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IMPACT OF CHANNEL ACCESS ISSUES AND PACKET LOSSES ON DISTRIBUTED OUTLIER DETECTION WITHIN WIRELESS SENSOR NETWORKS

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ABSTRACT

This work analyses the impact of channel access issues and packet losses on a distributed defective sensor detection algorithm. A theoretical analysis is performed to characterize the detection performance. Matlab simulation results for the detection algorithm are then provided. Finally, experimental results conducted on a real wireless sensor network involving the IEEE 802.15.4 standard are reported.

Index Terms—collisions, distributed outlier detection, MAC layer, outliers, wireless sensor networks.

1. INTRODUCTION

Distributed fault detection (DFD) is essential to the correct functioning of wireless sensor networks (WSN) applications [1]. A sensor is defined as faulty when it produces outliers, *i.e.*, off-scale readings which cannot be justified by the statistics of the measurement noise [2]. Outliers are harmful to the estimation accuracy of the WSN. Moreover, the transmission of the outliers among the nodes is a burden in energy-limited networks. The aim of a DFD algorithm is to identify the nodes equipped with a defective sensor that produces outliers, to the aim of removing them from the sensing operations of the WSN.

Recently, a DFD algorithm for large WSN has been proposed in [3] with a random network topology. Each node broadcasts its own local measurements to its neighbors, collects the measurements from its neighbors, and performs some *local outlier detection test* (LODT), only able to determine the *presence* of outliers in a set of measurements. The outcomes of the LODT are exchanged within the neighborhood. Finally, each node makes a decision on the status (good or defective) of its own sensor based on the results of the LODT in the whole neighborhood. The LODT considered in [3] is simple and effective even using only as few as two or three measurements. For this reasons, the DFD algorithm in [3], differently from the classical solutions, *e.g.*, [4, 5, 6, 7], does not need to manage a table of neighbors. Moreover, it has low complexity, low communication costs, low delay, and good performance in terms of non-detection rate (NDR) and false alarm rate (FAR).

The results presented in [3] assume ideal communication conditions between the nodes: collision avoidance mechanisms are ideal

and packet losses are neglected. This work proposes a modified version of the DFD algorithm introduced in [3] to take into account channel access and channel impairment issues. Considering a simple model of some collision avoidance mechanism, *e.g.*, CSMA/CA, both theoretical analysis and simulation results are presented.

Furthermore, the proposed algorithm has been implemented on the Data Sensing and Processing Testbed (DataSens), a part of the experimental facilities available within EuWiN@CNIT/Bologna. The testbed we adopted consisted of 20 or 41 wireless sensor nodes of type EMB-2530PA [8]. The TIMAC software stack [9], compliant with the IEEE 802.15.4 standard, has been used for the realization of the algorithm. The impact of the protocol stack and of real propagation conditions are investigated. The obtained results are compared with the simulation results to evaluate effectiveness of the algorithm. The proposed algorithm achieves good performance (both NDR and FAR are under 5%) within a short time (1s), even under an unstable communication environment.

2. NOTATIONS AND SYSTEM MODEL

Consider a set \mathcal{S} of $n_s = |\mathcal{S}|$ wireless sensor nodes randomly and uniformly deployed over a square of size $a \times a$ to take measurements of the same physical quantity. Let $\theta_i \in \{0, 1\}$ denote the status of the sensor of Node i . If it is defective, $\theta_i = 1$ and $\theta_i = 0$ otherwise. Define M_i as the data collected by the sensor of Node i . The statistical properties of M_i and M_j are significantly different if $\theta_i \neq \theta_j$. Introduce $\mathcal{D} = \{i \in \mathcal{S} : \theta_i = 1\}$ and $\mathcal{G} = \mathcal{S} \setminus \mathcal{D}$, representing the sets of nodes equipped with a defective sensor and with a good sensor, respectively.

