Neighbor sensor networks: Increasing lifetime and eliminating partitioning through cooperation

Kemal Bicakci a,⁎, Ibrahim Ethem Bagci b, Bulent Tavli a, Zeydin Palacı c

a TOBB University of Economics and Technology, Turkey
b Lancaster University, United Kingdom
c Mus Alparslan University, Turkey

A R T I C L E   I N F O

Article history:
Received 8 May 2012
Accepted 23 November 2012
Available online 10 December 2012

Keywords:
Wireless sensor networks
Linear Programming
Network lifetime
Disjoint partition
Cooperation

A B S T R A C T

In this paper we consider neighbor sensor networks which are defined as multiple wireless sensor networks under the administration of different authorities but located physically on the same area or close to each other. We construct a Linear Programming framework to characterize the cooperation of neighbor sensor networks in comparison to non-cooperating networks. We show that if neighbor sensor networks cooperate with each other for relaying data packets then this cooperation brings two advantages as compared to no cooperation case. First, lifetime of both networks is prolonged — the results of our analysis show that cooperation between neighbor sensor networks can significantly extend the overall network lifetime. Second, cooperation reduces the probability of disjoint partitions arising due to the limited transmission ranges of sensor nodes. When neighbor sensor networks cooperate, eliminating disjoint partitions is possible with sensors having shorter transmission ranges as demonstrated and quantified by our analysis.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

In wireless sensor networks (WSN), sensor nodes convey their data to the base station via multiple intermediate nodes used as relays. If relaying capability is not implemented in the network, then all sensor nodes should have a direct communication link to the base station. This requirement puts an upper limit on the extent of the area that can be covered by a network with a single base station due to the transmission range limitations of sensor nodes. Relaying is also desired for improving energy efficiency. Even if establishing a direct communication over a long distance is viable, it is usually not preferred over more energy-efficient alternatives which involve multi-hop communication.

In most sensor network applications, nodes have limited amount of unreplenishable battery energy. Thus, it is crucial to extend the lifetime of the network with energy efficient data collection and forwarding strategies. There are numerous such strategies (e.g., [1] and [2]) proposed in the literature. We argue that a strategy based on the exploitation of the cooperation between multiple sensor networks when they are deployed in physically close locations (what we call extitneighbor sensor networks), has the potential not only for extending the network lifetime but also for decreasing the probability of disjoint partitions which may occur due to temporary or permanent deterioration in transmission ranges of sensor nodes. A network is partitioned (i.e., disjoint partition) if the sensors in a specific area can communicate with neither the base station nor any other nodes that can communicate with the base station.

In this study, we model the cooperation between neighbor sensor networks through a Linear Programming (LP) framework and investigate the impact of cooperation on the network lifetime with comparative analysis of several different cooperation strategies. These strategies differ from each other by the presence or absence of communication between base stations and between sensor nodes of neighbor sensor networks. We also examine the effect of cooperation when the deployment areas of neighbor networks overlap to arbitrary amounts. Our target is to characterize the cooperation strategies and network parameters/scenarios from an energy efficiency and network partitioning perspective.

The rest of the paper is organized as follows. In Section 2 we summarize related work. Our LP models are introduced in Section 3. In Section 4 we present the results of our analysis to investigate various aspects of the lifetime elongation problem and the issue of disjoint partition in neighbor sensor networks. In Section 5 we finish up by giving concluding remarks.

2. Related work

We overview related work under two subsections: lifetime maximization in WSNs and cooperation in WSNs.

2.1. Lifetime maximization in WSNs

Lifetime maximization by decreasing energy consumption is one of the most studied topics in WSN research [1–7]. In [1,3], it was shown...
that a class of role assignment problems can be transformed into LPs based on network flows. In [2], the problem of WSN lifetime optimization was investigated through an LP model by considering the energy dissipations of both data communication and computation. In [4], the authors investigated the routing problem using an LP model. The objective of the linear program is to maximize the network lifetime. In [5], the authors compared two routing schemes using LP; the first one maximizes the network lifetime and the second one minimizes the total energy used.

To maximize sensor network lifetime, several studies explored clustering and aggregation mechanisms. Heinzelman et al. developed a clustered sensor protocol called LEACH [6]. The sensor nodes communicate with the cluster heads. The cluster heads aggregate the data and send it to the base station. Bandyopadhyay et al. proposed a hierarchy of cluster heads and showed that lifetime improvement depends on the number of clustering levels [7].

