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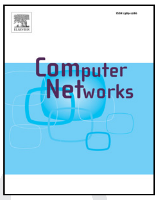

Hierarchical, collaborative wireless energy transfer in sensor networks with multiple Mobile Chargers☆

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ABSTRACT

Wireless energy transfer is used to fundamentally address energy management problems in Wireless Rechargeable Sensor Networks (WRSNs). In such networks mobile entities traverse the network and wirelessly replenish the energy of sensor nodes. In recent research on collaborative wireless charging, the mobile entities are also allowed to charge each other.

In this work, we enhance the collaborative feature by forming a hierarchical charging structure. We distinguish the Chargers in two groups, the hierarchically lower Mobile Chargers which charge sensor nodes and the hierarchically higher Special Chargers which charge Mobile Chargers. We define the Coordination Decision Problem and prove that it is NP-complete. Also, we propose a new protocol for 1-D networks which we compare with a state of the art protocol. Motivated by the improvement in 1-D networks, we propose and implement four new collaborative charging protocols for 2-D networks, in order to achieve efficient charging and improve important network properties. Our protocols are either centralized or distributed, and assume different levels of network knowledge.

Extensive simulation findings demonstrate significant performance gains, with respect to non-collaborative state of the art charging methods. In particular, our protocols improve several network properties and metrics, such as the network lifetime, routing robustness, coverage and connectivity. A useful feature of our methods is that they can be suitably added on top of non-collaborative protocols to further enhance their performance.

1. Introduction and contribution

In Wireless Sensors Networks (WSNs) the sensor nodes are equipped with small batteries and thus, the lifetime of the network is limited. Although there are several approaches that try to address this fundamental problem, the proposed solutions are still limited since the energy that is replenished is either uncontrollable (such as environmental harvesting approaches) or require the nodes to be accessible by people or robots in a very accurate way (such as battery replacement approaches).

However, the breakthrough of wireless energy transfer technology (see e.g. [2]) combined with rechargeable batteries with high energy density and high charge/discharge capabilities [3], has managed to directly address energy management and led to the paradigm of Wireless Rechargeable Sensor Networks (WRSNs). In such networks, special entities (called Chargers) are able to charge sensor nodes wirelessly. This procedure is called wireless charging. Thus, the limited available energy can be managed in a controllable and more efficient manner. This option introduced some new aspects that need investigation such

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☆ A preliminary version of this paper appeared in [1].

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as how Chargers should be deployed, how much energy each Charger should transfer to each sensor node or what is the minimum number of required Chargers in order to improve network properties such as lifetime, connectivity and coverage.

Another critical aspect that needs investigation is the effect of the exposure on the electromagnetic radiation, occurred by wireless energy transfer, in human health. Wireless charging may address more efficiently the problem of limited energy with respect to network properties if we use Mobile Chargers instead of simple Chargers. Mobile Chargers are called the devices which are able to both charge sensor nodes wirelessly and move throughout the network. This new capability introduced some additional options that need investigation such as how Mobile Chargers can coordinate or which is the trajectory that each Mobile Charger should follow.

The collaborative mobile charging approach proposed in [4] offers even more useful options. In this new charging method, Mobile Chargers are allowed to charge not only sensor nodes but also other Mobile Chargers. This new capability has been proven very important, since it provides better exploitation of the potentially limited available energy supplies.

The problem. Let a WRSN comprised of stationary sensor nodes and Mobile Chargers that can either charge the nodes or charge each other (collaborative charging). The transformation of the flat collaborative charging scheme to a hierarchical one (hierarchical, collaborative charging) imports new challenges for the network energy management. We aim at designing efficient protocols for the Mobile Chargers' coordination and charging procedure, in order to efficiently distribute and manage the available finite energy, prolong the network lifetime and improve key network properties such as coverage, routing robustness and network connectivity.

Our contribution. Since collaboration provides an efficient energy management potential, we envision collaboration in a hierarchical structure. More specifically, we propose a partition of Chargers into two groups, the hierarchically lower Mobile Chargers, that are responsible for transferring energy only to sensor nodes and the hierarchically higher Special Chargers that are responsible for transferring energy to Mobile Chargers. Using our hierarchical charging model, we first propose a protocol for 1-D networks that achieves a better performance ratio than known state of the art protocols, when the available energy supplies are limited.

Motivated by the improvement in 1-D networks we propose four protocols for 2-D networks as well. Our protocols differ on the available network's knowledge level (2-level knowledge, 1-level knowledge and no knowledge) as well as on their coordination procedure (distributed or centralized). Our No Knowledge No Coordination (NKNC) protocol actually serves as a performance lower bound since it assumes no network knowledge and does not perform any coordination. In contrast, our 2-Level Knowledge Centralized Coordination (2KCC) protocol assumes 2-level knowledge and performs centralized coordination. In between, our 2-Level Knowledge Distributed Coordination (2KDC) and 1-Level Knowledge Distributed Coordination (1KDC) protocols both perform distributed coordination but, since they assume different knowledge level, their coordination and charging procedures differ.

Moreover, the hierarchical solution that we provide can be easily added on top of non-collaborative protocols to further improve their performance (by applying the necessary transformations which depends on the existing charging model). In particular, we enhance a known state of the art protocol that does not use any collaboration, by adding a hierarchical collaborative charging structure and we show the added value of hierarchy.

2. Related work and comparison

Wireless energy transfer technology inspired a lot of researchers to investigate how to exploit it in WSNs efficiently. In [5], the authors used a realistic scenario where the sensor nodes are mobile and the Chargers are stationary. They proposed two protocols to address the problem of how to schedule the Chargers activity so as to maximize either the charging efficiency or the energy balance. Also, they conducted real experiments to evaluate the protocols' performance. In [6], the objective was to find a Charger placement and a corresponding power allocation to maximize the charging quality. They proved that their problem (called P^3) is NP-hard and proposed two approximation algorithms for P^3 (with and without fixed power levels) and an approximation algorithm for an extended version of P^3.

However, the exposure on the electromagnetic radiation that is caused by wireless energy transfer may lead to undesired phenomena for human health. That is why there are a lot of works that investigate this aspect and try to control the electromagnetic radiation. More specifically, in [7] the authors studied the Low Radiation Efficient Charging Problem in which they optimized the amount of "useful" energy that is transferred to nodes with respect to the maximum level of imposed radiation. In [8], the authors investigated the charging efficiency problem under electromagnetic radiation safety concern. More specifically, they formulated the Safe Charging Problem (SCP) of how to schedule the Chargers in order to increase the received power while there is no location in the field where the electromagnetic radiation exceeds a threshold value. They proved the hardness of SCP and proposed a solution which outperforms the optimal one with a relaxed threshold. Also, to evaluate the effectiveness of their solution, they conducted both simulations and real experiments.

The same research group in [9] studied the Safe Charging with Adjustable PowEr (SCAPE) problem which refers on how to adjust the power of the Chargers in order to maximize the charging utility of the devices while assuring that electromagnetic radiation intensity at any location on the field does not exceed a threshold value. They also proposed an (1-ϵ)-approximation algorithm for the problem and conducted simulations and real experiments to evaluate the algorithm's performance.

Although all above works have studied a variety of problems caused by wireless energy transfer and try to maximize the received power by the sensor nodes under various constraints, the usage of stationary Chargers does not exploit all the capabilities of the technology. The hard-

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ware device that is able to send energy wirelessly can be easily placed on top of a mobile robot ad thus transformed to a new mobile entity called Mobile Charger. Mobile Chargers are able to move throughout the network and charge the sensor nodes. The main difference between our work and all mentioned state of the art studies is that we use Mobile Chargers instead of stationary Chargers.

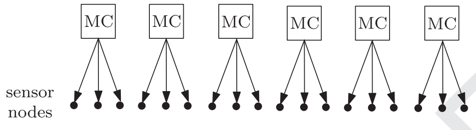
In [10–14] there has been considerable research work using a single Mobile Charger. In [10] the authors proposed a practical and efficient joint routing and charging scheme, where there are periodical information exchanges between nodes and the Charger on which the latter is based to schedule its charging activities. The approach in [11] proposed to utilize mobility for joint energy replenishment and data gathering. In [12], the authors studied the impact of the charging process to the network lifetime for a set of routing protocols by proposing a protocol that locally adapts the circular trajectory of the Mobile Charger to the energy dissipation rate of each sub-region of the network. In [13], the authors proposed distributed and adaptive protocols that use limited network information for efficient recharging. In [14], individual sensor nodes request charging from the Mobile Charger when their energy runs low.

All above works do not take advantage of the network capability to support more than one Mobile Chargers. Such approach is vital for the lifetime prolongation of large networks that consist of several thousand nodes (their maintenance is not feasible using only one Mobile Charger). In contrast to previous works, we use multiple Mobile Chargers in order to further exploit the network capabilities.

