Dynamic Protocol for the Demand Management of Heterogeneous Resources with Convex Cost Functions

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Increasing demand of resources has driven research towards design of mechanisms that address resource-demand management, which usually focus on balancing peak demand and optimal device scheduling. While balancing homogeneous sources is well known, the goal of this paper is to balance the demand of heterogeneous resources with a convex cost function as well as to encourage consumers to reduce their demand. We propose a novel dynamic protocol achieving both goals using a serial cost-sharing pricing mechanism. The pricing-mechanism design is strategy proof and budget balanced, whereas the protocol does not require the consumers to reveal their utility functions, and supports hierarchical organization of consumers. We initially applied the proposed approach to a multi-agent system, where the consumers are smart house devices controlled by a corresponding agent, which in turns negotiates the electricity price with a smart city. Experimental results show that the proposed protocol successfully reduces the total consumption and lowers the peaks while all the consumers in equilibrium are given a fair price. We further provide experimental results indicating advantages of serial cost-sharing pricing and tariff pricing mechanisms over the average cost-pricing mechanism that is commonly used in the resource-demand management.

Povzetek: V prispevku predstavimo mehanizem za uravnoteženje porabe heterogenih virov, katerih cenovne funkcije so konveksne.

1 Introduction

The rising demand of resources such as electricity, water, natural gas and oil along with a limited amount of natural resources increases the costs of resource supply [1]. Consumers are typically priced the same per-unit price for a resource, regardless of whether they increase or decrease their consumption.

Mechanisms that stimulate the use of electricity when its generation is cheap and depreciate its consumption when its generation is expensive, have already been proposed and implemented in the energy sector [9].

Similar mechanisms can be implemented for any other resource [13], although this is rarely done, since electricity demand management is recognised as the main resource-demand management problem. The main reason for this is that it is inefficient to build new power generation plants in order to meet peak demands, while there are parts of the day, when there is barely any demand at all. While other reports have focused on shifting the load from one part of the day to another [9, 12], we propose a mechanism to en-

courage consumers to reduce their consumption in general.

A resource-demand management mechanism that sets the same price for every consumer in advance does not fully exploit demand-management capabilities. Dynamic-pricing mechanisms were proposed in [3], [10] and [4]. In those papers, the price for the next time unit changes dynamically and is the same for every consumer. Additionally, such mechanisms require the consumers either to report their utility function (which raises privacy concerns) or to leave the decision about consumption to the consumers themselves (which is not as efficient as it could be). A dynamic-pricing mechanism that negotiates prices with every individual was proposed in [2]. However, their approach assumes that the consumers will report their consumption truthfully, which is not always the case. Distributed real-time electricity pricing mechanism was introduced in [8], however, due to intense communications requirements between the suppliers and consumers it takes time to calculate the optimum solution. Truth incentive demand management was proposed in [5]. The mechanism described in [5] has several desirable properties besides be-

ing truth incentive: it is proved to converge to a Nash equilibrium, it is budget balanced (the total cost of resource provision equals the total cost the consumers pay), and it reaches the global optimum (minimal peak-to-average ratio). However, it still raises some issues: the resource consumption of every consumer is known to everyone, consumers are only encouraged to shift their load to different parts of the day and not to reduce consumption, smaller consumption does not result in smaller per-unit price, and real-time pricing requires price prediction capabilities.

Further, the only known general technique for designing truthful and approximately budget-balanced cost-sharing mechanisms with good efficiency or computational complexity properties is due to Moulin [6].

In some ways similar to our approach is the trading market for the smart electricity grid described in [11]. The authors proposed continuous double auction for the smart electricity grid. However, their mechanism is not scalable nor it is dynamic. Further, [14] addresses similar problem – dynamic resource-demand management and it uses serial cost sharing mechanism. However, no comparison with other mechanism were made.

