2D-UBDA: A Novel 2-Dimensional Underwater WSN Barrier Deployment Algorithm

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***Abstract*—In this paper, we propose a new 2-Dimensional Underwater Barrier Deployment Algorithm (2D-UBDA) ensuring the barrier detection of toxic substances in a river. Our objective is to guarantee a full detection of chemical pollutant sources, while minimizing the deployment cost. To achieve this, first 2D-UBDA determines the potential deployment areas within a predefined target field installation and this, for each pollution source, by using a 3D-propagation model of a substance to predict its molarity in any point within the river. Then, based on an integer linear programming algorithm, 2D-UBDA selects the minimum number of sub-areas in which chemical sensors will be deployed by taking into consideration the intersections between the potential deployment zones of all pollution sources located upstream of the target field installation. To validate our proposal, the Pamplonita river located in Amazon rainforest is used as a case of study. Based on extensive simulations, 2D-UBDA outperforms the basic deployment strategies in terms of number of chemical sensors and successful detection of pollutant.**

Keywords: Underwater WSN, Barrier detection, Mixed-integer optimization.

I. Introduction

Even though "pure water is the world's first and foremost medicine[1]", more than 3.4 million people die each year from water related diseases[2]. Indeed, **UNICEF** estimates that a child dies at every 21 seconds because of a water-related illness. Unfortunately, lakes, rivers and key sources are tainted with pollution due to the lack of human awareness. Indeed, the latter use the natural reservoirs as garbage cans. In fact, various pollutants issued from sewage, wastewater and industry waste get spilled everyday into the streams and rivers. Such phenomena may be extremely harmful to people and the environment. Therefore, efficient solutions are overriding to thwart water pollution and protect the future of our kids. In this context, water monitoring plays a crucial role in the detection of water pollution. Much effort has been indeed put into building public awareness and involvement in protecting water resources around the world by engaging citizens to conduct basic monitoring of their local water bodies. However, even though such an approach appeals to common sense, it is still insufficient to detect the water pollution straightway.

This paper puts forward an innovative approach that aims to automate the water monitoring process, while ensuring a full-detection of chemical waste within a river. To do so, we propose a new 2-Dimensional (2D) underwater deployment algorithm, where underwater chemical sensors are efficiently deployed in a river forming barriers to detect the presence of toxic substances. It is worth pointing out that our research is developed within the scope of the European FP7 (i.e., 7^{th} Framework Program) "**GOLDFISH**" [1] project. The latter deals with water quality monitoring in the Amazon rainforest rivers.

As a continuation of our previous work [2], in this paper, we address the 2D barrier detection deployment problem of Chemical Sensors ($\mathcal{CS}$) within a target Field Installation ($\mathcal{FI}$). Indeed, in [2] we proposed a sub-optimal heuristic based on Backtracking algorithm, BT-FIDA. It minimizes the number of deployed geographical $\mathcal{FI}$s along a river, while ensuring the detection of a pollutant chemical substance regardless of its origin (i.e., position of pollution source). Note that each $\mathcal{FI}_i$ is responsible for the monitoring of one segment in the river located between the upstream $\mathcal{FI}_{i-1}$ and $\mathcal{FI}_i$. In fact, in [2] we assumed that each geographical $\mathcal{FI}$ ensured a barrier detection along the river width. By doing so, we did not focus on the deployment of chemical sensors within an $\mathcal{FI}$. It is straightforward to see that such an assumption is not realistic since a river is a 3-Dimension environment and the deployment is not trivial. To overcome this limitation, in this paper, we offer a new underwater sensor deployment algorithm, namely **2D-Underwater Barrier Deployment Algorithm** (2D-UBDA), based on a divide and conquer approach and an integer linear optimization. Our objective is to reduce the 2D barrier deployment cost by minimizing the number of deployed $\mathcal{CS}$s within each $\mathcal{FI}$, while guaranteeing a full-detection of any pollutant passing through the $\mathcal{FI}$ regardless of the position of pollution sources. Note that the barrier detection area is two dimensional (i.e., river's width and depth) since the position of an $\mathcal{FI}$ (i.e., river's length) is fixed by BT-FIDA. In other words, an $\mathcal{FI}$ can be seen as a wall in the river and 2D-UBDA calculates the minimal number of $\mathcal{CS}$s and their positions (i.e., width-y and depth-z) in the wall in order to ensure the full detection of pollutant.

The main idea behind our proposal is to delimit the potential geographic deployment areas for all pollution sources and take advantage of their intersections. 2D-UBDA selects the minimum number of sub-areas to deploy $\mathcal{CS}$s while covering maximum amount of pollution sources. Our proposal operates as follows. First, the positions of $\mathcal{FI}$s are calculated with BT-FIDA algorithm [2]. Then, each river branch connecting

[1]Slovakian proverb
[2]http://water.org/water-crisis/water-facts/water/

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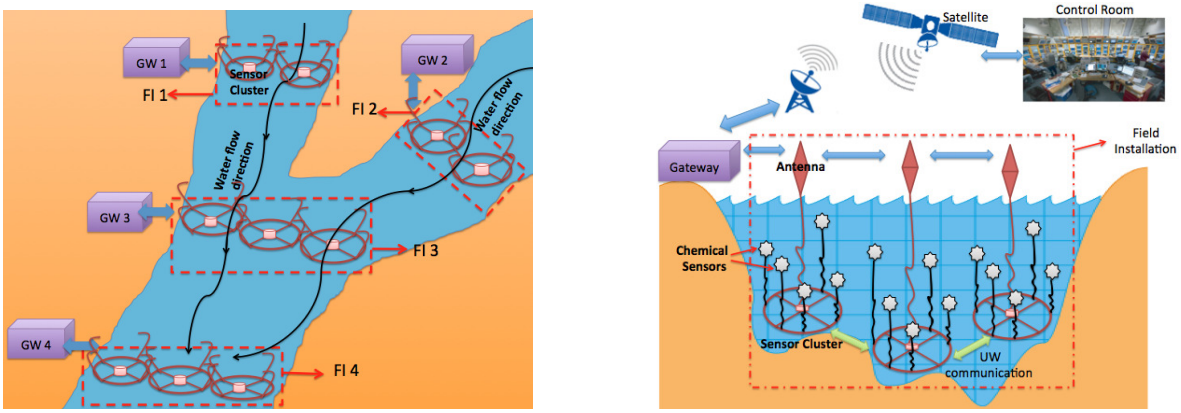