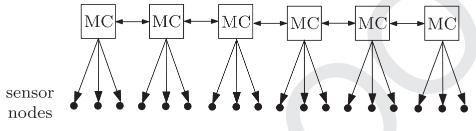
Proposed solutions with multiple Mobile Chargers have been presented in [15–18]. More specifically, in [15] the authors leveraged concepts and mechanisms from Named Data Networking (NDN) in order to design energy monitoring protocols that deliver energy status information to Mobile Chargers in an efficient manner. In [16], the authors studied how multiple Mobile Chargers can periodically coordinate and partition the sensor nodes in a balanced manner, according to their energy and adapt to network energy consumption. The proposed protocols were either distributed or centralized and used varying levels of network knowledge. In [17], the authors consider the minimum number of Mobile Chargers problem in a general 2-D network so as to keep the network running forever. More specifically, they partitioned the sensor nodes in subsets, one for each Mobile Charger such that any Mobile Charger, at each own period, visits its corresponding sensors, charges them and then gets back to the base station to recharge it's own battery.

In [18] the authors studied the recharging schedule that maximizes the recharge profit. Although there are a lot of works that make the realistic assumption of Mobile Chargers' battery constraints, in this work, the authors also introduce an other realistic assumption, that of Mobile Chargers' movement cost.

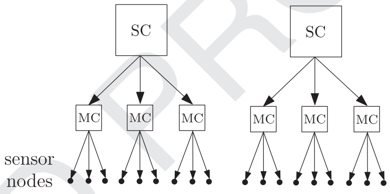
The usage of multiple Mobile Chargers without collaboration also does not exploit all capabilities of WRSNs. There is a work in the state of the art (in [4]) where the authors introduce a new charging paradigm, that of collaborative mobile charging, where Mobile Chargers are allowed to charge each other. They investigate the problem of scheduling multiple Mobile Chargers which collaboratively charge nodes over 1-D WRSNs, to maximize the ratio of the amount of payload energy to overhead energy, such that no sensor runs out of energy. However, in contrast to our work, they restrict their algorithms only in 1-D networks.



(a) Charging model with multiple Mobile Chargers.



(b) Collaborative charging model.



(c) Hierarchical, collaborative charging model.

Fig. 1. Energy flow models.

A preliminary version of this work has appeared in [1]. Here, we extend it by providing a variety of additional simulation results (different metrics and parameters), the proof that our problem is NP-complete and a more accurate and detailed bibliography review.

3. The model

Our model features four types of devices: N stationary sensor nodes, M Mobile Chargers which charge sensor nodes, S Special Chargers which charge Mobile Chargers and a single stationary Sink. The sensor nodes of wireless communication range r are uniformly distributed at random in a circular area of radius R. The Mobile Chargers and the Special Chargers are initially deployed at the center of circular area. The Sink serves only as data collector.

In our model, we assume that neither the Mobile Chargers nor the Special Chargers perform any data gathering process. Fig. 1 depicts the energy flow in *three different charging models*, including simple charging in WRSNs using multiple mobile Chargers (Fig. 1a), collaborative mobile charging (Fig. 1b) and our hierarchical collaborative charging model (Fig. 1c). The arrows abstract the energy flow from one device to another. The hierarchy of the charging model we propose is shown in Fig. 1c in which the Special Chargers that are the highest devices in terms of hierarchy can charge the Mobile Chargers and the Mobile Chargers can charge the sensor nodes. More specifically, the approach in Fig. 1a where each Mobile Charger charges its corresponding sensor nodes may lead to non-efficient energy management since if there is a Mobile Charger that

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consumes its energy with higher rate than others (e.g. its area is more critical), then the network will be disconnected despite the fact that there is still an amount of unused energy available to the network. In Fig. 1b, there is an improvement on energy management since Chargers may charge each other and so critical ones will be charged by others avoiding network disconnection. However, in Fig. 1c there is a more efficient energy utilization since it both provides a balanced energy consumption rate between Chargers and captures critical aspects of the network e.g. reduce the amount of energy used for movement.

We denote by E_{total} the total, finite, available energy in the network. Initially,

$$E_{total} = E_{sensors} + E_{MC}(t_{init}) + E_{SC}(t_{init}),$$

where $E_{sensors}$ is the total amount of energy shared among the sensor nodes, $E_{MC}(t_{init})$ is the total amount of energy shared among the Mobile Chargers and $E_{SC}(t_{init})$ is the total amount of energy shared among the Special Chargers. The maximum amount of energy that a single node, a single Mobile Charger and a single Special Charger may store is E_{sensor}^{max}, E_{MC}^{max} and E_{SC}^{max} respectively. Energy is uniformly split among the sensor nodes and the Chargers as follows:

$$E_{sensor}^{max} = \frac{E_{sensors}}{N}, \quad E_{MC}^{max} = \frac{E_{MC}(t_{init})}{M}$$
$$and \quad E_{SC}^{max} = \frac{E_{SC}(t_{init})}{S}.$$

At first, we deploy the sensor nodes uniformly in the circular network. Then, we divide our network into M equal sized slices, one for each Mobile Charger. Thus, every Mobile Charger is responsible for charging nodes that belong to its slice. We denote by D_j the set of sensor nodes that belong to slice j, i.e. to the jth Mobile Charger's group. Finally, we divide the Mobile Charges into S groups, one for each Special Charger. Thus, each Special Charger is responsible for charging the Mobile Chargers that belong to its group, denoted as C_k (for SC_k). Initially, these S groups are equally sized, i.e.

$$|\mathcal{C}_k| = \frac{M}{S} \quad (1 \le k \le S)$$

and the Mobile Chargers that belong to each group are given by the following formula:

$$\mathcal{C}_k = \left\{ j : j \in \left[(k-1)\frac{M}{S} + 1 \; , \; k\frac{M}{S} \right] \right\}, \quad (1 \le k \le S)$$

These groups may change during the protocol's coordination phase. More specifically, the Special Chargers communicate with each other and decide, according to their energy status, if they are still able to be in charge of the Mobile Chargers that belong to their group or they should delegate some of them to other Special Chargers.

The network operates under a quite heterogeneous data generation model. The energy consumption due to data generation is non-uniform between the nodes. Moreover, the underlying routing protocol is the multihop one (e.g. [19]) and so, the energy consumption for transferring the data to the Sink is also different between the nodes. In our model, the charging is performed point-to-point, i.e. only one sensor node may be charged at a time from a Mobile Charger, by approaching it at a suitably small distance so that the charging process is conducted with maximum efficiency (charging efficiency $\simeq 1$). Also, one Special Charger can charge one Mobile Charger at a time by approaching it very close. The time that elapses during the Charger's movement is considered to be very small compared to the charging time.

4. The coordination decision problem

Definition 1. Consider a set $\mathcal{S}$ of S Special Chargers. For each $SC_k (1 \le k \le S)$, we denote by $\mathcal{E}_k$ the percentage of its current energy level to the total amount of energy of all Special Chargers i.e.,

$$\mathcal{E}_k = \frac{E_{SC_k}}{\sum_{i=1}^{S} E_{SC_i}} \quad (1 \le k \le S).$$

Also, consider a set $\mathcal{M}$ of M Mobile Chargers. For each $MC_j (1 \le j \le M)$, we define $E_{MC_j}^{lack} = E_{MC}^{max} - E_{MC_j}$ the amount of energy that Mobile Charger j can receive until it is fully recharged and denote by ε_j the percentage of its energy lack to the total energy lack of all Mobile Chargers, i.e.,

$$\varepsilon_j = \frac{E_{MC_j}^{lack}}{\sum_{i=1}^{M} E_{MC_i}^{lack}} \quad (1 \le j \le M).$$

The Coordination Decision Problem (CDP) is to determine whether there exists a partition of the Mobile Chargers into S disjoint subsets, i.e. $\mathcal{X} = (\mathcal{X}_1, \ldots, \mathcal{X}_S)$ with

$$\bigcup_{k=1}^{S} \mathcal{X}_k = \mathcal{M}$$

such that

$$\sum_{j \in \mathcal{X}_k} \varepsilon_j = \mathcal{E}_k \quad (1 \le k \le S).$$

In other words, the problem is to determine whether there exists a partition of Mobile Chargers in S groups, one for each Special Charger, such that every Mobile Charger belongs to the group of exactly one Special Charger and for every Special Charger, the sum of percentages of the Mobile Chargers that belong to its corresponding group equals its percentage of current energy.

Theorem 1. *CDP is NP-complete.*

Proof.