To be successfully implemented in practice, a mechanism has to address all the above mentioned shortcomings. It has to be easily understood by consumers, it should change the prices dynamically and adapt them fairly to each individual according to the amount of resource consumed. Further, the mechanism should be truth incentive and should encourage lower resource consumption without asking the consumers to publicly reveal their demand or utility function. We propose a novel protocol that possesses those properties. It is based on the following three key ideas:

1. It ensures consumer satisfaction, by using a fair per-unit pricing of the resource;

2. It has built-in truth incentive and budget-balancing;

3. To preserve privacy, consumers do not have to reveal their utility functions.

The rest of the paper is structured as follows. In Section 2, we describe the problem domain to which our mechanism can be applied. In Section 3, we describe the proposed mechanism and its properties. Results from applying the mechanism to electricity demand management domain are presented in Section 4, while Section 5 concludes the paper with summary and discussion.

2 Problem domain

Our mechanism can be applied to a general resource-demand management problem (when there are many consumers that consume convexly priced resource), but for illustrative purposes we will make use of smart city domain to provide examples. The proposed protocol applies to a multi-agent system, where devices and appliances that consume a resource in one consumer unit (e.g., a smart house) are controlled by one agent – house representative agent. House representative agents interact with the negotiator agent forming a multi-agent system (Figure 1).

Agents participating in the proposed protocol are defined in Definition 1.

Definition 1. *Let $\mathcal{A}$ be a set of all agents in the system.*

Let d_{ij} be a particular device j in a house i. Let $hr_i \in \mathcal{A}$ be a house representative agent that is responsible for coordinating all devices d_{ij} in the house. Therefore, house i consists of devices and a representative agent and is denoted as H_i.

Let $n_r \in \mathcal{A}$ be a negotiator agent that is responsible for fair distribution of resource r per-unit prices.

Every house representative agent interacts only with the resource negotiator agent. House representative agents do not interact among each other.
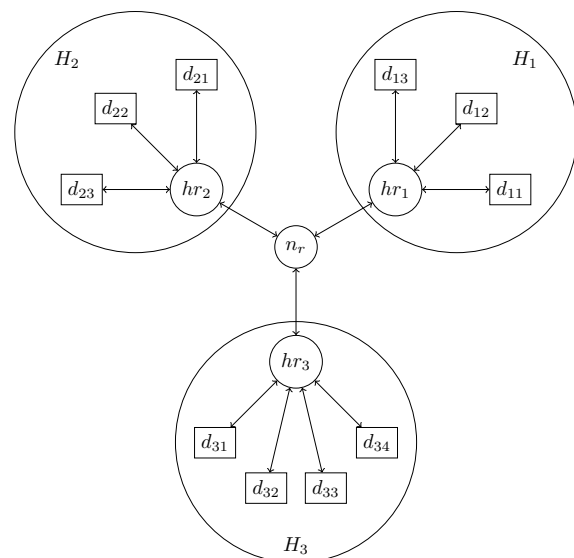

Figure 1: Multi-agent system example to which the protocol applies

We make the following assumptions for our problem domain.

House representative agents can control the devices in the house. House representative agents have the ability to switch the devices on and off. Further, agents can lower the power consumption of the device in finite number of discrete steps if gradual decrease of power consumption is supported by the device.

House representative agent strives to maximise consumer satisfaction. It is a primary goal of the house representative agent to consider users preferences, when negotiating with the resource negotiator. It is unacceptable for the inhabitant to pay a higher per-unit price for a resource than he was prepared to.

Cost function of a resource is convex, strictly increasing and non-constant. Examples of functions of this kind

are frequently used quadratic cost function and piecewise linear cost function [5].

3 The Protocol

The protocol defines a resource-demand management mechanism that enables the matching of resource demand with resource supply. Supply varies because resource provision usually depends on some independent variables (weather, fuel costs, taxes etc.). We assume that for one protocol run the supply and per-unit prices can be accurately defined in advance. Demand varies due to the supply and the consumer preferences. We assume that consumer preferences can be accurately defined in advance before each protocol run. Demand then depends only on the supply and using the proposed protocol the equilibrium can be reached.

