A Double-Auction Mechanism for Wireless Charging Networks

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***Abstract*—Wireless Power Transmission (WPT) is a technique to charge electrical devices (EDs) remotely. In WPT, power source (Smart Wireless Charger) transmits power wirelessly, using air as the medium, to EDs. In this paper, we present an Auction mechanism to obtain the energy trading between Smart Wireless Chargers (SWCs) and EDs. In our proposed Double-Auction based charging trade mechanism, our priorities are to increase utility of the SWCs as well as increase EDs utilities. In our proposal, first we analyze the system architecture of the WPT environment and then form an optimization problem for the auction system. We then, introduce two algorithms to solve the combinatorial optimization problem such that the wireless charging system is stable and have high efficiency. We have numerically analyzed our system using python, the results show that the proposed mechanism achieve higher total utility for the whole system with satisfying budget balancing, individual rationality and truthfulness.**

I. Introduction

Due to improvement in wireless access networks like, LTE, LTEA and wifi networks expansion, complex applications that needs more computational and communicational needs of the mobile devices are also increased. The mobile devices runs on battery power, which is always considered as a scarce resource. Many mobile devices has run out of power at a crucial moment, with mean lowering network usability and functionality [1]. Meanwhile, mobile devices need to be charged or replenish battery immediately. In reality, there are many ways for a mobile device to recharge its battery by using electrical source or visit some place supporting energy charging. However, every time a cable is needed for regularly charging the device. Now a days, the popularity and vast acceptance of Internet of Things (IoT) [2], [3], [4] has envisioned the idea of wireless chargers for dealing with mobile devices battery recharge with convenience.

Researchers have given much attention to deal with battery lifetime maximization of the mobile devices through reduce energy consumption [5] ,[6], [7]. However the battery outage of the mobile devices is still a very big issue. To help mobile devices can be charged without wired (wirelessly), the concept of Wireless Power Transmission (WPT) has been introduced in [8], [9], [10], [11] which opened a new paradigm in the field of mobile devices battery management. Currently, WPT is a novel paradigm for energy supply in wireless networks. On of the most discouraging factor in the WPT was the shorter transmission distance between ED and SWC, which was just a few centimeters. The challenging has been solved by Jouya and Dina in [12], they introduced a MagMIMO in which cell phone can be charged from a distance up to 2 m with transmission efficiency around 40 percent of $60W$ and increasing to 90 percent up to $1m$. It was a big step to touch the popularity of wireless charging in near future.

The goal of this paper is to introduce a new game theoretic framework for energy trading in WPT, referred to auction-based mechanism. When a number of EDs needed to recharged its battery and a numbers of SWCs available to supply the demand from EDs. For example, in some places like Coffee shop, there is existing a number of SWCs and many customers need to recharged their EDs. In summary, this paper introduces a mechanism for help EDs can find the best seller to matching and trading energy or help SWCs can find the best buyer to serve.

The rest of this paper is organized as follows. Section II reviews related work. Section III describes the system model and game model also the optimization formulation for optimal utilities of SWCs and EDs. Section IV-A,IV-B discusses the algorithm for double auction. Section IV-C presents the performance evaluation results. Section V summarizes the paper.

II. Related work

In 2006, a team at Massachusetts Institute of Technology (MIT) introduced Magnetic MIMO which focused the magnetic flux from multiple coils in a steerable beam and points it at the phone, in a manner analogous to multi-antenna beam-forming in wireless communications [12]. The work in [13] has study about the energy cooperation i.e., which energy of mobile devices can be transfered wirelessly to other devices. In 2015, mobile energy sharing network has been introduced for wireless communication networks [1]. They form a network in which the energy can transfer from one user to another depending on the current battery state, capacity of their batteries, the power consumption or energy requesting amount. They also consider the mobile environment where ED meet each other for transferring or sharing/receiving or recharging the energy for mutual benefit. The work in [14], dealt the wireless energy transfer or charging like data packet in which more energy can be transferred from one device to the other in one time slot. In [1], the authors presented energy sharing done via cable connection or wireless charging technology. However, in reality, many EDs run out of power at crucial time, which means ED needed to be charged regularly for which the device will have to pause other tasks. Authors of [15] have worked on minimizing the energy charging time, according to their technique the mobile devices can self-recharge its battery or exchange batteries with other devices. In [16], the author have focused on wireless energy charging technology for mobile phone charging and wireless sensor devices. The work in [11] have shown the wireless power transfer link when the transmitter and the receiver are either in the near-field or in the far-field region reciprocally.