(1) Given a partition $\mathcal{Y} = (\mathcal{Y}_1, \ldots, \mathcal{Y}_S)$ of Mobile Chargers into S groups, we can verify in polynomial time whether, for this partition, the groups are pairwise disjoint and the sum of percentages ε_j in a group equals the percentage of the corresponding Special Charger for every group. More precisely, for every Mobile Charger, we check all groups and verify if it belongs to exactly one group. If there is at least one Mobile Charger that does not belong to any group or belongs to more than one group then the given partition is incorrect. This takes $O(M)$ time and for all Mobile Chargers takes $O(M^2)$ time. Also, we examine for every group k if $\sum_{j \in \mathcal{Y}_k} \varepsilon_j = \mathcal{E}_k$. This computation takes at most $O(M)$ time. So, given a partition

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we can answer in $O(M^2)$ time if the partition is correct or not. Therefore CDP $\in$ NP.

(2) Assume a special case of the CDP where all Mobile Chargers have the same percentage of energy $\mathcal{E}_k = \mathcal{E}$. If this special case is NP-hard then the generic CDP is also NP-hard. In order to prove the hardness of CDP, we reduce the *Bin Packing Decision Problem* (BPDP) to it. An instance of the BPDP is the following: k is the number of bins, V is the capacity of each bin, Z is the number of items and x_i $(1 \leq i \leq Z)$ is the size of each item. We create an instance of CDP as follows: $S = k$ is the number of Special Chargers, $\mathcal{E} = V$ is the percentage for every Special Charger, $M = Z$ is the number of Mobile Chargers and $\varepsilon_j = x_j$ are the percentages of every Mobile Charger. A solution to this instance of CDP would provide an answer to the solution of *Bin Packing Decision Problem* which means that BPDP $\leq_m$ CDP. □

5. The charging protocols

We present a new protocol operating in 1-D networks and four new protocols operating in 2-D networks. Our protocols use hierarchical collaborative charging. Since there is plenty of research on how multiple Mobile Chargers can charge sensor nodes we focus on how we can efficiently use the available Special Chargers. In all protocols we investigate the following three design aspects:

Coordination: a Special Charger consumes its energy according to the energy depletion on its area, i.e. the energy consumed by the sensor nodes and the Mobile Chargers. This may lead to a non-balanced energy consumption between Special Chargers. For this reason, they should periodically change the area that they are responsible of by increasing or decreasing the number of the Mobile Chargers that belong to their group. This procedure may be distributed or centralized. In the centralized case, the computation is performed by a computationally powerful network entity, e.g. the Sink. In contrast, in the distributed case, each Special Charger locally communicates with its neighbors to learn about their energy status and then calculates the coordination action. In the distributed case, we assume that two adjacent Special Chargers can exchange one of their border Mobile Chargers. More specifically, imagine that SC_k is in charge of the following group of Mobile Chargers: $\mathcal{C}_k = \{MC_1, \ldots, MC_i\}$ and the SC_{k+1} has: $\mathcal{C}_{k+1} = \{MC_{i+1}, \ldots, MC_{i+c}\}$, $c > 0$. After computation, if there is going to be a coordination action then either MC_i will change group and go under SC_{k+1}'s responsibility, or MC_{i+1} will be under SC_k's responsibility.

Trajectory: every Special Charger has a group of several Mobile Chargers that it can charge. However, some of its corresponding Mobile Chargers may be more critical than others, so it should decide which one should be charged next in order to manage efficiently the available energy.

Charging policy: when a Special Charger has estimated which Mobile Charger should be charged, then it estimates how much energy should be given to it.

5.1. Protocols for 1-D networks

5.1.1. The model in 1-D networks

In 1-D networks we compare our protocol to a state of the art protocol [4]. In order to conduct a fair comparison in 1-D networks, we assume a quite identical model (and not the one described in Section 3). More specifically, we consider N sensor nodes that are uniformly distributed, unit distance apart, along a one-dimensional line network. All sensor nodes have the same energy consumption rate and the same battery capacity, denoted by b. Also, there are K Mobile Chargers of battery capacity B which consume c amount of energy per unit distance. Moreover, the Sink serves as data collector as well as an energy source. The only difference is that we assume that the Sink has finite energy supplies denoted as E_{total} in contrast to the proposed model in [4] where the Sink has unlimited energy supplies.

5.1.2. PushWait algorithm

The PushWait algorithm [4] assumes that the Mobile Chargers start from the Sink with full batteries, charge sensors, finally come back to the Sink, and then get themselves charged by the Sink. Both the movement of the Mobile Chargers and the process of wireless charging share the same pool of energy. Also, there are K rendezvous points denoted as L_i $(1 \leq i \leq K)$ where in each one a Mobile Charger stops moving forward. A noticeable point is that all Mobile Chargers return to the Sink after each scheduling cycle (in order to make the network able to run forever i.e., in each scheduling cycle they have exactly the same performance).

PushWait follows two main steps:

- MC_i charges sensors between L_{i+1} and L_i to their full batteries. At L_i, MC_i transfers energy to the rest Mobile Chargers, $MC_{i-1}, MC_{i-2}, \ldots, MC_1$ until they are at their full energy capacity. Then MC_i waits at L_i, and all of the other $i-1$ MCs keep moving forward.
- After $MC_{i-1}, MC_{i-2}, \ldots, MC_1$ return to L_i where MC_i waits for them, MC_i evenly distributes its residual energy among $i\,MCs$ (including MC_i). This will make them just have enough energy to return to L_{i+1}.

The above algorithm, needs a specific number of Mobile Chargers in order to charge in a round all N sensors. This is provided via a linear system that, given the number of sensors N, computes the number of necessary Mobile Chargers.

5.1.3. 1-D No Knowledge No Coordination (1D-NKNC)

In our hierarchical protocol, we use the same number of chargers that are used in PushWait, for a fair comparison. If K is the number of Mobile Chargers used in PushWait algorithm, given that network contains N sensor nodes, in our protocol, we separate them into two groups (Mobile Chargers and Special Chargers) as follows:

$$M = q \cdot K \quad \text{and} \quad S = (1 - q) \cdot K$$

where $q \in (0.75, 1)$ since we assume that the number of Special Charger is significantly lower than the number of Mobile Chargers.

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Note that *only* in this special case of 1-D network deployment, all Chargers (Mobile and Special) have the same battery capacity B. We divide the line network into M equal sized segments, one for each Mobile Charger. Each Mobile Charger is responsible for charging the sensor nodes in its area. We group the Mobile Chargers in S groups, one for each Special Charger. Each Mobile Charger charges the sensor nodes in its area sequentially over the line graph and when it arrives at the last node, it follows the opposite direction in order to reduce movement overhead. When the energy level of a Special Charger is low enough, i.e. its energy is enough for just walking to the Sink, it visits the Sink and gets charged. Mobile Chargers do not roam out of their region. Since the number of Special Chargers is significantly lower than the number of the Mobile Chargers, the energy consumed for movement is much lower and our protocol improves the efficiency ratio.

Coordination: there is no coordination between Special Chargers. In this protocol the Special Chargers do not change the Mobile Chargers initially assigned to them.

Trajectory: each Special Charger charges its corresponding Mobile Chargers sequentially. When it arrives to the last one, it changes direction and charges them in reverse order. Also, when it arrives at the first one, it changes direction again and so on. When its energy drops under a specific level, it visits the Sink, get recharged and then returns back to its previous position.

Charging policy: since in 1-D networks we assume a uniform consumption rate between nodes, there is a uniform consumption rate between Mobile Chargers. Thus, in order to reduce the movement overhead, Special Chargers charge each Mobile Charger at a maximum level.

In sensor networks with a limited amount of initial energy (stored in the Sink) it is important to exploit this energy optimally. The energy is consumed both for the Chargers' movement and for sensing activities. In this case, (1-D networks), in order to improve the efficiency ratio, our goal is to reduce the energy consumed for movement, denoted by $E^{overhead}$ and increase the amount of energy obtained by the nodes denoted by $E^{payload}$. The efficiency ratio is defined as follows:

$$efficiency\_ratio = \frac{E^{payload}}{E^{overhead}}$$

The PushWait algorithm proposed in [4] assumes that the Sink has unlimited energy supplies and so the authors investigated how many Mobile Chargers are needed to charge all sensor nodes in a scheduling cycle. In each cycle, Mobile Chargers charge all the sensor nodes and come back to the Sink without residual energy (only one Mobile Charger may have a small amount of residual energy). This algorithm ensures that the movement is minimized and thus, the achieved *efficiency_ratio* is optimal. In this work, we assume that the Sink has limited amount of energy and thus the PushWait algorithm runs for a specific number of scheduling cycles. Unlike PushWait, we do not have cycles and we compute the overall *efficiency_ratio* which is the rate of the total amount of energy obtained by sensor nodes over the total amount of energy consumed for both movement of Special Chargers and Mobile Chargers.

