Grx \quad (1)$$

173 “*Ptx*” is the effective isotropic radiated power and “*Grx*” is receiver’s antenna gain.

- We derived Expected Path Loss (*EPL*) of measured data from the linear polynomial fit. We calculated it as (18) with :

$$EPL = B + 10n \log_{10}(d/d_0) \quad (2)$$

174 “*B*” represents the path loss, “*n*” is the path loss exponent, “*d*” is the distance between
 175 the node and the base station and “*d*₀” means the 1km reference distance. For each base
 176 station, we measured the path loss. For instance, Fig. 10 and Fig. 11 depict measured
 177 path loss (black dots) and expected path loss (red curve) for two bases stations. The curve
 178 tagged in blue represents the free space path loss.

179 In order to evaluate our linear regression model, we take into account free space path loss as
 180 a reference to highlight the effect of the environment on received signal because it is almost
 181 impossible to model obstacles when tests are done in a real environment (19).

182 Since we could not browse all places within a fixed city during real life test, we performed
 183 coverage predictions depending on the results of the models. For each base station, we can now
 184 predict its coverage by giving a maximum *RSSI*.

185 By combining obtained results, we made a chart to highlight a link between the *PER* and the
 186 *RSSI* in Fig. 12. It shows the mean *RSSI* as function of *PER*. This could help to show packet
 187 error rate compared to a chosen *RSSI* to cover a place.

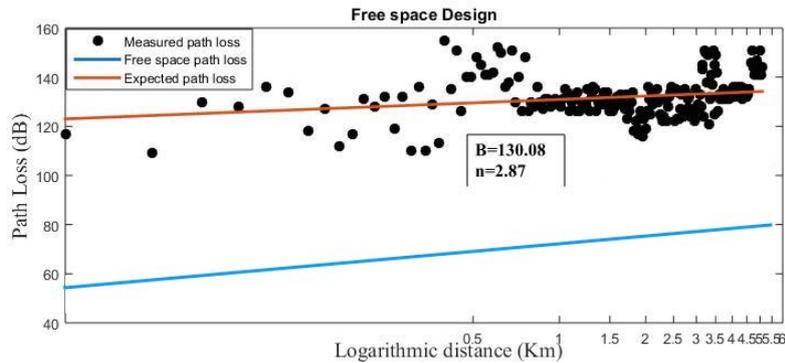


FIGURE 11 – Path Loss for a rural base station.

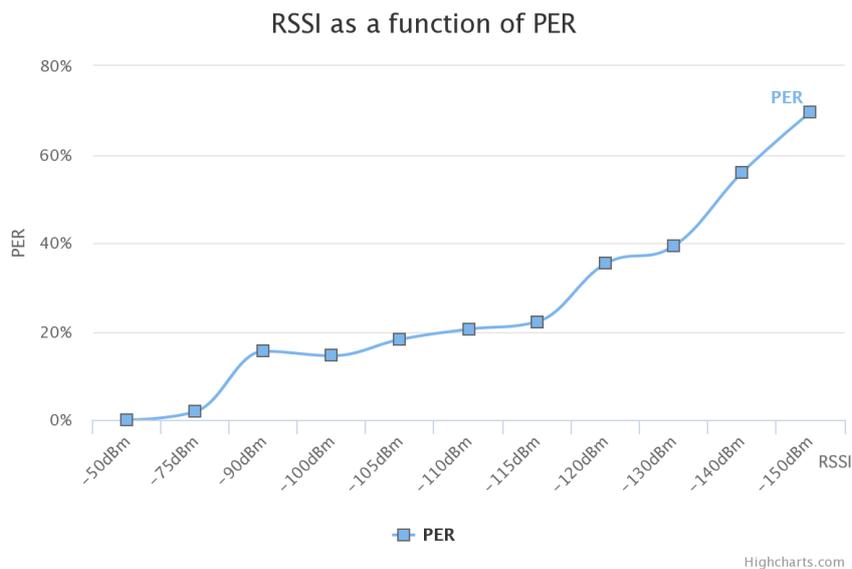


FIGURE 12 – The mean RSSI as function of the PER.