Each node i collects the data produced by its neighbors, using single hop communications, to perform some local outlier detection test (LODT). Let R_i be the communication range of Node i . Ideally, R_i is a constant \bar{r} and the set of neighbors of Node i is $\mathcal{N}_i = \{j \in \mathcal{S} | 0 < r_{i,j} \leq \bar{r}\}$. In practice, R_i is random and depends on the transmission power, the receiver sensitivity, and the path loss, *etc.* In presence of some collision avoidance mechanism, some nodes may also fail to access the channel. As a consequence, during a finite time interval, Node i can only successfully receive packets from a subset $\mathcal{N}'_i \subseteq \mathcal{N}_i$ of its neighbors. Let $\mathcal{V}_i = \mathcal{N}'_i \cup \{i\}$.

The LODT of Node i is then performed based on the realization $\mathbf{m}_{\mathcal{V}_i}$ of $\mathbf{M}_{\mathcal{V}_i} = [M_j]_{j \in \mathcal{V}_i}$, with the outcome

$$y_i = \begin{cases} 1, & \text{if some outlier is detected from } \mathbf{m}_{\mathcal{V}_i}, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

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This type of LODTs is easily available, for example, in the context of bounded-error estimation [10], see Example 1.

Example 1. Consider a situation where all sensors are measuring the same scalar quantity ξ . Assume that the measurements are corrupted by an additive and bounded noise in the interval $[-\nu, \nu]$, where $\nu > 0$. In absence of outlier, each interval $[m_i] = [m_i - \nu, m_i + \nu]$ of width 2ν centered around m_i should contain ξ . Consider now the intersection of all $[m_j]$

$$\left[\widehat{\phi}(\mathbf{m}_{\mathcal{V}_i}) \right] = \bigcap_{j \in \mathcal{V}_i} [m_j], \quad (2)$$

from which one deduces a low-complexity LODT

$$Y_i = \begin{cases} 1, & \text{if } \left[\widehat{\phi}(\mathbf{M}_{\mathcal{V}_i}) \right] = \emptyset, \\ 0, & \text{else,} \end{cases} \quad (3)$$

$\Pr \{Y_i = 0\}$ depends on the number of good measurements and of outliers, *i.e.*,

$$\Pr \{Y_i = 0 \mid |\mathcal{V}_i \cap \mathcal{G}| = n_0, |\mathcal{V}_i \cap \mathcal{D}| = n_1\} = h(n_0, n_1), \quad (4)$$

where h can be shown to be a non-decreasing function of n_0 and n_1 .

3. DFD ALGORITHM

Figure 1 presents a modified version of the DFD algorithm introduced in [3]. It consists of L_1 initial rounds and L_2 final rounds. Each round ℓ involves two transmission phases of identical duration Δt indexed by $k \in \{0, 1\}$. Define $p_i^{(\ell, k)}$ as the MAC payload that needs to be transmitted during Phase k of Round ℓ .

In each round ℓ , Phase 0 is for the transmission of measurements captured by the sensor of Node i at Round ℓ , *i.e.*, $p_i^{(\ell, 0)} = m_i^{(\ell)}$, and the reception of $p_j^{(\ell, 0)}$ with $j \in \mathcal{N}_i$. Define $\mathcal{V}_i^{(\ell, k)}$ as the set of nodes which have successfully transmitted their packet to Node i (including itself) during the transmission at Phase k of Round ℓ . Based on the measurements $\mathbf{m}_i^{(\ell)} = [m_j^{(\ell)}]_{j \in \mathcal{V}_i^{(\ell, 0)}}$, the LODT can be performed using (3) with the outcome $y_i^{(\ell)}$.

