Heuristic Channel Assignment Mechanism for WSN in Congested ISM Bands Based on QoS

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***Abstract*—Densely populated urban areas are continuously demanding an increase in the number of new services, many of them involving Wireless Sensor Networks (WSN). The dramatic increase in the use of WSN overcrowds the Industrial, Scientific and Medical (ISM) spectrum band. Parallel to this, other massive wireless devices such as local area networks (WLAN), Bluetooth, among others, occupy the same congested spectrum band. This scenario could be subject to uncontrollable levels of interference, leading to severe limitations on WSN performance. On this basis, this paper considers imperative the analysis of these types of future scenarios, under extreme capacities evaluating their operational limits, to find the appropriate mechanisms that will allow WSN to overcome urban interference restrictions. Then, under these considerations, a heuristic channel assignment mechanism with low processing levels is proposed. The heuristic mechanism substantially improves the performance of WSN under strong interferences distributing among the coordinators in the scenario, high channel capacities with a performance close to an optimum solution (developed in this work as a benchmarking solution), but well above those currently obtained by the standard channel allocation method.**

***Index Terms*—Channel assignment, congestion, ISM band, quality of service, wireless sensor networks**

I. INTRODUCTION

Recent technological advances in WSN technology [1], in conjunction with massive groups of people migrating to large cities, increase demand for new services [2], [3]. Nowadays, it is possible to have high concentrations of WSN sharing the ISM band with several other wireless systems, especially within dense urban scenarios of high buildings and multiple needs. The internet of things (IoT) [4], [5] contribute to applications employing many WSN to the planning and development of new cities [6], [7]. In this scenario, of large concentrations of wireless systems and user's demands for new services [8], there will be high band congestions and interferences among devices, such as WSN and WLAN, among others; which could be unsustainable [9], [10].

Modern cities include in their development WSN for the monitoring of many services, such as garbage collection, energy, lighting, traffic control systems, and autonomous vehicles [11], [12], among others, together with increasing demands for new wireless services [13]. In this situation, by not taking the appropriate measures, the performance of the WSN could be worse with unsustainable problems such as latencies, packet losses, decrease in the transmission rate, among others [14], [15]. Besides, these devices would be unable to properly handle larger volumes of information [16], restricting the deployment of new wireless access systems [17].

In its effort to mitigate the interference caused over the WSN, the scientific community has presented various proposals, which employ channel allocation techniques. In [18], an adaptive system was presented with the ability to observe the communication channels, and select the channel with the least interference at the node level, that is, the system can categorize and compare the 16 WSN channels in the ISM band, to choose the best. In [19], a prediction method used the statistical noise history of the channel, to predict its future behavior, thus being able to schedule the future use of free channels for the WSN. In [20], they proposed a channel change algorithm, with the help of a built-in sensor that allows interference detection, discarding the selection of interfered channels. The authors in [21] proposed and compared two algorithms, one of dynamic channel selection; and another, assisted by a spectral sensing device; the former being suitable for medium levels of congestion, while the latter performs better with higher levels of congestion.

However, given the accelerated increase in services with high spectral demand, the mentioned efforts may not be sufficient and, consequently, the devices, in the proposed scenario, could be subjected to unsustainable levels of interference [22], [23]. Unlike previous work that focused mainly on control techniques, in this article, it is a priority to obtain a certain quality of service through channel allocation mechanisms and interference control.

In this paper two contributions are presented, the first one analyzes the performance of the WSN in high interference environments, identifying the operating limits of these devices working uncontrollably in the ISM band. The second contribution is a heuristic proposal that considers operational characteristic parameters for the WSN, providing excellent results that require few computational resources to maintain a certain quality of service in the WSN.

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As benchmarking, an optimun solution representing the optimal solution achievable was developed, based on a modified simulated annealing (SA) algorithm [24].

This paper is organized as follows. Section II presents the system model employed to analyze WSN in congested scenarios, including spectrum characterization and performance metrics. The analysis of the behavior of WSN in congested ISM bands is covered in section III. The benchmarking and heuristic allocation mechanisms are presented in Section IV. In Section V, the performance of the proposed algorithms is evaluated. Finally, Conclusions and possible new lines of research are presented.

II. System Model

A. Scenario Description

In order to analyze the performance of the WSN, it is necessary to model an appropriate scenario, which allows the addition of other devices. WSN will be under various levels of interference from both other WSN and other systems like WLAN.

