A Wireless Sensor Network Based Water Monitoring System

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ABSTRACT

Several water quality monitoring systems were proposed in literature. However, these systems are highly expensive and complex, offer inaccurate pollution positions, and do not perform auto-diagnosis to recover from faults and cope with the characteristics of the monitored environment. In this paper, we propose a novel water quality monitoring platform which combines Wireless Sensor Networks (WSNs) and Radio Frequency Identification (RFID) systems. In fact, the system uses a set of fixed RFID tags that are deployed next to the waterway and a set of mobile sensor nodes which integrate RFID readers. This platform can offer several enhancements in comparison to the existing water monitoring platforms such as: reduced cost, low energy consumption, scalability, system performance monitoring, and tolerance to errors and loss of information.

Categories and Subject Descriptors

C.2 [**Computer-communication networks**]: Network protocols; B.4.1 [**Input/Output and data communications**]: Data communications devices—*transmitters, receivers*

General Terms

Algorithms, Design, Performance, Theory

Keywords

Water Quality Monitoring, Waterway, WSN, RFID.

1. INTRODUCTION

To cope with the ever-growing threat of water pollution, water quality measurements should be periodically undertaken in waterways[1]. Former and classical techniques of water monitoring rely on dispatching a team of water samplers and equipping them with sample bottles and test kits. Such an approach exhibits several challenging problems. First, the team should gain access to all locations to obtain representative samples. Second, the used approach does not efficiently locate pollution nor promote a timely response in case of contamination. Third, the manual collection of data is laborious and expensive.

To cope with the above challenges a water quality monitoring system should: a) rely on the use of spatially distributed autonomous sensors to monitor water quality and collect data; b) be extensible in terms of number of sensors, rate of sampling data to collect, and sensor sensitivity; c) be able to cope with different waterways topologies; d) allow to accurately locate pollution with a low cost; and d) integrate cheap and reusable equipments.

A number of water quality monitoring systems were proposed in the literature. These systems suffer from several limitations such as: small scale of monitored areas, expensive cost and complexity, low localization accuracy, and absence of information to self-diagnosis the system performance.

In [3], Ubiquitous Water pollution Monitoring Analysis and Information Services (UWMAIS) has been provided to monitor rivers pollution. It is based on fixed stations which are costly, and require human intervention. In [1], an Autonomous Surface Vehicle (ASV), which is able to navigate throughout waterways to continuously measure and collect a range of water quality properties and greenhouse gas emissions, was proposed. Such system is equipped with a set of navigation sensors including a GPS receiver to measure and localize water quality properties. However, it exhibits low localization accuracy due to the use of GPS, and shows the absence of infrastructure for remote collection. In [7], a Mobile Agents (MAs) based river water monitoring platform has been proposed. The system is expensive as it integrates PDAs. Moreover, no technique to monitor the network state is used. A water monitoring platform allowing remote data collection using a GPRS network was proposed in [10] and [5]. However, the solution is expensive, as it uses GPRS terminals. Other proposals [8, 9, 4] relied on the use of wireless sensor networks (WSNs) using ZigBee protocol. Collected data are relayed by ZigBee nodes to the base station, which forwards them through a GPRS/CDMA network. However, as these systems use fixed sensors, a high number of nodes are required to monitor a zone, and some small scale pollutions could remain undetected.

We propose in this paper a novel water quality monitoring system, for waterways, which uses a WSN together with a Radio Frequency Identification (RFID) system. A set of mobile sensors, integrating RFID readers, are injected at the

[1]A waterway represents any navigable body of waters including such as lakes, wadis, rivers, and canals.

Q2SWinet'12, October 24–25, 2012, Paphos, Cyprus.

entrance of the waterway and collected at the embouchure. These sensors, which are moving based on the water flow transported inside the waterway, are autonomous and in charge of collecting water quality measurements. A set of RFID tags are deployed on the waterway bank to let mobile sensors determine the location of detected pollutions and forward sensitive events to subsequent sensors that will pass through the same tag. To the best of our knowledge, we are proposing the first water quality monitoring system that integrates RFID (an extensive search in the Internet did not show a significant work related to ours). It is inspired from the pipeline monitoring and maintenance system SPAMMS [6] that the authors of this paper have developed. SPAMMS can not be applied directly to monitor waterways due to the fact that waterways, differently to pipelines, exhibits irregularities (e.g., variable the water flow velocity, existence of obstacles, variable waterway depth, width, and length).

The paper contribution is four-fold. First, in comparison to existing water monitoring platforms, the system is cost effective as it uses a low number of reusable and autonomous sensor nodes, and cheap passive RFID tags. Second, the system preserves the energy of sensors, avoiding the use of low accuracy and high energy consumption positioning systems (such as GPS). In the contrary it uses powerless and passive RFID tags to estimate sensors positions. Third, the system allows to auto-diagnosis itself by generating data useful to determine the location and the rate of blocked sensors, the speed of the water flow inside the waterway per zone, and more. Fourth, the system ensures tolerance to errors and loss of information since sensors duplicate the collected data by writing them to tags so that the subsequent sensors can collect and transport them to the analysis center.