Phase 1 is for the transmission by Node i of the LODT result $y_i^{(\ell)}$ as well as $\mathcal{V}_i^{(\ell, 0)}$ to indicate the other nodes which data were involved in the LODT just performed by Node i , *i.e.*, $p_i^{(\ell, 1)} = (y_i^{(\ell)}, \mathcal{V}_i^{(\ell, 0)})$. Node i also receives $p_j^{(\ell, 1)}$ from a subset of nodes $\mathcal{V}_i^{(\ell, 1)} \subseteq \mathcal{U}_i$. Denote

$$\mathcal{B}_i^{(\ell)} = \left\{ j \in \mathcal{V}_i^{(\ell, 1)} \text{ such that } i \in \mathcal{V}_j^{(\ell, 0)} \right\}. \quad (5)$$

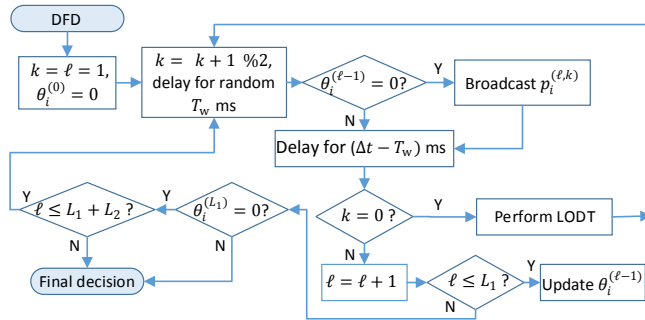


Fig. 1. DFD algorithm performed by Node i

Node i has two counters z_i and b_i , which are updated as follows

$$\begin{cases} z_i = z_i + \sum_{j \in \mathcal{B}_i^{(\ell)}} y_j^{(\ell)}, \\ b_i = b_i + \sum_{j \in \mathcal{B}_i^{(\ell)}} 1, \end{cases} \quad (6)$$

during Phase 1 of Round ℓ . Note that only LODT outcomes involving the data produced by Node i are added to z_i .

At the end of each initial Round ℓ with $\ell \leq L_1$, each node updates its estimated status $\hat{\theta}_i^{(\ell)}$ according to the values of b_i and z_i .

$$\hat{\theta}_i^{(\ell)} = \begin{cases} 1 \text{ (defective)} & \text{if } z_i = b_i, \\ 0 \text{ (good)} & \text{otherwise.} \end{cases} \quad (7)$$

Then z_i and b_i are reset to 0 at the end of the round. If $\hat{\theta}_i^{(\ell)} = 1$, then Node i remains silent during the next round, but still receives data from its neighbors to perform a LODT and has a chance to communicate again at the next rounds.

At the end of the initial rounds, the nodes with $\hat{\theta}^{(L_1)} = 1$ are finally decided as defective and stop broadcasting any packets. The nodes with $\hat{\theta}^{(L_1)} = 0$ continue during the L_2 final rounds, at the end of which a decision like (7) is taken.

To improve the probability of successful transmission, during each phase, Node i waits a random time T_w to broadcast its packet, with $\Pr \{T_w = t\} = 1/\Delta t$ for any $t \in \{1, 2, \dots, \Delta t\}$. Here Δt is an integer and the unit of time is ms. As Δt decreases, the nodes will have more difficulties to access the channel. This time constraint due to the MAC layer impacts the performance of the DFD algorithm as will be seen in what follows.

4. PERFORMANCE ANALYSIS

4.1. Assumptions

Consider an ideal situation where $\mathcal{N}_i = \{j \in \mathcal{S} \mid 0 < r_{i,j} \leq \bar{r}\}$. Then, the number of neighbors $|\mathcal{N}_i|$ of an arbitrary Node i which is not close to the boundary of the square of size $a \times a$, follows the binomial distribution

$$\Pr \{N_i = n\} = \binom{n_s - 1}{n} \bar{\lambda}^n (1 - \bar{\lambda})^{n_s - 1 - n} \quad (8)$$

with $\bar{\lambda} = \pi \bar{r}^2 / a^2$, and a^2 is the area of the whole region. Define $n_d = |\mathcal{D}|$ and $n_g = n_s - n_d$. Then the probability that Node i has n_0 nodes with good sensors and n_1 nodes with defective sensors and neighbors is

$$\begin{aligned} & \Pr \{|\mathcal{G} \cap \mathcal{N}_i| = n_0, |\mathcal{D} \cap \mathcal{N}_i| = n_1\} \\ &= \binom{n'_g}{n_0} \binom{n'_d}{n_1} \bar{\lambda}^{n_0} (1 - \bar{\lambda})^{n_s - 1 - n} = p(n_0, n_1, n'_g, n'_d, \bar{\lambda}). \end{aligned} \quad (9)$$