The protocol is designed by the following requirements:

- negotiation finishes in a finite number of steps,

- consumers are motivated to reduce resource consumption by the protocol itself,

- the protocol is truth incentive,

- the pricing is fair,

- the total cost of resource provision equals the total cost the consumers pay, i.e., the protocol is budget-balanced.

According to those requirements and design the proposed protocol is a variant of a Moulin mechanism [6] - iterative fair sharing procedure.

3.1 Informal Protocol Description

Informal description of the protocol follows. First the smart house owners define the maximum per-unit price they are prepared to pay for every operating state of every device. For instance, smart house owner can have a dish washer, a washing machine and a heat pump installed in the house. For the dishwasher the owner is prepared to pay the per-unit price of 0.12 EUR/kWh, for the washing machine 0.10 EUR/kWh, for the heat pump at maximum power 0.30 EUR/kWh since keeping the home warm is more important than washing the clothes, and for the heat pump at half of the maximum power 1.0 EUR/kWh since in the case of high resource demand the per-unit price will be higher but the owner is prepared to pay the high per-unit price in order to maintain the border level of comfort. Other resources, e.g. water or gas can be added in the same way. By stating all the per-unit prices the user defines the strategy of her house representative agent and the agent can participate in the mechanism defined by our protocol on behalf of the house owner. Since the house representative agent resides in the house and does not share the information about prices, the character of the home owner or her representative agent remains private information.

Our protocol is dynamic, meaning that it is repeated after some period of time has elapsed from the previous run. For some resources the per-unit price is expected to be more or less stable over time and does not change very often. Time elapsed between protocol runs in these cases can therefore be longer. However, per-unit prices of some resources can fluctuate rapidly. For instance, the per-unit price of electricity can change rapidly with the increasing use of renewable resources for its generation depends on the wind speed, solar radiation, water flow rate etc. Since those variables are hard to predict a day in advance, an hour or half an hour time intervals are assumed and the protocol must be able to support a large number of houses and perform all the calculations in a short period of time.

When a new time interval in which the decision about consumption has not been reached yet approaches, the negotiator agent triggers the protocol. First, it gathers the information about resource supply from the suppliers in order to construct a resource cost function. Then it asks every house representative agent it has connection to as to what is her preferred consumption. Since this is at the start of the protocol and no price has been set yet, every house representative agent responds with the highest required consumption. The negotiator agent then computes the per-unit prices individually for every house using some kind of a pricing mechanism and informs the house representative agents of the per-unit prices. It then again asks every house representative agent about their required consumption. The house representative agent can then either agree with the per-unit price and it responds with the same consumption as before or it can reduces the required consumption in the hope of a lower per-unit price. The proposed protocol guarantees that the per-unit price for lower consumption is either lower or in the worst case equal to the per-unit price of higher consumption. The cycle *ask for consumption - respond with consumption - compute per-unit prices* is repeated until every house representative agent is satisfied with the per-unit price and at that point the protocol run ends and an agreement is made stating that each house will consume the specified amount of the resource in the approaching time interval at the per-unit price that was set by the negotiator agent and agreed upon by the house representative agent.

When new time interval starts the house representative agents turns the devices and appliances in the home ON or OFF, depending on the agreements made. Every additional consumption of the resource, beyond the agreed one, is paid for at uniform maximal per-unit price that covers the costs of resource providers for additional amount of resource provision.

3.2 The Protocol Definition

During the run of the protocol many rounds take place with house representative agents reporting their desired con-

sumption to the negotiator agent and negotiator agent computing per-unit prices for every house representative agent.

The per-unit prices are computed individually for every consumer using Serial cost sharing mechanism [7]. The Algorithm 1 determines fair per-unit price for every consumer – lower consumption results in lower costs. Since the resource is convexly priced, it also results in lower per-unit pricing.