The proposed scenario consists of a modern urban area containing several apartments inside two blocks of buildings separated by a central street, as shown in Fig. 1. This scenario was selected, since it serves for the representation of a very high interference density, due to the possibility of containing the massive presence of access points (APs) and WSN devices. On the central street of the scenario, multiple sensors in a star topology are deployed, composed of a coordinator (C), to which its different sensors (S) are linked. Note that, at a transmission instant, only one sensor sends information to its respective coordinator. This instantaneous situation is being represented as a picture or snapshot, shown in the indicated figure, as a sensor-coordinator pair (S→C). Each sensor-coordinator pair maintains a separation distance r, besides the width and length of the street, are represented by a_1 and a_2, respectively.

WLAN are deployed in infrastructure topology inside each apartment, allowing APs to provide wireless access. A triangle within each apartment represents an AP. The buildings have the following dimensions height b_1, length b_2, and width b_3.

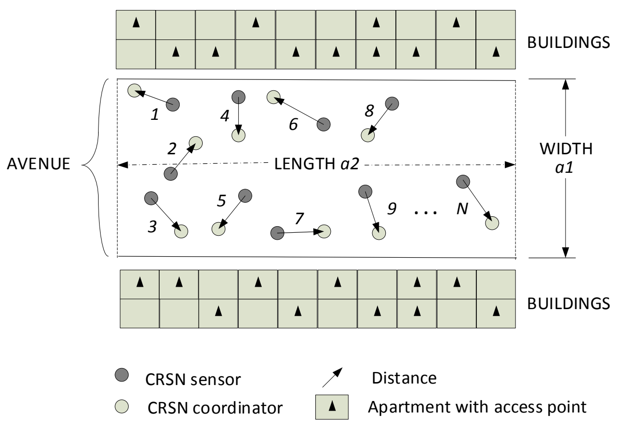

Fig. 1. Proposed WSN scenario, top view.

B. Spectrum Characterization

In an urban scenario like the one described above, the deployed WSN and WLAN share the same operating band (ISM), so that the WSN could be subject to interference, either from other WSN or from the WLAN. In the case of interference from other WSN, these are caused by co-channel interference from other nearby WSN, since, depending on the number of devices deployed, channel reuse would be necessary. A WLAN channel, depending on its location, can completely overlap several WSN channels. For example, WLAN channel 9 overlaps WSN channels 19, 20, 21 and 22 [14]. WSN channels have a bandwidth BW_z, and separation between center frequencies of Δf_z. On the other hand, WLAN channels used by the APs have a bandwidth BW_w and separation between center frequencies of Δf_w.

C. Performance Metrics

In this paper, the performance of the WSN is mainly given by the channel capacity that the coordinators can establish with their sensors [25]. In this sense, the channel capacity of any coordinator C_i can be calculated using the following expression:

$$\mathrm{CC}_i = B\log_2\left(1+\mathrm{SINR}_i\right) \tag{1}$$

where CC_i represents the channel capacity of the coordinator C_i, in bps; B is the bandwidth in Hertz; and, SINR_i represents the signal to noise ratio plus interference measured in the coordinator C_i; and, it is calculated as follows [26]:

$$\mathrm{SINR}_i = \frac{P^r_{S_iC_i}}{\sum_{j=1,j\neq i}^{N} I_{S_jC_i} + \sum_{l=1}^{K} I_{\mathrm{AP}_lC_i} + \mathrm{Noise}} \tag{2}$$

where $P^r_{S_iC_i}$ is the power received in the coordinator C_i from the sensor S_i, as can be seen in Fig. 2. Factor $\sum_{j=1,j\neq i}^{N} I_{S_jC_i}$ represents interference from other sensors $S_{j,j\neq i}$; and $\sum_{l=1}^{K} I_{\mathrm{AP}_lC_i}$ corresponds to the interference that comes from the APs. These cases of interference were already indicated in the previous section. Finally, the term noise represents the noise floor in the receiver.

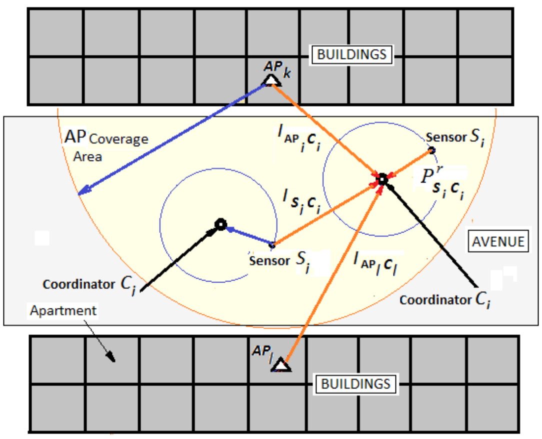

Fig. 2. Interference on a coordinator sensor pair.

