Incentivizing Truthfulness in Crowdsourced Parking Ecosystems

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Abstract—Limited parking space in urban environments has a severe social and environmental impact, because of time loss and unnecessary pollution while looking for free parking spaces. In a recent effort, we have developed the SocialPARK ecosystem to tackle this problem through the activation of a community of interacting citizens, parking companies and municipalities. SocialPARK offers an integrated platform for the provision of personalized parking functionalities as a service, auditing parking availability information through a crowdsourcing approach that gathers relevant information provided by users, parking vendors and municipalities. In this context, a central challenge in delivering trustworthy parking services is to ensure a truthful behavior of the involved (possibly unreliable) users. Towards this direction, we present two rewarding schemes that provably incentivize users to behave truthfully. Both schemes are based on virtual credits (points) that users earn for providing parking availability information. Apart from incentivizing truthful behavior, our schemes cater for point circulation, do not allow point overaccumulation, and prevent malicious users to aggregate points by misreporting.

I. INTRODUCTION

Limited information about parking space availability in urban environments has a severe social and environmental impact, because of time loss and unnecessary pollution, while looking for free parking spaces. Crowdsourcing has been used as a source of parking availability information, because it provides flexibility and a system based on it can be deployed at a large scale due to the low infrastructure cost. Mobile phone users, participating in such a crowdsourcing-based parking system, provide the sought parking availability information and receive in return some reward. The reward incentivizes the user participation to the system and can be either a monetary reward, a reputation reward, or a virtual credit (points) similar to those given by several web service providers (e.g., Facebook) and can be exchanged for monetary gains (e.g., discounts) in a store [4]. A central issue in this context concerns the quality and utilization of the crowdsourced data.

a) Related Work and Main Challenges: An example of crowdsourced-based parking availability application is Google’s OpenSpot [7], where mobile users are asked to provide information about free parking spaces, either when they release a parking space or when they notice a free parking space on the street. The users who contribute receive a reputation reward. PrimoSpot [2] and SpotAngels [10] are two applications in which users contribute in the creation of a database which contains data of city’s parking spaces. Both applications hire people to take photos and give specific information of city’s parking spaces. This information is stored in the database and hence the system provides parking rules and restrictions to the users. The users who have participated in data collection receive a small monetary reward.

Although the incentives have already been introduced as a mechanism for encouraging high-quality users’ participation [3], [5], there is still a need for complete, carefully designed incentivizing platforms for specific crowdsourcing-based parking services. Some examples of complete incentive-based platforms are Trucentive [6], Parkbid [8] and the incentivization of vehicle relocation in Vehicle Sharing Systems [1]. Trucentive [6] distributes a static amount of reward just when a user provides parking availability information, plus a dynamic amount of reward depending on the actual utilization by the system of this information. The drivers always have to pay money as soon as they receive the parking availability information, regardless of whether they manage to park or not. Parkbid’s [8] incentive system depends on many factors such as user’s reputation and utility of the parking space. Every user who contributes parking availability information to the system is accompanied with a variable which indicates the user’s reputation. The user’s actions increase or decrease his/her reputation. The incentivization of vehicle relocation [1] provides two incentive-based schemes, in order to make users return their rented bike to a station that is best for the overall system (social optimum), rather than to the most convenient station for them. Both Trucentive and ParkBid are provably truthful and budget feasible rewarding schemes [6], [8].