(a) $\mathcal{FI}$s deployment (b) Components of an $\mathcal{FI}$

Fig. 1. Architecture GOLDFISH water river monitoring system

two successive $\mathcal{FI}$s is subdivided into a set of equidistant points referring to the pollution sources. Afterwards, for each pollution source, a set of potential deployment areas located within an $\mathcal{FI}$ (i.e., wall) is generated thanks to the 3D substance molarity propagation model [3]. Note that the potential deployment areas are located in the vertical plane of the river, precisely located at the nearest downstream $\mathcal{FI}$. Then, an initial set including all the generated potential deployment areas and corresponding to all the potential source pollutions is generated. It is worth noting that two potential deployment areas may intercept. Hence, a second set of intersected areas is recursively generated and formed by the resulting intersection of potential deployment areas. Note that the elements of this set must be obviously disjoint. If it is not the case, the same process is recursively repeated until the latter condition is satisfied. Next, `2D-UBDA` generates the set of isolated potential deployment areas included in the initial set. Once the previous sets are generated, `2D-UBDA` handles the intersection set by selecting the minimum (i.e., optimal) number of elements while covering maximum number of pollution sources. At this stage, `2D-UBDA` makes use of an Integer Linear Programming (ILP) model. The number of selected zones will be exactly equal to the number of $\mathcal{CS}$, since only one chemical sensor is sufficient in each selected deployment area to cover its corresponding pollution sources. For those which are not covered, their potential deployment zones are necessary in the isolated set (i.e., no intersection). `2D-UBDA` browses sequentially the non-detected pollution sources and deploy **one** $\mathcal{CS}$ randomly in its corresponding potential deployment areas. To gauge the effectiveness of `2D-UBDA`, we compare it with various basic deployment algorithms: `Baseline`, `GRID`, `RANDOM` and `Grid-Uniform`. Simulation results on the Pamplonita river, located in Amazon rainforest, show that `2D-UBDA` minimizes the number of $\mathcal{CS}$s (cost) while ensuring a full detection. It is worth noting that as conceived in the FP7 GOLDFISH project, $\mathcal{CS}$s are attached to a fixed and rigid bar. The Latter is anchoring in the bottom of the river. Consequently, we can ensure that $\mathcal{CS}$s will not be impacted by the current of the river and will be located at the coordinates calculated by `2D-UBDA`.

The rest of this paper is organized as follows. The next section will describe the architecture of the river water monitoring system. In Section III, we will formulate the 2D underwater sensor barrier detection problem. Then, we will describe our proposal `2D-UBDA` in Section IV followed by a discussion of simulation results in Section V. In Section VI, we will summarize the main research papers related to the issue addressed in this paper. Finally, Section VII will conclude the paper.

II. Architecture of GOLDFISH System

As we defined in FP7 GOLDFISH project, the water river monitoring system is composed of a set of Field Installations ($\mathcal{FI}$s) deployed along the river and a set of gateways. In fact, each $\mathcal{FI}$ is associated with a single gateway deployed on a bank of the river. Hereafter, we will describe the components of the i) $\mathcal{FI}$ and ii) Gateway.

- ***Field Installation***: is formed by a set of clusters ensuring barrier detection of a river. Indeed, any chemical substance crossing the $\mathcal{FI}$ must be detected. Each cluster is composed of a set of static underwater Chemical Sensors ($\mathcal{CS}$) and one surface water wireless antenna. The set of clusters within each $\mathcal{FI}$ builds a static ad hoc network which alarms the gateway if any event is monitored. Note that a reactive or proactive routing protocol can be installed within a cluster network. Moreover, $\mathcal{CS}$ communicate with the cluster processing unit over wired cable. $\mathcal{CS}$s are attached to a fixed and rigid bar. The Latter is anchoring in the bottom of the river to the cluster processing unit.
- ***Gateway***: is a centralized node that collects all the detected events within an $\mathcal{FI}$. Moreover, it sends the detected alarms to the control room via cellular and/or satellite communication.

Fig. 1 summarizes the global architecture of the river water monitoring system and the components of an $\mathcal{FI}$.

III. Formulation of the Underwater Barrier Detection Deployment Problem

In this section, we will formulate the two dimensional underwater barrier detection deployment problem within an $\mathcal{FI}$. First, let us model the river as a volume with a 3D orthonormal coordinate system. The x, y and z-axis respectively measure the length (i.e., downstream), width (i.e., cross-stream) and depth (i.e., vertical direction) of each point in the river. It is worth noting that we address the 2D detection problem within one $\mathcal{FI}$. To be able to tackle the deployment of chemical sensors within an $\mathcal{FI}_i$, it is required that the deployment of $\mathcal{CS}$s in all the upstream $\mathcal{FI}_j$s ($1 \leq j \leq i-1$) has been done. To achieve this, we run the process through all the $\mathcal{FI}$s until we converge to the end of the river (i.e., sea or ocean). In other words, we deploy $\mathcal{CS}$s in $\mathcal{FI}$s from the top to the bottom.