Another metric used to measure the performance of the WSN in the proposed scenario is the feasibility, this is to determine the percentage of WSN coordinator devices deployed in the scenario, which can match or exceed a previously established threshold. The feasibility is given as a percentage value and calculated as follows:

$$F(\%) = \frac{\text{Coordinators with } \mathrm{CC}_i > \mathrm{CC}_{\mathrm{th}}}{\text{Total Number of Coordinators}} 100 \qquad (3)$$

III. Performance Analysis of WSN in ISM Congested Bands

To analyze the performance of WSN uniform deployments of WSN were made on the central street of the proposed scenario, and WLAN devices were represented by APs placed inside each apartment of the side buildings. Each floor containing APs could be enabled or disabled, to allow various levels of interference on the WSN.

Before starting with the indicated analysis it is necessary to know the parameters of the scenario for WSN devices and APs of the 2.4 GHz ISM band, which are: a_1=5 m; a_2=15 m; b_1=10 m; b_2=15 m; b_3=10 m; $\mathrm{PIRE}_{\mathrm{WSN}}$=10 dBm; BW_z=2 MHz; Δf_z=5 MHz; BW_w=22 MHz; Δf_w=5 MHz; Noise Floor=–120 dBm, $\mathrm{PIRE}_{\mathrm{APs}}$=30 dBm. They were used in simulations performed using MatLab software, on computers with Intel Core I7 3.4GHz processor and 8 GB of RAM.

In Fig. 3 (a) channel capacity vs number of sensor pairs is shown, and the following cases are observed: first, the least restrictive case of interference is when WSN are subjected only to co-channel interference between them, a situation shown by the CC_WSN curve; the second case is when the interference from the APs located on the ground floor of the buildings is added to the co-channel interference, which is shown by the CC_WSN AP+1 curve. Finally, the most restrictive level is when the co-channel interference of the WSN, is additionally affected by the interference from the APs of the first and second floor, situation signaled by the CC_WSN AP+2 curve.

The impact of these interferences is visible in the same figure since as the number of sensors on the stage increases, a noticeable decrease in the average channel capacity for the three indicated cases is observed. Thus, for example, for CC-WSN, it can be seen that, by increasing from 10 to 50 pairs of sensors on stage, the channel capacity is reduced by about 48.39%. On the other hand, it is possible to observe that the influence of the APs of the first floor (CC_WSN AP+1) is decisive in the calculation of the channel capacity. APs at street level, cause greater interference on WSN than those on the first floor, because of their proximity.

It is possible to observe that the effect caused by the APs located on the second-floor decrease channel capacity in a very small amount when compared to affectation caused by those on the ground and first floor. Since APs on the second floor (CC_WSN AP+2) are farther away than those on the first floor, their propagation losses are greater, resulting in considerable interference reductions when compared to that one caused by APs of the first or ground floors, on the WSN.

In Fig. 3 (b) Feasibility vs Number of Sensor Pairs is shown. The concept of feasibility defined in (3) and it is used to highlight the percentage of WSN that equal or exceed a threshold $\mathrm{CC}_{\mathrm{th}}$=250 Kbps. The feasibility has been calculated, for the three indicated interference cases, considering increasing amounts of sensor pairs deployed on each case.

The same graph shows that with the presence of only co-channel interference (CC_WSN) considering 10 sensors pairs in the scenario, approximately 90% of the sensors reach a channel capacity greater than 250 Kbps, which is to say, that their feasibility at this point is 90%. However, as the number of sensor pairs increases, a drastic decrease in the feasibility is obtained. Observing that with 20 pairs of sensors, the feasibility percentage decreases to 80%, meaning that 20% of the devices do not operate correctly. While, in the case of 80 pairs of sensors, the feasibility falls to an unfeasible value of 45%.

By including interference from APs placed on both the first (CC_WSN AP+1) and the second floor of the scenario (CC_WSN AP+2), the feasibility suffers an additional deterioration of approximately 10%, reaching 80% feasibility for 10 pair of sensors, and 37% for 80 pairs. Noting in the graph, a marginal affectation caused by additional APs placed on the second floor of the buildings observing the WSN AP+1 and the WSN AP+2 curves, with a small difference between them.

