The Problem of Cooperation Among Different Wireless Sensor Networks

Pedro O.S. Vaz de Melo,
Felipe D. da Cunha, Jussara M. Almeida,
and Antonio A.F. Loureiro
Federal University of Minas Gerais
Belo Horizonte, Brazil
olmo, fdcunha, jussara, loureiro
@dcc.ufmg.br

Raquel A.F. Mini
Pontifical Catholic University of Minas Gerais
Belo Horizonte, Brazil
raquelmini@pucminas.br

ABSTRACT

An important issue in the design of a wireless sensor network (WSN) is to devise techniques to make efficient use of its energy, and thus, extend its lifetime. When two WSNs are deployed at the same place and their sensors cooperate with the other networks forwarding their packets, the distance of the transmissions decreases and, therefore, the power consumption as well. The goal of this work is to examine the extent to which different WSNs can cooperate and save their energy. Simulation results reveal that different densities and data collecting rates among WSNs, the routing algorithm and the path loss exponent have major impact in the establishment of cooperation.

Categories and Subject Descriptors: I.6.6 [Simulation and Modeling]: Simulation Output Analysis

General Terms: Experimentation, Performance

Keywords: Cooperation, Wireless Sensor Networks, Simulation

1. INTRODUCTION

Mark Weiser, on his classical article *The computer for the 21st century* [11], imagined the ubiquitous computing as the future of the human-machine interaction, predicting the access to computational environments by any person, anywhere, at any moment. It is expected that computing devices should be attached to the most ordinary objects, such as clothes labels, cups of coffee, pens, or any type of personal object, completely imperceptible to the user, making their lives safer and more comfortable. And this is the context where the Wireless Sensors Network (WSN) [1] emerges as a way of making the vision of Mark Weiser with ubiquitous computing possible. WSNs are a special type of ad hoc networks that have the task of collecting data from the environment they are inserted and providing such information to the final user. The environmental data is collected by sensor nodes, that have severe restrictions in processing, memory capacity and energy, and then are transmitted to the sink node, that forwards it to the final user.

Because the sensor nodes are often powered by batteries with limited capacity and its replacement or recharge is impossible in many practical scenarios, the development of energy-efficient protocols is the major interest in the research related to WSNs. Within the energy consumption of the sensor node, the activity of data communication is the most significant [8]. Thus, techniques to reduce energy consumption in the data communication should be developed in order to extend the lifetime of sensor nodes. A simple way to save energy of a sensor node in the communication is making the sensor node communicate through multi-hop. This is done because the energy consumption varies exponentially with the distance that the data is transmitted [12]. Thus, the smaller the distance the data transmission is made, the lower the energy consumed by the sensor node that did the transmission.

One way to reduce the distance that sensor nodes communicate is increase the density of the network. The greater the density of the network, the lower the average distance between two sensor nodes in the network and less energy is needed for them to communicate. However, increasing the density of a network cannot always be feasible, since this may represent a significant cost in the design of a WSN and in its maintenance. As the ubiquitous computing predicts different networks at the same place, a way to increase the density of a WSN at a low cost is making two different WSNs use the sensor nodes from one another in the routing of their data.

When two WSNs, deployed at the same place, share their sensor nodes with the goal of making them send their messages at smaller distances, the two networks are saving their energy and extending their lifetime. Inspite of being obvious and simple, this idea brings many implications. Whereas a WSN has a rational and selfish character, it will only cooperate with other WSN if this provides services that justify the cooperation.

The objective of this work is to study the problem of cooperation between two WSNs deployed at the same place. The first contribution of this work is to identify the parameters that affect the establishment of cooperation and the benefits that the networks can get. The second contribution is a quantitative and methodical analysis of the individual and the interactive impact of four parameters considered key to the problem, which are the density and the data collection rate, the routing algorithm and path loss exponent. It was observed that different densities and data collection rates between WSNs, as well as the routing algorithm and the path loss exponent, significantly influence the establishment and the benefits the networks can obtain with the cooperation. Moreover, we show the values of these parameters that make the networks obtain benefits with the cooperation. These results may feed the future design of cooperation protocols between different WSNs.

The remainder of this paper is organized as follows. Section 2

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presents the related work. The description of the parameters that can influence the cooperation whether or not and the model of the experimental project are presented in Section 3. In Section 4, we show the results of the experimental projects. Finally, in Section 5, we present the conclusions of this work.