Algorithm 1: Serial cost sharing function

```
Serial_Cost_Sharing(f, c):
  N = length(c)
  sort c in increasing order
  p = []
  for i in range(N):
    p[i] = cost(i, f, c)/c[i]
  sort p in order to
    match original order of c

  return p
```

Algorithm 1 takes two inputs: resource cost function, denoted as f, and desired consumption vector, denoted as c, and returns a vector of per-unit prices p. Individual cost is computed by a function $cost(i, f, c)$ that takes as inputs the following parameters: consumer i, a sorted consumption vector c, and resource cost function f. Function $cost$ is defined recursively in Eq. (1).

$$cost(0, f, c) = 0$$
$$cost(i, f, c) =$$
$$\frac{f\left(\sum_{j=1}^{i-1} c[j] + (N + 1 - i) \cdot c[i]\right)}{N + 1 - i} -$$
$$- \frac{\sum_{j=1}^{i-1} cost(j, f, c)}{N + 1 - i} \qquad (1)$$

where N is the number of consumers participating in negotiation.

The cost function just needs to be convex, whereas any source, homogeneous or heterogeneous (water, gas, security and similar), can be added with the corresponding weights:

$$cost = \sum_{resource} \omega_{resource} \cdot cost_{resource}, \qquad (2)$$

where $resource$ is a specific resource type, $cost_{resource}$ is the cost of that resource type and $\omega_{resource}$ is the weight of that resource in the resource portfolio.

If any of the consumers does not agree with the per-unit price it receives and wants to further reduce its consumption anticipating a lower per-unit price, another round of negotiation takes place. In the following round, the desired consumption of individual consumer can be the same or lower. Negotiation stage ends when the demand is the same for every consumer in two consecutive rounds.

It is a requirement of the protocol that a consumer does not respond with strictly higher desired consumption than in the previous round.

3.3 The Protocol Properties

In this subsection we evaluate the proposed protocol according to the requirements stated at the beginning of the Section 3.

Lemma 1. *Assume there is a finite number of consumers and each consumer is in possession of finite number of devices or appliances and every device or appliance has finite number of resource consumption levels. Then the protocol finishes in a finite number of steps.*

Proof 1. *Assume that the protocol does not finish in finite number of steps. That means that consumption vector (a vector of consumptions of all the consumers) is different in each two consecutive rounds. That means that in every round at least one of the consumers reported strictly lower consumption than before. Since we assumed infinite number of steps at least one consumer can strictly lower her consumption infinite times. This contradicts the premise from the lemma. Therefore, our assumption is wrong and the protocol finishes in finite number of steps.* □

Definition 2. *Let f be a resource cost function, so that $f(x)$ is the total cost for the provision of x amount of resource. Let cost be a pricing mechanism used to determine the cost for every resource consumer. Let $\mathbf{c}$ be a consumption vector, denoting consumptions for all the N-consumers participating in the mechanism. The pricing mechanism is* budget-balanced *iff*

$$f\left(\sum_{i=1}^{N} c_i\right) = \sum_{i=1}^{N} cost(c_i).$$

The following two lemmas are a corollary of [7].

Lemma 2. *The pricing mechanism used in the proposed protocol is budget-balanced.*

Proof 2. *Let N be a number of consumers, let c be a consumption vector where c_i-s are increasingly ordered, let f be a resource cost function and let the cost be a serial cost sharing mechanism that is used in the proposed protocol. The costs of the largest consumer can be computed as*

$$cost(N, f, c) =$$
$$\frac{f\left(\sum_{j=1}^{N-1} c[j] + (N + 1 - N) \cdot c[N]\right)}{N + 1 - N} -$$
$$- \frac{\sum_{j=1}^{N-1} cost(j, f, c)}{N + 1 - N}$$
$$= f\left(\sum_{j=1}^{N} c[j]\right) - \sum_{j=1}^{N-1} cost(j, f, c).$$

Therefore,

$$\sum_{j=1}^{N} cost(j, f, c) = f\left(\sum_{j=1}^{N} c[j]\right).$$

$\square$

Definition 3. *Let per-unit price for the consumption x and using pricing mechanism p be denoted by $p(x)$. Let consumers A and B consume a_A and a_B amount of resource, respectively. A pricing mechanism p is* fair *iff for each a_A and a_B so that $a_A \leq a_B$, $p(a_A) \leq p(a_B)$ also applies.*

