Energy Consumption in Radio Networks: Selfish Agents and Rewarding Mechanisms

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Abstract. We consider the *range assignment* problem in ad-hoc wireless networks in the context of *selfish agents*: a network manager aims in assigning transmission ranges to the stations so to achieve a suitable network with a minimal *overall energy*; stations are not directly controlled by the manager and may refuse to transmit with a certain transmission range because this results in a power consumption proportional to that range.

We investigate the existence of payment schemes which induce the stations to cooperate with a network manager computing a range assignment, that is, *truthful mechanisms* for the range assignment problem.

1 Introduction

One of the main benefits of ad-hoc wireless networks relies in the possibility of communicating without any fixed infrastructure. Indeed, it just consists of a set of stations which communicate with each other via radio transmitters and receivers. Due to the limited power of the stations, *multi-hop* transmissions are in general unavoidable. That is, instead of sending the message directly from the source station to the sink station, the message is sent via intermediate stations. Another benefit of multi-hop transmissions is that they reduce the overall energy required by the communication.

Assigning transmission powers to stations which (i) guarantee a "good" communication between stations, and (ii) minimize the overall power consumption of the network gives rise to interesting algorithmic questions. In particular, these two aspects yield a class of fundamental optimization problems, denoted as *range assignment* problems, that has been the subject of several works in the area of wireless network theory [7, 5, 4].

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Unfortunately, the inherent *self-organized* nature of ad-hoc networks can complicate these problems even more. Since there is no central authority controlling the stations, we have to assume that they will act as selfish agents. That is, they will always try to optimize their own benefit, without considering the social cost of their behavior. This is exploited in the following model.

2 The Model

Range assignments without selfish stations. The instance of the range assignment problem consists of a complete weighted digraph $G(S, S \times S)$ and a graph property π. The set S denotes the set of stations. For $i, j \in S$, let C^i_j be the weight of the arc from station i to station j. This can be interpreted as the cost for sending a message from station i to station j.

The goal is to find the cheapest subgraph $G(S, E)$ that satisfies the graph property π. In general, we just write E to denote the subgraph.

The cost of E, also called communication graph, differs slightly from the one for wired networks. Let $E^i \subseteq E$ be the set of links emanating from station i and let $C^i = \{C^i_1, \ldots, C^i_n\}$ be the cost vector or them. Since station i can send a message to all its out-neighbors, provided it uses enough power to reach all of them, its cost depend only on the most expensive arc it has to provide. The cost of station i for maintaining the communication graph E, denoted by $\texttt{cost}^i$, is thus

$$\texttt{cost}^i(C^i, E) := \max_{j\,:\,(i,j)\in E} C^i_j.$$

Hence, the total cost of the range assignment E is

$$\texttt{cost}(\{C^1, \ldots, C^n\}, E) = \sum_{i \in S} \texttt{cost}^i(C^i, E).$$

Range assignment with selfish stations. We consider each station as a selfishly acting agent that *privately knows* part of the input: station i privately knows C^i that the manager must use for the computation of a feasible solution.

We assume that the range assignment is chosen by a network manager. In order to choose a low-cost solution, the manager needs information about the cost of the connections. So, in the first phase, every station i sends a vector $D^i = \langle D^i_1, \ldots, D^i_n \rangle$ to the network manager, where D^i_j denotes its *declared cost* for maintaining its link to station j. In an ideal world, we could assume that station i just sends the true values C^i. But since we assume that the station act selfishly, we have to assume that they lie to the network manager by declaring $D^i \neq C^i$. In the second phase, the range assignment is computed on the declared values and then implemented by informing the stations about E.

However, in order to be successful in this model, one needs to convince the stations to always tell the truth. This can be achieved by a so-called *mechanism*. A mechanism for a range assignment problem is a pair $(\textsc{alg}, P)$, where $\textsc{alg}$ is an algorithm that, on input $\mathcal{D} = \{D^1, \ldots, D^n\}$, returns a feasible range assignment $E = \textsc{alg}(\mathcal{D})$ and a payment vector $P = P(\mathcal{D}, E) = \{P^1, \ldots, P^n\}$, consisting of a payment for each station. Hence, agents, being selfish, will try to maximize their utility

$$U^i = P^i(\mathcal{D}, E) - \mathtt{cost}^i(C^i, E),\ i = 1, \dots, n.$$

A mechanism $(\textsc{alg}, P)$ is called *truthful* if any agent i can always maximize her utility by declaring the truth, i.e., when $D^i = C^i$. This has to hold for all possible declarations of the other agents.

