Wireless network planning and optimization in oil and gas refineries

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***Abstract*—The widespread adoption of wireless systems for industrial automation calls for the development of efficient tools for virtual planning of network deployments similarly as done for conventional Fieldbus and wired systems. In industrial sites the radio signal propagation is subject to blockage due to highly dense metallic structures. Network planning should therefore account for the number and the density of the 3D obstructions surrounding each link. In this paper we address the problem of wireless node deployment in wireless industrial networks, with special focus on WirelessHART IEC 62591 and ISA IEC 62734 standards. The goal is to optimize the network connectivity and provide practical deployment rules in complex industrial sites characterized by severe obstructions. The proposed node deployment approach is validated through a case study in an oil refinery environment. It includes an ad-hoc simulation environment that implements the proposed network planning approach using 2D models of the plant, providing connectivity information based on user-defined deployment configurations. Obtained results were validated by on-site measurements.**

I. Introduction

The opportunity to replace cabling by deploying battery equipped wireless sensor networks is now becoming of strategic interest for industrial automation [1]. The diffusion of wireless technologies calls for the development of virtual network planning software tools for accurate system deployment. Network planning is performed before on-site network installation and should be accurate enough to limit the need to oversize the design of the overall system, which is obviously an extra cost for the contractor. Making use of the 3D model of the industrial site (if available) during the design phase is also of utmost importance to achieve this result.

In industrial sites the radio signals are prone to blockage due to highly dense metallic structures. The prediction of the strength of the wireless signal power should therefore account for the 3D layout of scattering objects surrounding transmitter and receivers. In [2] a channel model based on the diffraction theory is proposed where the 3D model of the plant is used to classify the links based on the number and the density of the obstructions surrounding each link. Based on those results, in this paper we develop an optimization tool to support virtual network planning and deployment of relay nodes tailored for WirelessHART and ISA SP100 [3] mesh networking standards. The tool can be configured to optimally choose the positions of the infrastructure devices based on candidate sites for deployment, while the goal is to guarantee reliable and robust connectivity.

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The majority of published work on sensor network deployment limits its focus on simplified 1D and 2D environments where connectivity can be considered as a primary/secondary objective or as a constraint in the deployment problem [7]. Some attempts in the literature have been made towards the analysis of deployment and connectivity problems in 3D environments, although the topic is still considered as an open issue [4]. The network connectivity problem is indeed mostly considered under the assumption of simple binary communication disk models without looking at site-specific environmental constraints. Those approaches are very prone to failure in practical industrial applications.

An industrial network deployment consists of wireless field devices (FD) connected by multihop topology with a Gateway device (Network Manager) collecting data and rerouting to a wired network. The wireless architecture supported by the industry standards WirelessHART and SP100 is adopted here as reference for deployment testing. The network infrastructure consists of the following components: *i)* the Field Devices (FD) are the input/output field wireless instruments configured to support message relaying of adjacent FDs by decode and forward; *ii)* the Relays are special FDs serving as network infrastructure to improve connectivity by relaying data from the FDs to the Gateway (and viceversa); *iii)* the Gateway acts as access point and network manager, collecting the measurements acquired by the field devices. In practical settings, the Gateway is connected by cables (or by broadband wireless technology) to a common network manager node and thus also act as a translator between the WirelessHART/ISA standards and other wired industrial protocols (Foundation-Fieldbus, Profibus, HART, etc...).

In this paper we address the problem of optimizing wireless node connectivity for WirelessHART and ISA SP100 industrial networks. Network planning makes use of the prediction of the wireless link quality using a site-specific channel model

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TABLE I
POSSIBLE LINK TYPES (WITH NOMINAL RANGE)

Type I: LOS	$\bar{\sigma}_1 \simeq 1dB,\ r_1 \simeq 150m$
Type II: near-LOS	$\bar{\sigma}_2 \simeq 4dB,\ r_2 \simeq 100m$
Type III: obstructed-LOS	$\bar{\sigma}_3 \simeq 7dB,\ r_3 \simeq 60m$
Type IV: NLOS	$\bar{\sigma}_4 \simeq 12dB,\ r_4 \simeq 30m$
Type V: severe-NLOS	$\bar{\sigma}_5 \simeq 21dB,\ r_5 \simeq 15m$

based on 2.4GHz measurements, which can be applied with the support of our ad-hoc simulation tool, as further described.

