# Introducing Redundancy in the Radio Planning of LPWA Networks for Internet of Things

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Abstract: This paper presents an enhanced methodology in order to introduce redundancy requirements in the Low-Power Wide-Area (LPWA) networks radio planning for Internet-of-Things (IoT). The Jake's Curves were extended, allowing to compute new log-normal fading margins which traduce combined coverage and redundancy requirements. The methodology was applied developing a LPWA SIGFOX network simulator for a typical urban environment. The double and triple redundancy requirement produced a 10 dB increase in the log-normal fading margin, reducing the cell range to one half, which roughly quadruples the site density. In fact, assuring redundancy enhances the networks's quality of experience, but strongly increases the network investment in base-station equipment and site acquisition. This new approach allowed to compute new site grids and to introduce the concept of assisted planning for IoT networks, where the most suitable candidates among a site list will be automatically chosen, avoiding the inefficient and ineffective trial and error method in radio planning.

## 1 INTRODUCTION

Nowadays, Telecom engineers are being challenged to plan and deploy LPWA networks that can connect to modules requiring a single AA battery for 10 years of life time, and which will cost less than 5 euro each (Tom Rebbeck, Michele Mackenzie and Nuno Afonso, 2014).

This challenge is, in fact, already in motion, since LPWA networks are being built worldwide, boosting Machine-to-Machine (M2M) connections and the IoT.

It is believed that LPWA services can target a market of over 3 billion M2M connections by 2023 and generating over USD10 billion from connectivity revenues alone. LPWA networks open new market opportunities due to:

1. Low Cost. By selling cheap terminals and annual connectivity for some applications, LPWA networks will enable connectivity to a wide range of different services, from Smart Cities to agricultural and environment driven businesses.
2. No Power Source Required. By producing a wireless service that can operate for years using the same batteries, it opens the door to other markets, like gas and water metering.
3. Strong Propagation. The strong link budget with Maximum Allowed Path Loss (MAPL) values reaching 165 dB allows deploying less base-stations for the same coverage area, when compared with the traditional cellular solutions. Also it allows reaching deep indoor locations, which enables, for example, connecting meters located in basements and sensors monitoring sewer conditions.

Many of the LPWA technologies operate in license-exempt spectrum. Whereas license-exempt spectrum has some benefits, such as rapid time to market and no spectrum fees, clear disadvantages also exist, such as the lack of control and the likelihood of interference.

Concerning the chosen wireless technology, the ability to re-use the existing network infrastructure is very attractive for the already existing operators. Integrating LPWA services with the existing network infrastructure will reduce roll-out time, on going support and cost.

The technologies Clean-Slate (W. Guibene and K.



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E. Nolan and M. Y. Kelly, 2015) and Long Term Evolution (LTE) Machine-Type-Communications (MTC) (3GPP, 2014) or NB-IoT are being developed to be integrated with existing 2G, 3G and LTE networks. For these technologies, the aspects of network upgrade are being clarified; it may be as simple as a remote software upgrade but more likely hardware changes will be required, but with no modifications to the needed antennas. In contrast, proprietary technologies like SIGFOX, On-Ramp and Semtech (G. Margelis and R. Piechocki and D. Kaleshi and P. Thomas, 2015), require a purpose-built network to deploy their services. For the existing operators, this means still using existing sites, but additional integration and infrastructure, including antenna and base-station equipment, should be required. For a new operator entering in this market, the green field approach is possible, although new operators should perform agreements with the existent ones in order to perform site-sharing and reduce costs.

Whatever the case, sites have to be chosen among a (internal or external) site list, in order to fulfil coverage and capacity requirements. Moreover, when considering LPWA technologies, often base-station redundancy must be met, i.e., coverage requirements should be set not only for the serving base-station but also for neighbour base-stations, which should provide redundant coverage. This assures that the LPWA time diversity gain is achieved, hence enabling the uplink driven performance of small terminals, simultaneously connecting to up to three base-stations.