If $\theta_i = 0$, then $n'_g = n_g - 1$ and $n'_d = n_d$; otherwise $n'_g = n_g$ and $n'_d = n_d - 1$.

In IEEE 802.15.4 standard, the CSMA/CA mechanism is put at work by default, to avoid the collisions. The principle is to detect whether the channel is busy or idle before the transmission. If the channel is found to be busy, some back-off algorithm will take place. After a maximum number of back-offs, the node may fail to access the channel. In the proposed algorithm, each node independently choose a time index to access the channel to cooperate with the CSMA/CA. With a larger Δt , the probability of successful transmission increases, as less collisions occur.

The performance analysis of CSMA/CA is quite complicated, see, e.g., [11, 12]. Here we model the effects of the MAC layer by considering that each node successfully accesses the channel *independently* during a transmission phase with probability α_1 (Δt). The probability of successful transmission is denoted as α_2 (Δt). In general, $\alpha_1 \geq \alpha_2$. Then, due to collision, fading, and other issues, a packet might be lost with probability $\varepsilon = 1 - \alpha_2/\alpha_1$.

4.2. Average probability of detection P_D and false alarm P_{FA}

To perform the analysis of the probability of decision error after a single round of the algorithm, i.e., $\Pr\{\hat{\theta}_i^{(1)} \neq \theta_i\}$, one evaluates first $\Pr\{Y_i = 1\}$. The index of the round is removed to lighten the notations. Let $N_0^{(0)} = |\mathcal{G} \cap \mathcal{V}_i^{(0)} \setminus \{i\}|$ and $N_1^{(0)} = |\mathcal{D} \cap \mathcal{V}_i^{(0)} \setminus \{i\}|$. Similar to 9, one has

$$\Pr\{N_0^{(0)} = n_0, N_1^{(0)} = n_1\} = p(n_0, n_1, n_g', n_d', \lambda^{(0)}), \quad (10)$$

where $\lambda^{(0)} = \bar{\lambda}\alpha_2$ (Δt). From (4) and (10), one has

$$\begin{aligned} f_1(n_g, n_d, \lambda^{(0)}) &= \Pr\{Y_i = 1 \mid \theta_i = 0\} \\ &= \sum_{n_0=0}^{n_g-1} \sum_{n_1=0}^{n_d} h(n_0+1, n_1) p(n_0, n_1, n_g-1, n_d, \lambda^{(0)}), \end{aligned} \quad (11)$$

and

$$\begin{aligned} f_2(n_g, n_d, \lambda^{(0)}) &= \Pr\{Y_i = 1 \mid \theta_i = 1\} \\ &= \sum_{n_0=0}^{n_g} \sum_{n_1=0}^{n_d-1} h(n_0, n_1+1) p(n_0, n_1, n_g, n_d-1, \lambda^{(0)}). \end{aligned} \quad (12)$$

Define $N_0^{(1)} = |\mathcal{B}_i \cap \mathcal{G} \setminus \{i\}|$, $N_1^{(1)} = |\mathcal{B}_i \cap \mathcal{D} \setminus \{i\}|$. Knowing that $N_0^{(1)} = n_0$ and $N_1^{(1)} = n_1$, introduce

$$\mathcal{E}_i^{n_0, n_1} = \left\{ \frac{\sum_{j \in \mathcal{B}_i} Y_j}{n_0 + n_1 + 1} = 1 \mid N_0^{(1)} = n_0, N_1^{(1)} = n_1 \right\},$$

representing, according to (7), the event that Node i deems its sensor as defective. Thus, the conditional false alarm probability is $\tau_{FA}^{n_0, n_1} = \Pr\{\mathcal{E}_i^{n_0, n_1} \mid \theta_i = 0\}$ and the conditional detection probability is $\tau_D^{n_0, n_1} = \Pr\{\mathcal{E}_i^{n_0, n_1} \mid \theta_i = 1\}$.