Each river branch (i.e., x-axis) connecting two successive $\mathcal{FI}$s ($\mathcal{FI}_{i-1}$ and $\mathcal{FI}_i$) is subdivided into a set of equidistant points (i.e., discretized), denoted by $\mathcal{X} = \{x_i^0\}$, referring to the potential pollution sources which must be detected by the $\mathcal{CS}$s deployed in $\mathcal{FI}_i$ as illustrated in Fig. 2. Note that the deployment of $\mathcal{CS}$s within $\mathcal{FI}_{i-1}$ (i.e., upstream field installation) is done and we are handling the deployment problem within $\mathcal{FI}_i$ (i.e., downstream field installation). In order to predict the concentration level of a pollutant at $\mathcal{FI}_i$, we make use of a 3D substance molarity propagation model denoted by **Advection-Dispersion Equation** [3]. The latter model enables to estimate and predict the behavior of solutes over the river course. Formally, the concentration (i.e., molarity) of a pollutant chemical substance is equal to:

$$\mathcal{C}(x,y,z,t) = \frac{M}{(4\cdot\pi\cdot(t-t_0))^{\frac{2}{3}}\sqrt{D_x\cdot D_y\cdot D_z}} \times \exp\left[\frac{-(x-x_0-U\cdot(t-t_0))^2}{4\cdot D_x\cdot(t-t_0)} - \frac{-(y-y_0-V\cdot(t-t_0))^2}{4\cdot D_y\cdot(t-t_0)} - \frac{-(z-z_0-W\cdot(t-t_0))^2}{4\cdot D_z\cdot(t-t_0)}\right] \quad \text{(III.1)}$$

where x, y and z (unit is meter) are the coordinate of the monitoring point. We recall that x is the separating distance between the pollution source and the monitored point in the downstream, y is the cross-stream coordinate and z is the depth coordinate. t (unit is second) is the time when the level of pollutant will be monitored at point (x,y,z). M (unit is kilogram) is the mass of the contaminant. U, V and W are, respectively, the longitudinal, lateral and vertical velocity expressed in m/s. D_x, D_y and D_z are, respectively, the longitudinal, lateral and vertical dispersion coefficient expressed in m^2/s. Note that the origin of the coordinate is the target deployment field installation (i.e., $\mathcal{FI}_i$) as illustrated in Fig. 2. Note also that x_0, y_0, z_0 are the coordinates of pollution source. We respectively set y_0 and z_0 to river's width $\mathcal{Y}$ divided per 2 (i.e., centre of river) and 0 (i.e., water surface). t_0 is the time when the pollutant is spilled in the river. For simplicity, t_0 is initialized to 0.

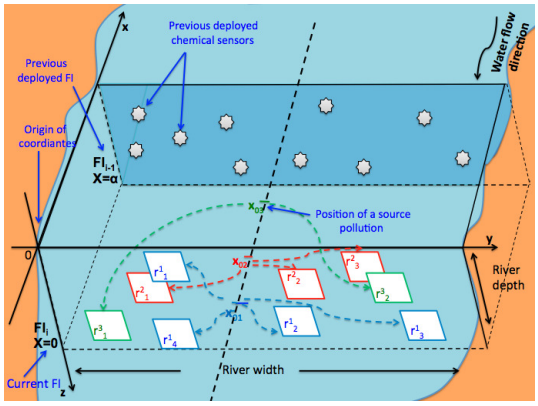


Fig. 2. 2D underwater barrier detection problem

Recall that our objective is to predict the concentration of the pollutant generated by the pollution source (x_0, y_0, z_0) when it reaches the level of $\mathcal{FI}$ (x,y,z). In other words, we evaluate the concentration of the pollutant within the Y-Z plane corresponding to $x_{\mathcal{FI}}$ since the position of the $\mathcal{FI}$ has already fixed by our previous proposal `BT-FIDA`. Since $\mathcal{FI}$ is the origin, $x_{\mathcal{FI}}$ is equal to 0. Hence, it is straightforward to see that x becomes a parameter and takes the value of 0. Moreover, based on the inputs of our partner **CapSenze** company[3] in the **FP7 GOLDFISH** project, the duration t separating the spilled instant and the detection instant ($\mathcal{T} = t - t_0$) is fixed to 3 hours. As a consequence, $\mathcal{C}(x,y,z,t)$ can be reduced to $\mathcal{C}(y,z)$ if the pollution source is fixed. Formally:

$$\mathcal{C}(y,z) = \frac{M}{(4\cdot\pi\cdot\mathcal{T})^{\frac{2}{3}}\sqrt{D_x\cdot D_y\cdot D_z}} \times \left[\frac{-(-U\cdot\mathcal{T})^2}{4\cdot D_x\cdot\mathcal{T}} - \frac{-(y-\mathcal{Y}-V\cdot\mathcal{T})^2}{4\cdot D_y\cdot\mathcal{T}} - \frac{-(z-W\cdot\mathcal{T})^2}{4\cdot D_z\cdot\mathcal{T}}\right] \quad \text{(III.2)}$$

Since the deployment of $\mathcal{CS}$s is costly in Amazon rainforest rivers, our objective is to propose a 2D (i.e., in the Y-Z plane) barrier detection deployment algorithm that minimizes the number of installed $\mathcal{CS}$s, while ensuring the full detection of the monitored upstream river's segment. In other words, we aim to find the best $\mathcal{CS}$s placement (i.e,. y and z) within an $\mathcal{FI}_i$ that minimizes the deployment cost while guaranteeing a barrier detection of all pollution sources located between the upstream of $\mathcal{FI}_i$'s river segment and the downstream of the previous $\mathcal{FI}_{i-1}$'s river segment.

To achieve our objective, we define for each pollutant source $x_i^0 \in \mathcal{X}$, a set of prominent deployment areas located within the current $\mathcal{FI}$ and denoted by $\mathcal{R}_i = \{r_j^i\}$. Note that $\mathcal{R}_i$ is generated thanks to the aforementioned 3D substance molarity propagation model (see equation III.1). Further details of $\mathcal{R}_i$'s generation will be explained in Section IV-A. For instance, in Fig. 2 the potential deployment areas $\{r_1^1, r_2^1, r_3^1, r_4^1\}$, $\{r_1^2, r_2^2, r_3^2\}$, $\{r_1^3, r_2^3\}$ respectively correspond to three pollution sources x_1^0, x_2^0 and x_3^0. In fact, to ensure the detection

[3] http://www.capsenze.se/About.html

of the pollutant substance within an $\mathcal{FI}$, the molarity of the substance must be greater than a predefined threshold ϵ_{sens}. Note that ϵ_{sens} is the detection sensitivity of the $\mathcal{CS}$ (i.e., hardware characteristic).