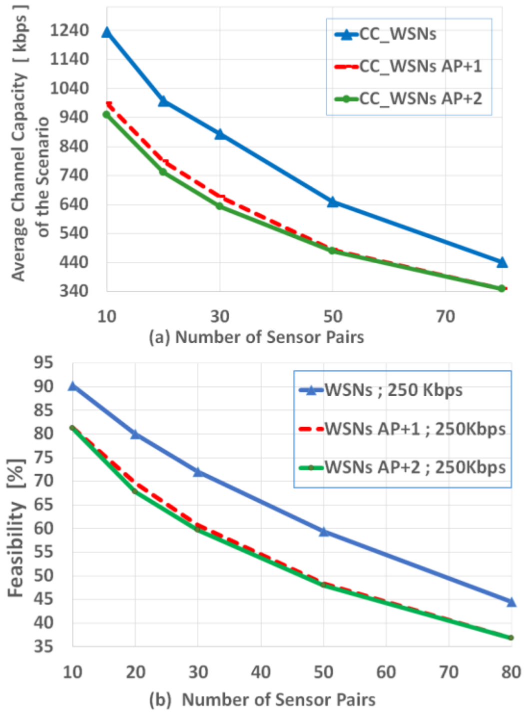

Fig. 3. The performance of WSN vs number of sensor pairs: (a) Channel capacity for different levels of interference and (b) feasibility for $\mathrm{CC}_{\mathrm{th}}$=250 Kbps.

The result of this analysis demonstrates that, without channel allocation mechanisms, the performance of the WSN is reduced drastically as the number of sensor pairs increases producing uncontrolled increments of interference. Considering 80% feasibility as an acceptable performance for a certain threshold, with no channel assignment mechanisms, WSN are limited to a maximum of 20 pairs of sensors in the proposed scenario. Constituting a strong restriction on the growth of the WSN and reaffirming the fact that the development and use of channel allocation mechanisms to mitigate the effects of interference is imperative.

IV. Channel Assignment Mechanisms

A. Mathematical Formulation

The set of values $C=\{C_1, C_2, \cdots, C_N,\}$ represents N pair of sensors with $C_i \forall i \in (1,\ 2,\ \cdots,\ N)$. The set of values AP={AP$_1$, AP$_2$, AP$_3$, ···, AP$_K$} represents K APs with $\mathrm{AP}_l \forall l \in (1, 2, \cdots, K)$. The set of values CC={CC$_1$, CC$_2$, ···, CC$_N$} represents N coordinators with $\mathrm{CC}_i \forall i \in (1,\ 2,\ \cdots,\ N)$. The set of values Ch=(Ch$_1$, Ch$_2$,···, Ch$_M$) represents N available channels with $\mathrm{Ch}_j \forall j \in (1,\ 2,\ \cdots,\ M)$

The recommended mechanisms compare their channel capacity, calculated with (2), with the previously defined CC$_{\mathrm{th}}$, to determine the feasible devices by using (3), that is, the percentage of those that do comply with the restriction imposed by the said threshold.

With this formulation, it is possible to select a utility function that allows the performance evaluation of the channel capacity of each coordinator expressed by [27]

$$u_{i,j} = \begin{cases} 1-(1-q)e^{-S(\mathrm{CC}_{i,j}-\mathrm{CC}_{\mathrm{th}})}, & \mathrm{CC}_{i,j} > \mathrm{CC}_{\mathrm{th}} \\ qe^{-S(\mathrm{CC}_{i,j}-\mathrm{CC}_{\mathrm{th}})}, & \text{other case} \end{cases} \tag{4}$$

This equation is a sigmoid function with values between zero and one, which compares channel capacity values used with the threshold CC$_{\mathrm{th}}$ and transforms them into utility values, that could be greater than 0.5 and less than 1 for coordinators exceeding CC$_{\mathrm{th}}$, and into lower 0.5 values greater than −1 when they are below the threshold. In case of coincidence with the threshold, it receives a value of 0.5. Thus, $u_{i,j}$ indicates the utility of coordinator i working on channel j; CC$_{i,j}$ is the channel capacity of coordinator i working on channel j; CC$_{\mathrm{th}}$ is the threshold channel capacity; q is a variable equivalent to the threshold, and S is the slope of the sigmoid.

After finding the utility that each coordinator has, using the assigned channels, it is necessary to obtain the performance of all coordinators. For this, the total sum of the U_T utilities of each coordinator is carried out in the selected operation channel:

$$U_T = \sum_{\mathrm{i}=1}^{\mathrm{N}} u_{i,j} \tag{5}$$

The representation of the overall performance of the sensor network is the value that must be maximized (6) to obtain the appropriate allocation that allows reaching the largest possible number of coordinators above the threshold:

$$\max U_T \tag{6}$$

s.t.

a) Coordinators C_i can make use of one WSN cannel at the time.

b) Access points AP$_l$, can make use of one WLAN cannel at the time.