II. CONNECTIVITY MODELING FOR INDUSTRIAL NETWORKS

Wireless connectivity models for industrial environments describe the site specific correlation between the size and the locations of the objects obstructing the line-of-sight (LOS) path (or Fresnel volumes) and the reliability of the wireless link in terms of received signal strength (RSS). For any link ℓ connecting a pair of FDs, the RSS γ_ℓ is modeled as [2]

$$\gamma_\ell = \underbrace{g_0 \times \sigma_\ell^{-1}}_{g_\ell(d)} \times s_\ell + n_\ell, \tag{1}$$

it combines three terms: *i)* a static component $\mathrm{E}[\gamma_\ell] = g(d)$ characterized by a distance d dependent LOS term $g_0 = g_0(d, \alpha)$ and a site specific *excess attenuation* σ_ℓ due to propagating wavefronts diffracting around the building blockage; *ii)* a random term s_ℓ accounting for the fading fluctuations; *iii)* superimposed disturbance n_ℓ due to hardware errors and interference. The measurements in [2] (see also Section 2.2) reveal that the main scatterers/objects that are responsible for the received signal power *excess attenuation* σ_ℓ are mostly confined within the first and second Fresnel zones [6] as these can be considered to contribute to the main propagating energy in the wavefield.

The distance-dependent static component (in dB scale) $g_0(d, \alpha)$

$$g_0(d,\alpha)|_{dB} = \begin{cases} g_0(d_0) - 20\log_{10}(d/d_0) & d \leq d_F \\ g_0(d_F) - 10\alpha\log_{10}(d/d_F), & d > d_F \end{cases} \tag{2}$$

describes the channel gain observed over the flat terrain and without obstructions. It is modeled as a function of the path-loss exponent α (see [6]) for $d > d_F$ where $g_0(d_0)$ is the free space channel gain measured at a reference distance $d_0 = 2$m, while $d_F = 2h_m h_p/\lambda > d_0$ is the Fresnel distance being a function of the wavelength[1] λ and of the antenna heights from the ground h_m and h_p for the pair of devices $\ell := (m, p)$, respectively. The path loss exponent can be reasonably set to $\alpha = 2$ in short range environments where ground reflections can be neglected, for $d \leq d_F$. Larger path loss exponents $\alpha > 2$ (with $\alpha = 2 \div 3$ typical) are caused by reflections from the ground and are observed in long-range cases for $d > d_F$.

[1]measured at carrier frequency 2470MHz - corresponding to IEEE 802.15.4 channel 23

A. Connectivity modeling by link classification

A general approach to wireless link quality modeling in arbitrary industrial environments affected by dense blockage is to classify the links based on C mutually exclusive *link categories* $\{\mathcal{C}_1, \mathcal{C}_2, ..., \mathcal{C}_C\}$. Any link $\ell \in \mathcal{C}_j$ classified as class j experiences a RSS γ_ℓ as in (1) where $\sigma_\ell \simeq \bar{\sigma}_j$, and with $\bar{\sigma}_j$ being the reference value for the *excess attenuation* characterizing the class j. The C site-specific probabilities

$$p_j = \Pr[\ell \in \mathcal{C}_j] \tag{3}$$

of links classified as $\mathcal{C}_j$ thus provide a description of the deployment site complexity in terms of spatial density of the building blockage. The probabilities $\{p_j\}_{j=1}^C$ are estimated here from the analysis of the 2D/3D model of the considered industrial site.