Let us introduce a binary variable a_j^i to indicate whether a chemical sensor $\mathcal{CS}$ is deployed in r_j^i or not. Note that j varies from 1 to $|\mathcal{R}_i|$. Hereafter, we formulate our 2D underwater barrier detection problem within a river field installation as follows:

$$\begin{aligned}
&\textbf{Minimize} && \textstyle\sum_{i=1}^{|\mathcal{X}|}\sum_{j=1}^{|\mathcal{R}_i|} a_j^i \\
&\textbf{Calculate} && \textbf{Coordinate } (y_j^i, z_j^i) \textbf{ of each } \mathcal{CS}_j^i \\
& && \textbf{within each } r_j^i \textbf{ if } a_j^i = 1 \\
&\textbf{Subject to:} && \\
& && \forall x_i^0 \in \mathcal{X} : \textstyle\sum_{j=1}^{|R_i|} a_j^i \geq 1 \\
& && a_j^i \in \{0,1\} \\
& && y_j^i, z_j^i \in \mathbb{R}
\end{aligned}$$

The first objective of the problem (i.e., **Minimize** $\sum_{i=1}^{|\mathcal{X}|}\sum_{j=1}^{|\mathcal{R}_i|} a_j^i$) formulates the cost of the deployment in term of the number of $\mathcal{CS}$s. The constraint (i.e, $\forall x_i^0 \in \mathcal{X} : \sum_{j=1}^{|R_i|} a_j^i \geq 1$) in the problem guarantees that each pollution source is covered by at least one $\mathcal{CS}$.

Our problem is a Mixed Integer Non-Linear Programming optimization problem, which has been proved to be NP-Hard [4]. To solve it, in the next section, we will propose a new 2D-Underwater Barrier Deployment Algorithm denoted by `2D-UBDA`.

IV. Proposal: 2D-Underwater Barrier Deployment Algorithm

Once the positions of $\mathcal{FI}$s are calculated thanks to our previous proposal `BT-FIDA` [2], we deal with the deployment of Chemical Sensors within each $\mathcal{FI}$ to guarantee the barrier detection (i.e., each pollutant passing through an $\mathcal{FI}$ is detected) and thus the whole river is fully covered. As stated earlier, our main objective is to find for each $\mathcal{FI}_i$ the optimal topology of $\mathcal{CS}$s which cover all pollutant sources located within the $\mathcal{FI}_i$'s upstream river segment and the $\mathcal{FI}_{i-1}$'s downstream river segment (i.e., between two successive Field Installations).

According to the problem formulated above (i.e., mixed integer optimization problem), we have to select the minimum potential deployment areas $\{r_j^i\}$ and to find the coordinates of all chemical sensors $\{y_j^i, z_j^i\}$. It is worth noting that, in order to detect the spilled pollutant for a specific pollution source x_i^0, it is sufficient to deploy **one** $\mathcal{CS}$ **anywhere** in its potential deployment areas $r_1^i, \cdots, r_n^i$. By exploiting this property, we can easily skirt the continuous variables $\{y_j^i, z_j^i\}$. The idea is to **delimit new tiny** potential deployment areas by taking advantage of $\{r_j^i\}$'s **intersections**. Hence, the problem is reduced to a minimization of the number of selected tiny potential deployment areas. In doing so, $\mathcal{CS}$s can be deployed anywhere within the latter selected areas.

Hereafter, we detail the main stages of `2D-UBDA`. First, the positions of $\mathcal{FI}$s are calculated with `BT-FIDA` strategy.

Algorithm 1: `2D-UBDA`

```
Inputs: River topology and pollution sources (X = {x_i^0})
Outputs: Final set of deployment zones (S*)
{F_i} ← BT-FIDA calculates the number and positions of FIs
S_1 ← {R_i}, generation of all potential deployment zones {r_j^i} for each pollution source x_i^0 ∈ X
(R_i = {r_j^i}, ∀i ∈ 1···|X|)
S_2 ← Recursively intersection of all potential deployment zones {r_j^i}, ∀i, ∀j
S_3 ← {R_k}, set of isolated potential deployment zones (no intersection)
S_4 ← ILP-optimization (S_1 \ S_3, S_2)
S_5 ← ∅
foreach R_k ∈ S_3 do
    S_5 ← S_5 ∪ {r_1^k}, r_1^k ∈ R_k
S* ← S_4 ∪ S_5
```

Then, the set of potential deployment zones $\mathcal{S}_1 = \{\mathcal{R}_i\}$ for each pollutant sources $x_i^0 \in \mathcal{X}$ is delimited. Afterwards, the set of disjoint intersection areas $\mathcal{S}_2$ between the aforementioned deployment zones $\{r_j^i\}$ is recursively constructed. Note that the set of potential deployment zones for a pollution source x_i^0 is $\mathcal{R}_i = \{r_j^i\}$. Next, the set of isolated deployment zones $\mathcal{S}_3$ is generated. It is formed by the potential deployment zones that do not intersect with any other areas. Thereafter, a minimum set $\mathcal{S}_4$ of selected deployment zones is built using an integer linear optimization. The latter set is increased with set $\mathcal{S}_5$ to build the final set of deployment $\mathcal{S}^*$. $\mathcal{S}_5$ contains only one potential deployment zone in each isolated element $\mathcal{R}_j \in \mathcal{S}_3$ in order to detect the sources of isolated sets. Finally, within the augmented set $\mathcal{S}^*$ only one $\mathcal{CS}$ is deployed anywhere within each element. More formally, our proposal is summarized in Algorithm 1. In the following, we will explain in depth the main `2D-UBDA` stages: i) *Generation of potential deployment zones* ii) *Construction of intersection zones*, iii) *Construction of isolated zones* and iv) *Generation of the optimal set of deployment zones*.