Coverage requirements are usually integrated using the Jakes approach (Jakes, William C. and Cox, Donald C., 1994). Starting from a coverage area requirement which is usually high (90% to 95% is typical), a log-normal fading margin is computed, which conditions the MAPL and the cell radius calculation, during the initial link budget. The cell radius and site distance is, in fact, the basis for producing a theoretical site grid, where the site locations are pin-pointed in order to commit the coverage requirements.

The aim of this paper is to present an enhanced methodology in order to extend the Jakes curves to scenarios where site redundancy is required, such as the LPWA networks. This allows to compute new site grids and to introduce the concept of assisted planning for LPWA networks, where the most suitable candidates among a site list will be automatically chosen, avoiding the inefficient and ineffective "trial and error" method.

The paper is organized as follows. Section 2 overviews the original Jake's curves and the coverage area probability determination. In the sequence, the extended Jakes curves are developed, considering redundancy, as simulations results are presented. Section 3 presents a case study for urban environment where the new results are applied to single, double and triple redundancy. Section 4 overviews the developed radio planning simulator, developed from scratch for this project, along with the introduction to the assisted planning concept. Finally, conclusions are drawn in section 5.

## 2 DETERMINATION OF COVERAGE AREA PROBABILITY

This section presents the research work around extending the Jakes area coverage probability for LPWA networks when considering site redundancy. Firstly, past work as in (Jakes, William C. and Cox, Donald C., 1994), (Rappaport, Theodore, 2001) will be overviewed. Secondly, the authors' additional work will follow.

### 2.1 The Jakes Approach for Computing of the Coverage Area Probability

Due to random effects of shadowing (large-scale fading) some locations within the base-station surroundings will presents coverage problems, *i.e.*, will be under a certain received signal threshold. It is often useful to compute how the border coverage reloads to the amount of area covered within the border. For a circular coverage area with radius $R$ centred on the base-station, let there be some desired received signal threshold $\gamma$.

In the following, the percentage of useful service area, *i.e.* the percentage of area with the received signal higher or equal to $\gamma$, $U(\gamma)$, is given as a known likelihood of coverage at the cell border.

Let $d$ represent the radial distance from the base-station. It can be shown that if $Prob(P_r(r) > \gamma)$ is the probability that the random received signal power, $P_r$, at $d = r$ exceed the threshold $\gamma$ within an incremental area $dA$, then $U(\gamma)$ is given by,

$$U(\gamma) = \frac{1}{\pi R^2} \int [Prob(P_r(r) > \gamma)]\, dA = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^{R} [Prob(P_r(r) > \gamma)]\, r dr d\theta \tag{1}$$

where,

$$[Prob(P_r(r) > \gamma)] = Q\left(\frac{\gamma - \overline{P_r(r)}}{\sigma}\right) \tag{2}$$

$\overline{P_r(r)}$ is the distance dependent received signal mean power, and $Q(z)$ is defined as,

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{\left(-\frac{x^2}{z}\right)} dx = \frac{1}{2}\left[1 - e^{\frac{z}{\sqrt{2}}}\right]. \quad (3)$$

As in (D. C. Cox and R. R. Murray and A. W. Norris, 1984), (P. Vieira and P. Queluz and A. Rodrigues, 2007), measurements have shown that for any value of $d$, the path loss, at a particular location $d$, $PL(d)$, is random and log-normally distributed around the mean distance dependent value.

Hence,

$$\begin{aligned} PL(d)\,[dB] &= \overline{PL(d_0)} + X_\sigma = \\ &\overline{PL(d_0)} + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma \end{aligned} \quad (4)$$

where $\overline{PL(d_0)}$ is the mean path loss at a reference distance $d_0$, $n$ is the path loss decay and $X_\sigma$ is a zero-mean Gaussian random variable with standard deviation $\sigma$ (in $dB$). Moreover, the distance dependent received power from the base-station $P_r(d)$ depends also on the base-station radiated power, $P_t$,

$$P_r(d)\,[dBm] = P_t\,[dBm] - PL(d)\,[dB]. \quad (5)$$

In order to determine the path loss as referenced to the cell boundary ($r = R$), it is clear that,

$$\overline{PL}(r) = 10nlog\left(\frac{R}{d_0}\right) + 10nlog\left(\frac{r}{R}\right) + \overline{PL}(d_0) \quad (6)$$

and equation (2) can be expressed as:

$$[Prob(P_r(r) > \gamma)] = Q\left(\frac{\gamma - \left[P_t - 10nlog\left(\frac{R}{d_0}\right) + 10nlog\left(\frac{r}{R}\right) + \overline{PL}(d_0)\right]}{\sigma}\right) \quad (7)$$