Two situations need to be considered. If Node i fail to access the channel, then $\mathcal{B}_i = \{i\}$, which means $\hat{\theta}_i = Y_i$. Otherwise $N_0^{(1)}$ and $N_1^{(1)}$ follow the binomial distributions with $\lambda^{(1)} = \bar{\lambda}\alpha_3$ (Δt), where $\alpha_3 = \alpha_2^2/\alpha_1$ is the probability that Node i received a packet in Phase 1 and this packet contains a decision involving the data of Node i successfully received by this neighbor. Thus

$$\begin{aligned} P_{FA} &= \alpha_1 \sum_{n_0=0}^{n_g-1} \sum_{n_1=0}^{n_d} \tau_{FA}^{n_0, n_1} \cdot p(n_0, n_1, n_g-1, n_d, \lambda^{(1)}) \\ &\quad + (1 - \alpha_1) f_1(n_g, n_d, \lambda^{(0)}). \end{aligned} \quad (13)$$

Similarly, the average detection probability is

$$\begin{aligned} P_D &= \alpha_1 \sum_{n_0=0}^{n_g} \sum_{n_1=0}^{n_d-1} \tau_D^{n_0, n_1} \cdot p(n_0, n_1, n_g, n_d-1, \lambda^{(1)}) \\ &\quad + (1 - \alpha_1) f_2(n_g, n_d, \lambda^{(0)}). \end{aligned} \quad (14)$$

The analysis of the iterative algorithm can be found in [3].

4.3. Effects of the MAC layer on P_D and P_{FA}

This section focuses on the affects of the channel issues and packet losses on P_D and P_{FA} . Assume a perfect LODT, i.e.,

$$h(n_0, n_1) = \begin{cases} 1, & \text{if } n_1 > 0 \text{ and } n_0 + n_1 > 1, \\ 0, & \text{otherwise,} \end{cases} \quad (15)$$

which means that an outliers is detected if and only if there exists at least two data and at least one outlier in the data provided by $\mathcal{V}_i^{(0)}$. With this setting, (11) and (12) have the closed forms

$$\begin{cases} f_1(n_g, n_d, \lambda^{(0)}) = 1 - (1 - \lambda^{(0)})^{n_d}, \\ f_2(n_g, n_d, \lambda^{(0)}) = 1 - (1 - \lambda^{(0)})^{n_g-1}, \end{cases} \quad (16)$$

where $n_s = n_g + n_d$.

If $\theta_i = 1$ and $|\mathcal{B}_i| > 1$, one is sure that $Y_j = 1$ for any $j \in \mathcal{B}_i \setminus \{i\}$. Hence, the only situation to have $\hat{\theta}_i = 0$ is $|\mathcal{B}_i| = 1$ and $|\mathcal{V}_i^{(0)}| = 1$, knowing that Node i successfully accesses the channel during Phase 0. One needs to evaluate

$$\begin{aligned} &\Pr\{|\mathcal{B}_i| = 1 \text{ and } |\mathcal{V}_i^{(0)}| = 1\} \\ &= \sum_{n=0}^{n_s-1} \binom{n_s-1}{n} \bar{\lambda}^n (1 - \bar{\lambda})^{n_s-1-n} (1 - \alpha_2)^n (1 - \alpha_3)^n \\ &= (1 - (\alpha_2 + \alpha_3 - \alpha_2\alpha_3)\bar{\lambda})^{n_s-1}. \end{aligned} \quad (17)$$

Define $\alpha_4 = \alpha_2 + \alpha_3 - \alpha_2\alpha_3$, then $P_{ND} = 1 - P_D$ is

$$P_{ND} = \alpha_1 (1 - \alpha_4 \bar{\lambda})^{n_s-1} + (1 - \alpha_1) (1 - \alpha_2 \bar{\lambda})^{n_s-1}. \quad (18)$$

One may easily show that P_{ND} is a decreasing function of α_1 , α_2 , and α_3 .