The main challenge in developing a crowdsourcing-based ecosystem for parking availability information is to obtain high-quality and truthful information given by possibly unreliable mobile users. Such an ecosystem should employ the proper incentive-based mechanisms in order to ensure the
trustworthiness of the provided information. Otherwise, we may end up with low-quality information, or the incentive-based scheme motivates them to give more and more information, even if it’s false, only for receiving (monetary) rewards.

b) Our Contribution: In this work, we present two incentive-based schemes, which have been designed in such a way to incentivize users to provide truthful, high-quality and useful parking availability information in a crowdsourcing-based parking ecosystem. Both our schemes use credits (points) as rewards for incentivizing users, who can then exchange them for discounts at the participating parking houses. The first scheme is based on a simple static approach, where users receive points for behaving truthfully, and which (points) are devaluated over time. The second scheme is based on a dynamic approach, in which users need to spend points for acquiring parking availability information by the ecosystem. We prove that both schemes are truthful and budget feasible. Their novel features are: (i) The rewards are set in such a way so that every user is incentivized to voluntarily participate by providing truthful parking information. (ii) Our point-systems are closed (the points which are spent by the users are returned back to the system) and do not allow overaccumulation of points. (iii) Our schemes prevent malicious users from misreporting in order to aggregate points and subsequently redeem them in the participating parking houses. Our incentive-based schemes have been implemented within the SocialPARK crowdsourcing-based ecosystem [9].

The rest of the paper is organized as follows. Section II presents an overview of the SocialPARK ecosystem. Section III presents our incentive-based schemes along with a comparison to related work. An evaluation of our schemes is presented in Section IV. We conclude in Section V.

II. THE SOCIALPARK ECOSYSTEM

The SocialPARK ecosystem tackles the parking availability problem through the activation of interacting citizens, parking companies and municipalities, towards a mutually profitable management of the publicly available parking space. The SocialPARK ecosystem unifies and centrally audits the availability, and coordinates the usage of publicly available parking spaces on the street, the private sector (e.g., super markets possessing under-utilized private parking spaces for their customers, and might be willing to commercially exploit them within the day), commercial parking houses, and municipalities. The usage of SocialPARK is targeted on an urban area and the availability of free parking spaces is audited via a crowdsourcing approach that gathers availability information provided by all the involved stakeholders.

SocialPARK offers personalized parking functionalities as a service (i.e., parking-as-a-service) to citizens and special groups, for (i) discovering in real-time and also reserving (whenever this is possible) free parking spaces, as well as navigate-to-park and park-and-ride services; (ii) creating a closed system of collaborative management and availability of parking spaces belonging to a special group of citizens (e.g., disabled, elderly, etc.); (iii) managing (either periodic, or spontaneous) queries for massive parking (e.g., for the cars of the employees of a company during weekdays, or for the cars of the spectators of a sports event); (iv) creating a novel value-chain, based on parking services and “good-practice” rewarding schemes towards a more efficient management of the entire parking space, for the sake of the community; and (v) providing parking brokerage services.

III. THE INCENTIVE-BASED SCHEMES

The design of an efficient incentivization scheme requires a model that will be effective for the system but also truthful. Setting up the proper incentives enables the users to provide truthful information.

In our case, we assume the participation to an urban crowdsourcing-based parking ecosystem of m actors (users or commuters) and n parking houses, which can be either commercial parking entities having their own parking spaces, or local municipalities which provide the parking spaces placed on the street. Our incentive-based schemes use virtual credits (a.k.a. points) as rewards for incentivizing the voluntary participation of the actors. The points can be exchanged for discounts provided by the participating parking houses in the SocialPARK ecosystem. We assume that the parking houses refill the system with an amount of virtual credits (points) per certain period (e.g., per month).

There are two types of actors in the system:
- **Informers** who provide parking availability information and receive in return reward points;
- **Receivers** who consume parking availability information in order to find an, optimal for them, available parking space.

The actors collect points according to their actions and then are able to spend them differently, depending on which incentive-based scheme they participate in. The actors that participate in the urban crowdsourcing-based parking ecosystem perform the following actions.

- **RF** Report a free parking space on the street, either by unparking from a particular parking space, or by simply observing an available parking space.
- **RP** Report successful parking at a given space.
- **PnR** Park without reporting.
- **UnR** Unpark without reporting.