According to the measurements in [2] $C = 5$ mutually exclusive link types have been identified as the ones that provide the best characterization of the wireless propagation in oil refineries. These are summarized in table I and visually illustrated in Fig. 1. Neglecting the effect of random disturbance n_ℓ in (1)[2], the nominal supported range r_j for each link class j is computed such that $g_\ell(r_j)|_{dB} = \beta$ with $\beta = -85dBm$ being the minimum RSS for reliable connectivity such that the probability of packet drop is below 10^{-3}. Any link with $g_\ell(d)|_{dB} < \beta$ is assumed as disconnected.

Type I: LOS ($\bar{\sigma}_1 \simeq 1dB$) link type is characterized by the absence of obstacles (with dimensions larger than the signal wavelength λ) within the 1st and 2nd Fresnel volumes. Obstacles outside those regions cause a maximum excess attenuation of $1dB$. The nominal range r_j is found as $r_1 \simeq 150m$ (with $\beta = -85$dBm).

Type II: near-LOS ($\bar{\sigma}_2 \simeq 4dB$) link type is observed in environments where a 'forbidden' sub-region of the 1st Fresnel volume around the LOS path is kept clear from obstacles. Obstacles outside the forbidden region cause an excess attenuation of $4dB$. Nominal range reduces to $r_2 \simeq 100m$.

Type III: obstructed-LOS ($\bar{\sigma}_3 \simeq 7dB$) link type is characterized by obstacles inside the forbidden region, while the direct path connecting the transmitter and the receiver is unobstructed. The nominal range is $r_3 \simeq 60m$.

Type IV: NLOS ($\bar{\sigma}_4 \simeq 12dB$) link type is characterized by objects obstructing the first Fresnel volume. The nominal range is $r_4 \simeq 32m$.

Type V: severe-NLOS ($\bar{\sigma}_5 \simeq 21dB$) link type refers to a severe NLOS environment where the first/second Fresnel regions are *completely* obstructed by one or more obstacles with significant size The nominal range is $r_5 \simeq 15m$.

B. Model calibration in oil refineries

In this section the proposed approach for the evaluation of the pairwise link channel qualities is validated by a database of radio measurements taken in different refinery sites to cover the most representative scenarios and link types. In Fig. 1