2.2. Cooperation in WSNs

The cooperation problem in multi-domain sensor networks is discussed in a game theoretic setting by several studies [8–10]. These studies suggest that the cooperation can be achieved without the use of incentive mechanisms. We note that in the game-theoretic modeling of the problem, the objective of each player (i.e., each domain) is to maximize its own payoff. On the other hand, modeling the cooperation as an optimization problem assumes that all players give their decisions in favor of overall network lifetime maximization. In this sense, optimization result provides an upper bound for the network lifetime obtained through applying game-theory.

As an optimization problem, cooperation between sensor networks deployed at the same physical location was previously studied and it was shown that multi-domain cooperation can extend network lifetime more than an order of magnitude when compared to non-cooperating domains of WSNs [11].

3. System model

An example topology to investigate the impact of cooperation between neighbor sensor networks is illustrated in Fig. 1. There are two sensor networks with disk-shaped topologies and both networks have equal areas. We note that as the typical example of a two-dimensional topology many previous studies (e.g., [6]) also employed disk-shaped topologies. The base station of each network is at the center of a disk with radius $R_{NET}$ and the sensor nodes are randomly deployed over the network area. The base station of network-$i$ is denoted as $BS_i$. We note that the Distance between the base stations ($R_{BS}$) is a parameter we used to investigate the relationship between the amount of overlap in deployment areas and the impact of cooperation on the network lifetime with various strategies as explained shortly.

We construct four Linear Programming (LP) models to investigate the impact of cooperation between neighbor sensor networks. These models and their acronyms are presented in Table 1. In our models, each sensor node-$i$ creates $s_i$ unit of data per unit time and the objective is to maximize $t$ (the time – in terms of unit time – passed until the first sensor node drains all its battery energy). Note that this network lifetime definition is widely accepted in sensor network community [12,5,6] and it should not be misinterpreted — when we examine the framework carefully it can be seen that to maximize the minimum lifetime, all nodes are forced to dissipate their energies in a balanced fashion, hence, sensor nodes in the network deplete their battery energies simultaneously.

Each node’s total energy expenditure for data communication is limited by its battery energy $e_n$. The reception and transmission energies are denoted as $E_{rx}$ and $E_{tx}$, respectively. While the transmission energy depends on the distance between the nodes, the reception energy does not [12]. We do not put transmission range limitations in our LP models. We consider transmission range limitations of sensor nodes in the context of disjoint partitions in Section 4. The network topology is represented by a directed graph $G=(V,A)$. Each set $V_k$ consists of all nodes that belong to network-$k$ and the set of network is denoted as $S$. The union of all $V_k$’s constitute the set $V$ (i.e., $V=\bigcup_{k\in\mathbb{K}}V_k$). We also define set $W_i$ which includes all nodes of network-$i$ except the base station of network-$i$ ($BS_i$). The union of all $W_i$’s constitute the set $W$ (i.e., $W=\bigcup_{i\in\mathbb{I}}W_i$). Furthermore, the union of all base stations constitutes the set $Z(=\bigcup_{k\in\mathbb{K}}BS_k)$. $A\equiv\{(k,i,j)\mid k\in\mathbb{K},i\in V,j\in V\}$ is the set of edges (arcs). Note that there are

---

1 We ignore other energy consumption factors in order to keep our model simple. We note that communication energy is the most dominant factor in most scalar sensor platforms e.g., 91% of the total energy expenditure in Telos scalar sensor nodes is due to communication [13].
multiple directed edges between nodes. Data belonging to network-$k$ flowing from node-$i$ to node-$j$ is represented as $f_{ij}^k$, constituting the variables of the optimization problem.

3.1. Isolated network (IN)

We use the IN model as the baseline to evaluate the lifetime improvement attainable with different cooperation strategies. The LP model for IN is presented in Fig. 2.

Eq. (1) states that all flows in the network are non-negative. Since we construct a model for an isolated network in this section the set of networks has only one element, we set $k=1$. Eq. (2) is the flow balancing constraint. The amount of data flowing into node-$i$ and data generated by node-$i$ is equal to data flowing out of node-$i$. Eq. (3) states that the energy dissipation on node-$i$ is limited by the energy budget of node-$i$ ($e_i$). Note that all flows terminate at the base station which is not energy-limited (i.e., Eqs. (2) and (3) applies to the members of set $W_k$ which does not include the base station of network-$k$).