## 2.2 The Enhanced Approach considering Base-station Redundancy

Consider the general implementation scenario presented in Figure 1. The base stations are placed on a regular grid, with fixed inter-site distances and positioned using a non-orthogonal $60^0$ Cartesian pair of axis (u,v). Each base-station will consider a service area limited by a cell radius, $R$.

Using this coordinate system, the distances $r_i$ from base-station $i$ to a generic point $P$ can be calculated as:

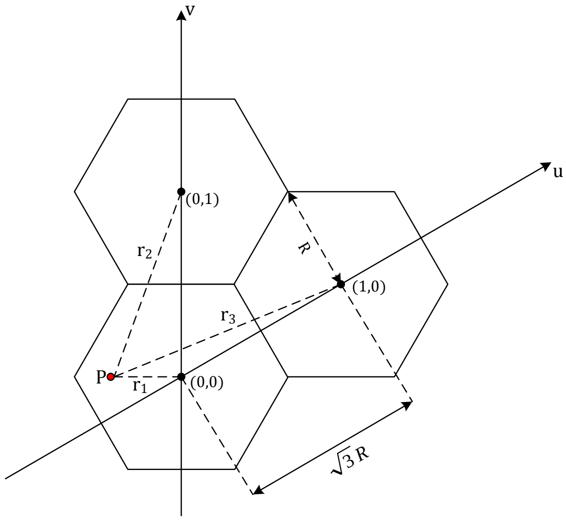


Figure 1: General implementation scenario.

$$r_1 = \sqrt{3\left(u^2 + uv + v^2\right)}R \quad (8)$$

$$r_2 = \sqrt{3\left(u^2 + u(v-1) + (v-1)^2\right)}R \quad (9)$$

$$r_3 = \sqrt{3\left((u-1)^2 + (u-1)v + v^2\right)}R \quad (10)$$

Starting up at equation (7) by choosing the signal level such that $\overline{P_r}(R) = \gamma$, $\gamma$ is given by,

$$\gamma = P_t - \overline{PL}(d_0) - 10nlog\left(\frac{R}{d_0}\right) \quad (11)$$

Additionally, $\gamma$ is being chosen in order to equal the mean received signal strength at the cell border, therefore for the $Q2$ (50%) percentile. It can be useful to consider a quite higher cell boundary $\gamma$ coverage probability, which can be added in the following way. Consider $LNF_{marg}$ as the shadow fading margin which changes the cell boundary coverage probability to a pre-defined value, typically higher than 50%. The probability of the received signal strength being higher than $\gamma$, where $\gamma$ is the signal strength threshold which guarantees the predefined cell border probability is, based on equation (7), and given by,

$$[Prob(P_r(r) > \gamma)] = Q\left(\frac{10nlog\left(\frac{r}{R}\right) - LNF_{marg}}{\sigma}\right) \quad (12)$$

Moreover, and as stated, LPWA networks often demand signal strength redundancy, *i.e.*, base-station radio planning should by performed considering that each terminal should have a coverage level not only dependent on the serving base-station (best server), but also from the surrounding base-stations. The redundancy level, $K$, which is the number of base-station that assures coverage is, in fact, an initial radio planning requirement, ranging from one to usually three, and dependent on the radio environment and the operator demand.