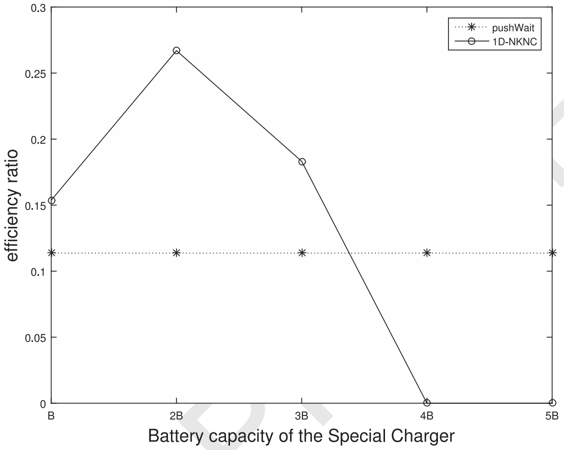

Fig. 2. Efficiency ratio over the Special Chargers' battery capacity.

For instance, if we run PushWait algorithm with input $E_{total} = 2000J$, $B = 80J$, $b = 2J$, $N = 29$, $c = 3J/m$, then the output is $K = 7$ and *efficiency_ratio*$= 0.11$.

After that, we run 1D-NKNC with input: $E_{total} = 2000$J, $B = 80$J, $b = 2$J, $N = 29$, $c = 3$J/m, $q = 0.75$ and thus, $M = 5$ and $S = 2$. The output is *efficiency_ratio*$= 0.15$, which is higher.

If in our method we change the model and apply a non-uniform battery capacity deployment, i.e. equip the Special Chargers with larger battery capacity but reduce the battery capacity of the Mobile Chargers such that the total battery capacity maintains the same $K \cdot B$, the efficiency ratio can become higher. That is because the Special Chargers will reduce the amount of times that they return to the Sink to get recharged and so reduce the energy consumed for movement. Actually, the efficiency ratio has a threshold behavior as shown in Fig. 2. The efficiency ratio is higher only when the battery capacity of each Special Charger takes a value lower than the threshold which is normal since if the battery capacity of the Special Chargers is higher than that, the battery capacity of the Mobile Chargers drops below a specific level, and they will not be able to charge sensor nodes any more. So, the efficiency ratio will be zero.

The total distance travelled by all chargers is a metric that indicates that our hierarchical protocol achieves better performance. More specifically, in the 1D-NKNC protocol, the distance travelled metric refers to the total distance that both the Mobile Chargers and the Special Chargers have covered during the whole process; recall that the PushWait algorithm only uses Mobile Chargers and, we only estimate the total distance travelled by them. Fig. 3 depicts the simulation results. The distance travelled when using the 1D-NKNC protocol is always lower than the distance travelled when using the PushWait algorithm.

Motivated by this demonstration of the potential power of the hierarchical approach, we propose hierarchical protocols for 2-D networks where Special Chargers have a little larger battery capacity than the Mobile Chargers.

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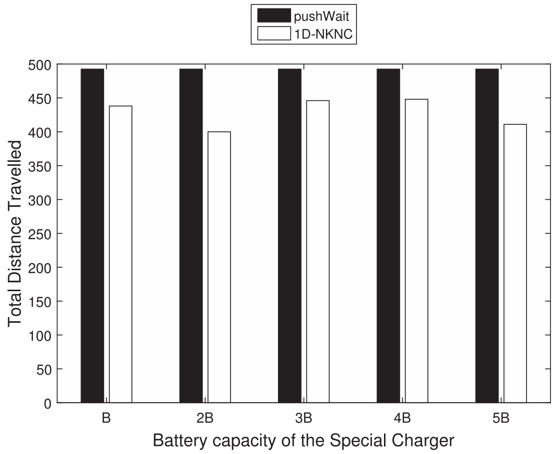

Fig. 3. Distance travelled by all chargers.

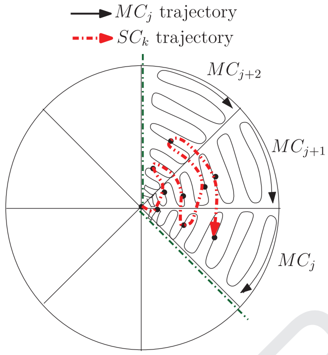

Fig. 4. NKNC trajectory.

5.2. Protocols for 2-D networks

5.2.1. No Knowledge No Coordination (NKNC)

The NKNC protocol is a generalization of 1D-NKNC protocol with the difference that the Special Chargers have higher battery capacity than the Mobile Chargers (E_{SC}^{max} and E_{MC}^{max}, respectively). This fact does not violate any model assumptions, since the available initial total energy remains the same, independently of the Chargers' battery capacity. More precisely:

Coordination: there is no coordination between Special Chargers.

Trajectory: each Special Charger charges the corresponding Mobile Chargers sequentially. When it arrives to the last Mobile Charger of its group, it changes direction and charges them again in a reverse order this time and so on, as shown in Fig. 4.

Charging policy: each Special Charger, charges each Mobile Charger in its group until its battery level is E_{MC}^{max}.

5.2.2. 1-Level Knowledge Distributed Coordination (1KDC)

The 1KDC protocol performs a distributed coordination among Special Chargers, i.e. every Special Charger SC_k can communicate with its left and right neighbors (SC_{k-1} and SC_{k+1}) and with the two Mobile Chargers that are on the boundaries of its region (and do not belong to its group). Also, this protocol assumes 1-level knowledge of the network, i.e. in order to perform the coordination it can use information only about Mobile Chargers' energy status (and not about the sensors' which lie one level lower).

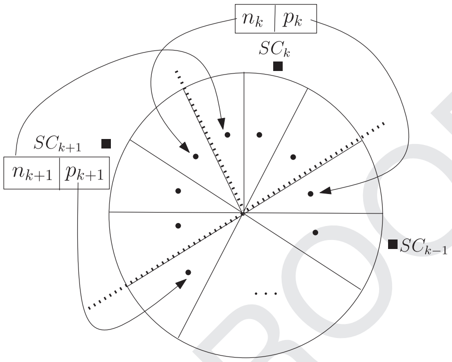

Fig. 5. Distributed coordination.

Coordination: in distributed coordination, we assume that a Special Charger knows which are the adjacent Mobile Chargers on the boundaries of its region. We call next the first Mobile Charger that belongs to the SC_{k+1} and previous the last Mobile Charger that belongs to SC_{k-1} as shown in Fig. 5. More specifically,

$$n_k = \min_{j\in C_{k+1}}\{j\} : \text{next Mobile Charger (belongs to } SC_{k+1})$$

$$p_k = \max_{j\in C_{k-1}}\{j\} : \text{previous Mobile Charger (belongs to } SC_{k-1})$$

During the coordination procedure, each Special Charger estimates its new region, i.e., the group of Mobile Chargers that it will be responsible of. In the distributed coordination case, as we already mentioned in Section 5, each Special Charger SC_k communicates with the Mobile Chargers n_k and p_k to get informed about their energy level. After that, the Special Charger estimates how much residual energy it would have by including n_k or p_k in its group, using the following following equations:

$$e_k^p = E_{SC_k} - \sum_{j\in\mathcal{C}_k} E_{MC_j}^{lack} - E_{MC_{p_k}}^{lack}$$

$$e_k^n = E_{SC_k} - \sum_{j\in\mathcal{C}_k} E_{MC_j}^{lack} - E_{MC_{n_k}}^{lack}$$

where $E_{MC_j}^{lack} = E_{MC}^{max} - E_{MC_j}$ is the amount of energy that MC_j can receive until it is fully charged.

After this procedure, each Special Charger SC_k communicates with its neighbors (SC_{k-1} and SC_{k+1}) to get informed about their residual energy. More specifically, the Special Charger SC_{k-1} sends the e_{k-1}^n value that represents its residual energy if it includes to its group the SC_k's first Mobile Charger. The Special Charger SC_{k+1} sends the e_{k+1}^p value which refers to its residual energy if it includes to its group the SC_k's last Mobile Charger.