Lemma 3. *The pricing used by the proposed protocol is fair.*

Proof 3 (sketch)**.** *Since resource cost function is convex and increasing, its derivative is also increasing. Since the derivative of the cost function represents the marginal price (per-unit price) of the resource provision, the per-unit price of the resource is higher when more of it is used. Serial cost sharing mechanism divides the cost in such a way that for the same amount of resource the consumers pay the same per-unit price and any additional consumption is paid at a different price. Since the per-unit price of additional consumed resource is higher, due to the increasing and convex cost function, so is the final per-unit price of a larger consumer. Therefore if $a_A \leq a_B$ then $p(a_A) \leq p(a_B)$.* $\square$

Definition 4. *Let the pairs $\{(c_i, p_i)\}_i$ represent the (consumption, price) pairs by which the consumer can state his preferences: for the consumption of c_i amount of resource the consumer is prepared to pay p_i per-unit price. Let $A = (c_A, p_A)$ and $B = (c_B, p_B)$ be two possible outcomes of the protocol. The consumer preferres A over B iff*

1. $c_A > c_B$ and $p_A \leq p_i$ where $c_i = c_A$, or

2. $c_A = c_B$ and $p_A < p_B \leq p_i$ where $c_i = c_A$.

In other words, the consumer prefers to consume the maximum possible amount of resource she can afford. In this case the following lemma applies.

Lemma 4. *Assume the definition of preference as in Definition 4. Further, assume the consumers are infinitely risk-averse. Then the proposed protocol is truth incentive and strategy-proof.*

Proof 4 (sketch)**.** *During the protocol the consumer can strategize by responding with the same level of consumption in two consecutive rounds of the protocol although she can not afford the per-unit price (according to her real preferences). That is because the per-unit price of the resource can lower when all other consumers lower their consumption. If the per-unit price lowers enough the per-unit price could become affordable for the strategic consumer. However, since no consumer has the full knowledge of all the consumers preferences or the resource prices, there is a*

positive probability that the per-unit price will not become affordable. If the consumer is infinitely risk-averse, she wants to avoid the worst possible results and therefore, she will not strategize. In every round the consumer will respond according to her preferences, which will guarantee a good outcome for her. Therefore, the proposed protocol is truth incentive and strategy-proof. $\square$

4 Experimental Results

Application of the protocol in electrical energy consumption domain is presented in this section. We carried out the experiment to examine the amount of electrical energy consumed and the average per-unit price of the electrical energy when using the proposed protocol.

4.1 Model description

While there are many variants for house representative agent implementation, the important properties of the house representative agent are:

1. It can reason about desired resource consumption in every round of the protocol, and

2. it can decide whether the offered per-unit price is satisfiable for the house.

In our experiment house representative agent possess the information about the electrical energy consumption of the devices and the information about consumers settings – maximal per-unit price for operating each device. This information is private to each house representative agent and sent neither to other house representative agents nor the resource negotiator.

The parameters for each house in our experiments were the following:

– Number of consumption levels: uniformly drawn integer number from the interval $[3, 15]$,

– Consumption level size: uniformly drawn real value from the interval $[0.1kWh, 1.5kWh]$,

– Acceptable per-unit price for every consumption level: drawn from normal distribution with mean $0.15EUR/kWh$ and standard deviation of $0.055EUR/kWh$.

A convex, strictly increasing piece-wise linear cost function was used for electrical energy pricing (suggested in [5]). It can be represented by a list of tuples (B_i, pup_i), where B_i is the amount of energy available for the per-unit price of pup_i. To obtain a convex function, we assume that lower priced energy is supplied first.

The parameters for cost function were the following:

– Number of tuples (B_i, pup_i): 50 tuples were used;

– Block sizes: on average each block was four time the size of total minimal level consumption;

– Block per-unit prices: drawn from normal distribution with mean 0.3EUR/kWh and standard deviation of 0.055EUR/kWh.

4.2 Electricity Consumption Experiment

In order to make a comparison of the serial cost sharing mechanism used in our protocol to standard cost sharing mechanism, the average cost sharing mechanism was also implemented [5].