If received signal strength independence is assumed between the transmitting base stations, which is valid considering a macro cell-topology with cell ranges of several kilometres, the signal strength coverage area probability with redundancy will be given by,

$$U(\gamma) = \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^{R}\left[Prob\left(P_r(r) > \gamma\right)\right] r dr d\theta =$$
$$\frac{3}{\pi}\int_u\int_v\prod_{i=1}^{K} Q\left(\frac{10 n log\left(\frac{r_i}{R}\right) - LNF_{marg}}{\sigma}\right)_{u^2+v^2\leq\frac{1}{3}} \quad (13)$$

With this approach, the coverage area percentage will be integrated within the serving cell radius $R$, but considering not only the server base-station but also the neighbour base-station coverage levels.

Moreover, a redundancy gain should be added, since the radio connection will assume multiple radio links affected by independent shadow fading. Specially along the serving cell border, shadow fading can significantly change the serving cell received signal strength, which will enable the connection being handovered to the surrounding cells, if the latter are in better radio connections. Hence, a combination gain must be added.

If combination by selection is set, the receiving terminal will consider the best cell for each location and the redundant coverage area probability is computed by,

$$U(\gamma) = \frac{3}{\pi}\int_u\int_v\prod_{i=1}^{K}$$
$$Q\left(\frac{10 n log\left(\frac{r_i}{R}\right) - LNF_{marg} + 10 n log\left(\frac{min(r_i)}{r_i}\right)}{\sigma}\right)_{u^2+v^2\leq\frac{1}{3}} \quad (14)$$

with $r_1$,$r_2$ and $r_3$ given by equations (8), (9) and (10), respectively.

Figures 2, 3 and 4 present the coverage area probabilities (in %) as a function of $\sigma/n$ for several values of border coverage, and for redundancy levels of one, two and three base-stations, respectively. $\sigma$ is the received signal strength standard deviation (in dB) and $n$ in the propagation decay. Hence, the $\sigma/n$ parameter characterizes the radio environment.

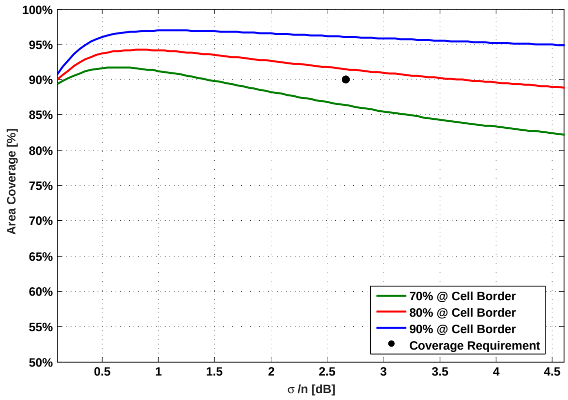


Figure 2: Area coverage for single redundancy.

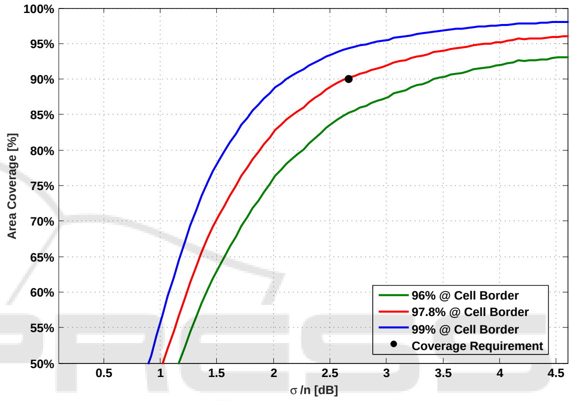


Figure 3: Area coverage for double redundancy.

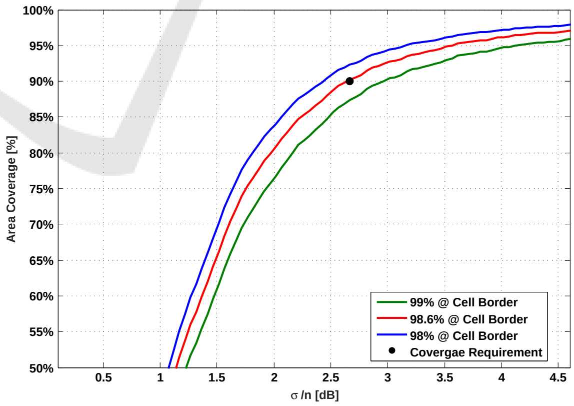


Figure 4: Area coverage for triple redundancy.