The remaining part of the paper is organized as follows. In the next section we discuss water monitoring system requirements. In Section 3, we give an overview of the system architecture and discuss the deployment scheme of RFID tags. Section 4 describes how data are organized in tags. It also describes the techniques used by sensors to locate pollution and communicate the collected information to the remaining nodes in the network. In Section 5 we describe the simulation results. Section 6 concludes the paper.

2. REQUIREMENTS FOR COST-EFFECTIVE WATER MONITORING SYSTEM

To cope with the limitations of existing approaches discussed in the last section, a WSN-based water quality monitoring system should fulfill the following requirements:

Scalability. To be able to monitor water quality in several geographic locations, the system should be designed independently of the topology and characteristics of the waterway (i.e., water level, water flow velocity, waterway maximal width and length). Even for a single waterway, these characteristics could change over time or dependently on the environmental conditions.

Cost-effectiveness. The benefits of the designed system should be carefully examined to ensure that the cost of the deployment does not exceed the expected benefits. Therefore, the system should be composed of low cost devices which are autonomous, reusable, do not execute complex algorithms, and do not lead to false decisions.

Localization accuracy. Each sensor node should locate the detected pollutions with a reasonable error. Several localization systems use to be used such as GPS. However such localization solution cannot be suggested in such type of application, since it is costly and could produce a position error of several meters.

Extensibility and customization. The system should be able to monitor a large variety of water quality parameters such as temperature, conductivity, dissolved oxygen, and turbidity. It should be easy possible to customize the system by integrating new sensors according to the used application.

Auto-diagnosis. In addition to water quality monitoring, the system should be able to track sensors trajectories so that if they are blocked, their current positions could be estimated. Sensors should not only be used to sense pollution events, but also to collect some measurements helping to determine at which extent the waterway is irregular (i.e., water stagnation, obstacles existence, variable water flow velocity).

Fault and error tolerance. The system should perform its functions despite the occurrence of errors that may happen when collecting, storing or communicating the sensed data. Since sensors could generate false positives and negatives, and since a polluted area could be traversed by several sensors, the collected data should be aggregated together and correlated to eliminate these errors. Another form of fault is related to the loss of sensors which lead to the loss of the collected information. To tolerate such error, collected information should be transported by more than one sensor.

Energy minimization. Since the proposed system is based on the use of WSNs, it should reduce energy by implementing an efficient communication approach. In this context, sensor nodes should follow sleep/wake up schedules, avoid losing energy by extensively writing and forwarding already detected events. In addition, the localization system to use should feature low energy consumption.

3. SYSTEM OVERVIEW

In this section, we will detail the architecture of the proposed system, and describe the RFID tags deployment scheme.

3.1 Architecture of the proposed system

The proposed system integrates sensing technology and RFID systems. It is mainly composed of mobile sensors nodes, and RFID readers and tags as described in Figure 1.

A set of mobile sensor nodes are injected at the entrance of a waterway, at regular interval, and collected at its mouth (i.e., the embouchure). These sensors, which are moving based on the water flow transported inside the waterway, are autonomous and in charge of acquiring water quality related measurements (e.g., pH, temperature, dissolved oxygen, turbidity). Each sensor node integrates an RFID reader to interact with tags, which are deployed on the waterway banks. Once sensors are collected the data they generates and transported are delivered to an analysis center.

The deployed tags are passive and distributed uniformly over one or two banks of the waterway (depending on its width). The distance separating every two successive tags is kept almost constant. Tags of this category (passive) are

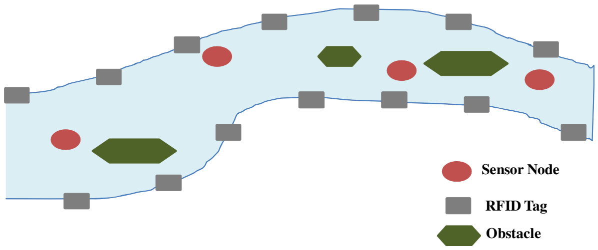

Figure 1: System architecture

cheap, small, do not use a battery, but simply draw power from the radio frequency wave transmitted by the RFID reader to power their responses by a technique known as backscattering, and are equipped with rewritable persistent storage memory. In the proposed architecture, we chose UHF tags so that the reading/writing range can reach 15 m. The RFID reader emission power is computed accordingly, so that the tag will receive enough energy to draw power and energize its circuit, and send the data stored in its memory. Thanks to their rewritable memory, these tags store data related to sensors mobility, sensitive events occurring in the waterways, pollution data collected by sensors, and tracking data useful to retrieve lost sensors. In particular:

a) Since each RFID tag has an unique identity, a sensor node locates itself with respect to the identity of the read tag. When a sensor detects a new pollution, it associates the data related to the performed measurements, to the pollution position, which is the identity of the last read tag.

b) Since a sensor could be lost or blocked within the waterway, each time it collects new pollution data it should immediately record them to the next available tag in the course of their trajectory. The subsequent sensors, passing through the same tag, will read and store these data in their internal memories to be delivered to the analysis center.