Between two adjacent Special Chargers the one with the higher energy supplies takes the other's boundary Mobile Charger in its group. Thus, the Special Charger with lower energy supplies is responsible for a smaller area. In the case that their energy supplies are the same they do not exchange any Mobile Chargers. More precisely, the coordination algorithm is the following:

```
$\underline{(SC_k, SC_{k-1})}$
if $(e_k^p > e_{k-1}^n)$ then
    $\mathcal{C}_k = \mathcal{C}_k \bigcup \{MC_{p_k}\}$
    $\mathcal{C}_{k-1} = \mathcal{C}_{k-1} \setminus \{MC_{p_k}\}$
else if $(e_k^p < e_{k-1}^n)$ then
    $\mathcal{C}_{k-1} = \mathcal{C}_{k-1} \bigcup \{MC_{n_{k-1}}\}$
    $\mathcal{C}_k = \mathcal{C}_k \setminus \{MC_{n_{k-1}}\}$
else
    There is not any exchange of Mobile Chargers
end if
$\underline{(SC_k, SC_{k+1})}$
if $(e_k^n > e_{k+1}^p)$ then
    $\mathcal{C}_k = \mathcal{C}_k \bigcup \{MC_{n_k}\}$
    $\mathcal{C}_{k+1} = \mathcal{C}_{k+1} \setminus \{MC_{n_k}\}$
else if $(e_k^n < e_{k+1}^p)$ then
    $\mathcal{C}_{k+1} = \mathcal{C}_{k+1} \bigcup \{MC_{p_{k+1}}\}$
    $\mathcal{C}_k = \mathcal{C}_k \setminus \{MC_{p_{k+1}}\}$
else
    There is not any exchange of Mobile Chargers
end if
```

Trajectory: Special Charger k should determine which Mobile Charger will be the next that will be charged prioritizing a Mobile Charger based on minimum energy and minimum distance. Considering this, SC_k chooses to charge MC_m where

$$m = \arg\min_{j\in\mathcal{C}_k} \left\{ \left(1+\frac{E_{MC_j}}{E_{MC}^{max}}\right)\cdot\left(1+\frac{d_{k_j}}{2R}\right)\right\}.$$

Charging policy: a Special Charger charges a Mobile Charger j according to its energy consumption rate r_{MC_j}. More specifically, a Mobile Charger with higher consumption rate (compared to the rest Mobile Chargers that belong to the Special Charger's group) should be charged with a higher amount of energy. Motivated by that, if by MC_m we denote the Mobile Charger that Special Charger k chose to charge, then the amount of energy that the Special Charger will give to it is $e = c_m \cdot \left(\min\{E_{MC_m}^{lack}, E_{SC_k}\}\right)$ where

$$c_m = \frac{r_{MC_m}}{\sum_{j\in\mathcal{C}_k} r_{MC_j}}.$$

5.2.3. 2-Level Knowledge Distributed Coordination (2KDC)

In contrast to previous protocols, the 2KDC assumes 2-level knowledge and thus, each Special Charger k compute e_k^p and e_k^n using information about both the Mobile Chargers and the sensor nodes, as follows:

Coordination:

$$e_k^p = E_{SC_k} - \sum_{j\in\mathcal{C}_k}\sum_{i\in\mathcal{D}_j} E_i^{lack} - \sum_{i\in\mathcal{D}_{p_k}} E_i^{lack}$$

$$e_k^n = E_{SC_k} - \sum_{j\in\mathcal{C}_k}\sum_{i\in\mathcal{D}_j} E_i^{lack} - \sum_{i\in\mathcal{D}_{n_k}} E_i^{lack}$$

After that, the coordination algorithm presented in 1KDC protocol's coordination phase is used.

Trajectory: each MC_j stores a list l_j of sensor nodes the energy level of which is lower than $E_{threshold}$. Special Charger k defines which Mobile Charger is more critical by making a query to each Mobile Charger in its group on the size of its list. A Special Charger should assign high priority to a Mobile Charger that has a large number of sensor nodes of energy lower than $E_{threshold}$. Thus, SC_k selects to charge MC_m where

$$m = \arg\max_{j\in\mathcal{C}_k} |l_j|.$$

Charging policy: since each Special Charger assumes 2-level knowledge, it computes the percentage of energy to transfer, according to the lack of energy in the slice of the selected Mobile Charger compared to the total energy lack in all slices that this Special Charger is responsible for. More precisely, Special Charger k transfers to MC_m an amount of energy $e = c_m \cdot \left(\min\{E_{MC_m}^{lack}, E_{SC_k}\}\right)$ where

$$c_m = \frac{\sum_{i\in\mathcal{D}_m} E_i^{lack}}{\sum_{j\in\mathcal{C}_k}\sum_{i\in\mathcal{D}_j} E_i^{lack}} \quad \in (0,1)$$

where $E_i^{lack} = E_{sensor}^{max} - E_i$ is the amount of energy that sensor i can receive until it is fully charged.

5.2.4. 2-Level Knowledge Centralized Coordination (2KCC)

The 2KCC protocol performs centralized coordination and assumes 2-level network knowledge. It assigns to each Special Charger a set of Mobile Chargers according to their residual energy. More precisely:

Coordination:

$$\mathcal{E}_k = \frac{E_{SC_k}}{\sum_{i=1}^{S} E_{SC_i}} \quad (1 \le k \le S), \quad |C_k| = \mathcal{E}_k \cdot M.$$

Trajectory: since each Special Charger assumes 2-level network knowledge, it takes into account information from both Mobile Chargers and sensor nodes in order to find good trajectories. Thus, SC_k prioritizes MC_m where

$$m = \arg\min_{j\in\mathcal{C}_k} \left\{ \alpha \cdot \frac{E_{MC_j}}{E_{MC}^{max}} + (1-\alpha)\cdot \frac{\sum_{i\in\mathcal{D}_j} E_i}{|\mathcal{D}_j| \cdot E_{sensors}^{max}} \right\}$$

with $\alpha \in (0, 1)$ a constant allowing to select the weight of each term in the sum.

Charging policy: same as 2KDC.

6. Performance evaluation

The simulation environment for conducting the experiments is Matlab 7.12. The Sink is placed at the center of the circular area. The number of sensor nodes is set to 2000, the number of Mobile Chargers to 15 and the number of Special Chargers to 3. In the simulations, the number of the Mobile Charges in non-collaborative protocols equals to the sum of the Mobile Chargers and the Special Chargers in the hierarchical protocols, so, in protocols that do not use Special Chargers, the number of Mobile Chargers is set to 18. Our simulations include 4000 generated events. For statistical smoothness, we apply several times the deployment of nodes in the network and repeat each

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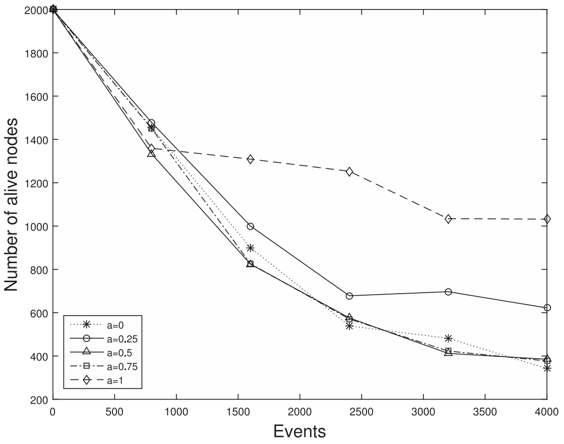
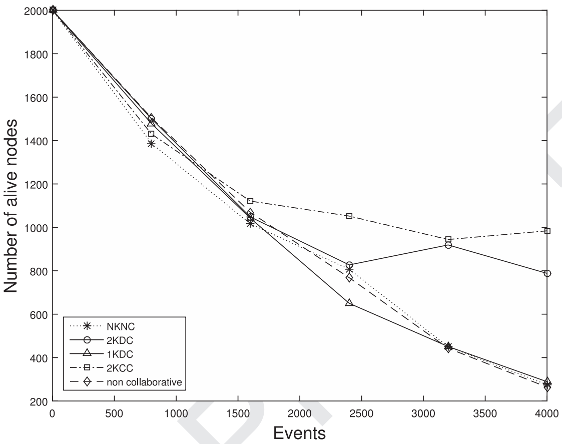
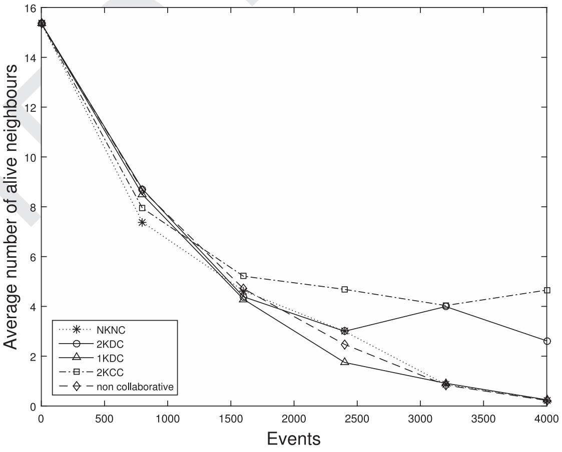


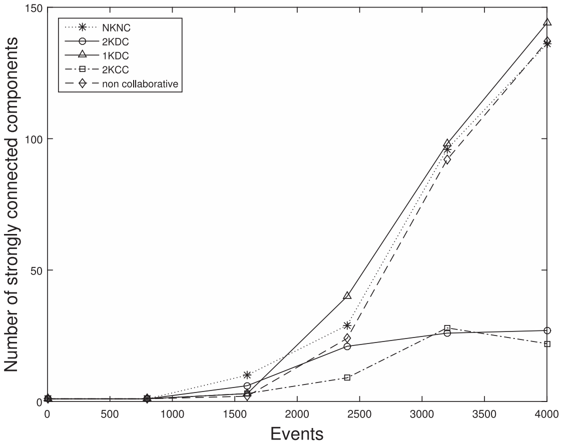
Fig. 6. Alive nodes over time (varying α).