2. RELATED WORK

The main difference between cooperation in traditional ad-hoc networks and in WSNs is that in the first, the node acts for its own benefit alone, forwarding messages only if this will bring some benefit to it. In WSNs the node is part of a team, i.e., its network, and acts to provide benefits to it, and should forward foreign messages if this brings benefits to any node of its network.

The problem of cooperation among different WSNs was studied in [4], in which the authorities of the networks define if their sensor nodes forward packets of other networks and ask for the other networks to forward their packets, based on their data collection rate and energy consumption. The results of [4] show that the networks converge basically into two states of equilibria, a non-cooperative, which no node provides and asks for services to nodes from another network, and a cooperative, which all nodes provide and ask services to nodes from another network. Moreover, it was found that when the network is very dense, the cost of receiving dominates the cost of transmission, making the algorithm converge to the non-cooperative equilibria. It was also shown that when the environment is hostile, that is, the value of the path loss exponent is high, there are strong incentives for cooperation.

The problem of routing among sensor nodes from different WSNs was also worked by [7], that showed that if the sensor nodes declare their costs for routing packets, the networks will have incentives to cooperate and share their sensor nodes. When a sensor node routes a packet coming from other network, it receives a payment that covers his cost. This payment is a credit that makes the sensor node request routing services from other network. Despite providing relevant theoretical content, the work in [7] does not cover several practical issues, such as, for example, if a network should share its sensor nodes even if it does not need to use the sensor nodes of the other network.

Finally, another work that addresses the problem of different WSNs deployed at the same place is described in [6]. In this work, the authors consider the possibility that sensor nodes from different networks may exchange favors from a varied nature among them, such as routing, sensing, processing and storing data. Because of this, a stable and beneficial solution for both networks is only viable if the owners of the networks sign a financial contract before the network deployment. This is the major problem of this model, that goes against the proposal of ubiquitous computing, where networks are deployed and withdrawn at any moment and a control over this may be impracticable.

3. EVALUATING THE PARAMETERS

3.1 Parameters

In this section, we present the parameters that might impact on cooperation. To the best of our knowledge, this is the first work that presents a contribution to identify all the parameters that might impact on the problem of cooperation among different WSNs. The first parameter to be discussed is probably the most relevant. The **density** of the network is a prime factor in the establishment of cooperation, dictating the average distance between neighbors sensor nodes. The higher the density of the network, the smaller is the distance between the nodes and the lower the cost of transmission between them. Besides this, as the density of the networks get higher, the interference and the congestion may also grow. Moreover, when the densities among the networks are different, the benefits with the cooperation may vary among them.

Another parameter that can impact on the establishment of cooperation is the network **data collection rate**. If two networks collect data at similar rates, it is expected that both networks will take advantage of foreign sensor nodes at, also, similar frequencies. As a network has a lower data collection rate than another, this network will have its sensor nodes used at a higher frequency that the frequency the other network uses its sensor nodes. This variation may reach a point where cooperation will imply in a higher energy consumption than it would occur if the network was not cooperating.

The **type of a sensor node** is another parameter that can affect the decision of cooperation by the networks. Different types of sensor nodes have different hardware restrictions and those restrictions impact on the energy consumption. If, for example, a network have sensor nodes equipped with solar energy, this network is unlikely to have any significant incentives to cooperate with another network, that does not have any energy harvesting device. However, if a network have sensor nodes with severe energy restrictions, then this network should cooperate whenever possible, as it will probably bring benefits to it. Another parameter related to the hardware of the sensor node is the bandwidth available to it. If the bandwidth is high, the impact of forwarding a small message may be small, too. On the other hand, if the bandwidth is low, the delay of forwarding a message will be high and probably the energy consumption will be high, too.

The energy consumption of the transmission of a message is related to the power the transmission is made. The higher the **transmission power**, the higher the transmission range and the energy consumed, which is proportional to d^{α} [12], where d is the achieved distance and α is the path loss exponent. Meanwhile, the **reception power** is constant and determines how much a sensor node is capable of listening. Different wireless devices have different quotients between the energy consumption in transmissions and in receptions [3]. In general, when the distances of communication between the nodes diminish significantly, the energy spent in transmissions also significantly reduces but, in contrast, the number of hops that a message travels increases considerably. When this happens, the cost of transmission may be dominated by the cost of the reception, making the number of receptions and their energy consumption do not compensate the economy in the transmissions.