A. Generation of potential deployment zones

In this stage, for each pollutant source $x_i^0 \in \mathcal{X}$ located within the river's segment covered by the current $\mathcal{FI}$, we delimit the set of deployment zones candidates $\mathcal{R}_i = \{r_j^i\}$. In fact, if we deploy one $\mathcal{CS}$ within at least one r_j^i , the pollution source x_i^0 is covered. To do so, `2D-UBDA` computes for each x_i^0, the set of potential deployment areas situated at $\mathcal{FI}$ in which the pollutant's molarity is still greater than the $\mathcal{CS}$'s sensitivity ϵ_{sens}. To calculate the above areas $\{r_j^i\}$ for each pollution source x_i^0, `2D-UBDA` resolves the following inequality thanks to the **Mathematica** programming language[4]:

$$\mathcal{C}^i(y,z) \geq \epsilon_{sens} \tag{IV.3}$$

where $\mathcal{C}^i(y,z)$ is the substance propagation model calibrated with respect to the pollution source x_i^0 using equation III.2.

[4]http://www.wolfram.com/mathematica/

Algorithm 2: Generation of potential deployment zones

Inputs: $\mathcal{X} = \{x_i^0\}$, ϵ_{sense}
Output: $\mathcal{S}_1$
$\mathcal{S}_1 \leftarrow \emptyset$
foreach $x_i^0 \in \mathcal{X}$ **do**
    $\mathcal{R}_i \leftarrow \texttt{Resolve}\left(\mathcal{C}^i(y,z) \geq \epsilon_{sens}\right)$
    $\mathcal{S}_1 \leftarrow \mathcal{S}_1 \cup \mathcal{R}_i$

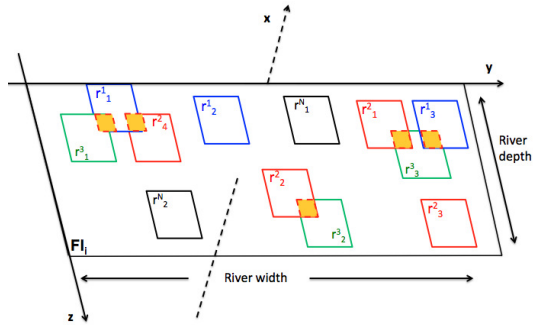


Fig. 3. 2D underwater potential deployment areas: intersection and isolated

We remind that the potential deployment areas (i.e., $\{\mathcal{R}_i\}$) are located in the vertical plane (i.e., Y, Z axis) of the current $\mathcal{FI}$. The associated pseudo-algorithm is presented in Algorithm 2.

B. Construction of intersection zones

Once the potential deployment areas are delimited, `2D-UBDA` recursively constructs a new set of deployment zones $\mathcal{S}_2 = \{m_k\}$. The latter includes all the intersection areas between all $\mathcal{R}_i$'s elements for all $\mathcal{R}_i \subset \mathcal{S}_1$. In other words, we calculate the intersection of $\{r_j^i\}$ for all i and j. Afterwards, `2D-UBDA` checks whether two elements of $\mathcal{S}_2$ containing joint areas (i.e., having intersection) exist. For instance, in Fig. 3, we notice that r_1^1 intersects with r_1^3 and r_4^2. If it is the case, the process is repeated until all the intersection areas become disjoint. The pseudo-code of this stage is summarized in Algorithm 3.

C. Construction of isolated zones

For each isolated deployment area $\mathcal{R}_k \in \mathcal{S}_3$, any potential deployment area $r_i^k \in \mathcal{R}_k$ does not intersect with any element $m_j \in \mathcal{S}_2$. Note that the set of isolated potential deployment areas is denoted by $\mathcal{S}_3$. Formally,

$$\mathcal{R}_k \in \mathcal{S}_3 \Longleftrightarrow \forall r_i^k \in \mathcal{R}_k, \forall m_j \in \mathcal{S}_2 : r_i^k \cap m_j = \emptyset \quad \text{(IV.4)}$$

That means that if we deploy $\mathcal{CS}$ in all the potential deployment areas $m_j \in \mathcal{S}_2$, the pollution sources which generate the potential deployment areas $\mathcal{R}_k \in \mathcal{S}_3$ (solving inequality IV.3) will not be detected. For instance, in Fig. 3, we notice that $\mathcal{R}_N = \{r_1^N, r_2^N\}$ does not intersect with any other potential deployment zones.

D. Generation of the optimal set of deployment zones

Finally, we generate the optimal set of deployment zones by selecting the minimum potential deployment zones $\{m_j\} \in \mathcal{S}_2$. The new optimal generated set, denoted by $\mathcal{S}_4$, is a subset of $\mathcal{S}_2$. $\mathcal{S}_4$ is calculated based on an integer linear optimization. In fact, `2D-UBDA` minimizes the cardinality of $\mathcal{S}_4$ while each pollution source x_i^0 generating potential deployment areas in $\mathcal{S}_1 \setminus \mathcal{S}_3$ (i.e., $\mathcal{S}_1$ minus $\mathcal{S}_3$) is covered. In other words, pollution sources generating potential deployment areas which intersect at least one element in $\mathcal{S}_2$ must be detected by at least one $\mathcal{CS}$ deployed in $\mathcal{S}_4$. We formulate this problem as an integer linear program as follows:

$$\begin{aligned} &\textbf{minimise} && \textstyle\sum_{j=1}^{|\mathcal{S}_2|} b_j \\ &\textbf{subject to:} && \\ &\forall\ 1 \leq i \leq |\tilde{\mathcal{X}}| && \textstyle\sum_{j=1}^{|\mathcal{S}_2|} \alpha_{ij}.b_j \geq 1 \end{aligned}$$

where $\tilde{\mathcal{X}} \subset \mathcal{X}$ referring to the set of pollution sources generating deployment areas in $\mathcal{S}_1 \setminus \mathcal{S}_3$. $\alpha_{ij} = 1$ if $m_j \in \mathcal{S}_2$ is a potential deployment zone induced by the pollution source $x_i^0 \in \tilde{\mathcal{X}}$, otherwise $\alpha_{ij} = 0$. b_j is the decision variable. $b_j = 1$ if a $\mathcal{CS}$ will be deployed in m_j, otherwise $b_j = 0$. To solve the above integer linear problem, `2D-UBDA` uses the `Branch and Bound (B&B)` algorithm [5], which ensures