Towards incentivizing actors to give truthful information, we design two incentive-based schemes. Both schemes consider that there are constraints on how many points the system can spend for incentives. In the first scheme, a receiver does not spend any points in order to get parking availability information, whereas an informer gains points for contributing parking availability information to the system, which are devaluated over time (if not spent). In the second scheme, a receiver of parking availability information is charged a given amount of points for it, which is nevertheless partially refunded if s/he cannot manage to park. In case of successful parking, s/he can also gain additional points, up to as many points as s/he spent, for acting as an informer when s/he releases the occupied parking space.
**A. Scheme-I: A simplified incentive-based scheme**

Let $P_j$ be the points a parking house contributes to the system within a certain period (e.g., a month). Thus, the system receives $\sum_{j=1}^{n} P_j$ points, per period, from all parking houses.

Each actor starts with 0 points and does not get any points, until s/he makes his/her first report. We take into account only the actions which provide information to the system (i.e., actions RF and RP) and these are also the actions for which an actor (informer or receiver) may gain points.

When an informer $i$ reports an available parking space (RF), either by reporting its availability on the street, or by reporting his/her un-parking action, s/he receives two types of rewards: an initial amount of static points $S_i$ and a bonus of $E_i$ points that are dynamically determined.

The $S_i$ static points are given as an incentive to $i$ to provide reliable parking availability information and thus the system can consequently distribute this information to potential receivers who are searching for an available parking space.

The $E_i$ bonus points are given to informer $i$, who provided the parking availability information, when a receiver $r$ indeed succeeded in parking at it. The amount of $E_i$ points is much larger than the static amount of $S_i$ points, since they are attributed to $i$ due to the validation of the provided information by $r$. In overall, assuming that a truthfully reported free parking space is exploited by the system with probability $p$, an informer $i$ who reports an available parking space receives an expected reward of $S_i + p \cdot E_i$ points. We take also into account the case where a malicious informer reports untruthfully the availability of a parking space, which may be (by chance) indeed available when some receiver $r$ tries to park in it.

In particular, the malicious informer $i$ receives a reward of $S_i + q \cdot E_i$, where $q$ is the probability that a randomly selected parking space is by chance free, when the receiver of this information arrives at it. It is natural to assume that $q < p$.

Moreover, the receiver $r$ who reports that s/he parked (RP) also gains $X_r$ points. The points awarded to each actor (informer or receiver) according to Scheme-I are summarized in Table I.

<table>
<thead>
<tr>
<th>Actor type</th>
<th>Reporting</th>
<th>No Reporting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver $r$</td>
<td>$X_r$</td>
<td>0</td>
</tr>
<tr>
<td>Informer $i$</td>
<td>$S_i + p \cdot E_i$</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE I**

**POINTS AWARDED TO EACH ACTOR, ACCORDING TO SCHEME-I.**

Scheme-I entails the following constraints on the earning points of an informer $i$ and of a receiver $r$:

$$X_r > 0$$  \hspace{1cm} (1)

$$S_i + p \cdot E_i > 0$$  \hspace{1cm} (2)

In this incentive-based scheme every actor can only gain points, depending on the reporting of his/her actions. Points can be spent as discounts for parking services offered by certain parking houses.

There are two possible misbehaviors that should be prevented: (i) the overaccumulation of points, when an actor does not spend any points, and (ii) the reporting of untruthful parking availability information during a day.

To avoid an overaccumulation of points by an informer, who may not spend any points and after a certain point in time will not have an incentive to continue contributing truthful parking availability information anymore, we introduce a devaluation factor $\delta$, $0 < \delta \leq 1$, of the aggregated points over time.

To prevent an actor from reporting false information within a day, by reporting available parking spaces which do not really exist in an effort to accumulate points, we set a smooth upper-bound on the static points $(S_i)$ which an informer can gain from his/her daily reports. In particular, an informer $i$ receives, for some $0 < \varepsilon < 1$, $e^{k-1} \cdot S_i$ points for his/her $k$-th daily report, $1 \leq k \leq R_i$, where $R_i$ is the total number of $i$’s daily reports. The goal is that a malicious actor does not aggregate enough points so that s/he can redeem them later on and gain parking discounts.