The value of the **path loss exponent** α is also a factor that impacts on cooperation and is related to the characteristics of communication environment [12]. Open areas have lower values for α as enclosed areas, with obstructions of any kind, have higher values for α. The higher the value of α, the greater the advantage for two nodes to communicate at lower distances d, since the energy consumed in the transmission is proportional to d^{α}. Thus, the value of α directly influence the cost-effective to transmit data at small distances, using multiple hops to traffic the message. The higher the number of hops, the higher the number of receptions. As the value of α increases, less is the distance needed to bring the reception cost to dominate the transmission cost and it is more likely, therefore, that cooperation brings benefits.

Also related to the cost of transmissions and receptions, the **message size** is a preponderant parameter to energy consumption. The larger the size of the message, the higher the energy consumption in the transmission and reception. Thus, the size of the message that the sensor nodes send on the network can be a decisive factor in the establishment of cooperation. The networks may have the same characteristics, but if the message size is different, one network benefit more from cooperation than the others because, while it cooperates forwarding small packets, the other cooperate forwarding their packets, that are larger.

Finally, the **routing algorithm** and their QoS parameters are significant parameter for the establishment of cooperation. In literature, there are several routing algorithms proposed for WSNs and their goals may be saving energy, reducing latency, reliability, among others [2]. For each goal and algorithm, the energy consumption with the data communication may vary and, thereby, the benefit from the cooperation. If, for example, the goal of an algorithm is to reduce the latency, the number of hops that a message travel should be as small as possible. If a WSN is using this algorithm to route their data, the cooperation with a WSN that uses a routing algorithm that prioritizes energy-saving, using the largest number of hops possible, may not become possible, once the need of a network conflicts with the need of the other.

3.2 Experimental Project Model

This section describes the model of the experimental project used to assess the impact of the parameters described in Section 3.1 in the establishment of cooperation among two WSNs N_1 and N_2 deployed at the same environment. Depending on the value of each parameter, cooperation can be beneficial to both networks, to only one, or even to no one. If the WSNs owners are capable of, through the characteristics of their networks, determine whether the cooperation will be beneficial to the networks, they may establish an agreement between them and let their sensor nodes cooperate with themselves. Moreover, knowing the impact of the parameters of cooperation, new protocols can be developed at the direction of allowing two WSNs to cooperate when this is beneficial to them.

In this work, we consider that when there is cooperation, any sensor node can and shall forward packets from other networks. Thus, the energy consumption of network N_i may be divided into the energy consumption with transmissions and the energy consumption with receptions of messages. Then, the difference ΔE_i between the energy consumption of the network when it does not cooperate and when it cooperates can be defined as $\Delta E_i = \Delta Tx_i + \Delta Rx_i$, where ΔTx_i and ΔRx_i are, respectively, the differences between the energy consumption with transmissions Tx_i^{NC} and Tx_i^{C} and receptions Rx_i^{NC} and Rx_i^{C} when, respectively, the network does not cooperate and when the network cooperates. If $\Delta E_i > 0$, the network N_i obtained benefits with the cooperation. The calculation of ΔTx_i and ΔRx_i is given, respectively, by $\Delta Tx_i = Tx_i^{NC} - Tx_i^{C}$ and $\Delta Rx_i = Rx_i^{NC} - Rx_i^{C}$.

One way to measure ΔE_i is through simulation. The biggest advantages of using simulation compared to experimenting in real systems are the low cost and high ease of changing the settings of the networks. Despite these advantages, the total number of simulations that can be performed varying each parameter at each level is almost infinite. To circumvent this, the initial assessment of the impact of the parameters is made through $2^k r$ factorial experimental projects [5], where k is the number of parameters that will be varied, called factors, r is the number of replications of the experiment and 2 is the number of levels of each factor.

A factorial project of the type $2^k r$ is an experimental project that aims to identify, among a list of parameters with a potential impact, those with major effects and if the interaction of these factors has significant effect in the variability of the data. Working on two levels per factor, the project allows, at a reasonable cost, to determine the effect of each factor and interaction with the average values of the results, and the percentage of variation in this data that is due to variation of each one of them. Moreover, there is the variability that arises because of the randomness and the experimental errors. Therefore, we must replicate r times the experiments for each configuration in order to get statistically significant results. It is an initial step to understand what, among a large number of alternatives, impacts substantially in the benefit of cooperation.