The curves were produced based on simulations and are the key for the LPWA network initial planning, considering redundancy. Firstly, the coverage area and redundancy level requirements are set, along with the radio environment characterization, building a triplet. Using the simulations, the triplet allows to index the border coverage level, which is used to compute the log-normal fading margin that reflects the initial requirements.

As an example, let us map the triplet in the previous figures, but considering the case study values presented in the next section 3 . A black "dot" represents 90% coverage area (y-axis), in a typical urban environment with $n = 3$ and $\sigma = 8$ dB ($\sigma/n$, x-axis). Considering a redundancy increase from single to triple, the border coverage probability for the focused environment, strongly increases, as expected. The associated log-normal fading margin, computed from a log-normal distribution for the considered probability also steps up, affecting the link budget and initial dimensioning.

Moreover, the log-normal fading margin in introduced in the LPWA link budget. Along with the log-normal fading margins, and for the considered technology, parameters like transmit power, receiver sensitivity, antenna gain, cable and combiner losses, receiver Low Noise Amplifier (LNA) gain, and penetration losses are used to calculate the MAPL. Then, and using a large-scale propagation model, typically tuned for the used frequency band, the cell range and site distance is calculated, allowing to reach a theoretical site location grid that mirrors the LPWA technological specifics, along with coverage and redundancy requirements.

For a chosen environment, a higher coverage area requirement produces a higher border coverage probability, increasing the log-normal fading margin and reducing the cell range. The redundancy level requirement has a strong impact in the log-normal fading margin, which rapidly grows, and originating a reduced cell radius. If strong redundancy is an issue, the site density will increase, along with the needed investment concerning number of base-stations. This will be properly quantified under a case-study in the next section.

# 3 A CASE STUDY FOR URBAN ENVIRONMENT USING SIGFOX

The methodology was applied to a LPWA network in a typical urban environment with $n = 3$ and $\sigma = 8$ dB. It is assumed that terminals are placed inside the buildings, hence, a 15 dB penetration loss is considered. A large-scale propagation model was used for the path loss calculations, after being tuned with RF measurements. The coverage area requirement is 90%, and 3 scenarios are set, using single, double and triple redundancy, respectively ($K = 1, 2, 3$).

The chosen LPWA technology was SIGFOX, which was picked as an example. It should be highlighted that the presented methodology is transversal to all point-to-area wireless technologies, which depend on a coverage area requirement.

SIGFOX is an LPWA operated telecommunication technology, dedicated to the IoT, currently deployed in Western Europe, San Francisco, and with ongoing tests in South America and Asia. It operates on sub-GHz frequencies, on ISM bands : 868 MHz in Europe/ETSI and 902MHz in the USA/FCC. SIGFOX uses an Ultra-Narrow Band (UNB) modulation, With a 162 dB budget link SIGFOX enabling long range communications. In uplink, the 14 dBm terminals transmit to the closest base-stations, which decode the signals and forward them to the network back-end.

Table 1 presents the log-normal fading margin ($LNF_{marg}$), cell range ($R$), inter-site distance ($ISD$) and site density ($SD$) for single, double and triple redundancy.

Table 1: Simulation results.

| $K$ | $LNF_{marg}$ [dB] | $R$ [km] | $ISD$ [km] | $SD$ $[site/km^2]$ |
|---|---|---|---|---|
| 1 | 5.91 | 2.17 | 3.75 | $8.18 \times 10^{-2}$ |
| 2 | 16.19 | 1.12 | 1.94 | $30.68 \times 10^{-2}$ |
| 3 | 17.47 | 1.03 | 1.78 | $36.28 \times 10^{-2}$ |

For the typical urban environment, the double and triple redundancy requirement produces a huge 10 dB increase in the log-normal fading margin, reducing the cell range to one half, which roughly quadruples the site density. In fact, assuring redundancy enhances the network quality, but also strongly increases the network investment in base-station equipment and site acquisition.