Definition 5. *Let f be a resource cost function and let c be a consumption vector. The average cost sharing mechanism for consumer i is defined as:*

$$averageCost(i, f, c) = \frac{f\left(\sum_{k=1}^{N} c[k]\right)}{\sum_{k=1}^{N} c[k]} \cdot c[i].$$

The protocol was run 2000 times with serial cost sharing mechanism and average cost sharing mechanism for every number of houses we specified – specifically 100, 500, 1000, 1500, 2000. The main variables we observed were the percentage of total possible consumption that was realized after the protocol run and the average per-unit price the consumers have to pay.

Since there was a large difference between the two pricing mechanisms a third mechanism was implemented that combines the average and serial cost sharing mechanisms.

Definition 6. *Let T be a number of possible different per-unit prices of the resource. Let c be a consumption vector, where consumptions are orderer from smallest to largest, and let N be a number of consumers. Now group the consumers into T equal sized groups where in t-th group there are all consumers with index from $(t-1) \cdot \left\lfloor \frac{N}{T} \right\rfloor + 1$ to $t \cdot \left\lfloor \frac{N}{T} \right\rfloor$. Total consumption for every group can be computed and new consumption vector for groups can be assembled*

$$c_T =$$

$$\left(\sum_{i=1}^{\left\lfloor \frac{N}{T} \right\rfloor} c[i], \sum_{i=\left\lfloor \frac{N}{T} \right\rfloor + 1}^{2 \cdot \left\lfloor \frac{N}{T} \right\rfloor} c[i], \ldots, \sum_{i=(T-1) \cdot \left\lfloor \frac{N}{T} \right\rfloor + 1}^{N} c[i] \right).$$

For each group the costs can be calculated using the serial cost sharing mechanism and a cost vector can be obtained $cost_T = (cost_1, cost_2, \ldots, cost_T)$. The per-unit price for consumer i in group t can be calculated using the average cost sharing mechanism

$$price_i = \frac{cost_t}{\sum_{k=(t-1) \cdot \left\lfloor \frac{N}{T} \right\rfloor + 1}^{t \cdot \left\lfloor \frac{N}{T} \right\rfloor} c[k]} \cdot c[i].$$

We call this mechanism a tariff pricing mechanism.

We have made the same experiments as before using the additional pricing mechanism, where we grouped the consumer into two equal sized groups. The final results are
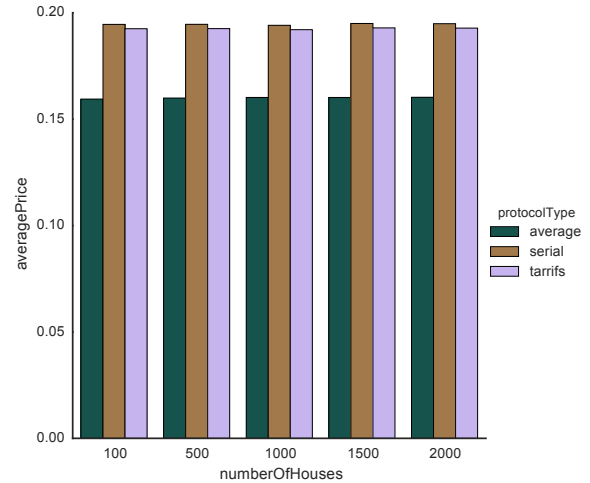

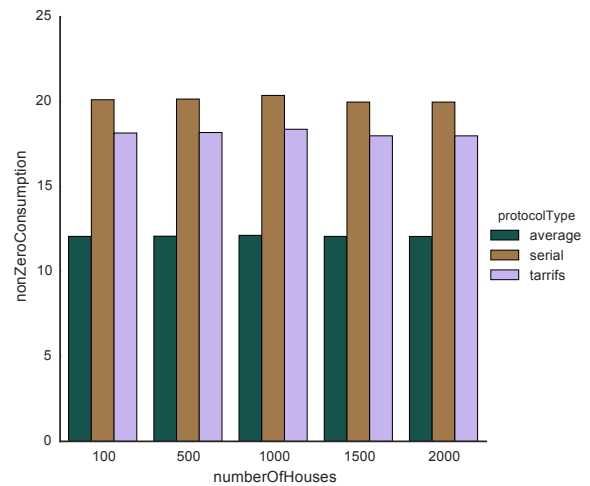Figure 2: Bar plot with number of houses and average per-unit prices on axes

Figure 3: Bar plot with number of houses and percentage of possible total consumption on axes

presented in Figures 2, 3 and 4. Every point or a bar represents the average of 2000 runs of the protocol.