From the results of factorial projects, we are able to perform simple experimental projects [5], which are more detailed, where only one parameter is varied and the others are kept fixed. In this way, we can vary a parameter at various levels in order to quantify, and possibly predict, the impact of this parameter in general situations. This can only be done if the interaction of the factors evaluated in the factorial project is not significant, so there would be a guarantee that the results of the simple projects include only information about the parameter that was varied.

The first step for performing these experimental projects is to determine what are the factors and what are the parameters that will be kept fixed. Given the parameters described in Section 3.1, we fixed size of the messages, the type of the sensor node and its transmission and reception power. This was done because different WSNs with different configurations of these parameters can be standardized so as to become equivalent. Still, to not lose generality, it was considered that the energy consumption to transmit a message to a unit of distance d is C_{Tx} and the energy consumption to receive a message is C_{Rx}. Thus, all values related to the energy consumption with data transmissions and receptions will be, respectively, in function of C_{Tx} and C_{Rx}. The other parameters described in Section 3.1 are the factors of the experimental projects.

Finally, it is important to describe the two routing algorithms that have been implemented in the data collection process. The two algorithms are spanning trees [10] with different goals and complementary strategies. The first algorithm we call $EnergyTree$ and is the same as described in [13], in which messages are routed using routes that have the lowest energy cost with transmissions possible. The second algorithm we call $DelayTree$, and it makes the messages be delivered to the sink node with the lowest delay possible. While the algorithm $EnergyTree$ makes the message be routed with the highest number of hops possible, the algorithm $DelayTree$ does the opposite, making the sensor nodes use their transmission power at its highest level, reducing the number of hops that the message can travel to the lowest possible. For an experimental project of the type $2^k r$, it is important that the factors have significantly different levels between them.

4. SIMULATION RESULTS

In this section two $2^k r$ experimental projects are described. The first project, described in Section 4.1, called Project Density-α, measures the impact of changing the density of the networks and changing the path loss exponent α. The second project, described in Section 4.2, called Project ΔDensity-λ, measures the impact of the differences between the densities and the data collection rates among the networks for each one of implemented algorithms, the $EnergyTree$ and the $DelayTree$. Moreover, in Section 4.3, simple projects are described according to the results of Project Density-α and Project ΔDensity-λ.

All simulations were made in the simulator *Network Simulator 2.31*. Moreover, it was considered that the sensor nodes are randomly deployed, forming a flat topology in a $40 \times 20\ d^2$ sensing field for Project Density-α and $35 \times 35\ d^2$ for the other simulations. The communication range of the sensor node is 5 d and it is considered that each sensor node knows its location. The sink node, shared by the two networks, is located at the center of the topology. This node has no energy restrictions and also knows the location of all sensor nodes. During the 1000 seconds of simulation, the events are generated according to a Poisson distribution with $\lambda_{Poisson} = 0.3$ events per second, as described in [9], and are detected a single time by a single node. All of our simulation results correspond to the arithmetic mean of r simulations, where r is the smallest sample size that provided the desired confidence [5].

4.1 Project Density-α

The project of this section has as a motivation the results presented in [4]. The algorithm proposed in this work, which is the only one we know that addresses only the problem of packet forwarding cooperation among different WSNs, has not achieved satisfactory results as the density of networks increases and as the path loss exponent α decreases. It was observed, for example, that the proposed algorithm is not able to make the networks cooperate when α is 2 and when the number of sensor nodes of the networks is 50, in a $40 \times 20\ d^2$ topology.

Because of this, the Project Density-α evaluates whether, despite the results of [4], two WSNs get benefits with the cooperation when the density of the networks and the α vary. The values of ΔTx_i and ΔRx_i are calculated based on these variations, in r replications, and they are similar for both networks, since the configuration of them is identical, each one having the same number of nodes n and communicating over the same value of α. Furthermore, the routing algorithm is the $EnergyTree$ and the sensing field is $40 \times 20d^2$, which are the same parameters used in [4]. The model for the calculation of ΔTx_i and ΔRx_i is, then:

$$\begin{aligned}\Delta Tx_i &= q_0^{Tx} + q_n^{Tx} X_n + q_\alpha^{Tx} X_\alpha + q_{\alpha n}^{Tx} X_n X_\alpha + e^{Tx}\\ \Delta Rx_i &= q_0^{Rx} + q_n^{Rx} X_n + q_\alpha^{Rx} X_\alpha + q_{\alpha n}^{Rx} X_n X_\alpha + e^{Rx},\end{aligned}$$