(a) Alive nodes over time.



(b) Average routing robustness.



(c) Graph connected components over time.

Fig. 7. Performance metrics.

experiment 100 times. For each experiment we simulate large numbers of data propagations and the average value is taken. The statistical analysis of the findings (the median, lower and upper quartiles, outliers of the samples) demonstrate very high concentration around the mean, so in the following figures we only depict average values.

In our simulations, we compare the performance of our 2-D protocols to a variation of the state of the art protocol (CC) proposed in [16] which is designed for 2-D networks as well, and divides the network into slices (one for each Mobile Charger) like our protocols. However, this protocol is non-collaborative, i.e. the Mobile Chargers do not charge each other and we label it as “non-collaborative” in our simulation figures.

In this paper, we focus on the following performance metrics: (a) *alive nodes over time*, that is the number of nodes with enough residual energy to operate, during the progress of the experiment, (b) *connected components over time* which indicates the number of strongly connected components of the network graph throughout the experiment, (c) *routing robustness* and *average routing robustness*, in terms of the nodes’ average alive neighbors during the progress of the experiment, (d) *coverage ageing*, that is the average coverage number (number of sensors having the point in their range) of 1000 randomly selected points in the network over time, and (e) *communication overhead* which refers to the number of messages transmitted between the network devices (Special Chargers, Mobile Chargers, sensor nodes and the Sink) in order to perform the various protocols’ procedures (coordination, trajectory and charging policy).

6.1. Fine-tuning of 2KCC protocol

One important performance metric is the network lifetime. We use it to decide which is the appropriate value of parameter α in 2KCC protocol. As shown in Fig. 6 the value that achieves the most prolonged lifetime is $\alpha = 1$. This is natural because, despite the fact that energy will eventually obtained by the sensor nodes, a Special Charger charges only the Mobile Chargers and so, it should take into account only their energy status and not the sensor nodes’. If the nodes of a slice do not have high energy supplies but the corresponding Mobile Charger has, the Special Charger may select it but the energy that will transfer will be very small (since its battery is not discharged very much). So, it would be better to take into account solely

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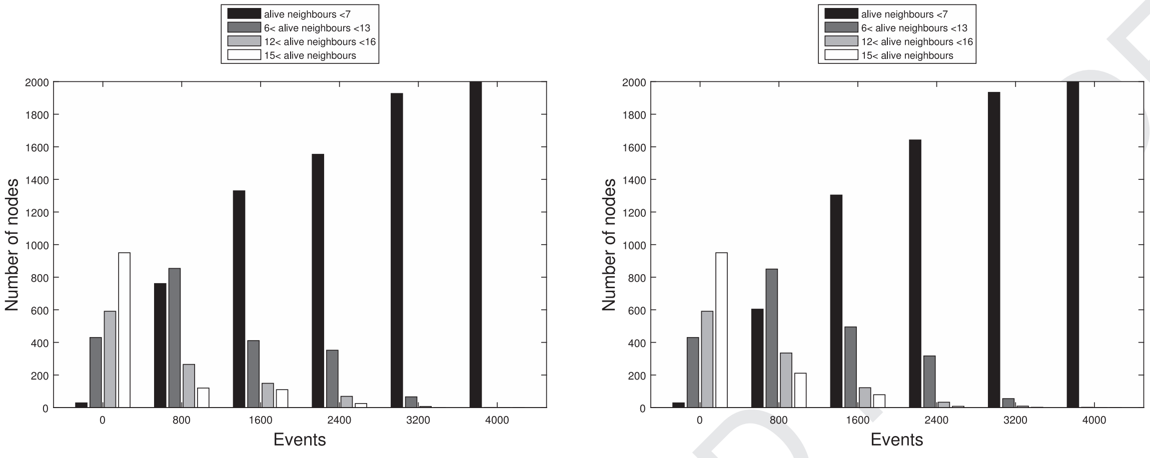
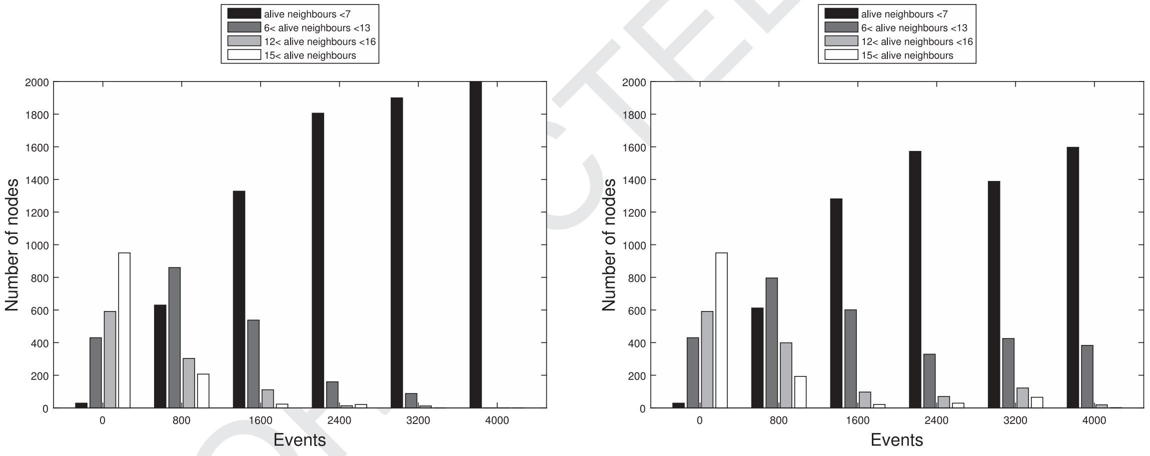
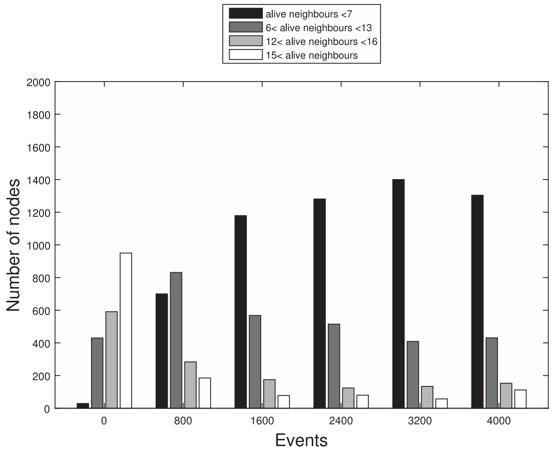


(a) NKNC. (b) non collaborative.



(c) 1KDC. (d) 2KDC.



(e) 2KCC.

Fig. 8. Routing robustness.