Algorithm 3: Construction of intersection zones

Inputs: $\mathcal{S}_1$
Output: $\mathcal{S}_2$
$\tilde{\mathcal{S}}_2 \leftarrow \emptyset$
foreach $\mathcal{R}_i \in \mathcal{S}_1$ **do**
    foreach $r_j^i \in \mathcal{R}_i$ **do**
        $\tilde{\mathcal{S}}_2 \leftarrow \tilde{\mathcal{S}}_2 \cup \{r_j^i\}$
$\mathcal{S}_2 = \emptyset$
for $i \leftarrow 1$ *to* $|\tilde{\mathcal{S}}_2|$ **do**
    for $j \leftarrow i+1$ *to* $|\tilde{\mathcal{S}}_2|$ **do**
        $m_{tmp} \leftarrow \texttt{Intersection}\left(m_i \in \tilde{\mathcal{S}}_2, m_j \in \tilde{\mathcal{S}}_2\right)$
        $\mathcal{S}_2 \leftarrow \mathcal{S}_2 \cup \{m_{tmp}\}$
if $\mathcal{S}_2 \neq \emptyset$ **then**
    repeat
        $\mathcal{S}_{tmp} \leftarrow \emptyset$
        for $i \leftarrow 1$ *to* $|\mathcal{S}_2|$ **do**
            for $j \leftarrow i+1$ *to* $|\mathcal{S}_2|$ **do**
                $m_{tmp} \leftarrow \texttt{Intersection}\,(m_i, m_j)$
                if $m_{tmp} \neq \emptyset$ **then**
                    $\mathcal{S}_{tmp} \leftarrow \mathcal{S}_{tmp} \cup \{m_{tmp}\}$
                else
                    $\mathcal{S}_{tmp} \leftarrow \mathcal{S}_{tmp} \cup \{m_i\} \cup \{m_j\}$
        Stop $\leftarrow$ false
        if $\mathcal{S}_2 = \mathcal{S}_{tmp}$ **then**
            Stop $\leftarrow$ true
        else
            $\mathcal{S}_2 \leftarrow \mathcal{S}_{tmp}$
    until *Stop* = *true*;

the convergence to the optimal solution (i.e., the minimum deployed $\mathcal{CS}$).

Note that to cover the isolated pollution sources (i.e., $\mathcal{X} \backslash \tilde{\mathcal{X}}$), for each isolated potential deployment area $\mathcal{R}_k \in \mathcal{S}_3$, it is sufficient to select **one** potential deployment area $r_j^k \in \mathcal{R}_k$ (e.g., the first one) to deploy **one** $\mathcal{CS}$. The union of selected areas aforementioned builds the set $\mathcal{S}_5$. Formally:

$$\mathcal{S}_5 \leftarrow \{r_1^k : r_1^k \in \mathcal{R}_k \quad \text{and} \quad \mathcal{R}_k \in \mathcal{S}_3\} \tag{IV.5}$$

Hence, the final set of deployment areas $\mathcal{S}^*$, that will host chemical sensors, is equal to:

$$\mathcal{S}^* \leftarrow \mathcal{S}_4 \cup \mathcal{S}_5 \tag{IV.6}$$

The number of chemical sensors $\mathcal{CS}$s to be deployed is equal to the cardinality of $\mathcal{S}^*$. Indeed, only one sensor is sufficient to be deployed anywhere within each element of this final set $\mathcal{S}^*$ to guarantee the detection of all pollution sources $\mathcal{X}$.

V. Performance Evaluation

In this section, we evaluate the performance of `2D-UBDA`. To do so, we will first detail the simulation environment. Then, in aim to compare our proposal, we will briefly describe the following underwater barrier deployment strategies: i) Basic strategy (`Baseline`), ii) Random placement strategy (`Random`), iii) Random grid strategy (`GRID-Random`) and iv) Uniform grid strategy (`Grid-Uniform`). Afterwards, we will define the performance metrics. Finally, we will illustrate the main results obtained and will highlight the strong points of `2D-UBDA`.

A. Simulation Environment

To evaluate `2D-UBDA` in real conditions, we perform simulations within the Amazon Rainforest river in Colombia named **Pamplonita**. It has a total length of 323.838 *Km*. It is characterized by an average width Y-axis and an average depth Z-axis respectively equal to 40 m and 2 m. It is worth pointing out that the choice of the river has been made within the scope of the FP7 European Goldfish project [1]. The map of the river is illustrated in Fig. 4.

In accordance to the sensor hardware tests done by our partner CapSenze in GOLDFISH project, the sensitivity of sensors ϵ_{sense} varies in $[10^{-6}; 10^{-5}]$ mol/L. Furthermore, the distance, denoted by d_s, between two successive potential pollution sources x_i^0 and x_{i+1}^0 is set to 200 m. In other words, the river segment is discretized and each point in the segment models a pollution source. Note that the parameters of the 3D substance propagation model within Pamplonita river (see equation III.2) D_x, D_y, D_z, M, U, V and W would be provided by CapSenze. Unfortunately, they are currently under investigation and we do not have the exact values. However, the upper and lower bounds of the above parameters have been calculated based on [6] [7]. Indeed, D_x, D_y and D_z vary respectively within $[10^{-1}; 10^{4}]$, $[10^{-2}; 1]$ and $[10^{-3}; 10^{-1}]$. The velocity (i.e., U, V and W) is in the range of 1 m/s. We randomly generate the above parameters (i.e., uniform distribution) within the afforded intervals. In doing so, the number of potential deployment zones $|\mathcal{R}_i|$ of any pollutant source x_i^0 follows a discrete uniform random distribution taking values in $\{1, \cdots, 5\}$. It is worth mentioning that `2D-UBDA` is a generic algorithm and can be used for any river topology and any 3D substance propagation model.