c) To be able to detect whether it is blocked or moving slowly, a sensor interrogates any RFID tag under its coverage, two times successively using the same frequency, to compute its actual speed. Based on the phase difference of the received signal, the sensor velocity with respect to the tag can be estimated [2].

d) The cost of the used sensor is typically low. However, depending on the measurements to be performed in the waterways, some probes could be expensive. Therefore, lost sensors should be located. In this context, a sensor periodically registers to selected tags that become under its coverage. Later, if it is lost, the data collected by the subsequent nodes that went across these tags, will help determining its position (such position should be typically in the vicinity of the last tag to which the lost sensor has registered). Note that a sensor is also expected to register to tags when its speed or battery energy goes under an acceptable value.

e) Due to the limited storage capacity of the passive tags deployed in the waterway, the tag memory may become quickly full, especially in locations where sensitive events happen (e.g., detection of pollution, sensors speed is slowing down). Therefore, sensors are usually required to delete data, stored in tags, that were transported enough number of times by previous sensors. In addition to deletion, a sensor should distribute data to be stored over the different deployed tags if their size exceeds the tag's free storage space. Such a feature, which will be more detailed in the subsequent sections of this paper, allows considering the set of deployed RFID tags as a distributed database, and alleviates constraints related to single tag capacity.

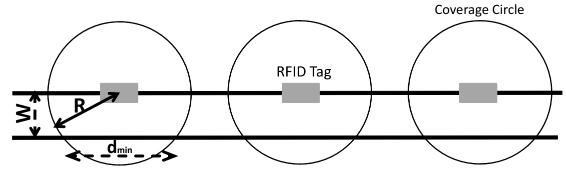

Figure 2: Tags deployment in one bank

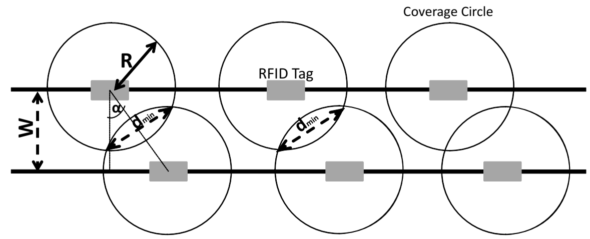

Figure 3: Tags deployed in the two banks

In the proposed system, a low number of sensors are injected to the waterway, at regular interval. Therefore, most of these sensors could not communicate together. In the other side, the tags are not only used as beacons, which simply announce their presence to the sensors, but they are also used to store sensitive information and events to be read and transported by subsequent sensor nodes.

3.2 Deploying RFID tags

The communication between sensors and tags should be periodically possible independently to the sensor trajectory. Each time a sensor passes through tag coverage, it should be able to read it twice to calculate its instantaneous speed and receive the stored content, update the tag content, and read it again to make sure that no error has occurred during writing. Therefore, the minimum period of stay of a sensor node in the coverage of a tag, say t_{stay}, is given by $t_{stay} = t_w + 3 \times t_r$, where t_w and t_r represent the period of time required by a sensor node to write and read the content of the chosen tag, respectively. Let $speed_{max}$ be the maximum speed of a sensor in the waterway (this value could be estimated in advance since it only depends on the characteristics of the waterway and the density of the sensor node), the minimum distance d_{min} that should be crossed by a sensor while being under the coverage of a tag and able to read/write to it, is given by: $d_{min} = speed_{max} \times t_{stay}$.

Depending on the width of the waterway, tags should be deployed in one or two banks. For a narrow waterway, tags could be deployed in one edge of the waterway, as shown in Figure 2. The distance d_{min} will be the intersection between the tag transmission coverage circle and the opposite bank of the waterway. Let R be the RFID writing range, the maximum width of the waterway W_{max}, which is able to support this type of tags deployment, is expressed as follows: $W_{max} = \left(R^2 - (d_{min}/2)^2\right)^{1/2}$. If the waterway wide starts to exceed W_{max}, tags should be placed in the two edges of the waterway as shown in Figure 3. Deployed tags can be directly opposite, or drifted by an angle "α". In this type of deployment, d_{min} will be equal to the maximal distance separating any two points in the zone obtained by the intersection of the coverage circles of the two opposite tags. Therefore, W_{max} will be given by: $W_{max} = 2 \times \cos(\alpha) \times \left(R^2 - (d_{min}/2)^2\right)^{1/2}$.

Deploying tags in one waterway bank reduces the number of deployed tags and decreases the deployment cost. However, tags are inexpensive devices and the lower is their reading and writing range the cheaper they will be. Moreover, by reducing the number of deployed tags, the storage capacity decreases. In addition, the larger is the distance separating the sensor node to the tag, the more will be the energy consumed by the sensor. Therefore, the deployment of tags in the two edges of the waterway can be considered as an efficient solution even if the width of the waterway is low.

Choosing the distance separating two successive tags should consider: a) The average number of events that may occur between two tags, such as pollution or obstacles. In fact, the greater is the number of events, the more memory space is required to store these events, and the more tags are required to be deployed; and b) The acceptable error of locating an occurred. As a position is an identity of the last crossed tag, the higher is the distance separating two tags, the lower will be the accuracy of the determined position.