In the case where $\theta_i = 0$, the probability of false alarm is more complex. Nevertheless, one has

$$P_{FA} \leq f_1(n_g, n_d, \lambda^{(0)}) = 1 - (1 - \alpha_2 \bar{\lambda})^{n_d}, \quad (19)$$

as $\mathcal{E}_i^{n_0, n_1} \subseteq \{Y_i = 1\}$. One may again easily prove that P_D and the upper bound of P_{FA} are increasing functions of α_1 , α_2 , and α_3 .

5. EXPERIMENTAL RESULTS

5.1. Impact of channel access issues

In a first set of experiments focusing on channel access issues, all the nodes are closely located and can receive packets from all other nodes. However, each node is assigned a random virtual location \mathbf{V} . Node i and Node j are virtual neighbors if $|\mathbf{V}_i - \mathbf{V}_j| \leq \bar{r}$, where \bar{r} is the virtual transmission range. \mathbf{V} is indicated in the MAC payload. Each node needs to determine whether Node i is its virtual neighbor. If $|\mathbf{V}_i - \mathbf{V}_j| > \bar{r}$, the packets received from Node i are ignored by Node j . This setting of virtual neighbors, compliant with the assumption in [3], facilitates the investigation of the impact of MAC layer. A special node, named *coordinator*, is used to manage the test procedure. At the beginning of each test, the coordinator broadcasts a start message. All the devices start then the DFD algorithm at the same time. After a desired number of independent tests, the coordinator collects the results from the other nodes.

Since all nodes have good sensors in the experiments, some nodes are manually assigned as defective, *i.e.*, their measurements are corrupted by a large constant offset. $n_s = 20$ wireless sensor nodes have been considered, among which $n_d = 3$ nodes are defective. An interesting problem is to compare the performance of algorithm with different number of initial and final rounds as a function of Δt . Independent experiments have been repeated 1000 times for each case. Figure 2 presents the experimental results performed on DATASENS platform, as well as the simulation results using Matlab. In the simulations, we set the probability of successfully accessing the channel as $\alpha_1 = \max\{1 - 0.14(n - 1), 0\}$, where n denotes the number of nodes that has chosen the same time window t_w to access the channel. With this setting, the simulation results and the experimental results are very close in terms of NDR.

For all cases, the NDR decreases as Δt increases, whereas the FAR decreases less significantly. As expected, a large Δt reduces the average number of nodes that have chosen the same t_w , and then increases α_1 . Therefore the performance of the algorithm becomes better with larger Δt . Moreover, both NDR and FAR become smaller as the number of initial rounds L_1 increases, considering the same Δt .

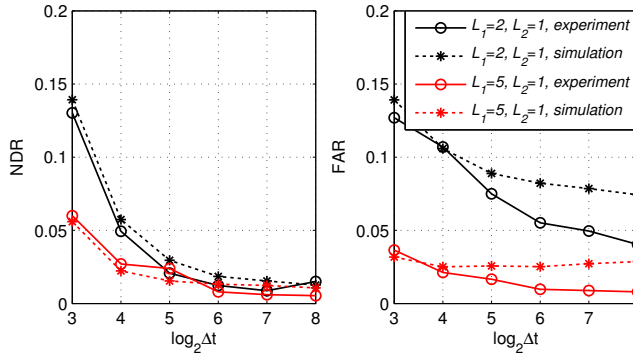


Fig. 2. Average NDR and FAR as functions of Δt for DFD algorithms with different L_1 and L_2 .