[2]Although the effect of interference is assessed in Section 4

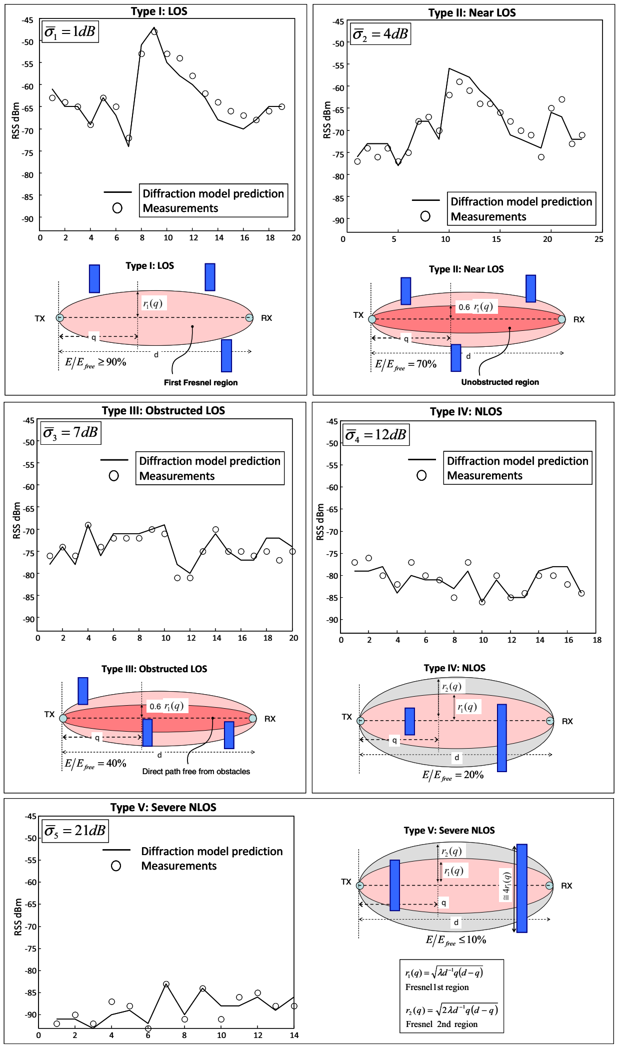

Fig. 1. Connectivity model calibration based on measurements in oil refinery sites. The predicted RSS values and the corresponding measurements are illustrated for each link type. Measurements are obtained from different areas of the same refinery site and correspond to links characterized by different obstruction configurations and distances. Classification of links is based on inspection of the 3D model of the plant.

the available measurements (circle markers) are partitioned by classifying the corresponding radio links through an inspection of the 3D model of the site. For each link type we compare the RSS observations with the predicted values (solid lines) based on the model defined in Sect. 2.A. The measurements analyzed highlight the accuracy of the proposed channel characterization and modeling approach. Prediction of link quality is reasonably tight for LOS types (with errors below 2dB) while smaller accuracy (approx. 5dB) is observed for NLOS types due to imperfect 3D layout descriptions.

III. Network planning and optimization

The multihop paradigm supported by both WirelessHART and SP100 standards has the merit of enabling extremely low power consumption and long battery lifetime, however it creates a network topology with characteristics that are quite different from those typically observed in cellular networks. This is more evident if we look to the device connectivity. While a mobile device in a cellular system is “connected” if it has a wireless link to at least one base station, in multihop topologies each device contributes to the connectivity of the entire network. The quality of device connectivity depends critically on the node spatial density and the complexity of the environment.

In what follows the optimization of the connectivity for virtual network deployment is based on the site-specific radio propagation model illustrated in Sect. 2. The model (1) is thus exploited here as instrumental to the RSS prediction, from which the quality of the radio link (and of the connectivity) can be inferred with some degree of accuracy that depends on the link classification process. After a first attempt to configure the network using our RFSim tool (detailed in Sect IV), a stress testing of the deployment design is recommended during a preliminary on-site survey to verify potential weaknesses highlighted during the virtual network configuration. Stress testing is performed by altering the position of the FDs and of the relay devices from the nominal position. Although not addressed in this paper, this procedure allows to measure how fluctuations of the RSS field could alter the connectivity structure.

Extensive work has been reported in the literature relating to wireless sensor and relay node deployment. The deployment strategies can be classified into static and dynamic [5], depending on whether the optimization is performed during network set-up or during network operation (for node repositioning, see [5]). In static environments, as those considered in this paper, data is periodically collected over preset routes. In such cases the problem of optimal node placement for connectivity maximization has been proven to be NP-hard for most of the formulations [7]. Several heuristics and rules have been therefore proposed to find suboptimal solutions based on graph theory [8].

Some more recent works considered the problem of connectivity in wireless multihop networks by investigating how broadcast transmissions can “percolate” in random networks [9]. Graph theory is therefore the natural framework for the exact mathematical modeling of complex network structures typically encountered in industrial environments [10]. In what follows the industrial network is modeled by an undirected graph $\mathcal{G}(\mathcal{N}, \mathcal{V})$ consisting of a set $\mathcal{N} = \{1, 2, ...N\}$ of N vertices identifying the position of the FDs (and of the Gateway) deployed in random industrial sites. The elements of $\mathcal{V}$ are the links ℓ connecting pairs of elements in $\mathcal{N}$: connectivity is simulated by assigning a class for each link $\ell \in \mathcal{C}_j$ with probability p_j while connection is observed when $d < r_j$ with d being the distance between the pair of