4. STRUCTURING RFID TAGS

In this section, we describe the structure of data to be stored in tags, and detail their use by sensor nodes.

4.1 Structuring tags content

We divide the rewritable memory of each RFID tag into: the fixed sensor identification (FSID) to identify the tag, control data, history data, urgent data, and pollution data.

Size	1 byte	2 bytes	2 bytes	2 bits
Field	MSID	TS	Speed	Iter-Num

Table 1: History record

Control Data determine the state of the data blocks available in the tag. Each block is assigned one bit to identify whether it is full or empty. The length of this field is equal to the number of chosen blocks.

History Data consist of a set of records to store history information about mobile sensors. Every record, as described in Table 1, is composed of: (a) mobile sensor identification (MSID) to identify the sensor recording this data; (b) timestamp (TS) representing the time instant at which the sensor writes to the tag under its coverage; (c) the speed (Speed) to indicate the speed of a sensor node when it crosses the tag; and (d) iteration number (Iter-Num) to specify the number of times that the record was transported by previous sensors. This type of record is used by sensors to register themselves so that their positions can be easily retrieved if they are lost.

Size	1 byte	2 bytes	2 bits	2 bytes	2 bits
Field	MSID	TS	Type	Info	Iter-Num

Table 2: Urgent record

Urgent Data consist of a set of records to store distress messages. Every record, as given in table 2, is composed of a set of: (a) mobile sensor identification (MSID) to identify the sensor recording the distress message; (b) timestamp (TS) representing the instant at which the sensor writes to the tag; (c) type of the distress messages (Type) to identify the mobile sensor state (low speed, blocked, or low energy); (d) details (Info) of the distress message (e.g., current speed of sensors, remaining battery energy); and (e) iteration number (Iter-Num) to specify the number of times that the record was read and transported by previous sensors.

Size	1 byte	1 byte	2 bytes	2 bytes	2 bits
Field	MSID	Pos	TS	(T,V)	Iter-Num

Table 3: Pollution record

Pollution Data consist of a set of records to store data about the detected pollution. Every record, as given in table 3, is composed of: (a) mobile sensor identification (MSID) to identity the sensor that has detected the pollution; (b) the detected pollution position (Pos) in the form of the identity of the nearest read tag; (c) timestamp (TS) specifying the instant of pollution detection; (d) a set of pairs (T, V) to specify for every measured water quality parameter T its value V; and (e) iteration number (Iter-Num) to specify the number of times that the record was transported by sensors.

4.2 Managing tags content

Each sensor is in charge of reading data records stored in every crossed tag, and storing them in its internal memory to be delivered to the analysis center. Typically, each time it reads records in tags, it should increment their associated Iter-Num fields. However, to preserve energy, a sensor will not write to every tag after it reads it, but if it should write to a tag, it should perform all updates (registration, pollution recording, and the increment of Iter-Num fields). Therefore, the increment of the field Iter-Num will not be always performed. Consequently, its value shows the minimal number of time of reading the record by sensors.

In the other side, due to the limited storage capacity of tags, each type of data is assigned a limited number of blocks. Therefore, after a certain number of writing operations, these blocks may become full. This is especially true as a sensor could detect several new pollution events in the vicinity of a tag and needs to store them. To overcome this limitation, the sensor may overwrite the record showing an Iter-Num value higher than a predefined threshold. However, in some cases, the tag memory becomes full while the values of Iter-Num fields of stored records are lower than that threshold. Consequently, if the sensor only overwrites the record showing the highest Iter-Num field, it would decrease the system performance. Indeed, the removal of certain records, which have not been read sufficiently, may increase the likelihood of losing them, especially when the sensors transporting these records, are blocked. Therefore, it would be preferable to distribute data throughout the different tags while avoiding, to the maximal possible, the removal of data that are not sufficiently transported. To cope with this issue a set of heuristics are proposed. In the reminder of this paper, a free record will stand for any record showing an Iter-Num value higher than the predefined threshold.

4.2.1 Sensor Node Registration Heuristics

As discussed previously, the sensor registration should be based on heuristics. Two heuristics will be proposed.

H_1*: Constant Distance/Period based Registration.* The sensor registers its identity into the visible tag, either if it has already read N previous tags without modifying their content, or a predefined period, say T, has elapsed. Even if the tag memory is full, the sensor overwrites the entry having the highest iteration number and registers its identity.

H_2*: Period/Speed based Registration.* The sensor registers its identity to the visible tag, either if a predefined period of time, say T, has elapsed, or the difference δ_{speed} between the actual speed and the maximal detected speed has increased above an acceptable value. This heuristic takes into account the fact that a waterway could be irregular and sensors are operating in a harsh environment. Even if the tag memory is full, the sensor node deletes the record having the highest iteration number and registers its identity.

4.2.2 Pollution Recording Heuristics

When detecting new pollution events, in the vicinity of a tag, the sensor node decides to store them in the first available tag if they are not already stored in it. However, if the same pollution is detected in the vicinity of another tag (we remind that pollutions are mobile), the sensor node considers it as a new pollution event.