188 IV APPLICATIONS AND FEATURES OF COWSHED NETWORK

189 Providing a low cost and reliable communication system for people living within white spot
 190 areas in order to help them communicating with their surroundings for various usages is the
 191 major objective of our work. For that, we added some functionalities in *COWSheD* project in
 192 order to meet those objectives.

193 4.1 Voice message

194 It's worth noticing that people who live in the Ferlo area are not often literate. Although we met
 195 representatives in the villages with a sufficient level of education to exchange text messages, we
 196 thought it would be useful to add to our system the possibility to send voice messages limited
 197 to 5 seconds. we have added an option in the mobile application to send a voice message that
 198 stops automatically after 5 seconds, this voice message is sent by the same method as when
 199 sending text messages to the Web server and is stored in a database. A shell script that runs like
 200 a daemon(refers to a type of computer program, process, or set of processes that runs in the
 201 background rather than under the direct control of a user) comes to retrieve it and send it to the
 202 *Arduino* card thanks to the process and the message is sent to the LoRa network by the arduino
 203 card.

204 LoRa bit rate is very low so sending voice notes takes a bit of time (approximately 5 minutes).



FIGURE 13 – A refrigerated milk car in Namarel village

205 In fact, we send 4000 bytes for a 5 seconds voice note with payloads of different sizes depending
 206 on the range and the transmitter configuration to reduce the packet loss ratio or to optimize the
 207 data rate.

208 All relay boxes receive the first payload of a voice note and are paused for the duration of the
 209 transmission in order to avoid possible collisions. It is important to remember that the receiver
 210 of the message is added during the sending process in the mobile application as for the text
 211 message.

212 4.2 Geographic location

213 In order to enable a geographical information system, we considered an offline map (*maps.me*)
 214 which is deployed in breeder's smart phones. The device can get data from remote connected
 215 devices using LoRa network. Therefore, geolocation service can be used in order to locate
 216 available water points and boreholes. According to our application, herders geographic location
 217 are retrieved from a *GPS*, and thus, we are able to send geographic location. These coordinates
 218 can be displayed by considering an offline maps like *maps.me*. Furthermore, *LG01* box is able
 219 to store herders geographic location (longitude, latitude) along transit transhumance roads.

220 4.3 Milk Collection

221 According to Ferlo region, the main source of women income is based on milk collection (25).
 222 There is a collection system based on the milk collection with pick-up cars (milk is contained in
 223 plastic buckets or aluminum cans) or at the collection centers equipped with refrigerated milk
 224 cars as illustrated in Fig. 13. The product of the collection is then transferred to a dairy where
 225 the milk is processed and bagged. The inhabitants of the nearby villages make the route on foot
 226 to bring their stocks. For the most distant villages, the use of the cart is more common. In case
 227 of high demand, the pick up moves to collect the milk but that has a cost. Indeed the fuel and
 228 the material resources necessary for the collection and the safeguarding of the milk are loads
 229 to be taken into account. On top of all those constraints, the impossibility to communicate with
 230 surroundings villages is a big issue for those women. *COWShEd* enables a new framework
 231 that helps in decision making to support logistical management for milk collection. (26)

TABLE 4 – Performance Evaluation

Range (Km)	Number of transmitted packets	Number of received packets	Packet error rate
0-5Km	1057	1037	2%
5-15Km	1727	1685	3%
15-20Km	903	862	5%
20-22Km	459	351	13%
Total	4146	3935	5%

232 **4.4 Geographic localization system for artisanal fishery**

233 Although, fisheries sector hold a prominent role in Senegalese economy according to foreign
 234 exchange earnings (exports) and vital needs of population (27), Senegalese GSM cellular net-
 235 works do not cover distance upper than 7 km from coasts. We obtained this information from
 236 real life test that has been done. We used two mobile applications (*inViu OpenCellID* and
 237 *network cell info lite*) and took screenshots of signal quality with respect to fixed positions
 238 as depicted in Fig. 14 and Fig. 15. The crossing positions during the test were mapped in Fig.
 239 16. By considering geographical coordinates of position where screenshots was taken, *RSSI*,