B. Description of the Optimum Solution Mechanism Used as Benchmarking

The optimum solution was developed from a centralized mechanism based on a modified SA technic. On each iteration, the algorithm tries to approach the optimal result, in such a way that the larger the number of iterations, the closer to the optimum it will be. The solutions used in this work as benchmarking were obtained for 30,000.00 iterations.

Once the algorithm is tuned defining the parameters necessary for optimal results (T_o, CR, $\in$), it is loaded into a central entity that is responsible for executing it periodically, allowing each coordinator to choose their optimal operating channel through an iterative process, which uses the utility function defined in (4). All this with the ultimate goal of maximizing the total sum of profits and reaching the highest channel capacities for all coordinators in the network.

Data: Temperature To, CR, $\in$, C_i, $N_{\max}$, $T_{\min}$, Ch$_j$

Results: $\max\left[\sum_{i=1}^{N} u_{i,j}\right]$

1. Select $T=T_o$, CR, $\in$, C_i, $N_{i,\max}$, $T_{\min}$
2. Starting with i=1
3. **while** Stop criteria not reached Verify
 ; If $N_{\max}$, $T_{\min}$ or convergence is reached
4. C_i; Coordinador i is chosen
5. Obtain a new **candidate channel** j: for $C_{i,j}$
6. Compute $\delta=U(i)-U(j)$
7. **if** $\delta<0$ **then**
8. $i=j$
9. **elseif** $\delta>0$
10. **if** random $[0,1] \le e^{-(\delta T)}$ then
11. $i=j$
12. **end** (10)
13. **elseif** $\delta=0$ **then**
14. **if** random $[0,1] \le e^{-(\in/T)}$ then
15. $i=j$
16. **end** (14)
17. **end** (7)
18. Add $C_{i,j}$ to results matrix
19. Update T=CR·T and number of iterations N_i
20. **If** $i=N$ **then**
21. $i=1$
22. **end** (20)
23. **end** (3)

Fig. 4. Pseudocode for the OPTIMUM Mechanism used as benchmarking.

The pseudocode for this algorithm is shown in Fig. 4 and works as follows: for each C_i coordinator, an initial random channel assignment selection is made selecting initial operational channels. In addition, some SA parameters are established, such as the temperature T at initial value T_0, which decreases with each iteration, reducing the probability of a channel change; the cooling rate CR, which is a factor used to reduce the temperature during each iteration; and, the predefined constant $\in$ that is used for probabilistic channel selection (line: 1). Then, the application of the algorithm in coordinator 1 (line: 2) is initialized. The algorithm begins to run iteratively using a while loop, in which several stop criteria are evaluated, such as $T_{\min}$, which is the minimum temperature that can be reached; $N_{\max}$, which is the maximum number of iterations attainable; or, when the convergence value Q is reached (line: 3). Coordinator C_i is chosen (line: 4). At this moment the process of selecting a new operating channel j begins, and it is known as the candidate channel (line: 5).

For the election of the candidate channel of the selected coordinator, the utilities produced with each of the available channels are evaluated; while the rest of the coordinators maintain their initial operational channels; proceeding later, to the evaluation of the utility sum corresponding to each channel. With these summations of utilities, a probabilistic selection of a utility value is made that will correspond to an operation channel that will be the selected candidate channel; then continue with the next step of the algorithm.

In the next step, the decision to maintain the current channel or to change to a new candidate channel depends on a comparison of the utilities obtained with the new channel. So, if $U(i)$ is its utility using the current channels i and $U(j)$, the utility with the new channel j; the new channel will be accepted, provided that $\delta = U(i) - U(j) < 0$ (line: 6-8). However, if, the candidate channel decreases the value of the utility, it can be accepted, with a probability that depends on the magnitude of the change and the operating temperature T. The mentioned probability is given by $P^r[\delta, T] = e^{-\delta T}$ (line: 9-12). On the other hand, if the utilities are equal, the change will be accepted with a probability that depends on the predefined constant $\in$ and the temperature T, $P^r[\in, T] = e^{-\in/T}$ (line: 13-16).

Otherwise, if neither of the last two conditions is true, the algorithm does not accept the candidate channel. Once the decision about the new channel is taken, matrix $C_{i,j}$ updates its values keeping the channel assignments j for each C_i coordinator (line: 18). The cooling rate factor CR is used to multiply the temperature T of the algorithm, such that its value decreases at each iteration while decreasing the probability of acceptance of a new channel (line: 19). The repetition of the operations that began with the while loop will continue until all N coordinators obtain a channel assignment. It is clear that, through this stochastic process, the algorithm avoids getting caught in a local optimum (lines: 20-22). The end code, in the last line, closes the while cycle (line: 23).

