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A Dios por permitirme seguir cumpliendo mi propósito.

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DEDICATORIA

A Dios por guiar mi camino cada día.
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CAPÍTULO I
EL PROBLEMA DE INVESTIGACIÓN

1.1 Introduction

Given the upgrade towards a production scheme whose main basis is the capa- bility of sharing data between all the devices from the system, Wireless Sensor and Actuator Networks (WSAN) have acquired a major roll within the current industry. One of the main appealing points of this type of networks is the high flexibility and scalability that they posses compared to wired architectures. How- ever, it does not surpass its predecessor in all fields. WSANs have not been able to fully replicate the bandwidth and reliability capacities of its predecessor, but in the industrial area this does not represent an impediment for their implementa- tion and usage. Many industrial applications based on real-time monitoring and audio streaming that involve sensors and actuators only need bandwidth rates up to 250 Kbps [9]. This results in standards like WirelessHART, ISA 100.11a, IEEE 802.15, and 6TiSCH being able to effectively satisfy the reliability need of the systems [15].

Many standards compatible with WSANs support real-time data traffic. Within the most popular ones we can find the Time-Syncronized Channel Hop- ping (TSCH), that stands out thanks to its outstanding features. TSCH has been opening up field in both industrial [3] and automotive [8] environments due to its characteristics of: Time-division multiple-access (TDMA), frequency diversity and centralized scheduling. Given this characteristics, this standard has gained a bigger usage in factory automation and process control applications. Thus, increasing the acceptance and integration of the concepts of Industry 4.0 and Industrial Internet of Things (IIoT) [13].

1.2. Justification

Real-time communications are a critical factor When developing smart fac- tory architectures to ensure a deterministic data exchange. In order to implement this technology into the systems, the channel access of TSCH becomes useful thanks to its predictable nature. This behavior increases the ease with which the operations can be performed. By using simultaneously the previous with a combination of centralized scheduling and routing algorithms, TSCH is able to provide safe operational bounds for Worst-case End-to-end delays and opera- tions with schedules. Many investigations on enhancing methods for real-time communications in TSCH have taken place. A large number of them focus on the scope of packet scheduling and standardize the routing using algorithms such as Shortest-path. However, as result of the former the final real-time performance of the systems tends to be sub-optimal.

In the following work a Real-time Wireless Routing Method for TSCH net- works approach is presented. The main objective of this type of algorithms is to improve and/or secure the real-time properties of a network using as basis routing decisions. Thus, a conflict-aware routing method for TSCH WSANs us- ing an Earliest-deadline-first (EDF) scheduler is developed. The aforementioned depicts a Minimal-overlap Shortest-path routing to reduce at minimum the path overlaps within the network data flows.

1.3. Objetivos.

1.3.1 Objetivo General.

Optimizar el overload en redes WSAN con la aplicación de modelos matemáticos.

1.3.2. Objetivo Específicos.

1. Analizar trabajos relacionados de optimización en redes WSAN mediante el uso de modelos matemáticos.
2. Diseñar la optimización en las redes WSAN con el modelo matemático propuesto.
3. Validar el rendimiento óptimo en las redes WSAN con el uso de simulación que permita verificar el desempeño del modelo matemático

CAPÍTULO II

2.1. State of the Art

Many studies have taken place about the topics of assessing and modelling real- time performance of networks with similar characteristics to TSCH structures, some of them depicted in [13,12,10,5,4,7,1,2]. A common point of the previous is how their main focus are packet scheduling algorithms based on priority. Aside from this similarity, the proposed works set a differentiation point by describing design methods that: use response time analysis [12], are based on network calculus [10,5], are the result of tests based on supply and demand [4], among others. However, all of these investigations are directed towards the performance guarantee when the networks face worst-case scenarios. In these cases, dynamic and fixed priority schedulers have also been analyzed, while the rest of the features of the network are assumed to have a standard behavior. In a similar way, there are a good amount of available works related to the topic of routing in TSCH networks. But only a reduced number them fit in the classification of real-time wireless routing. As example of this, the authors in [11]

describe tailored routing methods directed towards the enhance and guarantee of real-time performance of wireless networks. They proposed a conflict-aware real-time routing for Wireless HART networks which uses a fixed-priority policy scheduler. The basis of this work is a delay- analysis for TSCH like networks deviated from the real-time CPU scheduling theory covered in [6].

The information gathering prior to the development of this investigation work allowed the separation of the end-to-end delay analysis in two main components: i) the effects of the channel contention and ii) the effects resulting of the conflicts during the transmission. The first part can be conveniently mapped to the multiprocessor contention concept once the assumption of an equal number of cores and channels in TSCH networks is made. The later is always a component of wireless transmission scheduling given the model restriction of half-duplex transceivers to transmit/receive alternately. This condition can represent a challenge while working with mesh topologies because of its impact on end-to-end delays and scheduling operations.

One of the main works used as a key reference for this investigation is [16,14]. In a similar way to the former, the development depicted in the following focuses on the factor to improve routing decision, but targeting transmissions scheduled under EDF. Additionally, in contrast to the continuous generation of routes until reaching a schedulable one, this work proposes a set of paths with minimal overlap in advance to the test of the global schedulability

CAPÍTULO III
MARCO METODOLÓGICO

3.1. System Model

A general representation of a WSAN is shown in Fig. 1. This image depicts how the network is made of a finite number of $N \in \mathbb{N}$ nodes that include several field devices (actuators and sensors), multiple access points (APs) and a gateway. The interconnection of the field devices with the APs is done using a wireless medium. The resulting network presents a mesh topology that operates with half- duplex omnidirectional radio transceivers. The connection between the APs and the gateway uses a direct link, enabling this way a bidirectional communication among the field devices and elements outside the physical network such as: host applications, system controllers and network managers. Specifically in the case of networks managers, they are software modules commonly deployed in the gateway where they continuously run their programmed instructions. They are in charge of collecting the topological information of the network, with which they perform scheduling and routing operations.

For the following work there are some assumptions made about the net- work. i) The network is based on TSCH and uses a physical layer compatible with the IEEE 802.15.4 standard. ii) The network operates using a centralized multi-channel TDMA protocol all together with the functions of global synchronization. With the integration of the multi-channel feature the characteristic of concurrent transmission per-slot is enabled. It is based on channel hopping meth- ods that operate using a number of m active radio channels. The possible values that the m parameter can have are delimited by the expression $1 \leq m \leq 16 \in \mathbb{N}$.

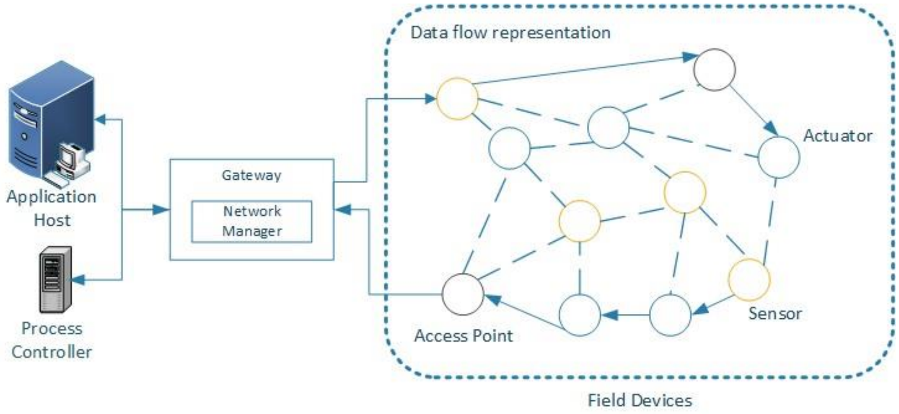

Fig. 1. Representation of a data flow in an Industrial WSAN

iii) The duration of the time slots is fixed to a value around 10ms. This value corresponds to a dedicated time interval used in the allocation of a single packet transmission. With this, a maximum number of $w-1$ re-transmissions with their corresponding acknowledgement transactions can take place, where $w \in N$.