# 4 THE IoT RADIO PLANNING SIMULATOR

In order to apply the developed methodology and to considerer not only the link budget approach but also to produce spatial simulations, a coverage prediction simulator was developed for IoT network planning. Section 4.1 will overview the simulator's architecture and section 4.2 will introduce the concept of assisted planning.

### 4.1 Planning Tool Architecture

The simulator was developed in *C#*, and its architecture is presented in Figure 5.

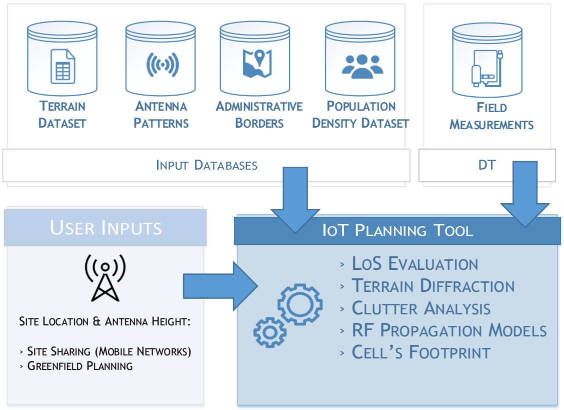


Figure 5: IoT network planning simulator's architecture.

The developed IoT simulator uses a large-scale empirical propagation model in order to predict the path loss and received signal strength for uplink and downlink. As inputs, it relies on Geographic Information System (GIS) datasets such as Terrain Digital Surface and Elevation Models, as well as the Clutter (Radio Environment) characterization. In addition, to accurately represent the antenna gain in each azimuth/elevation, it also uses the antenna radiation pattern model which is supplied by the vendor. Since the considered use case may be to offer distinct coverage and redundancy requirements for each geographical region and population density, it requires the geographical population distribution, as well as its administrative borders.

The median path loss is calculated depending on the distance, frequency, antenna effective height, Line-of-Sight (LoS) existence, diffraction losses and clutter type. To get the best prediction results, it is still necessary to adapt the model's parameters to local conditions and to the technology peculiarities of the IoT radio planning. In this context, Lisbon field measurements (using SIGFOX network) were also used, to the tune the model.

As outputs, it produces several thematic maps of individual base-station foot-print, global coverage, redundancy level, along with planning reports where the considered regions compliance to the pre-set coverage requirements are presented. As an example, Figure 6 represents the coverage footprint for a certain cell whilst Figure 7 presents the redundancy level for one of the Lisbon's simulations. Here, the red stands for the triple redundancy, the green for double, and finally the blue shaded area for the single redundancy ($K$).

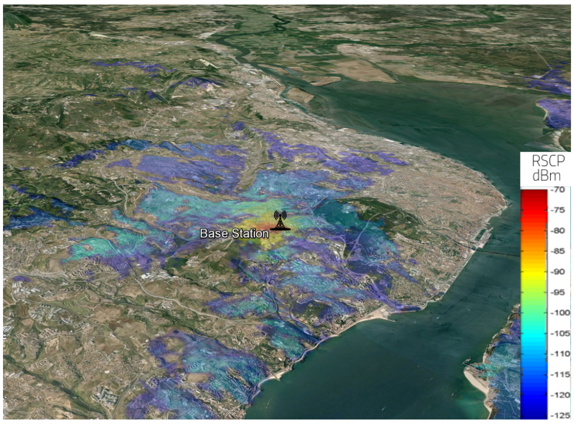


Figure 6: Coverage Footprint for a given cell.

Figure 7: Base-station redundancy level.

### 4.2 Assisted Planning

Using the presented methodology, it is possible to introduce a new concept dependent on the redundancy level, which will be named Assisted Planning. The assisted planning feature provides a way of picking the most suitable locations to plan the sites, in order to achieve the coverage and redundancy requirements in a specific region.

In fact, and as mentioned, new and already existent IoT operators should follow a site-sharing approach to reduce costs. Hence, they will have to pick the best sites from an existing candidate list, in order to build up the new network. The assisted planning helps the radio planner in this task, since supplies a cell grid already moulded to the specific radio environment and also coverage and redundancy requirements. Hence, using assisted planning, it is possible to automatically determine the best location to install the base-station, simply pin-pointing the location or by selecting it from a set of candidate locations.