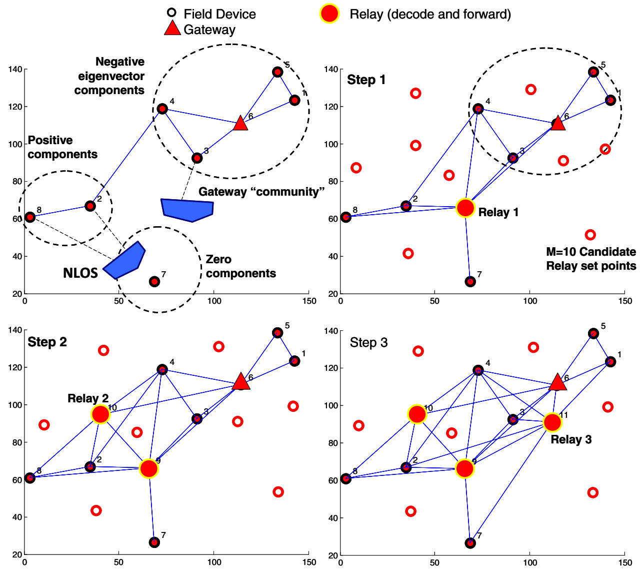

Fig. 2. Iterative relay node deployment algorithm: reference layout for illustration purpose. Example for $N = 8$ FDs and $M = 10$ relay candidate set points. $R = 3$ relays guarantee robust connectivity.

vertices. The network is said to be connected if for every pair of (distinct) nodes there exists at least one path connecting them. Two nodes joined by one link are referred to as adjacent: notice that adjacent nodes might be not neighbor in the spatial sense as it depends on the complexity of the environment (e.g., characterized by the probability p_j).

Algebraic Connectivity $a(\mathcal{G})$ will be used in the following section as an effective parameter to estimate how well the network is connected:

$$a(\mathcal{G}) = \lambda_2 \left[\mathbf{L}(\mathcal{G})\right], \tag{4}$$

it is defined as the second smallest eigenvalue[3] $\lambda_2 = \lambda_2 \left[\mathbf{L}(\mathcal{G})\right]$ of the $N \times N$ Laplacian matrix $\mathbf{L}(\mathcal{G})$ corresponding to graph $\mathcal{G}$ [12]. The term $a(\mathcal{G})$ provides a bound to the minimum number of removable FDs that can separate the graph into disconnected components: when condition $a(\mathcal{G}) > d$ is satisfied then the network connectivity is strong enough to tolerate up to d random node (or link) failures.

A. Relay deployment optimization

The deployment optimization can be in general applied to random networks modeled as graphs where connectivity depends on the complexity of the industrial site (i.e., in terms of probabilities p_j as detailed in Sect. 2). In what follows we propose an algorithm for relay placement that identifies the weaknesses of the network structure and in turn select the best position of relays such that reliable connectivity is observed (with some degree of robustness). The approach is thus intended for monitoring and control systems operating in time (and safety) critical conditions.

The proposed relay placement algorithm takes as input any network corresponding to a deployment of an arbitrary number N of FDs (comprising of the Gateway) in a random industrial field characterized by an arbitrary number of link types with connectivity modeled as in (1). Relay placement algorithm first identifies disconnected (or weakly connected) network structures of graph $\mathcal{G}$ and then iteratively choose the best $R \leq M$ relays among $M > N$ candidate relay positions[4] to connect those components with the Gateway node. The R relay nodes are added to form a new graph $\mathcal{G}^{(R)}$ while relay placement stops when $a(\mathcal{G}^{(R)}) > 1$.

Graph theory provides efficient tools for finding weakly connected (or disconnected) communities within complex network structures as observed in industrial environments. In what follows, these tools will be tailored as instrumental to optimal relay placement. A spectral graph partitioning scheme [10] is used to identify potential weakly connected communities by analyzing the eigenvalues $\lambda_i \left[\mathbf{L}(\mathcal{G})\right] \forall i = 2, ..., N$ of the Laplacian matrix and the corresponding eigenvectors $\mathbf{v}_i = \mathbf{v}_i \left[\mathbf{L}(\mathcal{G})\right]$ defined as $\mathbf{L}(\mathcal{G})\mathbf{v}_i = \lambda_i \mathbf{L}(\mathcal{G})$. When the network is divided into $q > 1$ communities then the $q - 1$ consecutive Laplacian eigenvalues $\lambda_2, ..., \lambda_q$ lie a small gap away from zero, while the value of the remaining eigenvalues provide a measure of the connectivity inside each sub-network. The signs of the N length eigenvectors components $\mathbf{v}_2, ..., \mathbf{v}_q$ are used to identify the positions of FDs in each community [11].