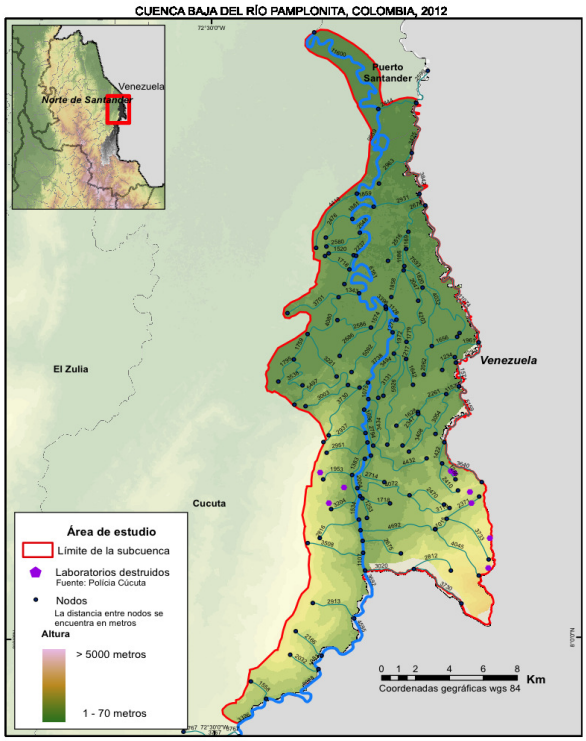


Fig. 4. Pamplonita: Amazon rainforest river map

All numerical results are calculated with confidence intervals corresponding to a confidence level of 99.7%. The number of simulations for each value is equal to 30 and tiny confidence intervals are not shown in the following figures. Simulation parameters are summarized in Table I

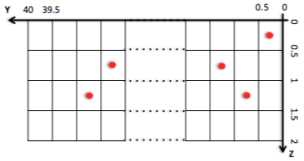
TABLE I
Simulation Parameters

ϵ_{sens} (mol/L)	d_s (m)	$\lvert\mathcal{X}\rvert$	$\lvert\mathcal{R}_i\rvert$	Y (m)	Z (m)
$[10^{-6}; 10^{-5}]$	200	30	$[1; 5]$	40	2

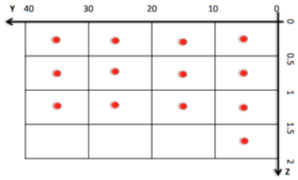
B. Deployment strategies

To gauge the effectiveness of `2D-UBDA`, we compare it with various deployment algorithms: `Baseline`, `Random`, `Grid-Random` and `Grid-Uniform`. Hereafter, we will briefly describe the related strategies.

1) `Baseline`: For each pollution source x_i^0, `Baseline` deploys one chemical sensor within its potential deployment area. The latter is selected randomly within $\mathcal{R}_i = \{r_j^i\}$ and the sensor is also randomly deployed in the selected deployment zone. It is straightforward to see that the number of deployed $\mathcal{CS}$ is linearly dependent on the number of pollutant sources (i.e., cardinality of $\mathcal{X}$).



(a) `Grid-Random`



(b) `Grid-Uniform`

Fig. 5. Grid-based deployment

2) `Random`: The main idea behind `Random` heuristic is to randomly place a fixed number of $\mathcal{CS}$s in the $\mathcal{FI}$'s Y-Z plane hoping to cover the maximum number of pollution sources $\{x_i^0\}$.

3) `Grid-Random`: As shown in Fig. 5(a), this scheme subdivides the $\mathcal{FI}$'s Y-Z plane into equal square cells (e.g., 0.5m $\times$ 0.5m). Each cell can host only one $\mathcal{CS}$ which is deployed in the cell's centre. Then, a fixed number of $\mathcal{CS}$s are randomly deployed in the squares.

4) `Grid-Uniform`: Similar to `Grid-Random` and as illustrated in Fig. 5(b), `Grid-Uniform` uniformly deploys a fixed number of $\mathcal{CS}$s within a grid. However, the latter is constructed according to the given number of chemical sensors. Indeed, the idea is to build the smallest (i.e., number of cells is very close to the number of chemical sensors to be deployed) and equilibrium grid (i.e., number of rows is very close to the number of columns). For example, if the number of $\mathcal{CS}$ is equal to 13, the grid's size is equal to 4×4.

C. Performance Metrics

The main performance metrics used to evaluate our proposal and compare it to the aforementioned deployment strategies are:

- $\mathcal{N}_{\mathcal{CS}}$: is the number of $\mathcal{CS}$s deployed within the $\mathcal{FI}$. This metric quantifies the cost of deployment.
- $\mathcal{R}_{det}$: the detection rate of the pollution sources located within the $\mathcal{FI}$'s upstream segment. This metric quantifies the quality of monitoring. Formally,

$$\mathcal{R}_{det} = \frac{\sum_{x_i^0 \in \mathcal{X}} 1_{x_i^0}}{|\mathcal{X}|} \tag{V.7}$$

note that $1_{x_i^0} = 1$ if x_i^0 is covered, otherwise $1_{x_i^0} = 0$.

D. Evaluation Results

Fig. 6 illustrates the number of pollution sources $\{x_i^0\}$ generated for each $\mathcal{FI}$ by `2D-UBDA`. We recall that based on our previous proposal `BT-FIDA` [2], the number of deployed $\mathcal{FI}$s within Pamplonita is equal to 23. Note that `2D-UBDA` is executed independently within each $\mathcal{FI}$. Hence, in order to evaluate its performance, it is sufficient to carry out the simulation within one $\mathcal{FI}$. In the following, we will test our proposal within the first Field Installation. The latter is responsible for monitoring of 30 pollution sources (i.e., cardinality of $\mathcal{X} = 30$).