$H_1^{'}$*: continuous attempts for regular writing.* This heuristic is mainly based on recording the pollution event only when there is a memory space in the tag. Since a sensor may detect several pollution events between two tags, the number of records to store may exceed the number of free records in the tag. In that case, each time the sensor detects a new tag, it tries to store in it the maximal number of detected event (that are not already stored in any tag). The subset of pollution events to be stored is selected randomly.

$H_2^{'}$*: continuous attempts for forced writing.* This heuristic is highly similar to $H_1^{'}$ except that the sensor node may systematically overwrite records showing an Iter-Num value higher or equal to 1.

$H_3^{'}$*: periodical attempts for forced writing.* Overwriting records showing an Iter-Num value higher or equal to 1, will not be tested systematically at every crossed tag. In the contrary, the next tag to be overwritten will become far from the current sensor location as the number of writing attempts increases. The distance (as a number of tags N_{tag}) separating the current and the next tag is expressed as: $N_{tag} = ND \times N_{deletion} + rand(1, N_{deletion})$, where: a) ND represents the number of overwriting performed by the sensor, since the last regular writing; and b) $N_{deletion}$ is the minimum number of tags separating two deletions.

4.2.3 Discussing the efficiency of heuristics

Heuristics selection mainly depends on the level of expected performance. In fact, the chosen heuristic will affect:

- The occupancy rate of tags storage space: the more is the occupancy rate of storage space in deployed tags, the higher will be the rate of consumed energy.
- The degree of loss of data: the system performance decreases when the degree of loss of data increases. The lower is the number of times a record is transported by a sensor node, the higher will be the likelihood of losing information if sensors are blocked or lost.
- The deletion rate of structures whose fields Iter_Num have not reached the threshold. In fact, the probability of losing the deleted structures increases when the value of the Iter_Num field decreases.
- The determined position accuracy of blocked sensors: to locate blocked sensors, records written in the crossed tags are used. The lower is the number of records, the less accurate will be the determined position.

When retrieving sensors, the data stored in their memories will be processed. These data allow to:

- Study the existence and evolution of pollution. Based on the pollutions detection instant and positions, we can examine the pollution speed over time and determine how they spread in the waterway over time.
- Determine the waterway state, and evaluate the implemented solutions performance. For example, it is possible to determine the number of copies of a single record that reach the analysis server.
- Calculate the average flow velocity in a zone between two tags, such that each deployed tag specifies an area, based on the average speed of sensors crossing tag location which specify this area during a specified period.
- Compute the average flow velocity of water, based on the average speed of sensor nodes that have inspected the waterway during an observation period. Specify the lost sensors location, using records retrieved from tags to which these sensors registered recently.

5. SIMULATION RESULTS

In this section, we will present the simulation model in a regular waterway environment, and describe the related results. Then, we will modify the simulation model to evaluate the performance of the system in harsh conditions.

5.1 Simulation in a regular waterway

In this simulation the waterway is supposed to exhibit a very low irregularity, so that no obstacles are available, and the water flow velocity is constant.

5.1.1 Simulation Model

We consider a waterway of $8 \times 2500\, m^2$. A set of 47 RFID tags are uniformly distributed in one bank of the waterway and separated by a constant distance. The water flow speed is kept constant and equal to 1.5 m/s. Besides, we suppose that there are no obstacles throughout the waterway.

The simulated RFID system is composed of passive UHF RFID tags[2] having a read range up to 12 m, and a reader [3] characterized by a read/write range up to 100 m and a data throughput equal to 115.2 kbit/s. The tag's user memory is partitioned as follows: a) 8 bits for FSID; b) 10 bits for control data; c)168 bits for history data; d) 88 bits for urgent data; and e) 200 bits for pollution data.

[2] http://www.gaotek.com/index.php?main_page=product_info&cPath=63_122&products_id=1468

[3] http://www.gaotek.com/index.php?main_page=product_info&cPath=63_134&products_id=1456

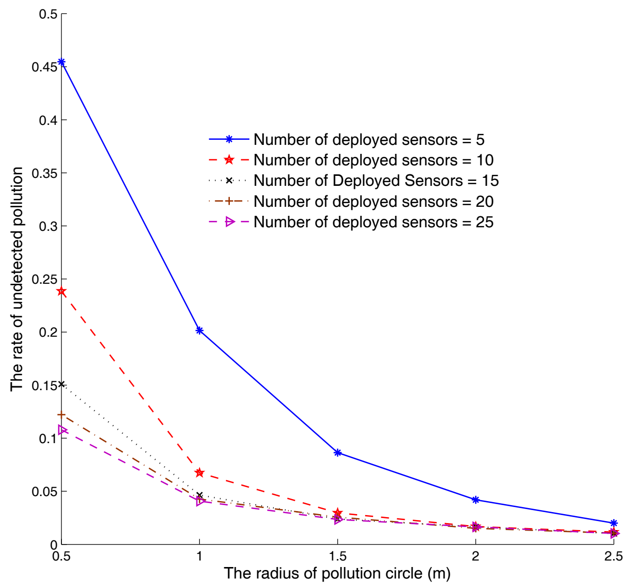

Figure 4: Variation of the rate of undetected pollutions in terms of radius of pollution circles