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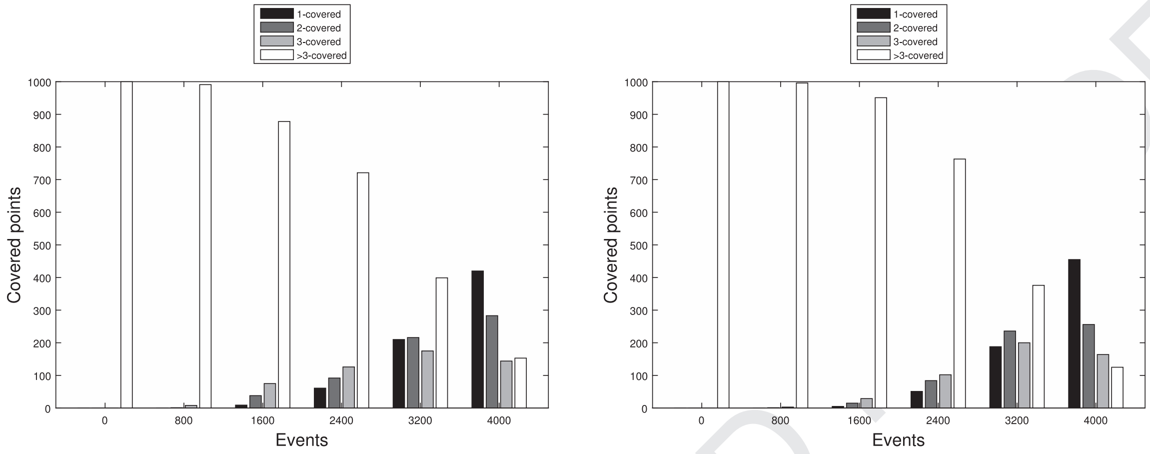
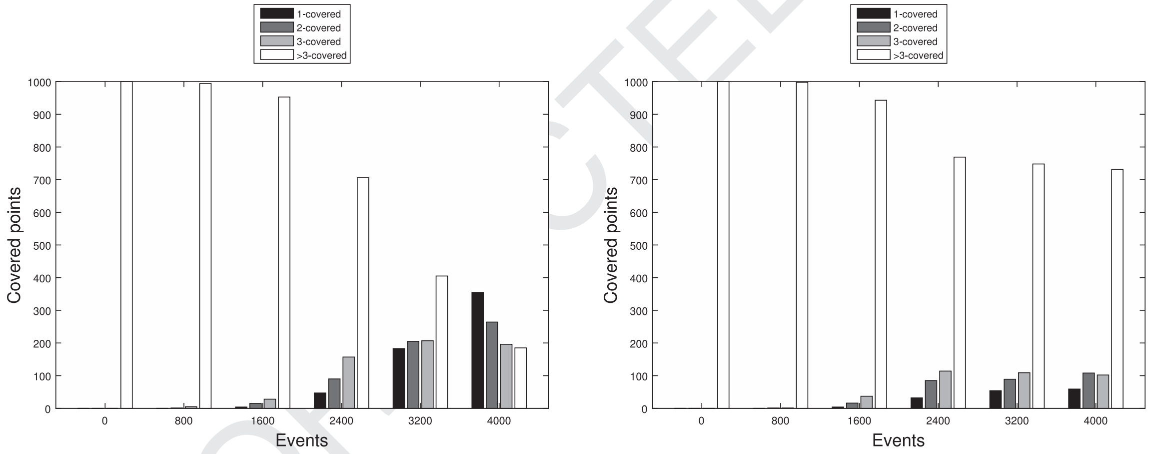
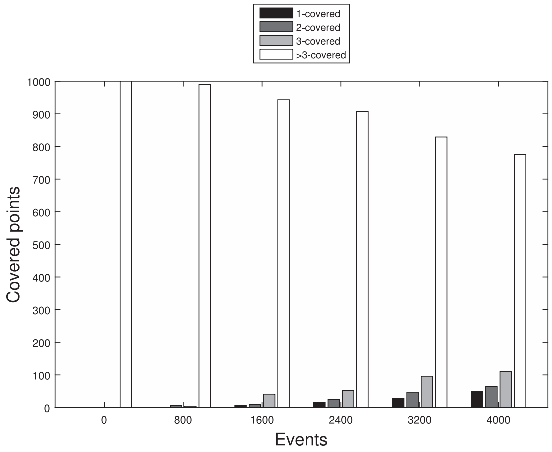


(a) NKNC. (b) non collaborative.



(c) 1KDC. (d) 2KDC.



(e) 2KCC.

Fig. 9. Coverage ageing.

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the Mobile Chargers' battery and decide to charge the one that has the smallest amount of energy. Thus, we set $\alpha = 1$ in all following simulations.

6.2. Protocols' impact on network properties

(i) The charging protocols that we propose manage to prolong *network lifetime* (i.e. alive nodes over time) as shown in Fig. 7a. As expected, the 2KCC outperforms the other protocols since it provides a centralized coordination algorithm which implies the most fair partition of Mobile Chargers among Special Chargers. Despite the fact that 2KDC may not achieve the best partition since its coordination procedure takes into account only adjacent Special Chargers it's performance is quite close to 2KCC's. We also observe that NKNC has quite the same performance with the non-collaborative case, since it does not perform any coordination or any sophisticated trajectory procedure.

(ii) *Routing robustness* is critical to ensure that all the generated data will arrive to the Sink. It is important that at least one path from each node to the Sink is maintained. A measure of routing robustness is counting the number of alive neighbors of each sensor node, because the greater this number is the lower the disconnection probability of the corresponding node is. Fig. 7b depicts the average routing robustness for our protocols. We observe that it follows the same pattern as network lifetime. This is natural since the reduction of alive nodes implies the reduction of alive neighbors. We also provide a more detailed routing robustness metric which is shown in Fig. 8. We investigate (for each protocol and various number of events) the quality of routing robustness. More specifically, we investigate four cases, the number of nodes that have <7 alive neighbors, the number of nodes that have ≥ 7 and <13 alive neighbors, the number of nodes that have ≥ 13 and <15 alive neighbors and finally, the number of nodes that have ≥ 15 alive neighbors. Of course, it is desirable each node to have as much alive neighbors as possible and consequently, a high white bar and a low black bar. As we can see in Fig. 8, NKNC and non-collaborative protocols' white bar is decreasing with a high rate in contrast to the 2KDC and 2KCC protocols which achieve a better routing robustness.

(iii) Another connectivity metric is the number of *strongly connected graph components*. Two different connected components cannot communicate with each other. This may lead to failures on delivering messages to the Sink. It is important to maintain a small number of connected components. Fig. 7c depicts the number of strongly connected components over time. As we can see, the 2KCC and 2KDC protocols outperform all others and maintain a small number of connected components for a large number of events. This is because sensor nodes are dying with low rates and the connections are maintained. Unlike 2KCC, the NKNC and 1KDC increase their number of connected components rapidly.

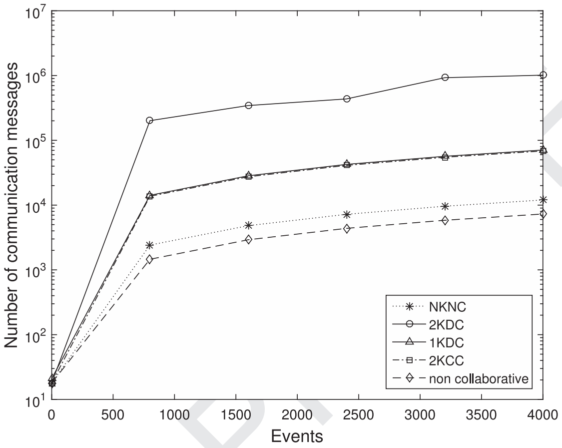

Fig. 10. Communication overhead.

(iv) *Point coverage*. This metric captures the assurance that some selected points in the network are covered by an adequate number of sensor nodes. This is an important aspect if we consider that in some applications, there are some selected points of the network that produce crucial sensing data that should be captured by nearby sensors. A point is *k*-covered if there are *k* sensor nodes that cover it i.e. it is inside their communication range. We deploy 1000 random points in the network and examine how many of them are less than 2-covered, 2-covered, 3-covered or greater than 3-covered over 4000 generated events. In Fig. 9 we can observe that the NKNC, non-collaborative and 1KDC rapidly decreases the number of greater than 3-covered points. 2KDC and 2KCC achieve good performance, since they decrease the number of covered points in a very low rate.

6.3. Communication overhead

Since the data, generated by sensor nodes, should be transferred to the Sink, we do not take into account the routing communication overhead, as it is decoupled from the charging process for each and every one of the presented protocols. On the contrary, for each of our protocols, the communication overhead is defined as the total number of messages transferred between the network devices for the execution of the protocol i.e., the number of messages exchanged between the nodes, the Special Chargers, the Mobile Chargers and the Sink in order to perform the coordination, the trajectory and the charging policy procedures. As depicted in Fig. 10, the NKNC and non-collaborative protocols have the lowest communication overhead which is normal since they do not have a coordination phase. Although the 2KCC protocol is a centralized one and one would expect to have the highest communication overhead, this is actually not true. On the contrary, it has lower overhead than the 2KDC protocol. Since they both have the same charging policy procedure,

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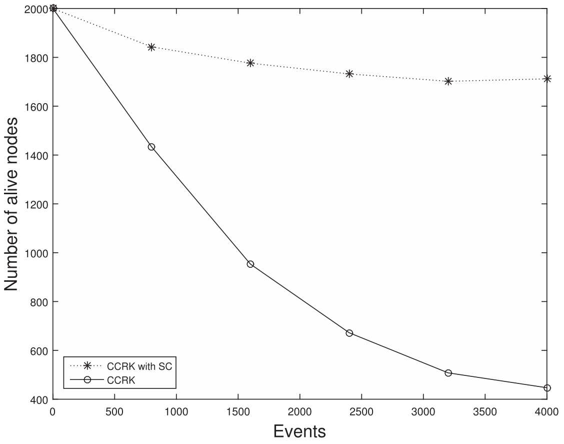


Fig. 11. Alive nodes over time.