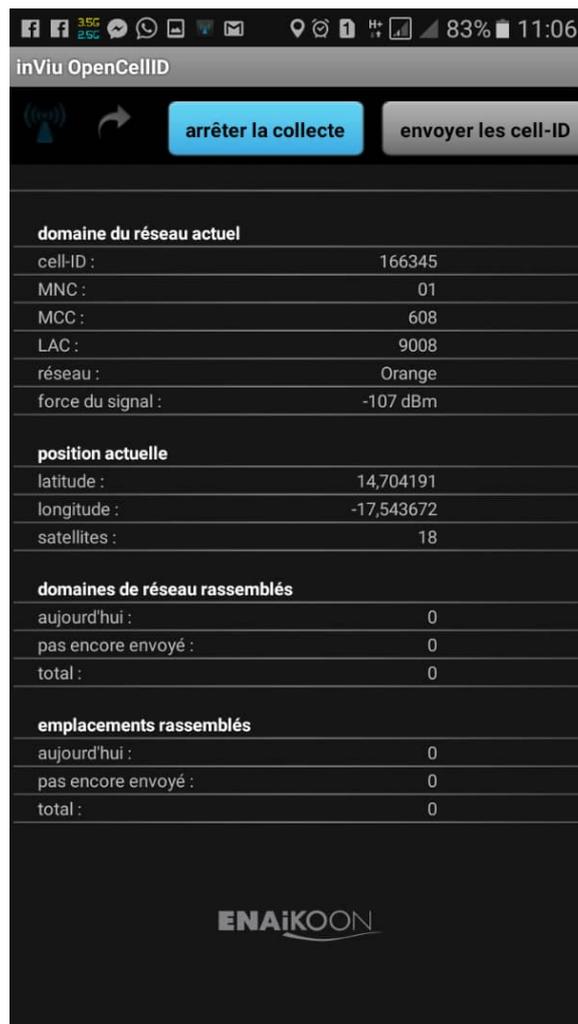


FIGURE 14 – 2G RSSI with “inViu OpenCellID” application

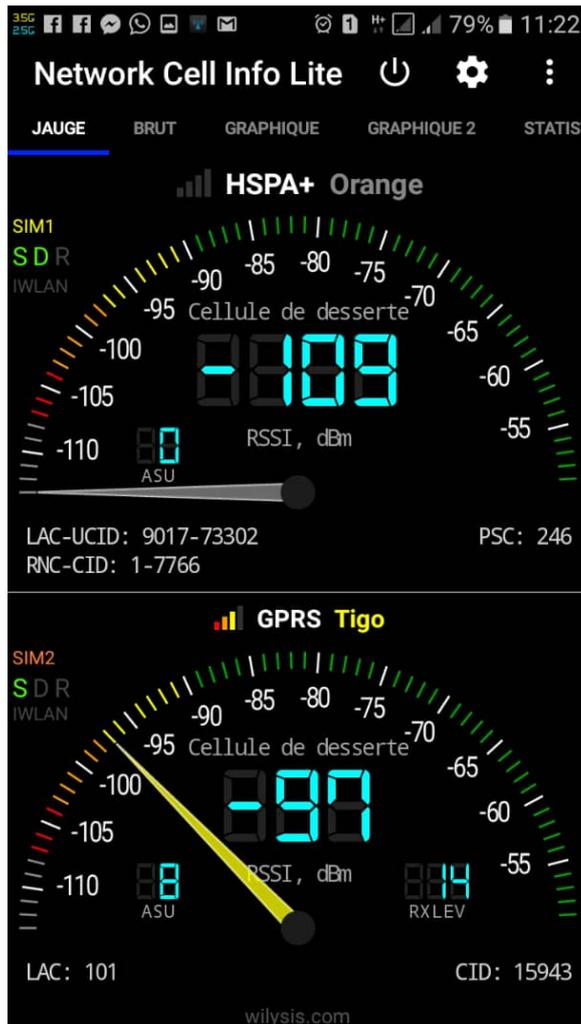


FIGURE 15 – 2G RSSI with Network Cell Info Lite application

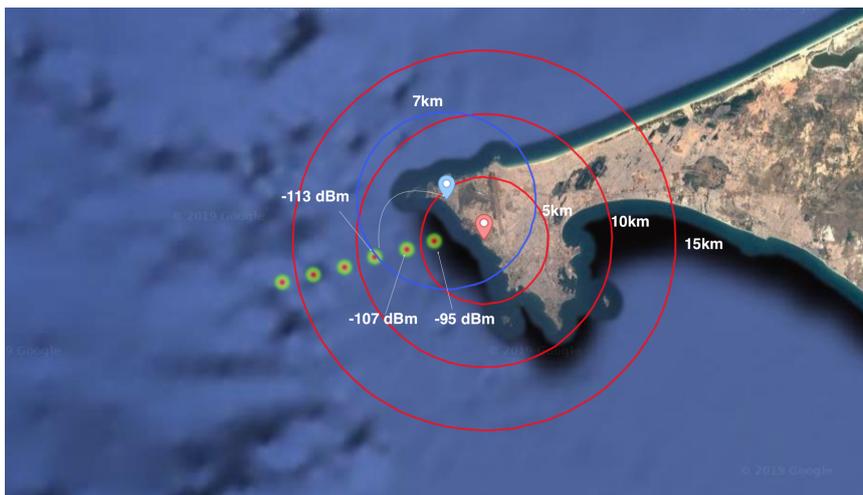


FIGURE 16 – 2G RSSI during test

240 Mobile Network Code (MNC), Mobile Country Code (MCC) and Location Area Code (LAC),
 241 we can find geographical coordinates of the Base station to which the cell phone was connected
 242 thanks to (24) and then know the distance between cell phone and Base Station. Blue and red
 243 center of origins are base station of operators to which our cellphone was connected. So the