In the operation of the presented WSAN, the sensor nodes have the capacity of periodically transmitting data to elements inside and outside the network. An example of this takes part when a sensor sends data to a remote controller as shown in Fig. 1. To reach the controller, the sensor needs to send information through the gateway. As result of this initial transaction, the external control element will send back in return control instruction for the actuators. It is considered that the transmissions performed during the data exchange take place using a basis of per-slot/per-hop events. They also follow predefined multi-hop routes when traveling by an uplink (origin point: sensor, end point: gateway) or by a downlink (origin point: gateway, end point: actuators). Both of these data transactions take place with rigorous delivery time limitations. As a method to decrease the complexity of the system, in this work it is considered that the generated routes are configured under source routing. Therefore, the routes for both uplinks and downlinks are simple and predefined. Following the results of the work depicted in [14], the maintenance of the network is considered to be a built-in centralized service which can be implemented in a next stage.

3.1.1. Network model

With the characteristics of the network depicted in the general system model, the network model can be represented as a graph G in function of $G = (V, E)$, where: i)V is the group of the nodes represented as vertices, and ii)E is the group of links between the nodes represented as edges. G is assumed to be connected, undirected and incomplete. This means that the number of links between nodes is lower than the total number of existing pairs. Talking about the total number of nodes is equivalent to talk about the total number of vertices $N = |V|$. From this total, one of the vertices corresponds to the network gateway leaving a $N - 1$ number of vertices for the field devices and APs. In a next stage of the model, the gateway will be considered as the node with the betweenness centrality, meaning that removing this node from the analysis will generate the greatest impact in the final network connectivity.

In the final network model, a subset $n \in N$ of the total number of field devices is considered to be operating as sensors and generate data. Thus, the final $(N - n) - 1$ is considered to be the amount of actuators.

3.1.2. Flow model

The set of m real-time network flows that occur during the operation of the network are described as a function of $F = (f_1, f_2, ..., f_m)$, where every data transaction is transmitted using an EDF methodology. Each of the elements of f_i has the characteristics of being periodic and constrained from end to end. Additionally, based on the fact that each flow is able to release almost an infinite number of transmissions, each of them is represented as a cluster containing the 4 elements of $f_i = (C_i, D_i, T_i, \varphi_i)$, where:

- C_i is the effective transmission time between the source and the destiny.
- D_i is the relative deadline.
- T_i is the period equivalent to the sampling rate of the sensors.
- φ_i is the routing path.

The ξ^{th} instance of the data transmissions is described as $f_{i,\xi}$, with $\xi \in N$. It happens at time $r_{i,\xi}$, such that $r_{i,\xi+1} + r_{i,\xi} = T_i$. With this and following the guidelines of the EDF policy, $f_{i,\xi}$ is required to reach its destination before its absolute deadline, resulting in $d_{i,\xi} = r_{i,\xi} + D_i$. With this, it is assumed that the model has a constrained deadline characteristic $D_i \leq T_i$ and allows only a single flow transmission within a time slot.

It can be remarked that C_i is an interpretation of the time required by a flow f_i to be transmitted in the cases when it is not is affected by the rest of the flows. Therefore, C_i is calculated as $C_i = \gamma_i \times w$, where: γ_i represents the total number of connections in the route path φ_i, and w is the amount of transmission slots that correspond to a flow in each connection also taking into account re- transmissions. In the following work, a fixed value of w is used in order to C_i to be only dependent on the topology and routing dynamics.

3.2. Problem Formulation

After the guidelines depicted in the previous section, the problem considered in the following work is to find the optimal set of flow paths which are able to reduce to the minimum the overall number of path overlaps between any pair of nodes in a network, given by a expression $\Psi_{opt} = (\Psi_1{}^{opt}, \Psi_2{}^{opt}, ..., \Psi_n{}^{opt})$.

Throughout this process the overall number of overlaps existing between the flows of F will be denoted as Ω. It is defined as the sum of all the individual node overlaps λ_{ij} that correspond to the routes of any pair of flows (f_i, f_j), where $i, j \in [1, n] \wedge i = j$.

During the development $F_0 = (f_1{}^0, f_2{}^0, ..., f_m{}^0)$ will be the denomination of the network flows corresponding to the original set. With this, the original set of flow paths $\Psi_0 = (\Psi_1{}^0, \Psi_1{}^0, ..., \Psi_m{}^0)$ is obtained using a shortest-path algorithm of the type hop-count.

Finally, the relationship $F_k = (f_1{}^k, f_2{}^k, ..., f_m{}^k)$ is defined to describe the k^{th} variation of the flows set F_0. This takes place when a sub-optimal group of routes $\Psi_k = (\Psi_1{}^k, \Psi_2{}^k, ..., \Psi_n{}^k)$ is considered. As result the parameter Ω_k is equivalent to the k^{th} total number of path overlaps generated.

An initial solution Ψ_0 and its corresponding Ω_0 can be formulated to the initial graph G in the form of:

$$minimize\ k\ \ \Omega_k = \sum_{\forall i,j \in [1,n\} \wedge i \neq j}^{n} \delta_{i,j}(\Psi_k) \qquad (1)$$

$$\text{subject to } \begin{array}{c} k \in [1, k_{max}], \\ \Psi_k \in [\Psi_1, \Psi_{kmax}] \end{array}$$

In the equation 1 the term $\delta i,j$ (Ψk) represents the amount of node overlaps generated between the nodes fik and fj k. As result of this we have that $\Omega = \Omega kmin$. In the end, the representation of the set of optimal routes is given by Ψopt. It is a term used to describe any of the group of paths depicted by Ψk resulting of $\Omega kmin$. $\delta i,j$ (Ψk).

3.3. Epsilon Greedy Heuristic Optimization Method

Based on the formalization of the problem depicted in the Equation 1, this work proposes a solution based on an epsilon greedy heuristic method that uses the exploration-exploitation tradeoff (EE). In this approach, an agent chooses be- tween k different actions and receives a reward based on the chosen action. In order for the agent to select an action, it is assumed that each one of them has a separate distribution of rewards $R = (r_1, r_2, ..., r_m)$ and at least one action generates the maximum numerical reward. Therefore, the probability distribution of the set of rs is different and unknown to the agent. With this on mind, the agent is developed with the main objective of identifying the proper actions related to the maximum reward R after a set of trials.

When developing an EE strategy, there are two actions that must find their balance of occurrence during execution. The first one, exploration allows an agent to improve its current knowledge about each action, hopefully leading to long- term benefit. Improving the accuracy of the estimated action-values, enables an agent to make more informed decisions in the future. On the other hand exploitation, chooses the greedy action to get the most reward by exploiting the agent’s current action-value estimates. But being greedy with respect to action-value estimates, may not actually get the most reward and lead to sub- optimal behavior. When an agent explores, it gets more accurate estimates of action-values. And when it exploits, it might get more reward. It cannot, however, choose to do both simultaneously, which is also called the exploration- exploitation dilemma.

The implementation of the aforementioned agent means the generation of an individual group of Ψ_k for every k^{th} iteration prior to the calculation of the corresponding Ω_k and R_k. After k_{max} iterations the smallest Ω_k with the highest R_k is designed as the Ω_k^{min}. The final algorithm consists in a 3 step solution where as a first an initial solution is calculated, then a greedy search is performed based on the previous, and finally the best solution is obtained from the results of the last search.

For the initial solution calculation the algorithm behaves as follows:

- During $k = 1$ the value of Ψ_k and r_k are obtained as a functions of the path overlaps resulting from Ψ_0. Ψ_1 is calculated as the set of weighted shortest paths from the graph $G_1 = (V, E_1)$. This one is a modified version of the unitary weighted graph G. In the previous each set of edges receives a weight based on the node overlapping degree resulting from the set Ψ_0.