C. Description of the Proposed Heuristic Solution Mechanism

The pseudocode used for the proposed heuristic mechanism, which we call Max, is expressed in Fig. 5. This mechanism is based on the "Best First" algorithm, which seeks to maximize the total utility value of the sensors in the network by assigning channels to the coordinators. The detailed explanation of the pseudocode is as follows: At the beginning random channels are assigned to all coordinators (line: 1); a while loop is initiated, verifying if the maximum number of iterations has been met or if the convergence criteria has been reached (line: 2); the first coordinator to be evaluated is selected (line: 3); the best channel is selected, through a special procedure indicated in the following subsection (line: 4); the resulting channel for the coordinator in question is added to a matrix of results (line: 5); the number of iterations is updated (line: 6). it is ascertained if all the N coordinators have been evaluated (line: 7); if true, i = 1 is done to start over with the first coordinator (line: 8); the last if condition ends (line: 9); indicates the completion of the while loop as long as the stop criteria are not met (line: 10).

Data: C_i, $N_{\max}$, Ch_i
Results: $\max\left[\sum_{i=1}^{N} u_{i,j}\right]$
1. Initial random channels are selected for
; each of the coordinators
2. **while** stop criteria not reached
; Verify if $N_{\max}$ is achieved or if
; the convergence criteria is obtained
3. C_i; Coordinador i is selected
4. "**best channel selection**" j for C_i
5. Add $C_{i,j}$ to results matrix
6. Update number of iterations N_i
7. **If** i=N ***then***
8. i=1
9. **end** (7)
10. **end** (3)

Fig. 5. Pseudocode for proposed heuristic mechanism.

D. Best Channel for the Proposed Heuristic Mechanism

The best channel refers to the choice of a candidate channel for a particular coordinator, while the rest of the assigned channels remains unchanged, to allow increments in total utility value. To explain this selection process, a simplified example is used, for only four coordinators with three channels, tabulated in Table I. Example that can be extended according to the needs, to a different number of coordinators and channels.

In the aforementioned example, once coordinator 1 has been selected within the MAX algorithm, coordinators 1, 2, 3 and 4 will have channels 12, 13, 11 and 11 as prior random selection, as it can be seen in Table I. Utilities, $u_{1,11}$, $u_{1,12}$ and $u_{1,13}$, are those of the coordinator 1 evaluated for the available channels 11, 12 and 13 respectively; $u_{2,13}$, is repeated for the three operation channels since the coordinator 2 must maintain its initial channel selection, just as the coordinator 3 maintains its initial channel 11 and the coordinator 4, also maintains its initial channel 11.

Once Table I is completed, the utilities corresponding to the performance of the coordinators on each channel are added, to choose the best channel for coordinator 1. The channel that contributes to the maximum utility sum for all coordinators is selected as the best channel of operation.

TABLE I: UTILITIES OF EACH COORDINATOR ON EVERY CHANNEL

Initial channel	Coordinator C_1	Ch_1=11	Ch_2=12	Ch_3=13
12	C_1	$u_{1,11}$	$u_{1,12}$	$u_{1,13}$
13	C_2	$u_{2,13}$	$u_{2,13}$	$u_{2,13}$
11	C_3	$u_{3,11}$	$u_{3,11}$	$u_{3,11}$
11	C_4	$u_{4,11}$	$u_{4,11}$	$u_{4,11}$

The algorithm continues with the selection of the best channel for each of the other three coordinators in Table I, completing the first iteration cycle for the example. As the algorithm continues, on each iteration, it approximates to a better global solution. The algorithm stops when it reaches a state of convergences or goes over a certain number of iterations.

V. Performance Evaluation of the Mechanisms

This section evaluates the performance of the mechanisms indicated in Section IV, through simulations considering the scenario modeled in Section II.

A. Simulation Set up

This is done with the use MatLab as a software tool, on Hewlett Packard Intel Core I7, 3.4GHz and 8GB of RAM computers for WSN and AP devices of the 2.4GHz ISM band.

Increasing pairs of WSN are placed randomly on the center street of the scenario, subject to different levels of interferences, due not only to co-channel interference from other WSN; but from points located inside the buildings, under worst case conditions. Power calculations are performed considering propagation losses for each device. Curves are obtained averaging the values of at least 100 random scenarios.

B. Configuration Parameter

The parameters used by the OPTIMUM algorithm are described below: CR = 0.7; q = 0.5; utility slope s = 35; $T_{\min}=1\times10^{-5}$; number of WSN channels = 16; number of WLAN channels = 11; maximum number of iterations $N_{\max}$ = 30000; $\epsilon = 1\times10^{-1}$. The parameters used by the Max algorithm are now described: q=0.5; s=35; number of WSN channels =16; number of WLAN channels =11; maximum number of iterations $N_{\max}$ =300.