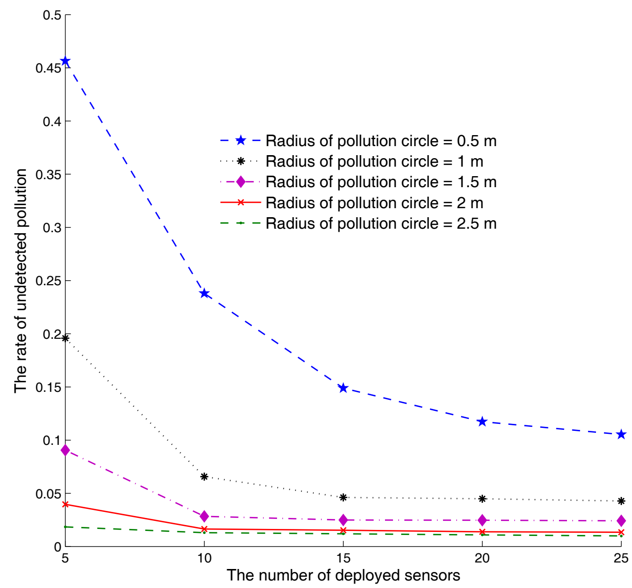

Figure 5: Variation of the Rate of undetected pollutions in terms of number of deployed sensor nodes

15 sensors are used, each one is injected every 200 time slots (a time slot is equal to 0.5 sec). Due to density difference, the speed of the sensor is set to 90% of the water flow velocity. Each time slot, the sensor selects a random direction which varies from $-\pi/3$ to $\pi/3$. Then, it moves with a fixed distance (0.675 m) according to the generated direction.

Polluted areas are simulated as circles distributed throughout the waterway, whose radius is equal to 2.5 m. The distance separating two tags is divided into space-slots of 6 m, at maximum one pollution can be generated within a space-slot, the abscissa of pollution center is in the middle of the space-slot, while the ordinate position is random. The number of pollution circles between two tags is randomly (uniform distribution) generated between 0 and the maximum number of pollutions, say Pol_{max}, given that Pol_{max} is selected between 1 and the number of space slots existing between two tags. The pollution speed varies randomly from 0 to 50% of water flow velocity. The simulation period is set to 9000 time slots.

5.1.2 Results description

We will evaluate the efficiency of our water monitoring system in terms of rate of undetected pollutions, accuracy of the detected pollution positions, and energy consumption.

Estimation of the Rate of undetected Pollution. Figure 4 illustrates the variation of the rate of undetected pollutions in terms of the radius of pollution circles. We denote by an undetected pollution a mobile pollution circle which has not been crossed by any sensor that went near the space slot where it is deployed. Five curves are depicted for a number of sensors ranging from 5 to 25. In the other side, Figure 5 illustrates the variation of the rate of undetected pollutions in terms of number of deployed sensors. Five curves are presented in the figure for a radius of pollution circles ranging from 0.5 to 2.5 m.

We deduce that the rate of undetected pollution highly decreases, when the number of deployed sensors increases, especially when the radius of pollution circles is low. In fact, the probability of crossing pollution circle of a small radius is low. So, when the number of sensors increases, the probability of crossing a pollution circle increases, and then the rate of undetected pollutions decreases. The rate of undetected pollutions slightly decreases, as the number of deployed sensors increases, especially when the radius of pollution circle is high. In fact, the probability of crossing a pollution circle by a sensor node, for a large pollution radius, is high. Moreover, even when increasing the number of sensors, the rate of undetected pollutions does not continue to decrease and does not reach zero for a high pollution radius. This is due to the fact that the position of some pollution circles is generated near the waterway bank, making the probability of detecting them very low.

Estimation of energy consumption. Let NR and NW be the number of tags reading requests, and tags writing requests, respectively, which are performed by a sensor during its movement throughout the waterway, P be the observation period, X be the quantity of energy consumed in a reading operation, which is assumed to be the quarter of the energy consumed in a writing operation. We suppose that the energy consumed during each 200 time slots is equal to the energy consumed in a reading operation. Therefore, the energy consumption $E(X,P)$ by a sensor during the observation period P may be expressed as follows: $E(X,P) = (NR + 4 \times NW + (P/200)) \times X$.