- The cost function in charge of weighting any edge $W_{i,j}(u, v)$ in G is defined as:

$$W_{i,j}(u, v) = 1 + \sum_{e=1}^{\delta i,j} \psi \tag{2}$$

Where $\psi \in R$ is a constant user defined parameter and $\delta_{i,j}$ is the number of node overlaps obtained from the routes Ψ_i^0 and Ψ_i^0 $\in \Psi_0, \forall i, j \in [1, n] \wedge i \neq j$

- With the previous it can be said that Ψ_1 and r_1 is obtained from the shortest- paths that corresponds to G^1, and Ω_1 is the overall number of overlaps related to them.
- Finally, it can be said that $[(\Omega_1 < \Omega_0) \; (\Omega_K^{min} = \Omega_1)] \wedge [\neg(\Omega_1 < \Omega_0) \rightarrow (\Omega_K^{min} = \Omega_0)]$

For the epsilon greedy agent the algorithm behaves as follows:

- It generalizes the search $_k$ of a Ω_K^{min} for any $k \in [1, k_{max}]$ by choosing between exploration and exploitation randomly. For this decision, the agent uses the value of epsilon as reference to the probability of exploiting over exploring.
- Then, the value of $G_k = (V, E_k)$ is defined as a modified version of $G_{k-1} = (V, E_{k-1})$.

In the end Ψ_k is calculated as function of Ψ_{k-1} and $[(\Omega_k < \Omega_K^{min}) \rightarrow (\Omega_K^{min} = \Omega_k)] \wedge [\neg (\Omega_k < \Omega_K^{min}) \rightarrow (\Omega_K^{min} = \Omega_K^{min})]$.

Finally to obtain the best solution the algorithm ends the calculations when $k \overset{k}{=} k_{max}$ and returns Ω^{min}. The quality of the final its proportional to the quality of the generated Ψ_k sets and to the number of iterations used during the calculus.

CAPÍTULO IV

RESULTADOS

4.1. Tests scenarios

In order to obtain a comparison data, random group of network topologies and flows are generated in order to test the performance of the resulting epsilon greedy heuristic (EE) compared to a shortest-path algorithm (SP). With the help of a network graphs generator, a set of 100 topologies are prepared for the analysis. Each graph was generated using a seed that defines a random matrix of $N \times N$ and a density Λ which can have a value in the range of $[0, 1] \in R$. The density value is obtained from the relationship $\Lambda = \lambda/N$ where λ represents the median nodes degree of the graph and takes values in the range of $[4, 12]$. The number of vertices used for in the generation seed is a constant value of $N = 66$. The gateway is chosen as the node with the highest betweenness centrality and a subset of $n \subset N$ of field devices are configured as sensors programmed to periodically transmit data to the gateway. As part of this experiment the value of n is limited within the range of $[2, 22]$. With the depicted set up, the group of shortest-path routes between the n sensors and the gateway are generated. This provides 100 instances of n possible routes.

The user defined parameter ψ adopts the same value as the graphs density Λ and the value of 100 for k_{max} parameter of the experiments. Each of the f_i flows generated for the 100 topologies can be defined as a cluster of 4 elements $f_i = (C_i, D_i, T_i, \varphi_i)$ as discussed in the Flow model. Each of the C_i values are directly obtained from the product of the number of hops times the path φ_i between the source and the destination times the number of transmissions assigned to each slot. In this work the value of the last parameter w was assumed as 2. The periods T_i were generated in the form of 2^p where $p \in N$ in the range of [4, 7]. Finally the value of D_i is assumed to be equal to T_i in order to obtain a implicit-deadline model.

4.2. Results

The performance of both EE and SP methods when optimizing the routing in the generated random graphs is described in the figures 2, 3, 4 and 5.

As it can be appreciated when comparing the performance of the proposed EE method with the SP strategy, the former is able to improve the results depicted by the later by a high margin. As shown in the Fig. 2, the node overlapping phenomenon that follows an exponential behavior is reduced in almost 50% with this values of λ, which gives a sight that in bigger networks this mitigation will be better. The positive effects of the overlap reduction are also visible in the Fig.4. Given the direct relationship between the overlaps and transmission conflicts, affecting one will proportionally affect the remaining. When analyzing the results of the Fig. 3 it can be appreciated that the affection to the length of the routes is almost negligible and is not likely to increase in bigger networks. Finally the positive befits of the EE optimization are appreciated with the difference in the schedulability ratio between the two methods.

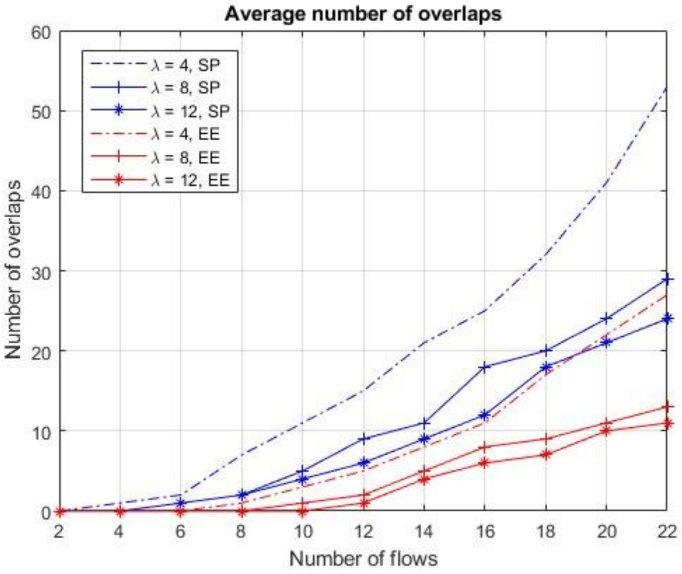

Fig. 2. Representation of the resulting average number of overlaps in the data trans- mission while using a variation of λ = [4, 8, 12]

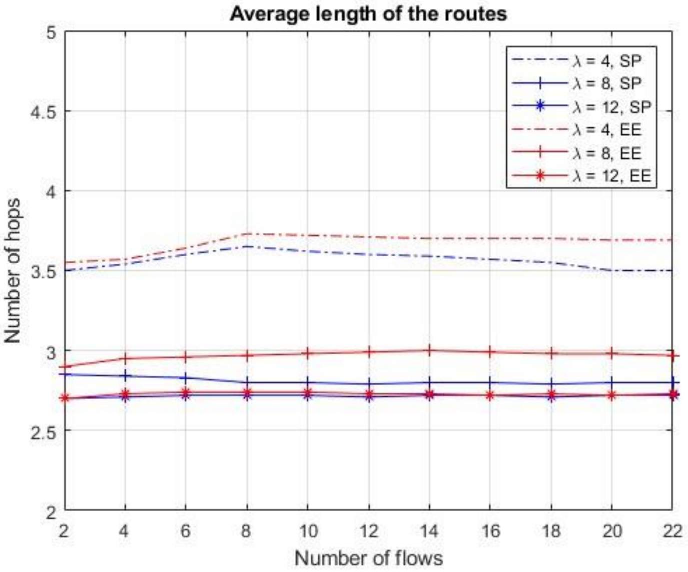

Fig. 3. Representation of the final average routes length using a variation of λ = [4, 8, 12]