3.2. Neighbor networks with node cooperation (NN-NC)

In the NN-NC model, sensor nodes of multiple neighbor networks cooperate with each other for data relaying. However, the extent of cooperation is limited to the sensor nodes only. Sensor nodes of network-$k1$ can relay the data of network-$k2$, however, data generated in network-$k1$ terminates at BS$_{k1}$—BS$_{k2}$ cannot participate in cooperative relaying. Fig. 3 illustrates the examples of data flows possible in NN-NC model. The LP model for NN-NC is presented in Fig. 4. Eq. (5) is the flow balancing constraint for sensor nodes. If node-$i$ belongs to network-$k1$ and is not the base station of network-$k1$, the total amount of network-$k1$’s data flowing into node-$i$ from the sensor nodes of network-$k1$ plus the total amount of data generated by node-$i$. Eq. (6) is the flow balancing constraint for base stations relaying the data of networks which they are not a member to the corresponding base stations. The amount of flow from BS$_{k1}$ to BS$_{k2}$ is equal to the total amount network-$k2$’s data sent to BS$_{k1}$ by the sensor nodes of network-$k2$. Energy balancing constraint (Eq. (11)) is not modified because base stations are assumed to have virtually unlimited energy sources. Note that NN-NC model can be interpreted as all networks have multiple base stations (i.e., all sensor nodes can use any base station as their own base station).

3.4. Neighbor networks with full cooperation (NN-FC)

In the NN-FC model, communication between base stations as well as cooperation between sensor nodes of different networks are allowed. Fig. 7 illustrates the examples of data flows possible in NN-BC model. The LP model for NN-FC is presented in Fig. 8. This is our most flexible model and can be formulated as if there is a single network having multiple base stations. In fact, NN-FC model is obtained by integrating NN-NC and NN-BC models. Eqs. (13), (14), and (15) are for sensor nodes transporting their own network’s data, sensor nodes relaying other networks’ data, and base stations relaying other networks’ data to the corresponding base stations, respectively.

4. Numerical analysis

We first note that since there are no closed form solutions for LP problems, in general, we perform our analysis through numerical evaluations of the LP models.
In NN-NC model, sensor nodes can relay the packets of nodes belonging to another network.

Maximize $t$
Subject to:

$$f^k_{i_j} \geq 0 \ \forall (k, i, j) \in A$$

$$\sum_{j \in (W \cup BS_k)} f^k_{i_j} = \sum_{j \in W} f^k_{i_j} + s, \ \forall k \in S, \ \forall i \in W_k$$

$$\sum_{j \in (W \cup BS_k)} f^k_{i_j} = \sum_{j \in W} f^k_{i_j}, \ \forall k \in S, \ \forall i \notin W_k$$

$$E_{ee} \sum_{k \notin W} \sum_{j \in W_k} f^k_{i_j} + \sum_{k \notin W} \sum_{j \in W_k} E_{ee,i_j} f^k_{i_j} \leq c, \ \forall k \in S, \ \forall i \in W_k$$

In NN-BC model, packets can be sent to the base station of another network.
In our analysis, we use the energy model introduced in [12], where the amount of energy to receive a bit is represented as $E_{rx} = \rho$ and transmit a bit as $E_{tx} = \rho + \varepsilon d_{ij}^\alpha$. Here, $\rho$ is the electronics energy (50 nJ), $\varepsilon$ is the amplifier energy (100 pJ), $d_{ij}$ is the distance between node-$i$ and node-$j$, and $\alpha$ is the path loss exponent. All nodes have the same initial energy ($e_i$) in all our analysis. Since we are interested only in lifetime ratios, the numeric value of initial energy is not relevant for our analysis.

In our analysis, we exemplify neighbor sensor networks with two disk-shaped networks with equal areas as illustrated in Fig. 1. Each network has a base station (BS). In the NN-BC model, sensor nodes can communicate directly with each other without any intermediary nodes. In the NN-FC model, sensor nodes can relay the packets of nodes belonging to another network and packets can be sent to the base station of another network.

In our analysis, we use the energy model introduced in [12], where the amount of energy to receive a bit is represented as $E_{rx} = \rho$ and transmit a bit as $E_{tx} = \rho + \varepsilon d_{ij}^\alpha$. Here, $\rho$ is the electronics energy (50 nJ), $\varepsilon$ is the amplifier energy (100 pJ), $d_{ij}$ is the distance between node-$i$ and node-$j$, and $\alpha$ is the path loss exponent. All nodes have the same initial energy ($e_i$) in all our analysis. Since we are interested only in lifetime ratios, the numeric value of initial energy is not relevant for our analysis.

In our analysis, we exemplify neighbor sensor networks with two disk-shaped networks with equal areas as illustrated in Fig. 1. Each network has a base station (BS). In the NN-BC model, sensor nodes can communicate directly with each other without any intermediary nodes. In the NN-FC model, sensor nodes can relay the packets of nodes belonging to another network and packets can be sent to the base station of another network.
network is centered at its base station and 100 sensor nodes are randomly deployed in the area. All sensor nodes generate data at a constant rate ($s_i$). Again, due to reporting only lifetime ratios, the numeric value of data generation rate is not relevant for our analysis. The analysis is performed for two different path loss exponents ($a = 2$ and $a = 4$) and two different network areas ($10^4$ m² and $10^6$ m²). We use GAMS [14] to solve the LP models. Each data point presented in the graphics is the average of 100 different random topologies. All LP models are solved using the same node distributions.