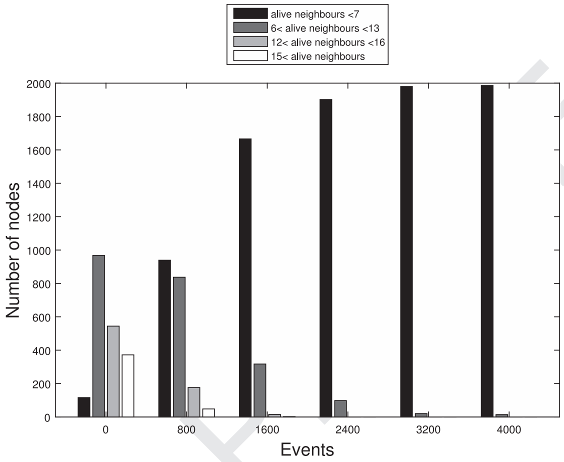
the overhead difference is due to the coordination and trajectory procedures. Although they differ in the trajectory procedure, the overhead is similar because in the 2KCC protocol each Special Charger communicates only with its corresponding Mobile Chargers; observe that we have set $\alpha = 1$. In the coordination procedure of 2KDC, each Special Charger communicates with all sensor nodes of its region and with the sensor nodes that belong in the slices of the Mobile Chargers that are on the boundaries of its region and belong to the adjacent Special Chargers. In contrast, in the 2KCC protocol, each Special Charger communicates only with the Sink to calculate its region.

6.4. Impact of knowledge

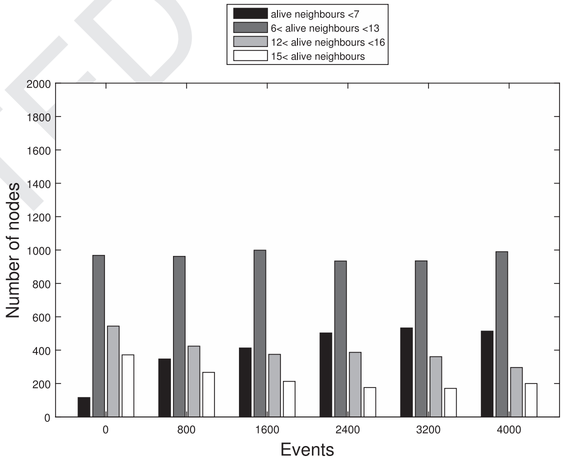
By observing the performance of the above protocols we conclude that the amount of knowledge is one of the most determinant factors. 2KDC always outperforms 1KDC and also the NKNC that has no knowledge at all. Since the coordination procedure depends on the amount of knowledge, this difference in performances indicates that the greater the amount of available knowledge the better the protocol's performance. However, as depicted in Fig. 10, the level of knowledge also induces communication overhead.

6.5. Adaptivity of our hierarchical protocols

A notable additional value of hierarchical collaborative charging is that it can easily be added on top of the non-collaborative charging protocols and further improve their performance. Fig. 11 depicts the improvements in terms of lifetime, of a state of the art protocol proposed in [15]. We transform their algorithm by converting some Mobile Chargers to Special Chargers and applying hierarchy using one of our hierarchical protocols (2KCC) to achieve performance improvement. Then, we compare the proposed non-collaborative algorithm with our hierarchical, as shown in Fig. 12.



(a) CCRK.



(b) CCRK with hierarchy.

Fig. 12. Adaptivity of hierarchy: Routing robustness.

6.6. Partition of the chargers

We recognize that the problem of finding the best partition of chargers into Special Chargers and Mobile Chargers needs investigation and we plan to address it in future work. However, we can provide an intuition of the effect of the partition on our 2KDC protocol performance. At first, we divide 25 chargers in two different ways. In the first case, there are 5 Special Chargers and 20 Mobile Chargers and in the second case, the Special Chargers are set to 10 and the Mobile Chargers are set to 15. As depicted in Fig. 13, the 2KDC protocol's performance with respect to the alive nodes over time metric is different. After that, we conduct simulations where we keep the number of one kind of chargers fixed and set various values on the other one. More specifically, in Fig. 14a, we set the number of Special Chargers to 3 and the number of Mobile Chargers to 15, 20 and 30 respectively. We observe that, as the number of Mobile Chargers is increasing, the number of alive nodes over time is decreasing. This is logical, since each Special Charger is responsible for more

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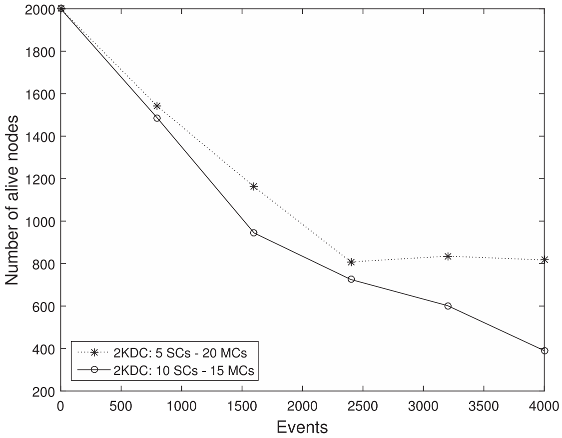
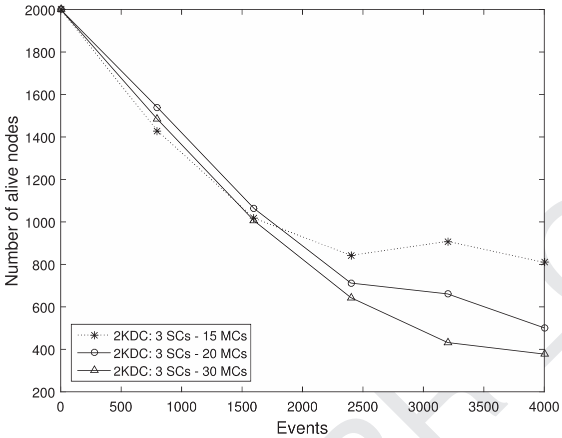
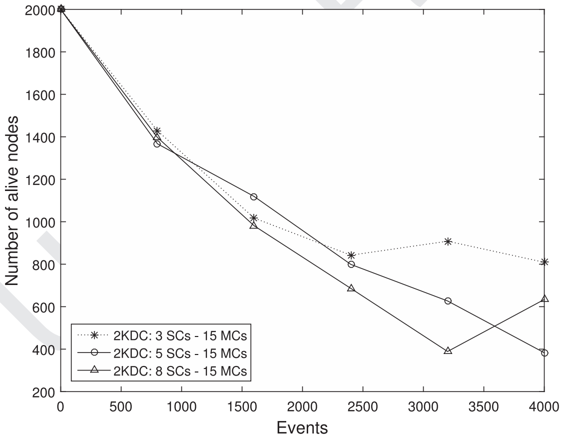


Fig. 13. Alive nodes over time: same number of chargers.



(a) Varying the number of Mobile Chargers.



(b) Varying the number of Special Chargers.

Fig. 14. Alive nodes over time of 2KDC protocol.

Mobile Chargers and is not able to charge them in due time. On the second case, we set to 15 the number of Mobile Chargers and vary the number of Special Chargers (3, 5 and 8). As we observe in Fig. 14b, the smaller the number of Special Chargers is, the better the protocol's performance becomes.

7. Conclusion and future work

In this work we study the problem of efficient collaborative wireless charging in Wireless Sensor Networks. We propose a new design approach, according to which, the set of chargers is partitioned into two groups, one hierarchically higher, called Special Chargers and one hierarchically lower, called Mobile Chargers. The Mobile Chargers are responsible for charging the sensor nodes whereas the Special Chargers charge Mobile Chargers. This hierarchical structure provides a more controllable and balanced energy replenishment of the network. We investigate what are good trajectories that Special Chargers should follow to charge Mobile Chargers, how much energy they should give and what are good coordination procedures to perform. Moreover we provide a useful hierarchical add-on that can be added on top of non-collaborative protocols in order to enhance their performance.

For future research, we plan to address non-uniform cases of the network deployment, since in many scenarios the network deployments are limited by the underlying terrain. We also plan to investigate which is the optimal number of Chargers and what is the best partition of them into Special Chargers and Mobile Chargers. Another future research direction is the case where a Charger can deliver energy simultaneously to more than one devices with high efficiency using the technology developed e.g. in [20].

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