The example of figure 2 is highlighted to illustrate the iterative relay node deployment approach using a reference layout. In what follows, the effect of severe NLOS propagation is considered by simulating a simplified industrial environment characterized by $C = 2$ mutually exclusive link types modeling severe NLOS (now indicated by $j = 1$) and near LOS ($j = 2$) propagation, respectively. The corresponding attenuation parameters are detailed in table I. The approach can be extended in RFsim for an arbitrary number of link types, however we found that these classes mostly provide a reasonably accurate representation of the wireless propagation in oil refineries.

In the example, $N = 8$ FDs are deployed in a random field characterized by a NLOS probability of $\Pr[\ell \in \mathcal{C}_1] = 20\%$ (while $\Pr[\ell \in \mathcal{C}_2] = 80\%$ models the corresponding probability of near-LOS propagation). FD 7 is isolated as surrounded by obstacles while wireless propagation experiences severe NLOS. The network consists of $q = 3$ communities: the first one contains the 50% of FDs and corresponds to nodes $\mathcal{N}_1 = \{1, 3, 4, 5, 6\}$ with $[\mathbf{v}_2]_{i \in \mathcal{N}_1} < 0$. These nodes are connected to the Gateway (node 6) in one-hop. The second one (corresponding to nodes $\mathcal{N}_2 = \{2, 8\}$ with $[\mathbf{v}_2]_{i \in \mathcal{N}_2} > 0$) is weakly connected with $\mathcal{N}_1$, finally the third component $\mathcal{N}_3 = \{7\}$ contains the isolated node 7 with $[\mathbf{v}_2]_{i \in \mathcal{N}_3} \simeq 0$. At first iteration, the relay is chosen among $M = 10$ candidate

[3] By definition of Laplacian matrix $\lambda_1(\mathbf{L}(\mathcal{G})) = 0$.

[4] Candidate relay positions should be identified during commissioning or pre-commissioning of the plant.

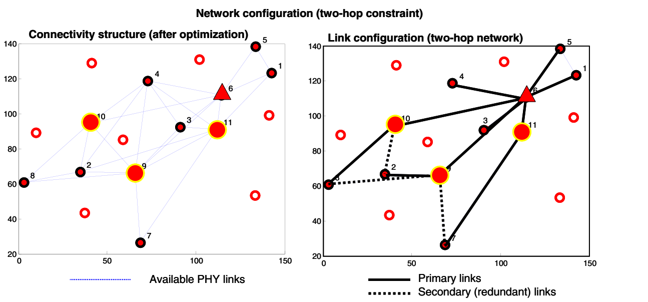

Fig. 3. Network configuration for two-hop connectivity. A subset of PHY links (primary and secondary links) are chosen for WirelessHART network configuration using the same reference layout of Figure 3.

TABLE II
NODE PROPERTIES

Device type	(Field Device, Relay Node, or Gateway)
Protocol	(WirelessHART, or SP-100)
Operation frequency	(800 MHz, 900 MHz, or 2.4 GHz)
Channel	1 to 15
Transmission Power	(-10 dBm, 0 dBm, or 10 dBm)
Height	(from 1m to 6m)
Antenna	(type and gain)

set points in such a way to connect node 7 with the Gateway community $\mathcal{N}_1$. The new graph $\mathcal{G}^{(1)}$ of $N+1$ devices is now weakly connected as $a(\mathcal{G}^{(1)}) = 0.65$. At second step a new relay is chosen to connect community $\mathcal{N}_1$ and $\mathcal{N}_2$: nodes 2 and 8 can exploit a secondary path connecting with the Gateway node. In the final step a third relay provides $a(\mathcal{G}^{(3)}) = 1.23$ while an alternative path is established for FD 7. To conclude, for the considered topology the additional deployment of $R = 3$ relay nodes guarantees reliable connectivity as $a(\mathcal{G}^{(3)}) > 1$.