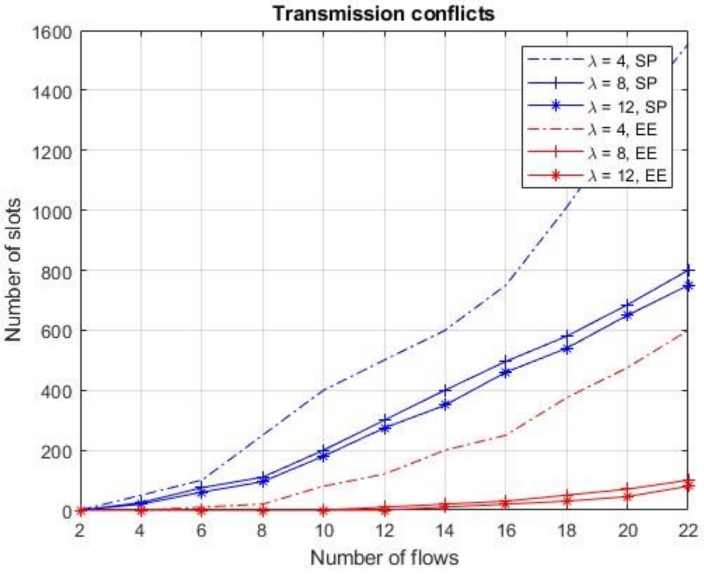

Fig. 4. Representation of the average conflict occurrence when using a variation of λ = [4, 8, 12]

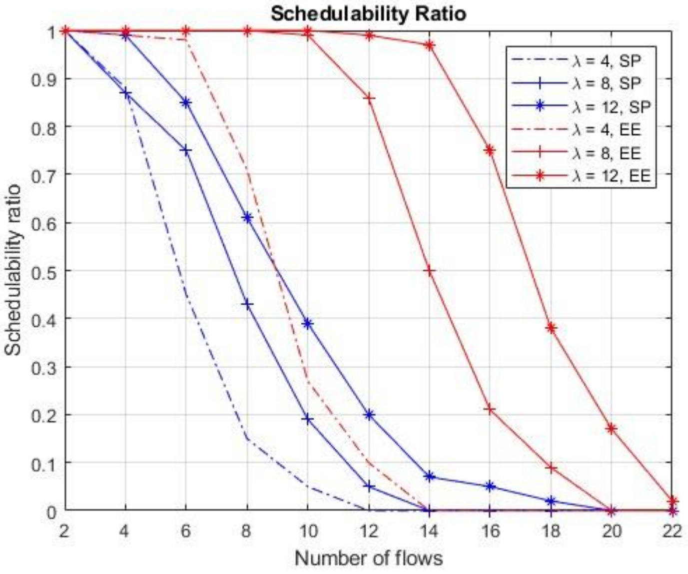

Fig. 5. Representation of final schedulability ratio while using variation of λ = [4, 8, 12]

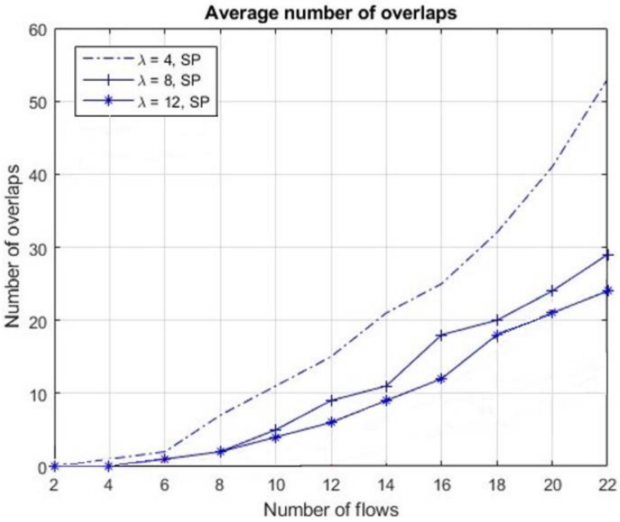

Fig. 6. Representation the SP of the resulting average number of overlaps in the data transmission while using a variation of λ = [4, 8, 12]

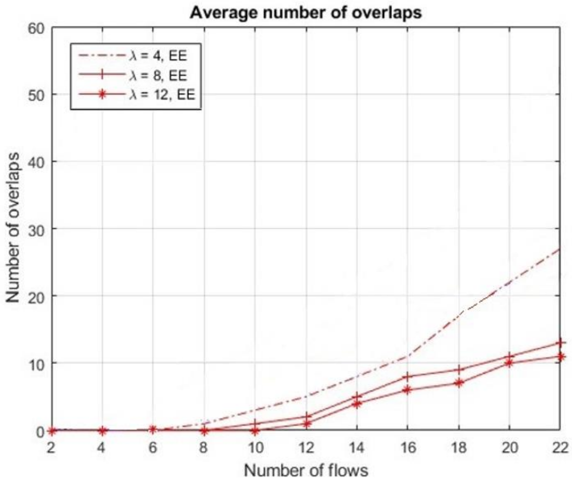

Fig. 7. Representation the EE of the resulting average number of overlaps in the data transmission while using a variation of λ = [4, 8, 12]

CAPÍTULO V

CONCLUSIONES, BIBLIOGRAFÍA Y ANEXOS

5.1. Conclusions

As final result of the present investigation work, an effective real-time routing method for WSANs based on TSCH that uses an EDF policy is developed. The usage of a greedy heuristic method allowed the final controller to improve the real-time component of the data exchange in the network. This was done by reducing the total amount of overlaps in the paths generated for the traveling information. Additionally parameters as the number of transmission conflicts and schedulability ratio were also improved as side effect of the operation of the proposed controller. It was tested with 100 randomly generated network graphs and compared with one of the most commonly used optimization methods, the hop-count method. The usage of an epsilon greedy heuristic algorithm for the minimization of overlaps in the transmission routes turned out to be an optimal network performance enhancer. After analyzing the test data of both scenarios it was clearly appreciated that the presented algorithm obtained improvements that almost reached effectiveness levels of 50%.

The positive results of the former work demonstrated that the routing process in networks can be optimized and still has room left for its growth. Theoretically, autonomous intelligent structures developed using machine learning algorithms are able to reach even higher levels of performance in tasks such as optimizing. With this in mind, the future steps in this line of investigation is the improving of the routing in WSANs with the usage of machine learning algorithms.

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5.3 Anexos

5.3.1. Anexo 1 - Carta de aceptación de artículo profesional.

Fecha: 21-06-17 [12:34:58 CEST]
De: WorldS4 2021 <worlds42021@easychair.org>
Para: Marcelo V Garcia <mgarcia294@ikasle.ehu.es>
Asunto: WorldS4 2021 notification for paper 118

Dear Marcelo V

Garcia, Ref:

118

Title: Optimization of the Overlap Shortest-Path Routing for TSCH Networks

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With regards and best wishes. Program Secretary, WorldS4 2021

SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks

----------------------- REVIEW 1 -----------------
---- SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks
AUTHORS: Marcelo V Garcia

----------- Overall evaluation -------
---- SCORE: 2 (accept)
----- TEXT:
Much effective paper written on Optimization of the Overlap Shortest-Path Routing for TSCH Networks

- The introduction provides a good, generalized background of the study.

- Elaborate the statement in section 5
The first one, exploration allows an agent to improve its current knowledge about each action, hopefully leading to long term benefit.

- Avoid un - necessary highlighting of the words.

- Recommended for Inclusion.

----------------------- REVIEW 2 -----------------
---- SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks
AUTHORS: Marcelo V Garcia

----------- Overall evaluation -------
---- SCORE: 2 (accept)
----- TEXT:
Authors are suggested to consider the following revisions.

- Abstract is relevant and satisfactory.

- The purpose of the study should be justified as per the paper authors.

- How authors have made the use of shortest-path algorithm in the paper ?

- References are good and authors have shown their other work published also in similar area.

- Authors are requested to follow the guidelines issued by springer or the paper may be rejected by the publication board at a later stage.