Figs. 9 and 10 present normalized lifetimes for cooperation strategies as functions of $R_{BS}$ for $a = 2$ and $a = 4$, respectively. Normalization is achieved by dividing absolute lifetime values by the corresponding absolute lifetime value of IN model. For both $a = 2$ and $a = 4$, the highest lifetime gains are achieved with NN-FC and as $R_{BS}$ increases, lifetime gains of all strategies converge to unity. For $a = 2$, while the lifetime gain achieved is lowest with NN-NC for $10^4$ m² area, NN-BC has the lowest lifetime gain for $10^6$ m² area which suggests that node cooperation is more effective in prolonging lifetime than base station communication for sparser network deployments whereas base station communication is more effective than node cooperation for denser networks. For $a = 4$, regardless of the network area, the lowest lifetime gain is with NN-BC (i.e., for $a = 4$, node cooperation always provides higher lifetime gain than base station communication). For $a = 2$, lifetime gains achieved by cooperation strategies are higher in the sparser deployment. For $a = 4$, lifetime gains of NN-NC and NN-FC are higher in sparser deployment case whereas for NN-BC network area does not have a significant impact on lifetime gain. Figs. 9 and 10 jointly reveal that, in general, lifetime gain is higher in harsher propagation environments ($a = 4$).

Our analysis show that we can extend the network lifetime of neighbor WSNs significantly by node cooperation and/or base station communication. It is interesting to observe that the lifetime gain increases as the distance between two base station increases till the distance reaches a threshold value (until the overlap between two networks decreases and reaches an optimum). After this threshold, lifetime gain starts decreasing. The exact value of this threshold depends on the model used as well as on the network area. Another interesting observation is that modest lifetime gains are still possible even if there is no overlap between two networks (i.e., $R_{BS} > 2R_{NET}$). Cooperation does not lead to any significant lifetime gains for $R_{BS} > 2.5R_{NET}$ (e.g., for $R_{BS} > 2.5R_{NET}$, lifetime gains in all our results are less than 1%).

In addition to lifetime prolongation, cooperation of the nodes of neighbor networks also improves network connectivity by reducing the probability of disjoint partitioning ($p_{DP}$). Note that from disjoint partitioning perspective NN-FC and NN-NC (sensor nodes of different networks can cooperate) are equivalent, hence, we group these strategies under Node Cooperation Positive (NC-P) class. Likewise IN and NN-BC (sensor nodes of different networks cannot cooperate) are also equivalent and they are grouped under Node Cooperation Negative (NC-N) class. Fig. 11 presents $p_{DP}$ as a function of maximum transmission range of sensor nodes ($R_{NODE}$) for different $R_{BS}$ values. The deployment area is chosen as $10^4$ m², which results in an average inter-node distance of 11.28 m. For a given scenario, $p_{DP} = 1$ means that there is at least one node which cannot communicate with the rest of the networks in all 100 random topologies. If there is no disjoint partitioning observed in all of the random topologies then $p_{DP} = 0$. Fig. 11 shows that $p_{DP} = 1$ for $R_{NODE} ≤ 7$ m and $p_{DP} = 0$ for $R_{NODE} ≥ 21$ m. The effect of node cooperation manifests itself as an effective increase in node density, hence, for $7 m < R_{NODE} < 21 m$, $p_{DP}$ is lower for NC-P model as compared to NC-N model. As the overlap between two networks decreases, $p_{DP}$ increases (e.g., for NC-P with $R_{NODE} = 10$ m, $p_{DP} = 0.87$ with $R_{BS} = 0.5R_{NET}$ is less than $p_{DP} = 0.99$ with $R_{BS} = R_{NET}$).

5. Conclusion

In this study, we analyze the impact of cooperation between neighbor sensor networks on the network lifetime. The LP framework
we propose provides a theoretical basis to investigate the network lifetime gains for various cooperation strategies and in different deployment scenarios. We also address the issue of disjoint partitioning in the context of cooperating neighbor sensor networks. The results of our analysis quantify the decrease in disjoint partition probability when sensor nodes of different networks cooperate with each other. As a future work, we plan to investigate the impact of cooperation in neighbor sensor networks on other performance metrics such as packet delay and throughput.

References