3 Truthful VCG Mechanisms

The theory of mechanism design dates back to the seminal papers by Vickrey [10], Clarke [3] and Groves [6]. Their celebrated *VCG mechanism* is still the prominent technique to derive truthful mechanisms for many problems (e.g., shortest path, minimum spanning tree, etc.). In particular, when applied to combinatorial optimization problems (see e.g., [8, 9]), the VCG mechanisms guarantee the truthfulness under the hypothesis that the optimization function is *utilitarian*, that is, the optimization function is equal to the sum of the single agents' valuations, and that ALG computes always the optimum. The second condition can be weakened to the following [9].

Property I: An algorithm ALG has property I if the solution it returns is optimal among all the solutions in its output set.

Let us denote by $\mathcal{D}^{-i}$ the set of declarations $\mathcal{D} \setminus D^i$. The payment scheme is of the form

$$P^i = -\sum_{j \neq i} \mathtt{cost}^j(D^j, E) + h^i(\mathcal{D}^{-i}),$$

where $h^i(\cdot)$ is any function independent from D^i. Intuitively, these mechanisms achieve truthfulness by relating the utility of an agent with the total cost of the solution chosen by the mechanism: The better the solution the higher the utility. In order to formalize this statement let us consider the utility of agent i.

$$\begin{aligned} U^i &= P^i - \mathtt{cost}^i(C^i, E) \\ &= h^i(\mathcal{D}^{-i}) - \mathtt{cost}^i(C^i, E) - \sum_{j \neq i} \mathtt{cost}^j(D^j, E) \\ &= h^i(\mathcal{D}^{-i}) - \mathtt{cost}(\langle \mathcal{D}^{-i}; C^i \rangle, E). \end{aligned}$$

Since $h^i(\mathcal{D}^{-i})$ is independent of D^i, agent i tries to minimize $\mathtt{cost}(\langle \mathcal{D}^{-i}; C^i \rangle, E)$. Hence, his declaration should be chosen such that the algorithm returns a solution $\tilde{E}$ which minimizes $\mathtt{cost}(\langle \mathcal{D}^{-i}; C^i \rangle, E)$. This can be achieved simply by declaring the truth, assuming that the mechanism has property I.

Many range assignment problems are known to be NP-hard or even log APX-hard. We therefore cannot expect to find an algorithm that always returns the optimal solution. Therefore, we have to go for property I. The main problem we are faced with in the area of truthful mechanisms for range assignment problems thus is to find good approximation algorithms ALG with property I.

4 Previous Related Work and Open Problems

Range assignment problems are widely studied. For a survey, the reader is referred to [4]. A very interesting version is the Euclidean version, where the stations are point in the Euclidean plane and the cost to send a message from i to j is $C_j^i = \mathrm{dist}(i,j)^\alpha$, where $\mathrm{dist}(i,j)$ is the Euclidean distance between i and j and $\alpha \geq 1$ is a constant. This model admits a polynomial-time 2-approximation algorithm [7].

The only case in which a mechanism is known is the case $\alpha = 1$. There, the $\frac{\sqrt{5}+1}{2}$-approximation algorithm by Călinescu and Zaragoza [2] can be turned into a mechanism [1]. Also in [1], it was observed that the approximation ratio of this algorithm was improved to 1.5.

Several interesting problems are open in this area. First of all, in would be nice to design mechanisms for other types of range assignment problems. Furthermore, one could think of different models of privacy. For instance, one can assume that the protocol has a partial knowledge of the network topology. Finally, even though the VCG method is the major technique in order to obtain efficient truthful rewarding mechanism, a fundamental future research is to develop alternative methods to manage selfish behavior in the context of energy consumption in wireless networks.

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