5.2. Impact of a real environment

In a second set of experiments, the DFD tests are performed in a more realistic situation where the network is not fully connected. The essential step is to properly choose the transmission power (TxP) of the nodes to have some acceptable coverage distance. The power amplifier (PA) of every device is turned off. The PA of the coordinator keeps functioning and its TxP is set to its maximum to better monitor the test procedure. Figure 3 shows the network topology where $n_s = 41$ nodes are randomly deployed over the right side of Wireless Communication Lab (Wilab) of the University of Bologna. The WSN covers an area of $15 \times 4 \text{ m}^2$. The position of nodes remains unchanged, each node has a given probability to be defective in each test. In our tests, the defective probability is set to be 15%, the DFD is performed with $L_1 = 5$ and $L_2 = 1$.

Figure 4 illustrates the average DFD performance in different areas and using different TxP, based on 1000 independent tests. The results show that the nodes in the center have lower NDR and FAR than those at sides, considering the same TxP. As is intuitive, the performance of DFD suffers from boundary affects. Three different TxP are considered with their values $P_1 > P_2 > P_3$. Comparing the average NDR and FAR of the nodes in the center, the results highlight that NDR converges faster as TxP decreases, whereas the

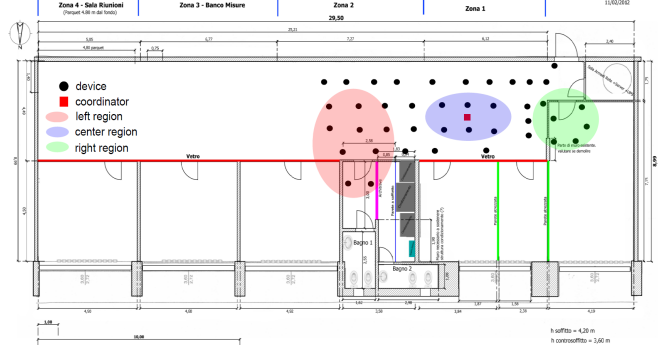


Fig. 3. Node distribution in WiLab

variation of FAR is not significant. Note that the total execution time of the algorithm is $t_e = 2\Delta t(L_1 + L_2)$. The results show that after $t_e = 2 \times 2^6 \times 6 = 768 \text{ ms}$, both NDR and FAR of the nodes in the center are less than 5%, with P_1 and P_2 .

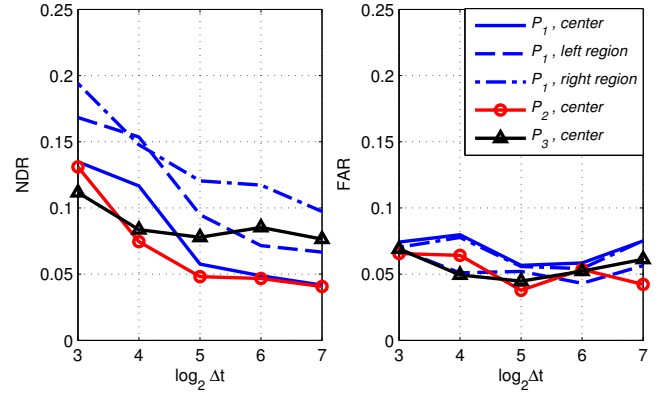


Fig. 4. Average NDR and FAR as functions of $\log_2 \Delta t$ for different transmission power and different area of the testbed.

6. CONCLUSION

This paper presents a novel distributed algorithm to detect the nodes with defective sensors. The algorithm is robust against imperfect communication conditions. Channel access issues and packet losses have been considered in the analysis and the simulations. This algorithm is also implemented on the real WSN to verify our results. The iterative algorithms with a larger L_1 achieve a better performance under the same time constraint.

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