5.3.2. Anexo 2 – Artículo profesional de alto nivel

Optimization of the Overlap Shortest-Path Routing for TSCH Networks

Javier Caceres-Navas[1] and Marcelo V. Garcia[1,2][0000−0002−7138−3913]

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Abstract. A wider usage of wireless technologies throughout the lower levels of the automation pyramid is one of the results of the integration of the concepts of Industry 4.0 and Industrial Internet of Things (IIoT). Among the most popular communication standards used in the current industrial paradigm we can find the: IEEE 802.15, ISA100.11a, 6TiSCH and the Wireless-HART. One of the main reasons behind the user preference towards the aforementioned is their characteristic of supporting Real-Time data traffic in Wireless Sensor and Actuator Networks (WSAN). This variety of communication options has been the starting point of many studies and researches about the topic of prioritized packet scheduling. However, only a few works have been developed related to improving real-time performance compared to the amount of works mentioning the previous. Using this fact as a basis, the following work proposes an epsilon greedy heuristic agent whose main work objective is the reduction of the overlap in Shortest-Path routing for WSANs using the policy of earliest-deadline-first (EDF) to schedule packet transmission.

Keywords: Real-time · Wireless Networks · Network Algorithm · Path optimization.

1 Introduction

Given the upgrade towards a production scheme whose main basis is the capability of sharing data between all the devices from the system, Wireless Sensor and Actuator Networks (WSAN) have acquired a major roll within the current industry. One of the main appealing points of this type of networks is the high flexibility and scalability that they posses compared to wired architectures. However, it does not surpass its predecessor in all fields. WSANs have not been able to fully replicate the bandwidth and reliability capacities of its predecessor, but in the industrial area this does not represent an impediment for their implementation and usage. Many industrial applications based on real-time monitoring and audio streaming that involve sensors and actuators only need bandwidth rates up to 250 Kbps [9]. This results in standards like WirelessHART, ISA 100.11a, IEEE 802.15, and 6TiSCH being able to effectively satisfy the reliability need of the systems [15].

Many standards compatible with WSANs support real-time data traffic. Within the most popular ones we can find the Time-Syncronized Channel Hopping (TSCH), that stands out thanks to its outstanding features. TSCH has been opening up field in both industrial [3] and automotive [8] environments due to its characteristics of: Time-division multiple-access (TDMA), frequency diversity and centralized scheduling. Given this characteristics, this standard has gained a bigger usage in factory automation and process control applications. Thus, increasing the the acceptance and integration of the concepts of Industry 4.0 and Industrial Internet of Things (IIoT) [13].

Real-time communications are a critical factor When developing smart factory architectures to ensure a deterministic data exchange. In order to implement this technology into the systems, the channel access of TSCH becomes useful thanks to its predictable nature. This behavior increases the ease with which the operations can be performed. By using simultaneously the previous with a combination of centralized scheduling and routing algorithms, TSCH is able to provide safe operational bounds for Worst-case End-to-end delays and operations with schedules. Many investigations on enhancing methods for real-time communications in TSCH have taken place. A large number of them focus on the scope of packet scheduling and standardize the routing using algorithms such as Shortest-path. However, as result of the former the final real-time performance of the systems tends to be sub-optimal.

In the following work a Real-time Wireless Routing Method for TSCH networks approach is presented. The main objective of this type of algorithms is to improve and/or secure the real-time properties of a network using as basis routing decisions. Thus, a conflict-aware routing method for TSCH WSANs using an Earliest-deadline-first (EDF) scheduler is developed. The aforementioned depicts a Minimal-overlap Shortest-path routing to reduce at minimum the path overlaps within the network data flows.

2 State of the Art

Many studies have taken place about the topics of assessing and modelling real-time performance of networks with similar characteristics to TSCH structures, some of them depicted in [13,12,10,5,4,7,1,2]. A common point of the previous is how their main focus are packet scheduling algorithms based on priority. Aside from this similarity, the proposed works set a differentiation point by describing design methods that: use response time analysis [12], are based on network calculus [10,5], are the result of tests based on supply and demand [4], among others. However, all of these investigations are directed towards the performance guarantee when the networks face worst-case scenarios. In these cases, dynamic and fixed priority schedulers have also been analysed, while the rest of the features of the network are assumed to have a standard behaviour.

In a similar way, there are a good amount of available works related to the topic of routing in TSCH networks. But only a reduced number them fit in the classification of real-time wireless routing. As example of this, the authors in [11] describe tailored routing methods directed towards the enhance and guarantee of real-time performance of wireless networks. They proposed a conflict-aware real-time routing for WirelessHART networks which uses a fixed-priority policy scheduler. The basis of this work is a delay- analysis for TSCH like networks deviated from the real-time CPU scheduling theory covered in [6].

The information gathering prior to the development of this investigation work allowed the separation of the end-to-end delay analysis in two main components: i) the effects of the channel contention and ii) the effects resulting of the conflicts during the transmission. The first part can be conveniently mapped to the multiprocessor contention concept once the assumption of an equal number of cores and channels in TSCH networks is made. The later is always a component of wireless transmission scheduling given the model restriction of half-duplex transceivers to transmit/receive alternately. This condition can represent a challenge while working with mesh topologies because of its impact on end-to-end delays and scheduling operations.

One of the main works used as a key reference for this investigation is [16,14]. In a similar way to the former, the development depicted in the following focuses on the factor to improve routing decision, but targeting transmissions scheduled under EDF. Additionally, in contrast to the continuous generation of routes until reaching a schedulable one, this work proposes a set of paths with minimal overlap in advance to the test of the global schedulability.

3 System Model

A general representation of a WSAN is shown in Fig. 1. This image depicts how the network is made of a finite number of $N \in \mathbb{N}$ nodes that include several field devices (actuators and sensors), multiple access points (APs) and a gateway. The interconnection of the field devices with the APs is done using a wireless medium. The resulting network presents a mesh topology that operates with half-duplex omnidirectional radio transceivers. The connection between the APs and the gateway uses a direct link, enabling this way a bidirectional communication among the field devices and elements outside the physical network such as: host applications, system controllers and network managers. Specifically in the case of networks managers, they are software modules commonly deployed in the gateway where they continuously run their programmed instructions. They are in charge of collecting the topological information of the network, with which they perform scheduling and routing operations.

For the following work there are some assumptions made about the network. i) The network is based on TSCH and uses a physical layer compatible with the IEEE 802.15.4 standard. ii) The network operates using a centralized multi-channel TDMA protocol all together with the functions of global synchronization. With the integration of the multi-channel feature the characteristic of concurrent transmission per-slot is enabled. It is based on channel hopping methods that operate using a number of m active radio channels. The possible values that the m parameter can have are delimited by the expression $1 \leq m \leq 16 \in \mathbb{N}$.

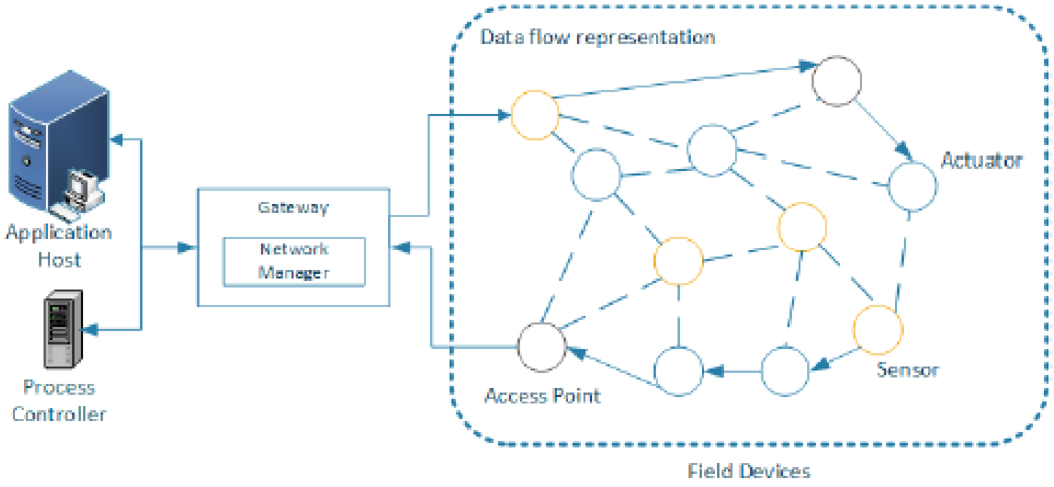

Fig. 1. Representation of a data flow in an Industrial WSAN

iii) The duration of the time slots is fixed to a value around $10ms$. This value corresponds to a dedicated time interval used in the allocation of a single packet transmission. With this, a maximum number of $w-1$ re-transmissions with their corresponding acknowledgement transactions can take place, where $w \in \mathbb{N}$.