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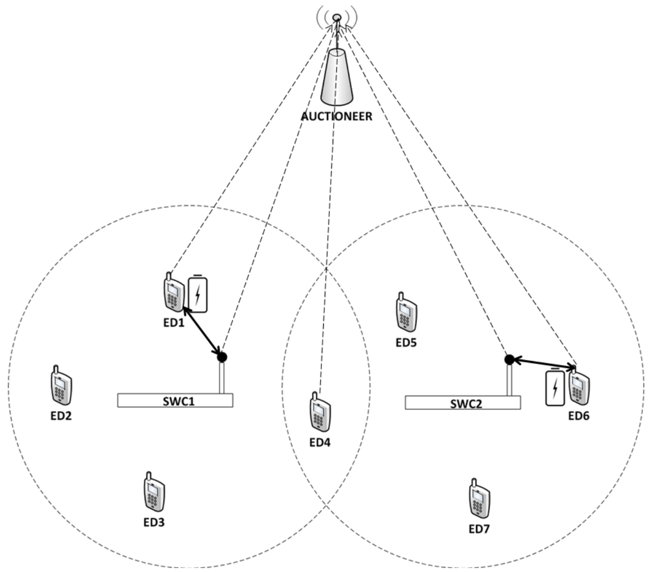

Figure 1. System model

III. System model and problem formulation

In this section, we are introducing the system model and describe the game model. After that we formulated the problem in then use Double Auction game theoretical approach to solve it.

A. System model

We consider a system in with a set of N electrical devices in the fixed location covered by a wireless base-station s (Access Point,etc,.). In this place, there are M SWCs available to support the energy replenishment. In WPT, power can be transfered wirelessly in an air gap to EDs. Which means that, EDs can be charged without wired, cable or physical connections. In the system, we consider the situation in which there are multiple ED's contesting to couple with a limited number of SWCs for charging. Since one SWC can charge only one ED at a time, therefore only a subset of the ED's demand can be full filled. Our model is to define the Auction based-mechanism to obtain which ED and SWC can be match, similarly to say that demand of an ED will be served by which SWC. If EDs want to charged its battery, they have to send the information to auctioneer offers price per unit of energy (bidding) and the amount of unit they want to buy. On the other hand, SWCs will send the information about their offer price per unit of energy to served the demand from EDs (asking) and the number of amount they can serve (capacity). The auctioneer collect all of the bid and ask information. In the Figure 1, we have shown the model that some of EDs can be served by multiple SWC, and some other EDs can be served by one SWC only. After collecting all of the bids and asks, the auctioneer decides winning buyers and winning sellers. The trading occurs after wining buyers pay to auctioneer and winning sellers receive payment from auctioneer.

B. Auction Model

Let $\mathcal{N} = \{1, 2, \ldots, N\}$ is the set of N EDs, and $\mathcal{M} = \{1, 2, \ldots, M\}$ is a set of the M SWCs. Each $m \in \mathcal{M}$ (resp. seller) submit its bid (resp. ask) privately to the auctioneer and each $n \in \mathcal{N}$ also submit its bid (resp. bidding) with respect to sellers. We then denoted the bid vector of EDs n as $\mathbf{b}_n = \{b_n^1, b_n^2, \ldots, b_n^M\}$ where b_n^m is the bid for seller $m \in \mathcal{M}$. The bid value of n includes the amount of energy and price per unit of power. The amount of energy ED can buy depends on its battery status and denoted as $\mathcal{C}_n$. Consequently, the bid matrix consisting of the bid vector of all EDs is defined as $\mathcal{B} = \{\mathbf{b}_1; \mathbf{b}_2; \ldots; \mathbf{b}_N\}$. On the other hand, the ask vector of all SWCs is denoted by $\mathcal{A} = \{a_1, a_2, \ldots, a_M\}$, where $a_m \in \mathcal{A}$ is the ask of the SWC m. Considering for each SWC have their limited amount of power selling let denoted as Γ_m. The auctioneer decides winning buyer set $\mathcal{B}_w \subseteq \mathcal{N}$ and the winning seller set $\mathcal{M}_w \subseteq \mathcal{M}$. Let γ_n is the price per unit needed to be paid for the auctioneer. The utility of buyer $n \in \mathcal{N}$ defined by:

$$U_n = \sum_{m=1}^{M} (\zeta_n - \gamma_n) x_{n,m} \tag{1}$$

Let δ_m is the payment from auctioneer to winning seller $m \in \mathcal{M}$. The utility of seller m defined by:

$$U_m = \sum_{n=1}^{N} (\delta_m - \xi_m) x_{n,m} \tag{2}$$

where ζ_n, ξ_m denotes *true valuation* of buyer n and seller m, respectively. The true valuation of EDs can be considered as loss generality when ED n receive power transmitted from SWC m.