B. Network configuration

In this section the network configuration is optimized by assigning a subset of the PHY links to reliably connect FDs with the Gateway node. The algorithm assigns the (single or two hop) routing paths from the FDs to the Gateway in such a way to guarantee the minimal use of relays. To address practical delay (and real-time) constraints typical for industry standard applications, the maximum number of hops connecting each FDs with the Gateway is here limited to 2. The optimization approach minimizes the number of FDs connected with the Gateway throughout the relays. Position of relays is identified in Sect. 3.A. The optimization results are illustrated in Fig. 3: primary links are highlighted in solid lines while secondary (alternative) links for FDs connecting to relays are in dashed lines.

An on-site testing of the virtual network configuration should be performed by altering the position of the FDs from the nominal position and thus by measuring the potential weaknesses of the deployment.

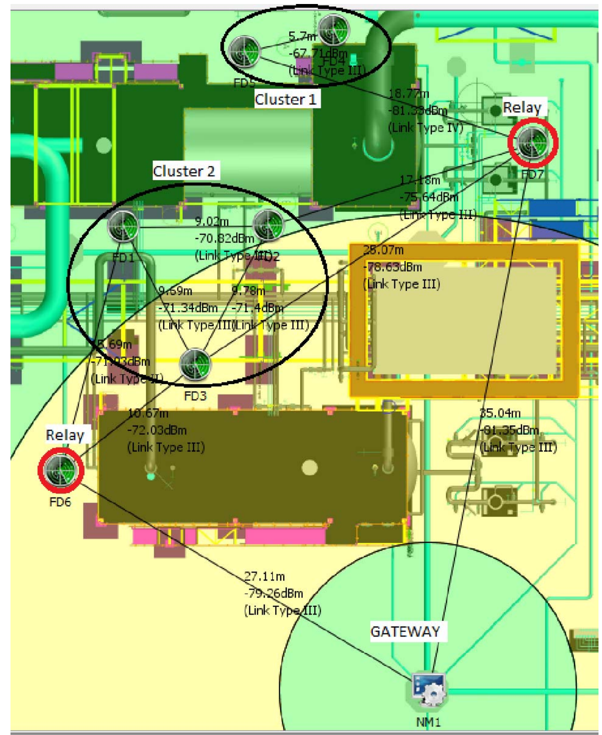

Fig. 4. Scenario where the Gateway NM1 located at 2m above ground requires two relay nodes (FD6 and FD7, see red circle markers) to achieve the full connectivity of two disconnected clusters: cluster 1: (FD1, FD2, FD3) and cluster 2: (FD4, FD5), respectively. FDs are located at ground level.

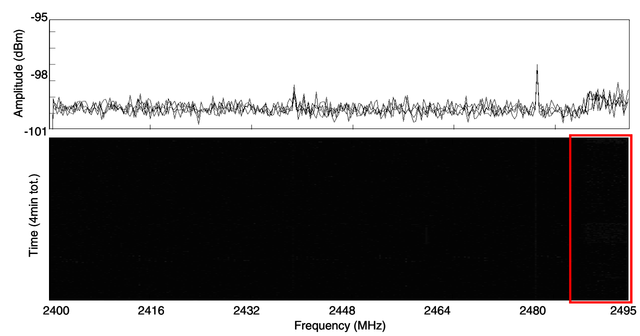

Fig. 5. Measured RF interference power spectral density (over 2400-2495MHz band) - Flare unit site.