C. Simulation Results

For the evaluation of the proposed mechanisms, a scenario with a random channel assignment was used as an initial reference, which from now on will be called REF.

In Fig. 6 (a), the curves of the average channel capacity in Kbps are shown, for the OPTIMUM and the Max mechanisms, together with the REF reference curve, plus a channel capacity curve applying to the scenario the channel assignment used by the 802.15.4 standard for sensor networks, which we name as STANDARD. The simulations were performed for 10 to 100 sensors distributed evenly on the scenario indicated in Section II.

As it can be seen in this graph, the CC OPTIMUM curve represents the optimal solution, which is the best possible solution for the operational limit of 250 Kbps, but with a high computational cost (300,000.00 iterations). While the CC MAX curve is a solution with much fewer iterations (300), which nevertheless maintains average channel capacity values, slightly lower and close to OPTIMUM; proving its convenient performance. On the other hand, the values achieved both by CC REF corresponding to the REF reference curve, and by CC STANDARD, corresponding to the channel allocation mechanism of the standard, are well below those achieved by the two proposed mechanisms.

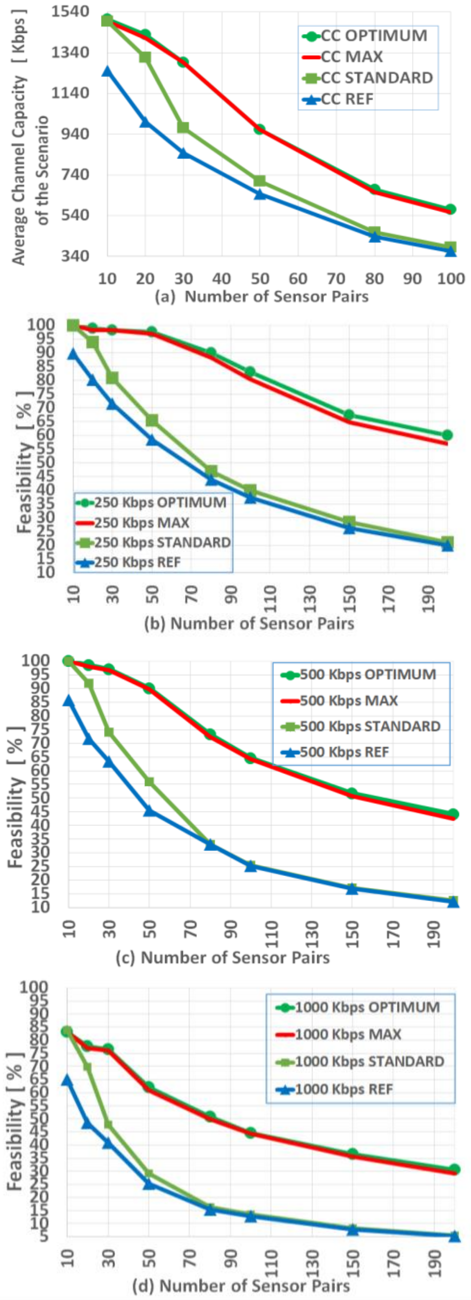

Fig. 6. (a) Average channel capacity for the two channel assignment mechanisms plus standard channel assignment method and reference REF vs number of sensor pairs, (b) feasibility for the two channel assignments mechanisms with a threshold of CC_{th} =250 Kbps, (c) feasibility for the two channel assignments mechanisms with a threshold of CC_{th} =500 Kbps, and (d) feasibility for the two channel assignments mechanisms with a threshold of CC_{th} =1000 Kbps.

From Fig. 6 (a) it is possible to observe that both the OPTIMUM and the MAX mechanism have an average channel capacity of approximately 1494 Kbps when evaluated with 10 sensor pairs, maintaining a substantial difference with the REF values, which at that point reach an average channel capacity of 1250 Kbps. While, for 100 pairs of sensors, the OPTIMUM and the MAX values descend to 555 Kbps and both the REF and the STANDARD even more to 365 Kbps. The deterioration of the average channel capacity stands out as the number of sensor pair increase, ratifying the behavior of the

MAX mechanism, close to the OPTIMUM and much better than the REF and the STANDARD.