From the experiments we concluded that a number of houses has a negligible effect on the observed variables when model like ours is used. The largest effect has the type of the protocol used: protocol with serial or average cost sharing mechanism. Since the consumers are different and some are prepared to pay more for the same amount of resource the consumption increases when using the protocol with serial cost sharing. It is the advantage of the serial cost sharing to produce personalized per-unit prices according to the amount of resource used. For that reason also, the average per-unit price increases when using serial cost sharing. However, every consumer still receives the amount of the resource she is prepared to pay for. And according to definition 4 maximal consumption within the limits is the preferred result. Therefore, serial cost sharing
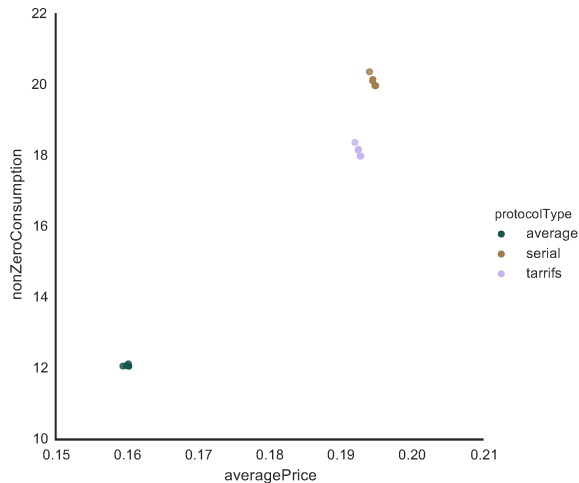
Figure 4: Scatter plot with average per-unit prices and percentage of possible total consumption on axes

mechanism is the preferred mechanism.

By using only two groups the results of the protocol using tariff pricing are much more similar to the protocol using serial cost sharing than the average pricing. Consumption and average per-unit price increase due to the flexible pricing mechanism used.

5 Discussion & Conclusion

We have proposed a truth incentive mechanism that encourages the reduction of consumption of convexly priced resources and can be easily understood by consumers. Further, the mechanism scales linearly with the number of consumers, since the per-unit prices can be easily computed.

The novel protocol ensures consumer satisfaction when the consumer is truthful and deals also with heterogeneous resources. But there are also some problems associated with our approach. First, since one can not predict the consumption of others and does not know the exact resource cost function, one can not predict the possible outcome of the protocol. Therefore, it is not rational to agree to a higher per-unit price than one is willing to pay. Second, the algorithms that deals with homogeneous resources [6] find optimal solutions and have several desired properties. Our algorithm meets some of the desired requirements but needs several rounds to achieve that, however the number of cycles is still less than in general Moulin mechanisms.

Since serial cost sharing was used the proposed mechanism is budget-balanced. The stopping of the protocol was discussed in Subsection 3.3. However, one of the main assumptions used to prove the stopping was that after every round of the negotiation the consumer does not demand strictly higher desired consumption. Although not addressed in the proposed version of the protocol, additional mechanism could be implemented to release this assumption and still maintain the the stopping property.

Further work will include the analysis of the consumer behaviour when the protocol is applied repeatedly with the same consumers and the same resource negotiator. Additionally, other agent organization structures will be considered in order to enable the protocol implementation in real-life scenarios.

The proposed protocol demonstrates various desired properties beside being truth incentive and scalable. Due to its efficient resource reduction capabilities it is considered to be applicable to the sustainable smart city domain.

6 Acknowledgements

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