In the operation of the presented WSAN, the sensor nodes have the capacity of periodically transmitting data to elements inside and outside the network. An example of this takes part when a sensor sends data to a remote controller as shown in Fig. 1. To reach the controller, the sensor needs to send information through the gateway. As result of this initial transaction, the external control element will send back in return control instruction for the actuators. It is considered that the transmissions performed during the data exchange take place using a basis of per-slot/per-hop events. They also follow predefined multi-hop routes when traveling by an uplink (origin point: sensor, end point: gateway) or by a downlink (origin point: gateway, end point: actuators). Both of these data transactions take place with rigorous delivery time limitations. As a method to decrease the complexity of the system, in this work it is considered that the generated routes are configured under source routing. Therefore, the routes for both uplinks and downlinks are simple and predefined. Following the results of the work depicted in [14], the maintenance of the network is considered to be a built-in centralized service which can be implemented in a next stage.

3.1 Network model

With the characteristics of the network depicted in the general system model, the network model can be represented as a graph G in function of $G = (V, E)$, where: $i)V$ is the group of the nodes represented as vertices, and $ii)E$ is the group of links between the nodes represented as edges. G is assumed to be connected, undirected and incomplete. This means that the number of links between nodes is lower than the total number of existing pairs. Talking about the total number of nodes is equivalent to talk about the total number of vertices $N = |V|$. From this total, one of the vertices corresponds to the network gateway leaving a $N-1$ number of vertices for the field devices and APs. In a next stage of the model, the gateway will be considered as the node with the betweenness centrality, meaning that removing this node from the analysis will generate the greatest impact in the final network connectivity.

In the final network model, a subset $n \in \mathbb{N}$ of the total number of field devices is considered to be operating as sensors and generate data. Thus, the final $(N-n)-1$ is considered to be the amount of actuators.

3.2 Flow model

The set of m real-time network flows that occur during the operation of the network are described as a function of $F = (f_1, f_1, ..., f_m)$, where every data transaction is transmitted using an EDF methodology. Each of the elements of f_i has the characteristics of being periodic and constrained from end to end. Additionally, based on the fact that each flow is able to release almost an infinite number of transmissions, each of them is represented as a cluster containing the 4 elements of $f_i = (C_i, D_i, T_i, \phi_i)$, where:

- C_i is the effective transmission time between the source and the destiny.
- D_i is the relative deadline.
- T_i is the period equivalent to the sampling rate of the sensors.
- ϕ_i is the routing path.

The ξ^{th} instance of the data transmissions is described as $f_{i,\xi}$, with $\xi \in \mathbb{N}$. It happens at time $r_{i,\xi}$, such that $r_{i,\xi+1} + r_{i,\xi} = T_i$. With this and following the guidelines of the EDF policy, $f_{i,\xi}$ is required to reach its destination before its absolute deadline, resulting in $d_{i,\xi} = r_{i,\xi} + D_i$. With this, it is assumed that the model has a constrained dead-line characteristic $D_i \leq T_i$ and allows only a single flow transmission within a time slot.

It can be remarked that C_i is an interpretation of the time required by a flow f_i to be transmitted in the cases when it is not is affected by the rest of the flows. Therefore, C_i is calculated as $C_i = \gamma_i \times w$, where: γ_i represents the total number of connections in the route path ϕ_i, and w is the amount of transmission slots that correspond to a flow in each connection also taking into account retransmissions. In the following work, a fixed value of w is used in order to C_i to be only dependent on the topology and routing dinamics.

4 Problem Formulation

After the guidelines depicted in the previous section, the problem considered in the following work is to find the optimal set of flow paths which are able to reduce to the minimum the overall number of path overlaps between any pair of nodes in a network, given by a expression $\Psi_{opt} = ({\Psi_1}^{opt}, {\Psi_2}^{opt}, ..., {\Psi_n}^{opt})$.

Throughout this process the overall number of overlaps existing between the flows of F will be denoted as Ω. It is defined as the sum of all the individual node overlaps $\lambda_i j$ that correspond to the routes of any pair of flows (f_i, f_j), where $i, j \in [1, n] \wedge i \neq j$.

During the development $F_0 = ({f_1}^0, {f_1}^0, ..., {f_m}^0)$ will be the denomination of the network flows corresponding to the original set. With this, the original set of flow paths $\Psi_0 = ({\Psi_1}^0, {\Psi_1}^0, ..., {\Psi_m}^0)$ is obtained using a shortest-path algorithm of the type hop-count.

Finally, the relationship $F_k = ({f_1}^k, {f_1}^k, ..., {f_m}^k)$ is defined to describe the k^{th} variation of the flows set F_0. This takes place when a sub-optimal group of routes $\Psi_k = ({\Psi_1}^k, {\Psi_2}^k, ..., {\Psi_n}^k)$ is considered. As result the parameter Ω_k is equivalent to the k^{th} total number of path overlaps generated.

An initial solution Ψ_0 and its corresponding Ω_0 can be formulated to the initial graph G in the form of:

$$\begin{aligned} \underset{k}{\text{minimize}} \quad & \Omega_k = \sum_{\forall i,j \in [1,n] \wedge i \neq j} \delta_{i,j}(\Psi_k) \\ \text{subject to} \quad & k \in [1, k_{max}], \\ & \Psi_k \in [\Psi_1, \Psi_{kmax}] \end{aligned} \tag{1}$$

In the equation 1 the term $\delta_{i,j}(\Psi_k)$ represents the amount of node overlaps generated between the nodes ${f_i}^k$ and ${f_j}^k$. As result of this we have that $\Omega = {\Omega_k}^{min}$. In the end, the representation of the set of optimal routes is given by Ψ_opt. It is a term used to describe any of the group of paths depicted by Ψ_k resulting of ${\Omega_k}^{min}$.

5 Epsilon Greedy Heuristic Optimization Method

Based on the formalization of the problem depicted in the Equation 1, this work proposes a solution based on an epsilon greedy heuristic method that uses the exploration-exploitation tradeoff (EE). In this approach, an agent chooses between k different actions and receives a reward based on the chosen action. In order for the agent to select an action, it is assumed that each one of them has a separate distribution of rewards $R = (r_1, r_2, ..., r_m)$ and at least one action generates the maximum numerical reward. Therefore, the probability distribution of the set of rs is different and unknown to the agent. With this on mind, the agent is developed with the main objective of identifying the proper actions related to the maximum reward R after a set of trials.

When developing an EE strategy, there are two actions that must find their balance of occurrence during execution. The first one, exploration allows an agent to improve its current knowledge about each action, hopefully leading to long-term benefit. Improving the accuracy of the estimated action-values, enables an agent to make more informed decisions in the future. On the other hand exploitation, chooses the greedy action to get the most reward by exploiting the agent's current action-value estimates. But being greedy with respect to action-value estimates, may not actually get the most reward and lead to sub-optimal behaviour. When an agent explores, it gets more accurate estimates of action-values. And when it exploits, it might get more reward. It cannot, however, choose to do both simultaneously, which is also called the exploration-exploitation dilemma.