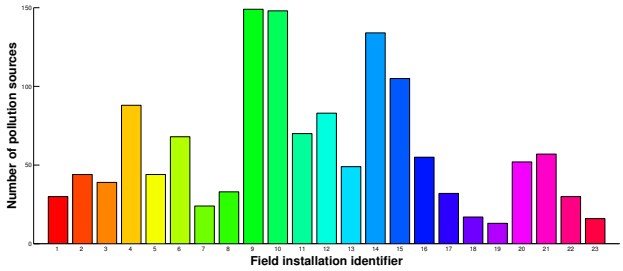


Fig. 6. Number of pollution sources ($|\mathcal{X}|$) per $\mathcal{FI}$

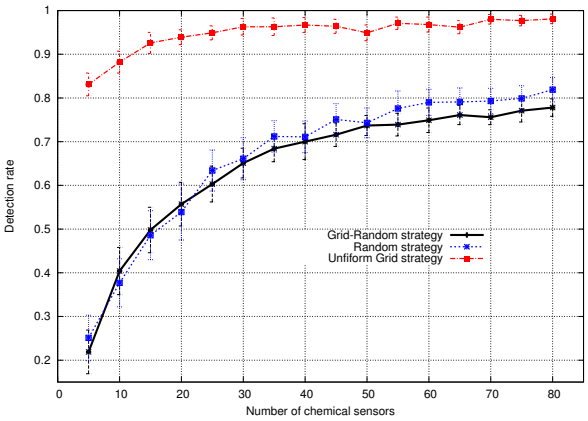


Fig. 7. $\mathcal{R}_{det}$ w.r.t the number of deployed $\mathcal{CS}$s

Our strategy `2D-UBDA` deploys only 11.1 ± 2.4 $\mathcal{CS}$s and ensures a full detection of pollution sources $\mathcal{X}$. Knowing that the number of potential pollution sources is equal to 30, we can deduce that the deployed $\mathcal{CS}$s are able to sense more than one pollution sources. In average, each $\mathcal{CS}$ monitors 3 pollution sources thanks to the judicious deployment of `2D-UBDA`. Contrary to the `Baseline` approach that deploys one $\mathcal{CS}$ for each pollution source and thus needs 30 $\mathcal{CS}$s to ensure a full-barrier detection. `2D-UBDA` optimizes the deployment of sensors by making use of the intersection zones. We can conclude that our proposal considerably reduces (i.e., divided by 3) the deployment cost.

Fig. 7 illustrates the detection rate $\mathcal{R}_{det}$ of the pollution sources according to the number of deployed $\mathcal{CS}$s. In fact, with all strategies `Grid-Uniform`, `Grid-Random` and `RANDOM`, the full detection is not reached even with 80 $\mathcal{CS}$s deployed. Indeed, the deployment of 80 chemical sensors approximately represents 8 times more than the number of $\mathcal{CS}$s deployed by `2D-UBDA` ensuring the full detection of pollution sources $\mathcal{X}$. It is straightforward to see that our proposal `2D-UBDA` deeply outperforms the Random and Grid based strategies since it reaches a full-detection with only 11.1 ± 2.4 deployed $\mathcal{CS}$s.

We can observe in Fig. 7 that `Grid-Random` and `RANDOM`

generate similar performances. This can be explained by the fact that both methods perform a random deployment within the plane Y-Z of $\mathcal{FI}$. It is worth noting that `Grid-Uniform` generates better results compared with the two former methods. Indeed, thanks to the uniform topology within the grid, chemical sensors are likely to reach more potential deployment zones $\mathcal{R}_i$s and thus cover more pollution sources $\{x_i^0\}$. We conclude that our strategy `2D-UBDA` significantly minimizes the deployment cost compared with the related deployment strategies and ensures the full monitoring of pollution sources.

VI. Related work

Wireless sensor network deployment is a challenging issue that has attracted both academia and industry. However, despite the high number of papers dealing with it, few research papers focus on underwater deployment problems. Indeed, to the best of our knowledge, there is no research paper tackling the 2D underwater barrier detection for water monitoring in rivers. In fact, we address a new concept which is the underwater barrier detection. Hereafter, we will describe the main deployment strategies dealing with barrier coverage in wireless sensor networks.

Many research papers have tackled the barrier coverage issue of terrestrial sensor networks. We notice that a barrier within a 2-dimensional target region is defined as a chain of sensors uniformly spread from one end of the strip to the opposite end. Thanks to the adjacent positions of sensors, a set of overlapping sensing zones may come out. Hence, an intruder will never be able to pass under or over such a chain without being detected. In [8], the authors prove that deploying sensors uniformly along straight lines across a given region is the easiest and the best way to establish an efficient barrier coverage. Likewise, in [9] camera sensors are deployed along a line segment to ensure full-view barrier coverage. Moreover, in order to ensure a cost-effective barrier coverage, in [10], the authors put forward mobile sensors capable of moving along a line segment. In [11], many approaches are proposed. Indeed, the idea is to make use of vehicles and aircrafts to drop a large number of sensors along predetermined routes. Unfortunately, despite the effectiveness of the aforementioned proposals, they cannot be applied in our context. In fact, our case concerns an underwater barrier detection which takes into account the molarity of the substance and not the sensing range as the barrier coverage case. Moreover, the river is a 3D environment, where the placement of sensors strongly depends on the propagation of the spill in the river. Hence, a line-based deployment is not sufficient to cover all pollutant sources.

In [12], a 2D coverage algorithm is proposed in which Voronoi diagrams were used to partition the target field into cells. Then, a genetic algorithm was applied to determine the best positions for k additional mobile nodes maximizing the area coverage inside each cell. Unfortunately, we cannot run such an algorithm in our underwater Field Installation since the positions of chemical sensors depends on the position of the pollutant source (i.e., molarity of the substance) and the objective is to ensure a full-detection. However, in [12], the placement of a sensor strongly depends on the positions of its neighbors in order to ensure full-coverage of the target area. Consequently, advanced strategies are required to define the best barrier shape that will ensure a full detection.

In this context, 3D underwater barrier coverage strategies are proposed in [13] [14] [15] where the sensing area of a sensor is formulated as a **sphere** (i.e., 3 dimensional). Moreover sensors are assumed to be mobile [14] [15] and need to move from an initially deployed position to an another one in order to construct an optimized 3D barrier coverage. Unluckily, such strategies are still inapplicable to the river environment. Indeed, in our case, the detection range of a chemical sensor is tiny and the substance must touch the sensor to be detected. In other words, we have to deploy sensors according to the mobility and molarity of pollutant in the river.

VII. Conclusion

In this paper, we studied the underwater barrier deployment problem for water pollution monitoring in a river. We proposed a new 2D Underwater Barrier Deployment heuristic named `2D-UBDA` based on Mixed Integer Non Linear Programming Optimization Problem. Based on extensive simulations within the Pamplonita river in Amazon rainforest, the results obtained show a good level of performance of our proposal compared with related strategies in terms of deployment costs and the successful detection rate of pollution in the river.

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