The notation $x_{n,m}$ in the above equation is the binary value that represents whether the buyer and seller are coupled or not. When $x_{n,m}$ is 1, it means buyer n will sell to seller m, and 0 for otherwise. In this model, we assume that buyer can win at most one bid or can be matched at most with one seller and vice versa, represented by

$$\sum_{n=1}^{N} x_{n,m} \leq 1, \forall m \in \mathcal{M} \tag{3}$$

and the seller can win or matched at most one seller, represent as

$$\sum_{m=1}^{M} x_{n,m} \leq 1, \forall n \in \mathcal{N} \tag{4}$$

From the economic perspective, there are three properties an auction mechanism design must achieve: *Budget balance, individual rationality, truthfulness* [17]

C. Problem Formulation

Consequently, we formulated the problem of this model follow

$$\underset{x}{maximize} : \sum_{n=1}^{N} U_n + \sum_{m=1}^{M} U_m \tag{5}$$

$$\textit{subject to:} (3), (4) \tag{6}$$

$$\sum_{n=1}^{N} \mathcal{C}_n x_{n,m} \leq \Gamma_m, \forall m \in M \tag{7}$$

$$x_{n,m} = \{0, 1\}, \forall n \in N, \forall m \in M \tag{8}$$

Our objective is to maximize the total utility of the system with respect to both sides: seller and buyer(SWCs, EDs). Where the first constraint represents that at a specific time, one SWC can be provide service at most one ED. Similarly the second constraint is that one ED can be matched with one SWC at most. Due to the binary variable then the problem become a combinatorial optimization.

IV. Evaluation

Algorithm 1 BUUM($\mathcal{N}, \mathcal{M}, \mathcal{A}, \mathcal{B}, N, M$)

Input: $\mathcal{N}, \mathcal{M}, \mathcal{A}, \mathcal{B}, N, M, \mathcal{C}, \Gamma$
Output: $\mathcal{N}_w, \mathcal{M}_w, \mathcal{I}$

1: $\mathcal{N}'_w \leftarrow \emptyset, \mathcal{M}'_w \leftarrow \emptyset$
2: **for** $n \in \mathcal{N}$ **do**
3:     **if** $((U_n(\mathcal{A}_m) \geq U_n(\mathcal{A}_{-m})) \cap (\mathcal{C}_n \leq \Gamma_m) | \forall m \in \mathcal{M})$ **then**
4:         $\mathcal{N}'_w \leftarrow \mathcal{N}'_w \cup \{n\}$
5:         $\mathcal{M}'_w \leftarrow \mathcal{M}'_w \cup \{m\}$
6:     **end if**
7: **end for**
8: $\mathcal{N}_w \leftarrow \emptyset, \mathcal{M}_w \leftarrow \emptyset, \mathcal{I} \leftarrow \emptyset$
9: **for** $n \in \mathcal{N}'_w$ **do**
10:     **if** $U_n(\mathcal{A}_m) > U_{-n}(\mathcal{A}_m) | \forall m \in \mathcal{M}'_w$ **then**
11:         $\gamma_n, \delta_m \leftarrow \frac{\mathcal{B}_{n,m} + \mathcal{A}_m}{2}$
12:         $\zeta_n \leftarrow \mathcal{B}_{n,m}, \xi_m \leftarrow \mathcal{A}_m$
13:         $U_n \leftarrow U_n(m)$
14:         $U_m \leftarrow U_m(n)$
15:         $\mathcal{I} \leftarrow \mathbf{I} \cup \{(n, m)\}$
16:         $\mathcal{N}_w \leftarrow \mathcal{N}_w \cup \{n\}$
17:         $\mathcal{M}_w \leftarrow \mathcal{M}_w \cup \{m\}$
18:     **end if**
19: **end for**
20: **return** $\mathcal{N}_w, \mathcal{M}_w, \mathcal{I}$

A. Buyers' utilities maximization (BUUM)

In this section we discuss about the utility maximization of buyers. We separated the algorithm in three phases, first phase is the winning candidate selection, the second phase is deciding the winning buyer, the third phase is the announcement buyer and seller get won.