IV. RF PROPAGATION AND DEPLOYMENT SIMULATOR

This section describes our *RF Propagation Simulator* (RFSim) created for assisting the planning of a wireless deployment within industrial environments. The aim of RFSim is to predict the quality of the RF signal along the industrial facility under consideration. This happens at the design phase of the plant, before any real equipment is physically deployed.

RFSim works as follows. In the first step, the user must import the CAD file of the industrial facility into RFSim (currently, it works with a proper file format). This file might include or not the wireless nodes that will constitute the network under design. If there are no nodes, the user must create nodes and insert them in appropriate positions of the plant. This works for the three types of nodes under consideration: Field Device (FD), Relay Node, or Gateway (Network Manager). Each node should be properly characterized, according with the parameters presented in table II. The next step is performing the simulation.

After the simulation runs, RFSim colorizes the background of the plant according to the RF quality computed during the simulation. As it can be observed in Figure 4, the simulation generates different regions of signal strength that are functions of the link types presented in table I. Besides, RFSim also plots the possible links that can be established by the simulated equipments. The link is only shown if it is considered reliable ($\gamma_\ell >$ -85*dBm*).

The simulation process takes into consideration the connectivity model of Sect. 2. As previously discussed, such model requires a link classification, which should be done using one of the five different link types summarized in table I.

A. Case study in an oil refinery site

In this section we focus on a deployment simulation carried out in the Flare unit area within an oil&gas refinery located in Italy. As shown in Fig. 5 before the test we used a 2.4GHz spectrum analyzer to detect possible co-channel interferers in the band 2.400-2495GHz. Although no RF activity was detected, the band 2.485-2495GHz is subject to a 5dB higher interference power and might cause disturbance over the IEEE 802.15.4 channel 26. The Gateway node was thus configured to operate over the channel 23 (not subject to interference), while blacklisting of channel 26 is recommended.

Figure 4 presents a simulation study from a $150m \times 50m$ oil refinery site area. In such study, the field devices (FD1 to FD5) and the Gateway (NM1) are located in pre-defined positions. The simulator was used for testing connectivity and optimize the relay placement. The example of figure 4 highlights a typical case in oil refineries where two large cylindrical vessels cause the network to be separated into disconnected (or "weakly" connected) clusters or "communities" of FDs. For all cases the FDs are deployed at ground level. In particular, the simulation results show that the field devices FD1-FD3 and FD4-FD5, respectively constitute two isolated communities that are both out of range of the Gateway. Therefore it was necessary to find appropriate positions for the relay nodes.

Relay deployment optimization addressed in section 4 is focused on "weakly" connected networks. These are defined in general as groups (or clusters) of wireless devices such that there is a higher density of edges within groups than between them. As show in figure 4, the positions of the two relays (FD6 and FD7) are optimized to connect both clusters with the Gateway. As these nodes where positioned, their links were classified according to a visual inspection of the 3D plant, following the procedure explained in the previous section. The link from node FD6 and the Gateway was classified as of Type III, while the link of FD7 was classified as of Type IV. Such deployment guaranteed that the network topology is fully-connected and that redundant paths are available. More specifically, the relay FD6 is deployed to connect cluster 2 (FD1-FD3) with the Gateway, while the relay FD7 provides two alternative routing paths for cluster 1 (FD4-FD5) by relaying data either directly to the Gateway or to cluster 2.

V. Concluding remarks and open issues

The paper presented a new approach for supporting the deployment of industrial networks, looking at oil refineries as relevant case study. An ad-hoc simulation tool named RFSim has been developed to allow the prediction of the link quality information before any real deployment is conducted. It uses as input the CAD file from the site under analysis and computes the link quality according to site-specific link types that characterize the density and the size of obstructions limiting the radio propagation.

The obtained simulation results were compared with on-site measurements and seem very confident. Based on the developed site-specific connectivity modeling, we also proposed a network optimization strategy that has been tested by simulations in an oil refinery area. The next step of this work will be to automate the node positioning process within the simulation tool. Additionally, we aim at creating an interface that allows collecting and processing on-site measurements and confront them with the simulation results.

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