Let $A_i(D)$ be the total points up to day $D$ an informer $i$ can receive, and let $E_i^{k}$ be the bonus of the $k$-th report. Then:

$$A_i(D) = \left( \sum_{k=1}^{R_i} e^{k-1} \right) S_i + \sum_{k=1}^{R_i} \theta \cdot E_i^{k} + A_i(D-1) \cdot (1-\delta)$$  \hspace{1cm} (3)

where $\theta$ equals $p$ (resp. $q$), if $i$ is truthful (resp. untruthful). If after a certain number of days, a repeated misbehavior (untruthful reporting) is observed by some informer $i$, then we set $\delta = 1$.

We now turn to the sustainability of the overall virtual credit (point) system. Let $Y$ be the maximum number of points that the system gives to actors (informers and receivers) for reporting parking availability information. Then, $Y = X_r + S_i + p \cdot E_i$, which occurs when an informer $i$ has already truthfully reported his parking and un-parking actions, and a receiver $r$ used this information to park. Assuming that $Z$ is the number of reported available parking spaces within a period, it turns out that the quantity $Y \cdot Z$ is the maximum amount of points distributed by the system to the actors.

Consequently, within a certain period, the points that are contributed to actors from the system should be at most equal to the points that the parking houses contribute to the system.

This implies that Scheme-I entails the following constraint for the sustainability of the overall virtual credit (point) system

$$\sum_{j=1}^{n} P_j \geq Y \cdot Z \cdot \alpha$$  \hspace{1cm} (4)

where $\alpha > 1$ is a static factor that multiplies the quantity $Y \cdot Z$ so that the system does not run out of points, if some unpredicted spending situation occurs.

Let $A_j$ be the total number of requests made by the actors within a certain period, on a specific parking house $j$, in order to receive discounts in exchange of points. Assume that an actor should spend $N$ from his/her aggregated points, in order to get the offered discount by parking house $j$. Then, the number of points $P_j$ contributed to the system by the parking house $j$, should be at least equal to the total number of discount
requests multiplied by $N$. This also implies that Scheme-I entails another sustainability constraint:

$$P_j \geq A_j \cdot N \quad (5)$$

In order to prevent malicious actors from having the opportunity to redeem points earned (by making untruthful reports) in contributed parking houses, we demand that:

$$\frac{S_i}{1-\varepsilon} \leq N \quad (6)$$

We are now ready to prove that Scheme-I is both truthful, i.e., no actor has the incentive to give false information, and budget feasible, i.e., the system will never run out of points.

**Theorem 1**: Scheme-I is truthful and budget feasible.

**Proof (sketch)**. We start with truthfulness. Relations (1) and (2) ensure that all the actors maximize their own amount of points by providing information and hence have the incentive to report their actions to the system.

An actor cannot keep gaining points without spending them. The gradual devaluation of points accumulated in previous days, see Relation (3), guarantees that overaccumulation of points is not possible. Moreover, if an informer $i$ makes untruthful reports, then s/he will receive $\left(\sum_{k=1}^{\infty} \varepsilon^{k-1} \cdot S_i \leq \sum_{k=0}^{\infty} \varepsilon^k \cdot S_i = \frac{S_i}{1-\varepsilon}\right)$ points within a day, which do not suffice to claim any discount from a parking house, due to Relation (6). Hence, within a day, points which have been aggregated by fake reports are not exploitable.

The system also audits the validation of availability reports provided per actor by other actors who succeed in using the reported parking space. This way, the system keeps some indirect “credibility” statistics per actor. If an actor repeatedly provides unverified reports, then after a certain point of time SocialPARK will not reward this actor with any additional points for his/her next reports, by setting for him/her the devaluation factor $\delta$ in Relation (3) equal to 1. Hence, it is ensured that the actors maximize their rewards by being truthful, both in the short term and in the long term.