Figures 8 and 9 present the assisted planning grid for the single and triple redundancy scenarios, respectively. For triple redundancy, the ISD strongly reduces, as already mentioned.

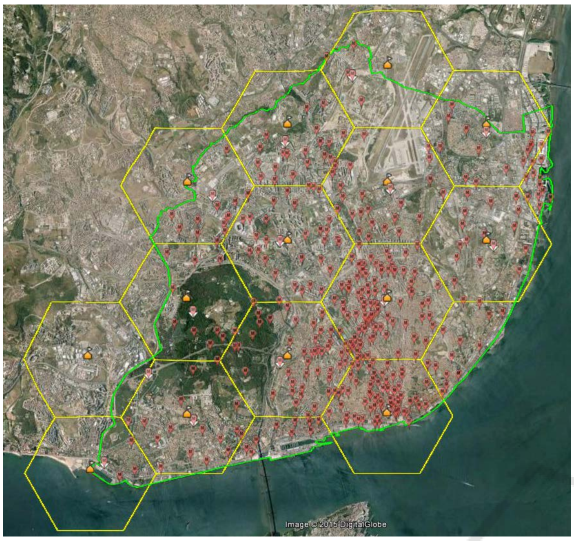

Figure 8: Assisted planning for single redundancy scenario.

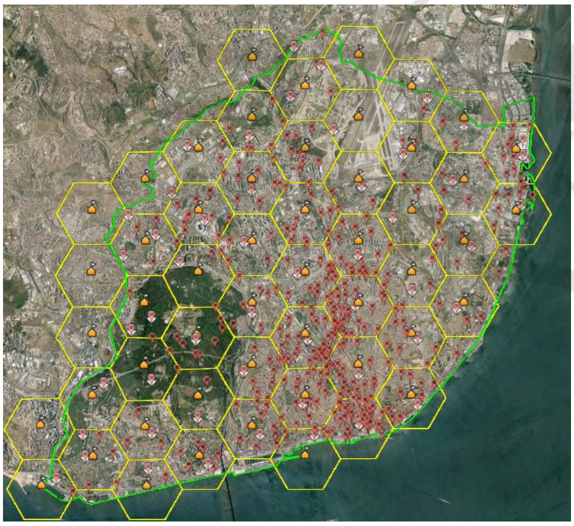

Figure 9: Assisted planning for triple redundancy scenario.

The yellow planning grid, which is set for each region according to its terrain and clutter characteristics, reveals an average site separation, dependent on the redundancy level which the network is trying to achieve.Both figures consider a 90% coverage area target, but for different redundancy levels which impose different site distance separations, as mentioned.

In this case, a set of candidate locations for site-sharing is available (represented by red markers), along with the yellow markers that represent the best theoretical site locations. The assisted planning feature picks the best sites, after a ranking procedure, where not only distance to theoretical markers is considered, but also the location height, type of radio environment and construction limitations.

## 5 CONCLUSIONS

This paper presented an enhanced methodology in order to introduce redundancy requirements in the LPWA networks radio planning for IoT. The Jake's Curves were extended, allowing to compute new log-normal fading margins which traduce coverage and redundancy requirements.The presented methodology is transversal to all point-to-area wireless technologies, which depend on a coverage area requirement, from emerging LPWA technologies (*e.g* SIGFOX, On-Ramp, Semtech) to existing cellular technologies which are focusing on IoT integration (NB-IoT).

The methodology was applied to a LPWA SIGFOX network in a typical urban environment. The double and triple redundancy requirement produced a huge 10 dB increase in the log-normal fading margin, reducing the cell range to one half, which roughly quadruples the site density. In fact, assuring redundancy strongly increases the network investment in base-station equipment and site acquisition.

This new approach allowed to compute new site grids and to introduce the concept of assisted planning for IoT networks, where the most suitable candidates among a site list will be automatically chosen, avoiding the inefficient and ineffective "trial and error" method in radio planning.

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