1) *Winning candidate selection:* Line 1 to 7 of algorithm 1 is showing the winning candidate selection. For each $n \in \mathcal{M}$, $m \in \mathcal{M}$ is a candidate wining buyer if and only if $U_n(\mathcal{A}_m) \geq U_n(\mathcal{A}_{-m})$, where $\mathcal{A}_{-m} = \{a_1, a_2, ..., a_{m-1}, a_{m+1}, ..., a_M\}$ represent asks of any seller in $\mathcal{M}$ without m. If m satisfy the constrain in *step 3*, m is added in the winning candidate sellers. The constraint in *step 3* mean the demand from ED could not be greater the capacity of SWC, and the utility at m is the maximum for n.
2) *Deciding winning buyer*: line 8 to 19 of algorithm 1 is determine the winning buyers $\mathcal{N}_w$. *Winning sellers* $\mathcal{M}_w$, *determine pricing* γ_n, δ_m, *true valuations* ζ_n, ξ_m, *utilities* U_n, U_m *and the mapping function between buyer and seller* $\mathcal{I}$. At the end of first phase, we get a set of potential buyers and sellers. To find down the winning buyer, for any $n \in \mathcal{N}'_w$ we want to find n such that $U_n(\mathcal{A}_m) \geq U_{-n}(\mathcal{A}_m)$.
If m and n is the winning couple, the trade is occurred at price:
$$\gamma_n = \delta_m = \frac{\mathcal{B}_{n,m} + \mathcal{A}_m}{2} \tag{9}$$
The auctioneer determine true valuation of buyer at $\zeta_n = \mathcal{B}_{n,m}$ and true valuation of sellers at their asks $\xi_m = \mathcal{A}_m$.
3) *Announcement of auctioneer* The auctioneer announcement for each seller and buyer whether they won or not based on the mapping function $\mathcal{I}$.

Algorithm 2 SEUM($\mathcal{N}, \mathcal{M}, \mathcal{A}, \mathcal{B}, N, M$)

Input: $\mathcal{N}, \mathcal{M}, \mathcal{A}, \mathcal{B}, N, M, \mathcal{C}, \Gamma$
Output: $\mathcal{N}_w, \mathcal{M}_w, \mathcal{I}$

1: $\mathcal{N}'_w \leftarrow \emptyset, \mathcal{M}'_w \leftarrow \emptyset$
2: **for** $m \in \mathcal{M}$ **do**
3:     **if** $((U_m(b_n^m) \geq U_m(b_{-n}^m)) \cap (\mathcal{C}_n \leq \Gamma_m) | \forall n \in \mathcal{N})$ **then**
4:         $\mathcal{N}'_w \leftarrow \mathcal{N}'_w \cup \{n\}$
5:         $\mathcal{M}'_w \leftarrow \mathcal{M}'_w \cup \{m\}$
6:     **end if**
7: **end for**
8: $\mathcal{N}_w \leftarrow \emptyset, \mathcal{M}_w \leftarrow \emptyset, \mathcal{I} \leftarrow \emptyset$
9: **for** $m \in \mathcal{M}'_w$ **do**
10:     **if** $U_m(b_n^m) > U_m(b_{-n}^m) | \forall n \in \mathcal{N}'_w$ **then**
11:         $\gamma_n, \delta_m \leftarrow \frac{\mathcal{B}_{n,m} + \mathcal{A}_m}{2}$
12:         $\zeta_n \leftarrow \mathcal{B}_{n,m}, \xi_m \leftarrow \mathcal{A}_m$
13:         $U_n \leftarrow U_n(m)$
14:         $U_m \leftarrow U_m(n)$
15:         $\mathcal{I} \leftarrow \mathbf{I} \cup \{(n, m)\}$
16:         $\mathcal{N}_w \leftarrow \mathcal{N}_w \cup \{n\}$
17:         $\mathcal{M}_w \leftarrow \mathcal{M}_w \cup \{m\}$
18:     **end if**
19: **end for**
20: **return** $\mathcal{N}_w, \mathcal{M}_w, \mathcal{I}$

B. Sellers' utilities maximization (SEUM)

In this section, we discuss about the utility maximization of buyers. We separated the algorithm in three phases, first phase is selection of potential buyers, the second phase is deciding the winning sellers and determine pricing, the third phase is the announcement of winning buyers and sellers.

1) *Winning candidate selection:* For each $m \in \mathcal{M}$, and $n \in \mathcal{N}$ is a potential wining buyer/seller pair if and only if $U_m(b_n^m) \geq U_m(b_{-n}^m)$, where $b_{-n}^m = \{b_1^m, b_2^m, ..., b_{n-1}^m, b_{n+1}^m, ..., b_N^m\}$ represent bids of any buyer in $\mathcal{N}$ without n. If n satisfy the constrain in *step 3*, n is added to the potential winning buyers.
2) *Deciding winning buyer and determine pricing*: At the end of first phase, we get a set of potential buyers and sellers. The auctioneer determine whether buyer and seller won or not based on its true valuation ζ_n and ξ_m. If m and n is the winning couple, the trade is occurred at price determine in (9).
3) *Announcement of auctioneer*: The auctioneer announce the winning sellers and buyers pairs on the bases of mapping function $\mathcal{I}$.