where q_0^{Tx} and q_0^{Rx} are, respectively, the average values for ΔTx_i and ΔRx_i. The coefficients q_n^{Tx} and q_n^{Rx} are, respectively, the ones that represent the effect of the number of nodes n in the networks on the averages q_0^{Tx} and q_0^{Rx}. The coefficients q_α^{Tx} and q_α^{Rx}, in turn, are the ones that account for the effect of the α on q_0^{Tx} and q_0^{Rx}. The coefficients $q_{\alpha n}^{Tx}$ and $q_{\alpha n}^{Rx}$ are those that account for the effect of the interaction between the two factors on q_0^{Tx} and q_0^{Rx}, respectively. The constants e^{Tx} and e^{Rx} are the experimental errors of the models. X_n and X_α are, respectively, categorical variables that assume values -1 and 1 to indicate the level of the factors n and α, and are described in the Table 1.

Table 1: Configuration based on X_n and X_α

X_n , X_α	n	α
-1	50	2
1	200	4

The Table 2, which was made in the form of the result tables described in [5], describes the results of the Project Density-α. Each line shows the average values of ΔTx_i, which is based on C_{Tx}, and ΔRx_i, which is based on C_{Rx}, obtained from r simulations for each configuration defined by the levels of n and α, given by X_n and X_α, respectively. Thus, the first line shows the average values of ΔTx_i and ΔRx_i when X_n and X_α are -1, that is, n is 50 and α is 2. The line q^{Tx} (q^{Rx}) presents the effect of each factor over the average values of ΔTx_i (ΔRx_i), while the line $\%q^{Tx}$ ($\%q^{Rx}$) represents the percentage of the variation of the data explained by each factor, indicating, then, the impact of the factors on the values of ΔTx_i and ΔRx_i. Thus, the coefficient q_n^{Tx} is -9.61×10^6, indicating that when the value of X_n is -1 ($n = 50$), ΔTx_i is added by -9.61×10^6, and when X_n is 1 ($n = 200$), ΔTx_i is subtracted by 9.61×10^6. The column $X_n X_\alpha$ presents the results of the interaction between the two factors. We can observe that while the cooperation has resulted in positive values for ΔTx_i, it resulted in negative values for ΔRx_i, as expected. We can also observe that the coefficient q_n^{Tx} is negative, indicating that the benefit in transmissions with the cooperation decreases as the density of the two networks increases. This occurs because the smaller the density of networks, the greater the distance among the nodes and the larger are the benefits of increasing the number of hops that the messages are routed. This may also be proved by the high percentage of the variation explained by the coefficient $q_{\alpha n}^{Tx}$, of 24%, indicating that decreasing the density and increasing the value of α implies in a higher gain with the cooperation.

Table 2: Results of the Project Density-α

X_n	X_α	$X_n X_\alpha$	ΔTx_i	ΔRx_i
-1	-1	1	$6,94 \times 10^2$	$-5,59 \times 10^2$
-1	1	-1	$4,42 \times 10^7$	$-7,51 \times 10^2$
1	-1	-1	$3,67 \times 10^3$	$-1,18 \times 10^3$
1	1	1	$5,76 \times 10^6$	$-1,83 \times 10^3$
$-9,61$	$12,5$	$-9,61$	$\boldsymbol{q^{Tx}(\times 10^6)}$	-
24%	40%	24%	$\boldsymbol{\%q^{Tx}}$	-
$-4,25$	$-2,11$	$-1,15$	-	$\boldsymbol{q^{Rx}(\times 10^2)}$
40%	10%	3%	-	$\boldsymbol{\%q^{Rx}}$

As for the metric ΔRx_i, besides the fact that it is negative for all configurations, we can also observe that the coefficient q_0^{Rx} is an order of magnitude higher than the other coefficients. This indicates that cooperation by itself, regardless of the value of n and α, already induces a significant increase in the amount of receptions, which also explains the high value of the percentage of the variation explained by e^{Rx}, which is $100\% - 53\% = 47\%$. The only factor that affects significantly the average is n, once increasing the density of the network also increases the number of the possible hops a message can travel.