The implementation of the aforementioned agent means the generation of an individual group of Ψ_k for every k^{th} iteration prior to the calculation of the corresponding Ω_k and R_k. After k_{max} iterations the smallest Ω_k with the highest R_k is designed as the ${\Omega_k}^{min}$. The final algorithm consists in a 3 step solution where as a first an initial solution is calculated, then a greedy search is performed based on the previous, and finally the best solution is obtained from the results of the last search.

For the initial solution calculation the algorithm behaves as follows:

- During $k = 1$ the value of Ψ_k and r_k are obtained as a functions of the path overlaps resulting from Ψ_0. Ψ_1 is calculated as the set of weighted shortest paths from the graph $G_1 = (V, E_1)$. This one is a modified version of the unitary weighted graph G. In the previous each set of edges receives a weight based on the node overlaping degree resulting from the set Ψ_0.
- The cost funtion in charge of weighting any edge $W_{i,j}(u,v)$ in G is defined as:

$$W_{i,j}(u,v) = 1 + \sum_{e=1}^{\delta_{i,j}} \psi \tag{2}$$

  Where $\psi \in \mathbb{R}$ is a constant user defined parameter and $\delta_{i,j}$ is the number of node overlaps obtained from the routes Ψ_i^0 and $\Psi_i^0 \in \Psi_0, \forall i, j \in [1, n] \wedge i \neq j$
  .
- With the previous it can be said that Ψ_1 and r_1 is obtained from the shortest-paths that corresponds to G^1, and Ω_1 is the overall number of overlaps related to them.
- Finally, it can be said that $[(\Omega_1 < \Omega_0) \rightarrow (\Omega_k^{min} = \Omega_1)] \wedge [\neg(\Omega_1 < \Omega_0) \rightarrow (\Omega_k^{min} = \Omega_0)]$

For the epsilon greedy agent the algorithm behaves as follows:

- It generalizes the search of a Ω_k^{min} for any $k \in [1, k_{max}]$ by choosing between exploration and exploitation randomly. For this decision, the agent uses the value of epsilon as reference to the probability of exploiting over exploring.
- Then, the value of $G_k = (V, E_k)$ is defined as a modified version of $G_{k-1} = (V, E_{k-1})$.
- In the end Ψ_k is calculated as function of Ψ_{k-1} and $[(\Omega_k < \Omega_k^{min}) \rightarrow (\Omega_k^{min} = \Omega_k)] \wedge [\neg(\Omega_k < \Omega_k^{min}) \rightarrow (\Omega_k^{min} = \Omega_k^{min})]$

Finally to obtain the best solution the algorithm ends the calculations when $k = k_{max}$ and returns Ω_k^{min}. The quality of the final its proportional to the quality of the generated Ψ_k sets and to the number of iterations used during the calculus.

6 Tests scenarios

In order to obtain a comparison data, random group of network topologies and flows are generated in order to test the performance of the resulting epsilon greedy heuristic (EE) compared to a shortest-path algorithm (SP). With the help of a network graphs generator, a set of 100 topologies are prepared for the analysis. Each graph was generated using a seed that defines a random matrix of $N \times N$ and a density Λ which can have a value in the range of $[0,1] \in \mathbb{R}$. The density value is obtained from the relationship $\Lambda = \lambda/N$ where λ represents the median nodes degree of the graph and takes values in the range of $[4,12]$. The number of vertices used for in the generation seed is a constant value of $N = 66$. The gateway is chosen as the node with the highest betweeness centrality and a subset of $n \subset N$ of field devices are configured as sensors programmed to periodically transmit data to the gateway. As part of this experiment the value of n is limited within the range of $[2,22]$. With the depicted set up, the group of shortest-path routes between the n sensors and the gateway are generated. This provides 100 instances of n possible routes.

The user defined parameter ψ adopts the same value as the grapsh density Λ and the value of 100 for k_{max} parameter of the experiments. Each of the f_i flows generated for the 100 topologies can be defined as a cluster of 4 elements $f_i = (C_i, D_i, T_i, \phi_i)$ as discussed in the Section 3.2. Each of the C_i values are directly obtained from the product of the number of hops times the path ϕ_i between the source and the destination times the number of transmissions assigned to each slot. In this work the value of the last parameter w was assumed as 2. The periods $T_i$were generated in the form of 2^p where $p \in \mathbb{N}$ in the range of $[4,7]$. Finally the value of D_i is assumed to be equal to T_i in order to obtain a implicit-deadline model.

7 Results

The performance of both EE and SP methods when optimizing the routing in the generated random graphs is described in the figures 2, 3, 4 and 5.

As it can be appreciated when comparing the performance of the proposed EE method with the SP strategy, the former is able to improve the results depicted by the later by a high margin. As shown in the Fig. 2, the node overlapping phenomenon that follows an exponential behaviour is reduced in almost 50% with this values of λ, which gives a sight that in bigger networks this mitigation will be better. The positive effects of the overlap reduction are also visible in the Fig. 4. Given the direct relationship between the overlaps and transmission conflicts, affecting one will proportionally affect the remainig. When analysing the results of the Fig. 3 it can be appreciated that the affection to the length of the routes is almost negligible and is not likely to increase in bigger networks.Finally the positive befits of the EE optimization are appreciated with the difference in the schedulability ratio bwetween the two methods.

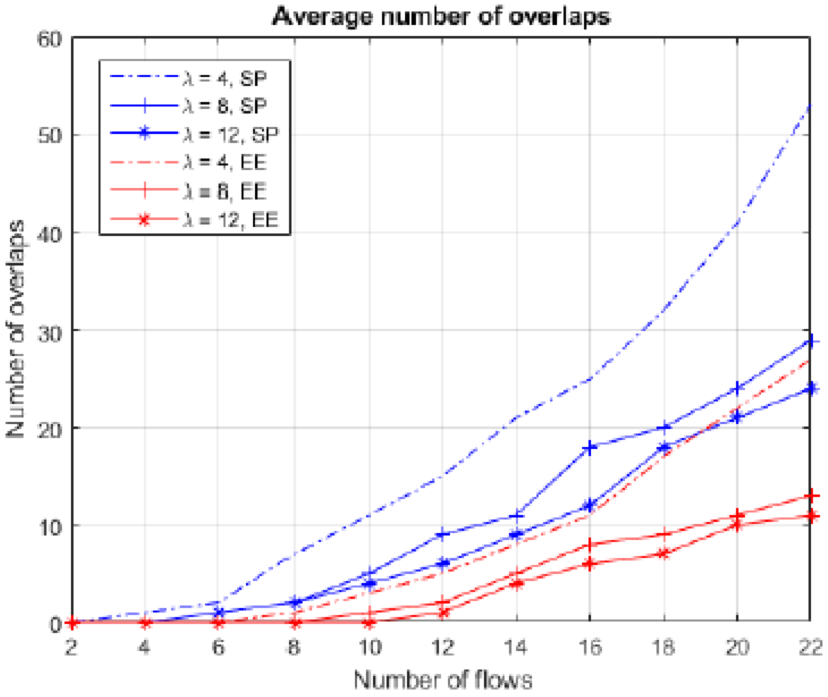

Fig. 2. Representation of the resulting average number of overlaps in the data transmission while using a variation of $\lambda = [4, 8, 12]$