Figure 6 illustrates the variation of the average of energy consumption by sensors in terms of the distance separating two successive tags. Five curves are depicted according to the maximum number of polluted areas that could exist between two tags. The energy consumption of sensor nodes decreases with the increase of the distance that separates

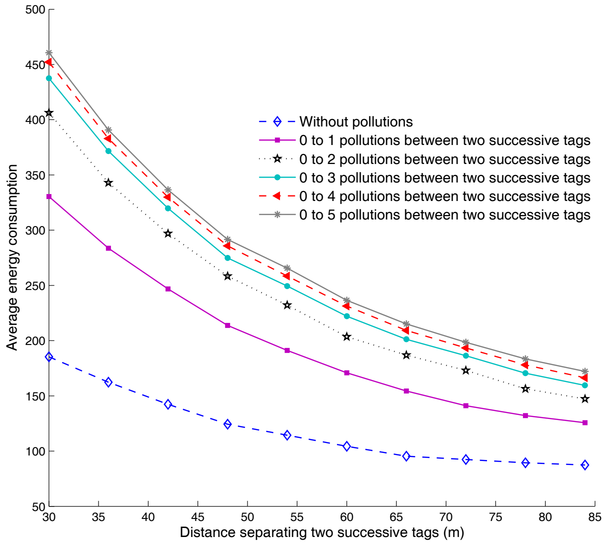

Figure 6: Variation of energy consumption in terms of distance separating two successive tags

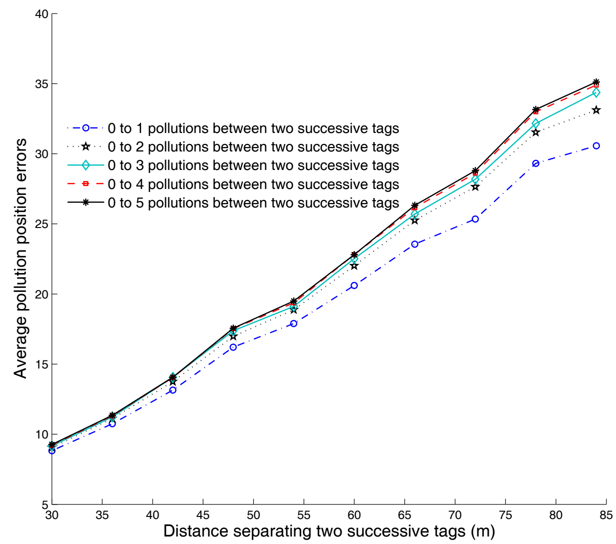

Figure 7: Variation of average pollution positions errors in terms of the distance separating two tags

two tags, since a rising of that distance leads to a diminution of the number of deployed tags. Moreover, we notice a rapid decrease of the average of energy consumption from a distance value to another, especially for a high number of pollution areas between two tags. In fact, the increase of the number of pollutions increases the number of new records to store in tags, leading to an overflow of the deployed tags.

Estimation of pollution positions errors. We denote by a pollution position error, the difference between the position of the detected pollution and the position of the referenced tag. Figure 7 illustrates the variation of the positions errors of all detected pollutions, in terms of distance separating two tags. Five curves are depicted according to the maximum number of pollutions between two tags. Based on these curves, we notice that the average of pollution position errors increases when the distance separating two tags decreases. Indeed, the greater is this distance, the more is the number of pollution circles to be placed, and then the greater is the probability that the pollution will be positioned far from the referenced tag. For the same distance separating two tags, the average of pollution position errors increases when the maximum number of pollutions between two successive tags increases. Indeed, the greater is the number of pollution circles, the more is the likelihood that the latest pollution circle will be positioned far from the referenced tag.

5.2 Simulation in an irregular waterway

We extend the simulation model of Subsection 5.1 so that the waterway irregularity is taken into consideration. We vary randomly (using a uniform distribution) the water flow from 0 to 1.5 m/s, and the sensor speed from 0 to 1.35 m/s. To implement the heuristic H_1, the two thresholds N and T are set to 5 tags, and 533 time slots, respectively. In addition, to implement the heuristic H_2 the values of T and δ_{speed} are set to 533 time slots and 1 m/s, respectively. We consider four combinations of heuristics, each one of them uses one registration heuristic together with one pollution heuristic: $(H_1, H_2^{'})$, $(H_1, H_3^{'})$, $(H_2, H_2^{'})$, and $(H_2, H_3^{'})$.

Let $\triangle N_{Writing}$ be the total number of writing requests executed by sensors on tags, divided by the number of deployed tags. Let n be the number of deployed tags, and $N_{Writing}$ be the total number of writing in tags performed by all sensors. $\sigma_{Tag-Sol}$ is expressed as follows:

$$\sigma_{Tag\_Sol} = \left(\sum_{i=1}^{n} \left(N_{Writing\ Tag[i]} / N_{Writing} - 1/n \right)^2 / n \right)^{1/2}$$

Figures 8 and 9 illustrate the variation of $\triangle N_{Writing}$ and $\sigma_{Tag-Sol}$, respectively, in terms of maximum pollution number between two tags. We can notice that $\sigma_{Tag-Sol}$ decreases, when $\triangle N_{Writing}$ increases. In fact, the higher is $\triangle N_{Writing}$, the more tags are solicited, and the lower is $\sigma_{Tag-Sol}$. In addition, when the maximum number of pollutions that separate two tags is low, we can notice that: a) the value of $\triangle N_{Writing}$ for $(H_1, H_2^{'})$ and $(H_1, H_3^{'})$, is lower than the value of$\triangle N_{Writing}$ for $(H_2, H_2^{'})$ and $(H_2, H_3^{'})$; and b) the value of $\sigma_{Tag-Sol}$ for $(H_1, H_2^{'})$ and $(H_1, H_3^{'})$ is higher than the value of $\sigma_{Tag-Sol}$ for $(H_2, H_2^{'})$ and $(H_2, H_3^{'})$.