In Fig. 6 (b) feasibility is presented instead of channel capacity. That is the number of sensor pairs that meet a certain channel capacity, which for this case has been considered to be the value of 250 Kbps. The measurements began in 10 sensor pairs, reaching feasibility of almost 100% for the OPTIMUM, MAX and STANDARD mechanisms. These simulations were carried out considering a maximum of 200 sensor pairs, observing that for this amount, the feasibility decreases drastically to 60% with the OPTIMUM algorithm and reached only 57% with the MAX. This behavior suggests that for quantities of 150 sensor pairs or more, the WSN would have serious difficulties in their performance.

The graph shows that, in the case of 10 sensor pairs, with the MAX technique (250 Kbps MAX), practically 100% of the devices meet the required channel capacity of 250Kbps. While with REF (250 Kbps REF), only 90% of the devices reach the required channel capacity. That is, the MAX mechanism at this point of low congestion of devices, exceeds REF by 10%. However, at this reference point, the standard method also delivers 100% of devices complying with the required capacity.

The performance superiority of the proposed mechanism, MAX, stands out at this point, which allows for 100 pairs, to reach a feasibility of 80%, a value defined in Section III as the minimum acceptable performance threshold. However, from 150 pairs onwards, there is a critical deterioration of the feasibility (65%), even for this technique.

Feasibilities with thresholds of 500 and 1000 Kbps are presented in Fig. 6 (c) and Fig. 6 (d). These results corroborate the effectiveness of the tested mechanisms for different channel capacity thresholds.

Another way to analyze the performance of these mechanisms is with the cumulative density functions (CDF) corresponding to each of the previously plotted curves, set at the point of 80 sensor pairs in the scenario, as in Fig. 7. The CDF represents the percentage of coordinators that meet a certain channel capacity.

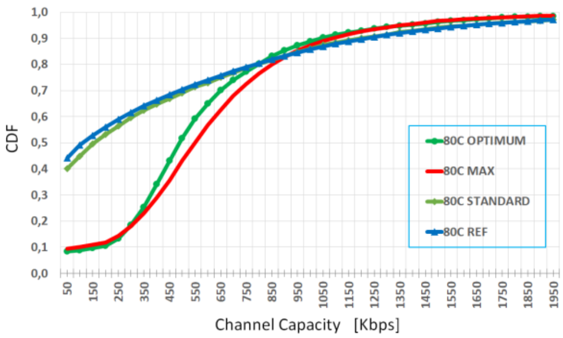

Fig. 7. CDF for the two proposed channel assignment mechanisms with 80 sensor pairs and a threshold CC_{th} =250 Kbps.

Fig. 7, shows that for speeds slower than the reference of 250 Kbps, when considering the OPTIMUM mechanism only 10% of its devices do not accomplish the desired speed, while with the MAX mechanism 12% of devices do not accomplish the desired speed. In the same figure, with the STANDARD curve, it can be appreciated that about 55% of its devices are below the reference, while in the REF curve approximately 57%. Indicating at this point the OPTIMUM mechanism performs the best, closely followed by the MAX and far from the STANDARD and the REF representation.

From all this we can conclude that the MAX mechanism presents a favorable alternative, to provide better channel capacities to the WSN coordinators, working in a high-density urban scenario, since their behavior is close to the OPTIMUM, without requiring too many processing resources.

VI. Conclusions

The double contribution given in this work has allowed: First, the evaluation of the performance of WSN in the proposed scenario, demonstrating for various levels of interference the critical degree of congestion that these devices could reach in the ISM band when operating in high-density urban areas of modern cities. Secondly, the proposal of a heuristic channel assignment mechanisms called MAX, which substantially improves the performance of WSN under strong interferences and the development of an OPTIMUM solution used as benchmarking. It is evident that the channel selection mechanism MAX represents a convenient solution for the proposed problem. This mechanism distributes among the coordinators in the scenario, high channel capacities close to the OPTIMUM solution but with low processing levels, presenting results well above those currently obtained by the standard channel allocation method. However, when the congestion levels of the proposed scenario exceed 150 sensor pairs, it can be seen that the proposed mechanisms begin to be insufficient, even though their values are still higher than the Standard reference. At this point, this work opens up new research areas, such as the use of additional channels from Primary bands or the implementation of the proposed MAX mechanism. Additionally, instead of a centralized work scheme for the coordinators, a distributed work scheme embedded in each of the WSN devices could be used.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Carlos Valdivieso and Francisco Novillo conducted the research; Aristóteles Amat and Alfredo Nuñez-Unda developed the algorithms and simulations; Carlos Valdivieso, Aristóteles Amat and Alfredo Nuñez-Unda analyzed the data; Carlos Valdivieso and Alfredo Nuñez-Unda wrote the paper; all authors approved the final version.

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