An interesting conclusion from the results of this project is related to the quotient C_{Tx}/C_{Rx}. In the case that the difference between ΔRx_i and ΔTx_i is the smallest, the quotient C_{Tx}/C_{Rx} must be greater than $0,8$ to ΔE_i be greater than 0, that is, for cooperation to be beneficial. This shows that, despite the results of [4], which the proposed algorithm does not reach states of cooperation when $n = 50$ and $\alpha = 2$, there is much to explore in the problem of cooperation among different WSNs.

From the Project Density-α we also conclude that the density of the networks, the path loss exponent and their interaction significant influences on ΔTx. As for the ΔRx, we conclude that only the density presents a significant impact, but that is still lower than the impact of the experimental errors. This leads to the need for new experiments, so that the impact of the density of the networks can be evaluated separately for different values of the path loss exponent, since the interaction of them is high. We hope that these experiments precisely explain the high value of the percentage of variation explained by e^{Rx} in ΔRx. These experiments are described in Section 4.3.

4.2 Project ΔDensity-λ

The project of the previous section considers that the configuration of the two networks is identical, which rarely makes the cooperation not to be beneficial. In this section we describe the Project ΔDensity-λ, which aims to assess the impact of the factors in ΔTx and ΔRx when the configuration of the networks is different. The factors of this project are the quotient between the densities of the networks δn, the quotient of the data collection rates of the networks $\delta\lambda$ and the routing algorithm that both use, $EnergyTree$ and $DelayTree$.

In order to capture the impact related to the differences between the networks, only one of the two will have its configuration varied. The network that will have its configuration fixed will be, by definition, the network N_1 and the network that will have its configuration varied will be the network N_2. Thus, the factors are responsible for changing the configuration of the network N_2 to undermine the benefits that the network N_1 will have by cooperating. When δn is 0.5, the network N_2 has half of the sensor nodes of the network N_1 and, when $\delta\lambda$ is 2, the network N_2 collects data at a rate two times higher than the network N_1. The model that describes ΔTx_1 and ΔRx_1 for the experimental project of this section is similar to the one described in the previous section. The table 3 describes the values that the factors δn, $\delta\lambda$ and routing algorithm can have. When δn is 0.5, the network N_2 has half of the sensors that the network 1 has and, when $\delta\lambda$ is 2, the network N_2 collect data at a rate two times higher than the network N_1.

Table 3: Configuration based on X_δ, X_λ, X_R

X_δ, X_λ, X_R	δn	$\delta\lambda$	Routing Algorithm
-1	0, 5	2	$DelayTree$
1	1	1	$EnergyTree$

Table 4 presents the results obtained from the Project ΔDensity-λ. We can observe that the three factors can be considered significant, and that when the network N_2 has its density reduced and/or its data collection rate increased, the value of ΔTx_1 decreases, as it was expected. Moreover, we can verify that although the use of the algorithm $DelayTree$ diminishes the value of ΔTx_1, when the densities and the data collection rates are the same between the networks, this algorithm presents the highest value for ΔE_1 in the results of this project, with the network N_1 saving its energy consumption even on receptions, indicating that its is worthy to cooperate independently of quotient C_{Tx}/C_{Rx}.

As for the variation of ΔRx_1, we can observe that the network N_1 always consumes more energy with receptions when their sensor nodes were cooperating and forwarding messages from the network N_2, except when the algorithm used by them is the $DelayTree$ and their densities and data collection rates are the same. Moreover, the algorithm is also the factor of the highest impact in ΔTx_1, indicating that this should be carefully considered in the development of protocols for cooperation between different WSNs. The value of the parameter δn also has a significant impact on ΔRx_1, because as the density of the network N_2 decreases, more nodes from the network N_1 have to route messages coming from the network N_2. Finally, except in the case which the densities and the data collection rates of the two networks are equal, the value of ΔE_1 is always negative, indicating that the network always loses with the cooperation, regardless the quotient C_{Tx}/C_{Rx}.