The difference between the curves related to $(H_1, H_2^{'})$ and $(H_2, H_2^{'})$, as well as $(H_1, H_3^{'})$ and $(H_2, H_3^{'})$, depend on the variation of the sensor speed. In fact, the use of heuristic H_2 leads the sensor to register its identity before achieving the period T. Therefore, the registration of sensors will be distributed on tags according to the variation of their speed.

The two curves related to $(H_1, H_2^{'})$ and $(H_1, H_3^{'})$, as well as $(H_2, H_2^{'})$ and $(H_2, H_3^{'})$, show an overlapping when the maximum number of pollutions between two tags is low. However, we start to notice the difference between these curves, starting from a maximum number of pollutions separating two tags equal to 4. Indeed, this difference appears when a number of tags start to exhibit a storage overflow. Furthermore, when the difference between these curves appears in the two figures, we can notice that: (a) $\triangle N_{Writing}$ related to heuristic $H_2^{'}$ is lower than $\triangle N_{Writing}$ related to

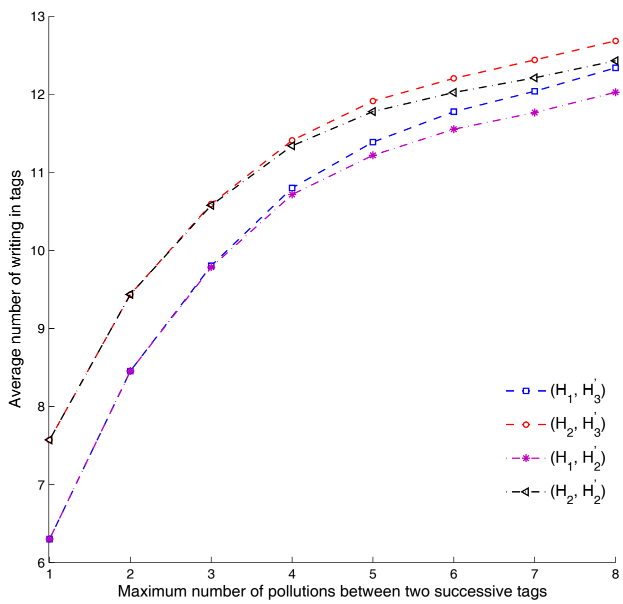

Figure 8: Variation of average number of writing in terms of maximum number of pollutions

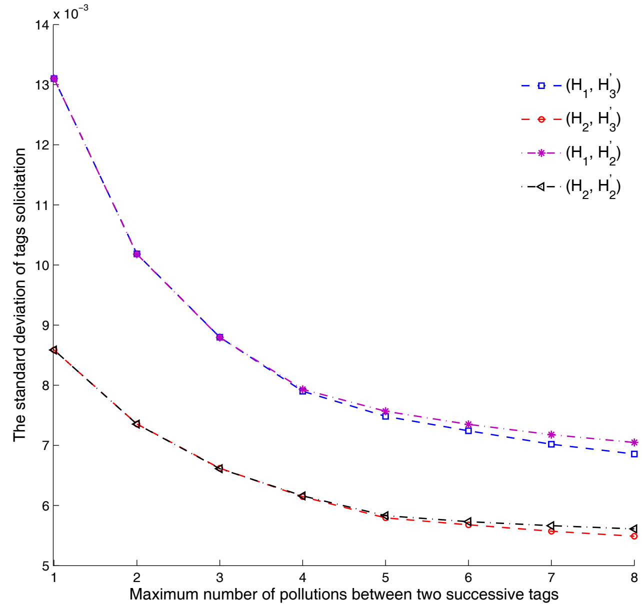

Figure 9: Variation of standard deviation of tags solicitation in terms of maximum number of pollutions

heuristic $H_3^{'}$; and (b) $\sigma_{Tag-Sol}$ related to heuristic $H_2^{'}$ is higher than $\sigma_{Tag-Sol}$ related to heuristic $H_3^{'}$. Indeed, based on $H_2^{'}$, pollution data will be recorded to tags that are in the vicinity of pollution positions. Then successive sensors, which enter the same pollution area, may detect that this pollution has been reported by previous nodes in the visible tag, and thus, they do not require reporting the event in tags another time. However, based on $H_3^{'}$, the same data pollution will be recorded several times in different tags.

6. CONCLUSION

We proposed a novel water quality monitoring system which uses a mobile WSN and an RFID system. A set of tags are deployed on the waterway banks, allowing sensors to determine the detected pollution positions, and write sensitive events. These information will be collected by subsequent nodes providing tolerance to loss of data if some sensors are blocked. The system allows to locate lost sensors, and preserve energy thanks to the use of passive tags for localization. In a future work, we propose to secure access to tags, and schedule sleep/wake-up cycles to extend sensors lifetime while guaranteeing the efficient storage of events.

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