C. Numerical results

For the numerical analysis, we assume that the number of buyers are ranging from 15 to 50. The price offered by sellers is $a_m \in (0, 1)$, the bid value of buyer $b_n^m \in (0, 1)$ are uniformly distributed. The amount of power that the seller can supply is $\Gamma_m \in [1, 10]$, units and the amount of power buyer needs is $\mathcal{C}_n \in [1, 10]$ are randomly distributed. For the comparison of our proposal and the optimum solution (which is combinatorial), we show the results of SEUM, BUUM and the optimal solution come from *Gurobi* solver[18]. In the figure 4, we have shown that the gap between optimal solution and our proposed one is very small.

In the figure 2 , we have shown that, depend on the bid value and the ask value, each user will get different utility such that the

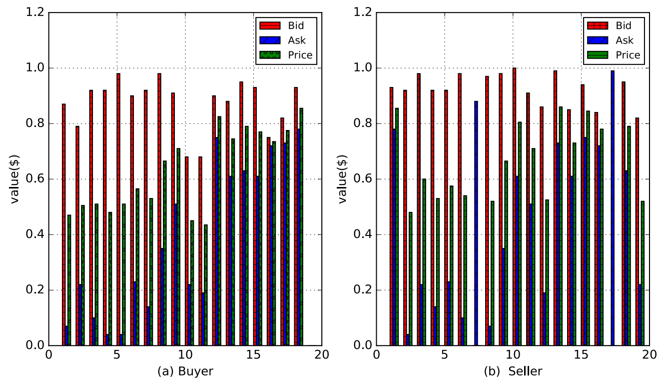

Figure 2. Individual Rationality

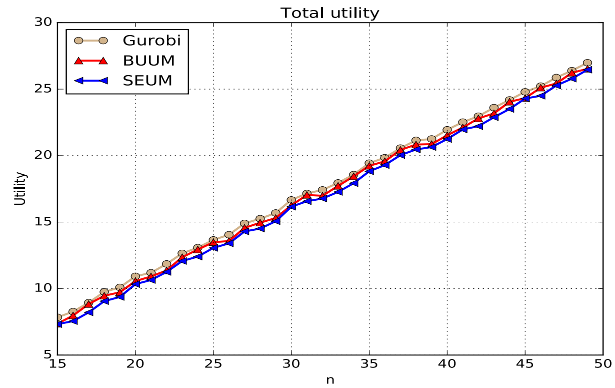

Figure 4. Comparison of SEUM, BUUM, and optimal solution

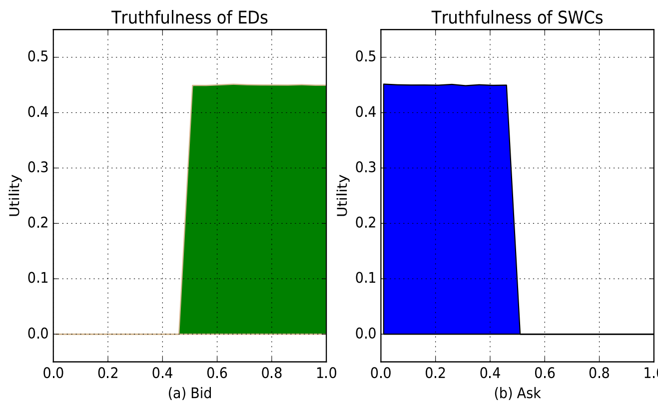

Figure 3. Truthfulness

price and payment satisfy the following properties: In the figure 3 is showing that buyers or sellers cannot improve their utilities no matter what other bids it selects. We evaluate the truthfulness of BUUM and SEUM for buyer. We have run the simulations 1000 times and calculate utility that the buyers achieved with different bids and utility that sellers can achieve with different asks.

V. Conclusion

In this paper, we presented a Double-Auction based trading mechanism between Smart Wireless Chargers and electrical devices for wireless charging. This study shows us that by applying our proposed mechanisms (BUUM and SEUM) for determining which ED to be allocated to which SWC that give win-win result for both of them and the allocation is also feasible keeping the network condition in consideration. We intensively evaluated the proposed mechanism by implementing it in python. The analytical results shown that proposed scheme significantly enhances the performance and achieves very near optimal solution. For the future work, we intend to study the problem in more detail and evaluate it in real operating environment to validate the proposal and its performance.

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