Table 4: Results of Project ΔDensity-λ

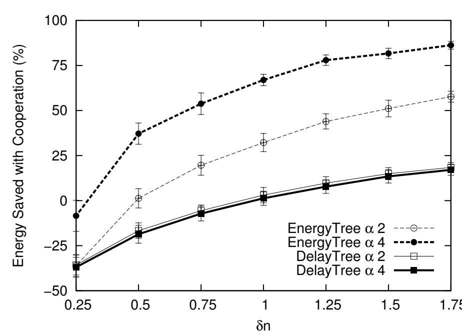
X_δ	X_λ	X_R	ΔTx_1	ΔRx_1
-1	-1	-1	-1.44×10^5	-8.03×10^2
-1	-1	1	-5.84×10^3	-3.60×10^3
-1	1	-1	-5.23×10^3	-2.84×10^2
-1	1	1	-1.69×10^2	-2.90×10^3
1	-1	-1	-4.79×10^4	-2.84×10^2
1	-1	1	-67.91	-1.48×10^3
1	1	-1	1.05×10^3	96.57
1	1	1	3.75×10^3	-1.07×10^3
3.19	3.06	2.63	$q^{Tx}(\times 10^3)$	-
0.34	0.31	0.23	$\%q^{Tx}$	-
0.62	0.26	-0.96	-	$q^{Rx}(\times 10^3)$
0.25	0.05	0.60	-	$\%q^{Rx}$

From the Project ΔDensity-λ we can conclude that the factors δn, $\delta\lambda$ and routing algorithm are significant to explain the variation of the value of ΔTx. For ΔRx, only the routing algorithm and the factor δn were significant. A common point in the two metrics is that, in the way the simulations were designed, the interaction of the factors was not significant, so that they can be evaluated individually and, from this, we can quantify the gain or loss that each of the factors imply on ΔTx and ΔRx. The results of this evaluation will be described in the next section.

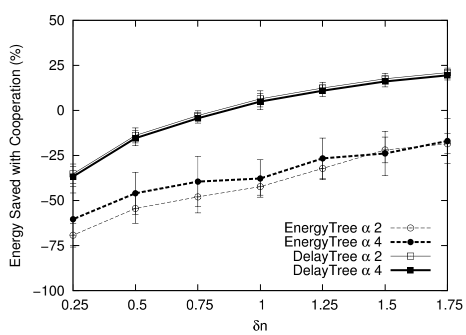
4.3 Individual Evaluation of the Parameters

Once seen that different densities and data collection rates among WSNs, as well as the routing algorithm and the path loss exponent α, significantly influence the establishment of cooperation, it is necessary to evaluate the performance of each of these factors alone. As the interaction of the factors with the routing algorithm and with the path loss exponent were the most significant in the factorial projects, they will be treated separately. So, in this section, the simulation results exhibit the behavior of the energy saving in transmissions and receptions for both routing algorithms implemented, $EnergyTree$ and $DelayTree$, each one communicating with two values of α, 2 and 4. We evaluate the percentage of energy savings in transmission and reception from measured values of ΔTx_1 and ΔRx_1 that describe, respectively, how much the network N_1 won or lost with the cooperation on its energy consumption with transmissions and receptions of messages. The vertical lines in the points of the graphics of this section represent, for each value, a confidence interval of 95%.

As done in the Project ΔDensity-λ, in the following results, the network N_1 maintains its configuration fixed and network N_2 has its configuration varied. The factor δn and the factor $\delta\lambda$ imply, respectively, the number of times that the density and the data collection rate of the network N_2 is greater than the one of the network N_1. Figures 1-a and 1-b illustrate, respectively, the impact of the factor δn in the values of ΔTx_1 and ΔRx_1. We can observe that the value of α do not impact on the energy savings when the routing algorithm used is the $DelayTree$ and this value impacts significantly when the routing algorithm used is the $EnergyTree$. This occurs because, while the $DelayTree$ algorithm does not consider the energy consumption in the process of generating the spanning tree, the algorithm $EnergyTree$ considers, being influenced by the value of α. However, because the confidence intervals are overlap, the value of ΔRx_1 is similar in the routing algorithms for the two values of α, once the number of hops that a message travels is similar despite the α influence on the routes.