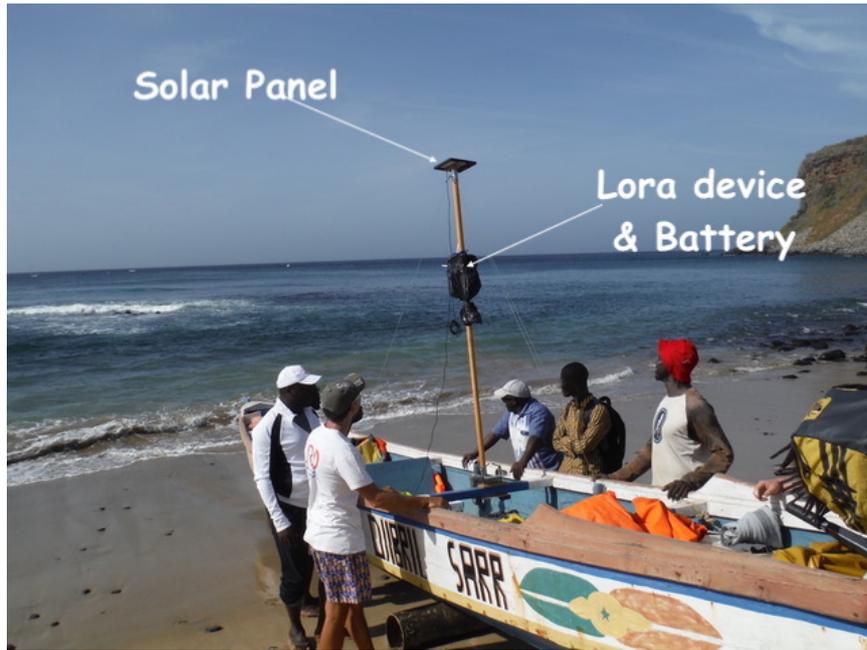


FIGURE 17 – Mobile Relay in the Canoe

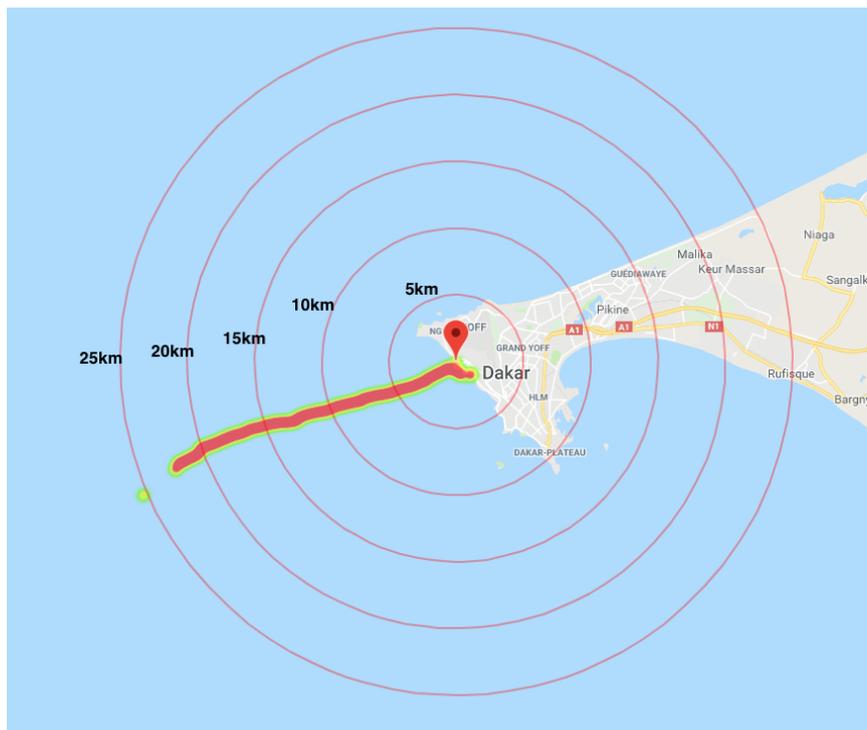


FIGURE 18 – Received Signal with RSSI higher than $-95dBm$

244 distance between the cell phone and the base station is not the same depending on it. We then
 245 made two circles to calculate and highlight the exact distance. This lack of coverage is the rea-
 246 son why there is no rescue communication system for dugout canoes that fishes over that limit.
 247 The social and human conditions are difficult, including safety problems at sea (21) (around
 248 100 deaths per year). Artisanal fishing boats are usually made of a wooden shell of local de-
 249 sign, on which is fitted an outboard engine that can go up to at 60 horses. Dugout canoes are
 250 emblematic in Senegal, therefore their integration into modern fishing landscape of tomorrow

251 will rely on their capacity for modernization. Indeed, at present, the embedded electronics is at
252 best made up of the cell phones of the crew and a GPS “hand” of the captain (22). Similarly,
253 conventional centralized marine positioning systems (*VMS* or *AIS*) are not shipped for econo-
254 mic reasons. As results, the distribution of dugout canoes remains unknown to the institutions in
255 charge of fisheries monitoring. Although Senegalese government is trying to equip some dugout
256 canoe with geolocation system, they still have issues to equip everyone because of the equip-
257 ment price. Proposing a low cost solution is one of their critical objectives. *COWSheD* enables
258 a given fisherman to send maydays in case of crash to a control center or other fishermen that
259 are located within its vicinity. It would also allow fisherman to communicate one to each other