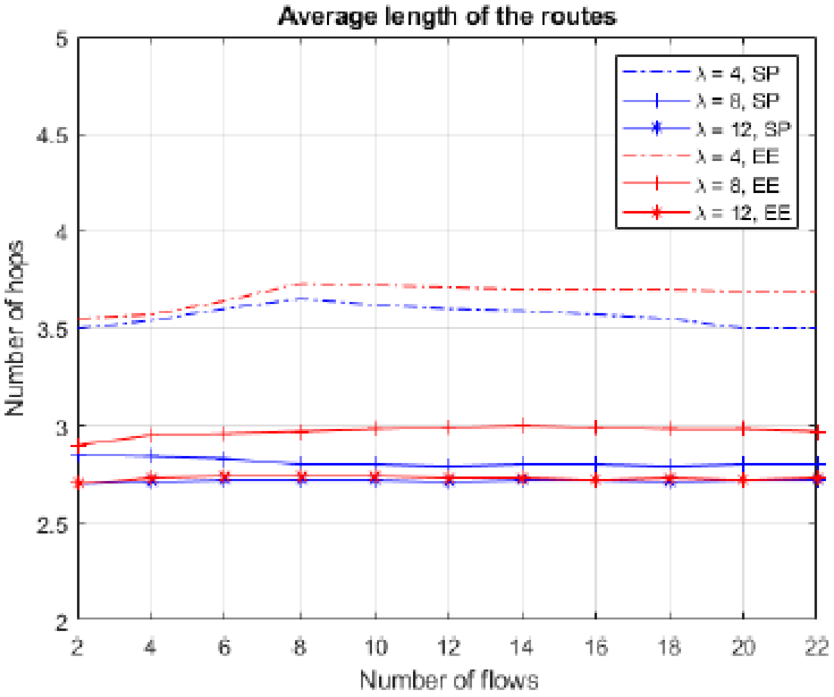

Fig. 3. Representation of the final average routes length using a variation of $\lambda = [4, 8, 12]$

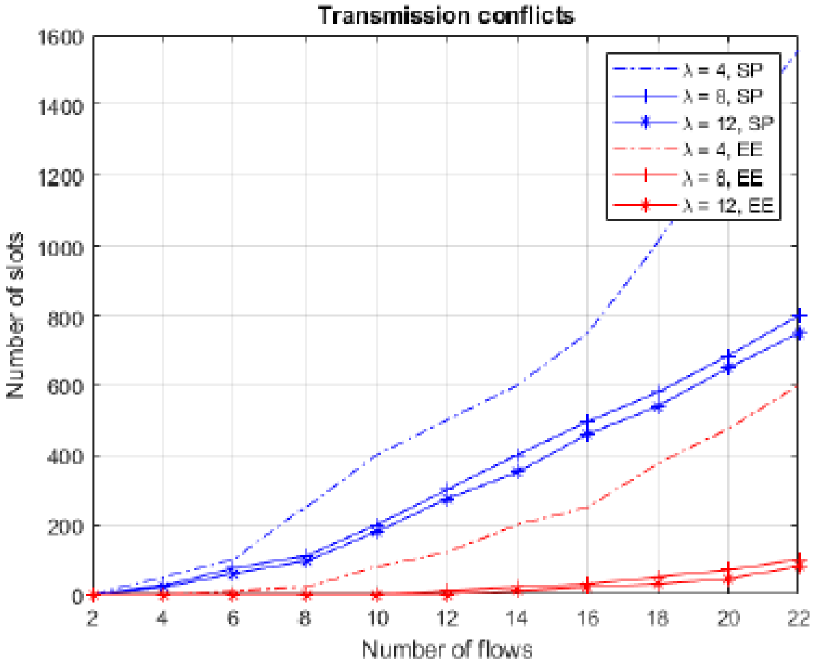

Fig. 4. Representation of the average conflict occurrence when using a variation of $\lambda = [4, 8, 12]$

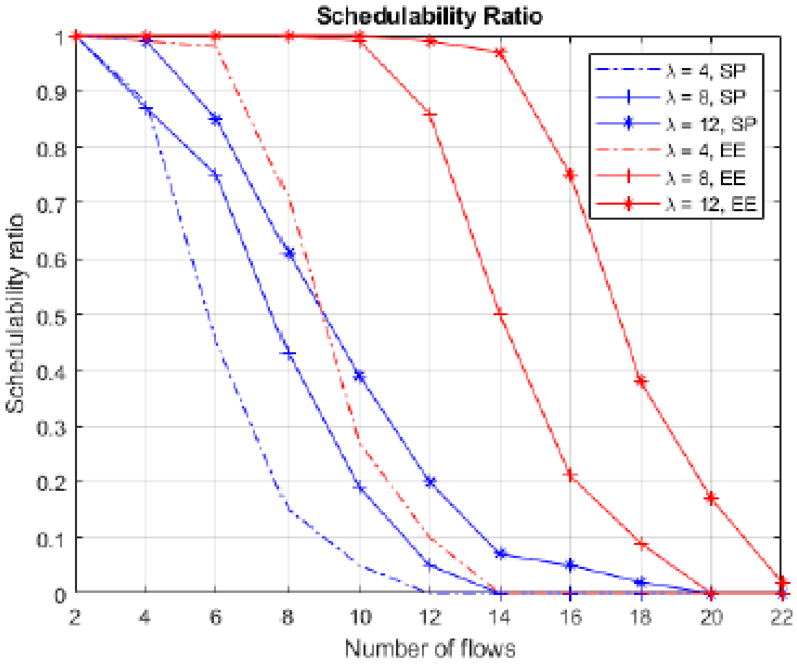

Fig. 5. Representation of final schedulability ratio while using variation of $\lambda = [4, 8, 12]$

8 Conclusions and Future Work

As final result of the present investigation work, an effective real-time routing method for WSANs based on TSCH that uses an EDF policy is developed. The usage of a greedy heuristic method allowed the final controller to improve the real-time component of the data exchange in the network. This was done by reducing the total amount of overlaps in the paths generated for the traveling information. Additionally parameters as the number of transmission conflicts and schedulability ratio were also improved as side effect of the operation of the proposed controller. It was tested with 100 randomly generated network graphs and compared with one of the most commonly used optimization methods, the hop-count method. The usage of an epsilon greedy heuristic algorithm for the minimization of overlaps in the transmission routes turned out to be an optimal network performance enhancer. After analyzing the test data of both scenarios it was clearly appreciated that the presented algorithm obtained improvements that almost reached effectiveness levels of 50%.

The positive results of the former work demonstrated that the routing process in networks can be optimized and still has room left for its growth. Theoretically, autonomous intelligent structures developed using machine learning algorithms are able to reach even higher levels of performance in tasks such as optimizing. With this in mind, the future steps in this line of investigation is the improving of the routing in WSANs with the usage of machine learning algorithms.

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5.3.3. Anexo 3 - Matriz point to point de revisores

With regards and

best wishes.

Program Secretary,

WorldS4 2021

SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks

----------------------- REVIEW 1 ---------
------------ SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks
AUTHORS: Marcelo V Garcia

----------- Overall evaluation
----------- SCORE: 2 (accept)
----- TEXT:
Much effective paper written on Optimization of the Overlap Shortest-Path Routing for TSCH Networks

- The introduction provides a good, generalized background of the study.

- Elaborate the statement in section 5
The first one, exploration allows an agent to improve its current knowledge about each action, hopefully leading to long term benefit.

- Avoid un - necessary highlighting of the words.

- Recommended for Inclusion.

----------------------- REVIEW 2 ---------
------------ SUBMISSION: 118
TITLE: Optimization of the Overlap Shortest-Path Routing for TSCH Networks
AUTHORS: Marcelo V Garcia

----------- Overall evaluation
----------- SCORE: 2 (accept)
----- TEXT:
Authors are suggested to consider the following revisions.

- Abstract is relevant and satisfactory.

- The purpose of the study should be justified as per the paper authors.

- How authors have made the use of shortest-path algorithm in the paper ?

- References are good and authors have shown their other work published also in similar area.

- Authors are requested to follow the guidelines issued by springer or the paper may be rejected by the publication board at a later stage.