(a) Savings over ΔTx_1



(b) Savings over ΔRx_1

Figure 1: Energy savings reached from the variation of δn

It is also important to point out that when the routing algorithm used is the $DelayTree$, the network N_1 saves energy in transmissions with the cooperation only after the value of δn is higher or equal to 1, and still, in a not significant way, taking into account the high value of δn. On the other hand, when the algorithm used is the $EnergyTree$, the network N_1 saves energy in transmissions with the cooperation even when the value of δn is lower than 1. When the value of α is 4, the network N_1 saves its energy in transmission even when the density of the network N_2 is a third of its own and it may yet achieve a saving of 80% when the density of the network N_2 is 75% greater than its own. In contrast, the algorithm $EnergyTree$ always makes the network N_1 consume more with reception of messages, because the simple fact of establishing cooperation increases the density of the network and, therefore, increases the number of hops that messages travel, increasing the number of receptions. However, the algorithm $DelayTree$ is even able to make the network N_1 save energy with receptions when the value of δn is greater or equal to 1. Finally, it is important to point out that the growth of the curves illustrated in Figure 1 is similar to a logarithmic growth.

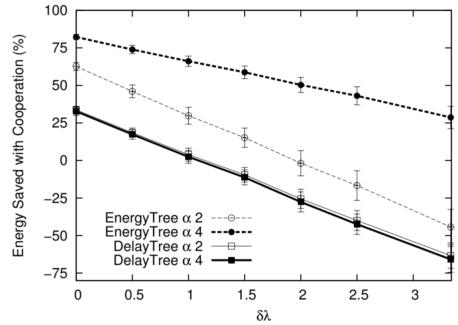
Figures 2-a and 2-b illustrate, respectively, the impact of the factor $\delta\lambda$ in the value of ΔTx_1 and ΔRx_1. We can observe that the value of α does not impact on the value of ΔRx_1, because the value of α does not affect the number of hops that a message travels when the number of events of the networks is changed. Moreover, we can also observe that the value of α do not impact on ΔTx_1 for the $DelayTree$, because this algorithm does not consider the value of the energy consumed in the transmissions in the generation of its spanning tree. An important observation about the $DelayTree$ is that the value of $\delta\lambda = 1$ defines values of $\delta\lambda$ for which the network N_1 saves and does not save energy in transmissions when cooperating. When the routing algorithm is the $EnergyTree$, the network N_2 may have a data collection rate twice as high when $\alpha = 2$ and three times higher when $\alpha = 4$, and still the network N_1 saves its energy in transmissions when cooperating.

Regarding the energy savings in receptions, again the value of $\delta\lambda = 1$ divides values of $\delta\lambda$ for which the network N_1 saves and does not save energy when using the algorithm $DelayTree$. In turn, the algorithm $EnergyTree$ only saves energy in receptions when $\delta\lambda$ is close to 0, that is, when the data collection rate of the network N_2 is not significant, showing that cooperation has a relevant impact on the increase of the energy consumption of receptions for this algorithm. Finally, the curves illustrated in Figure 2 show a linear variation in relation to the value of $\delta\lambda$.

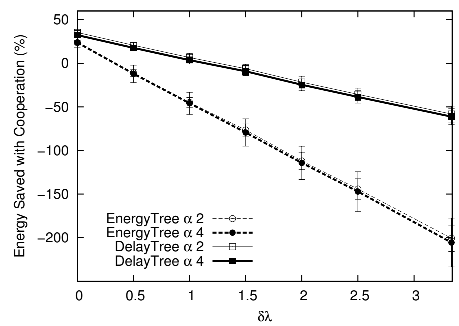
In this section we have shown that the energy savings with the cooperation for a network has a logarithmic grow as we increase the density of the other network. Finally, when we increase the data collection rate of a network, the other shows a linear decrease in its energy savings with the cooperation. The routing algorithm and the path loss exponent α are almost constant factors in determining the energy savings of a network for the analyzed metrics and implemented routing algorithms.

5. CONCLUSIONS

This work is a methodical and quantitative study of the problem of cooperation between different WSNs deployed at the same place. Theoretically, when different WSNs are deployed at the same place and these cooperate to make their sensor nodes forward messages coming from other networks, all networks receive benefits, as their reduce average transmission distances and, consequently, the energy consumption also reduces. But this is not always true, because depending on the configuration of each network, cooperation cannot be beneficial to all and then, it may not happen.



(a) Savings over ΔTx_1



(b) Savings over ΔRx_1

Figure 2: Energy savings reached from the variation of $\delta\lambda$

We presented experimental projects that evaluate the impact of different parameters on the establishment of cooperation. Simulation results showed that cooperation between WSNs with different densities and data collection rates may not be beneficial to all of the networks, depending on the value of these factors. Moreover, we show that the routing algorithm can significantly influence on the benefit of cooperation and should then be considered relevant on the design of a protocol to make different WSNs cooperate.

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