260 when when they are further than 7 km from the coast, a geographical localization system that
261 sends to neighborhood the actual position of each dugout canoe is added.

262 We perform real life test where we have a base station located at 105m of height and mobile
263 relay in a boat as illustrated in Fig. 17. We sent 4146 packets and received 3935. The packet
264 error rate was roughly 5%. Table 4 shows test performance with packet error rate as a function
265 of covered distance. Fig. 18 shows received signal with *RSSI* higher than $-95dBm$. We had
266 up to 22km distance coverage with respect to test done within the sea.

267 V CONCLUSION

268 By leveraging Low Power Wide Area Networks (*LPWANS*), we proposed a mesh-based prof of
269 concepts communication system for white spot areas. In order to achieve an efficient transmis-
270 sion system either on urban area or rural area, we proposed a linear regression model for path
271 loss estimation. Afterwards, a communication architecture that underpins use cases and sce-
272 narios deployment, such as text and voice messages, geolocation system, milk collection and
273 geographical localization system for fishery, within *Dakar* peninsula and *Namarel* village is
274 outlined.

275 However, due to large distance that separate inter-tier users and the lack of centralized equip-
276 ment our mesh network acts as a delay tolerant network. In addition, the use of radio channel for
277 communication can lead to co-channel interference. As future work, we plan to ensure channel
278 availability, enable frequencies reuse and provide an efficient information routing. Considering
279 fixed collector boxes that are located at points of interest such as water points or boreholes is
280 also planned as part of this work.

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