We now turn to the budget feasibility. The system collects points from the participating parking houses and distributes points only after an action is made by an actor. Relation (4) ensures the points’ availability of the system, while relation (5) ensures that the points provided by a parking house to the system are at least equal to those that are returned to this parking house. Hence, Scheme-I is budget feasible.

**B. Scheme-II: An accounting-based incentivized scheme**

Our second incentive-based scheme, Scheme-II, shares similarities with Scheme-I, but also differs in various aspects. The key differences are: (i) A receiver now “buys” parking availability information from the system, by spending some of his/her points. The requested information about available parking spaces is encrypted and sent to the receiver, who can see the details (e.g., exact address, time of availability of the specific parking space, etc) only after consent to consume a certain amount of points for it. If (for any reason) s/he cannot manage to park, then part of the points spent are refunded to him/her. (ii) There is no devaluation of points over time.

The notation used in Scheme-I is also valid for Scheme-II, unless explicitly stated otherwise.

In Scheme-II, every actor receives an initial amount of points upon registration to the SocialPARK ecosystem, in order to be able to spend them to receive the first parking availability information. The actor does not get any further points, until s/he provides his/her own reports. We take into account only actions which provide parking availability information (e.g., report successful parking, report unparking, report an available parking space on the street, report unsuccessful parking) to the system, for which the actor (informer or receiver) is rewarded.

Assume that some receiver $r$ submits to the system a query for parking availability information. S/he initially receives the encrypted parking availability information. Consequently, s/he chooses either to discard the encrypted information, or to consume $B_r$ points and receive the decrypted details of the proposed available parking spaces. If $r$ reports that s/he managed to park successfully (RP), then s/he gets back $X_r$ points. If, on the other hand, $r$ reports that s/he did not manage to park due to various reasons (e.g., false information, already occupied parking space, etc.), then $R_r$ points are refunded to $r$. Note that $\max \{X_r,R_r\} \leq B_r$.

<table>
<thead>
<tr>
<th>Points per usage of space $s$</th>
<th>Successful parking @ $s$</th>
<th>Unsuccessful parking @ $s$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Informer</strong> $i(s)$</td>
<td>$T$</td>
<td>$S_i + p \cdot E_r$</td>
</tr>
<tr>
<td></td>
<td>$U$</td>
<td>$S_i + q \cdot E_r$</td>
</tr>
<tr>
<td><strong>Receiver</strong> $r(s)$</td>
<td>$T$</td>
<td>$-B_r + X_r + S_r + p \cdot E_r$</td>
</tr>
<tr>
<td></td>
<td>$U$</td>
<td>$-B_r + X_r + S_r + q \cdot E_r$</td>
</tr>
</tbody>
</table>

**TABLE II**

**Points awarded to each actor depending on truthfulness of reports; $T =$ truthful, $U =$ untruthful.**

Let us now discuss the points awarded to each actor (informer or receiver) of Scheme-II, which are summarized in Table II. The points earned by an informer $i(s)$ who reports (truthfully or untruthfully) the availability of a parking space $s$ are provided in the first two rows of Table II and were already analyzed in Scheme-I.

Now, consider a receiver $r(s)$ who is about to park in a parking space $s$ indicated to her by the system. S/he initially spends $B_r$ points for “buying” the exact information about $s$. If s/he reports truthfully his/her successful (initially parking, and later unparking) actions, then s/he gains $X_r$ points for parking reporting and $S_r + p \cdot E_r$, for the unparking action. In case that s/he truthfully reports that s/he did not manage to park, she gets a refund of $R_r$ points.

If, on the other hand, $r(s)$ reports untruthfully that s/he did not manage to park in $s$, although s/he indeed parked, then s/he is only refunded by the system an amount of $R_r$ points. Finally, in case that $r(s)$ does not manage to park, but reports successful parking and unparking actions, s/he gains $X_r$ points for the parking report and $S_r + q \cdot E_r$ for the unparking report.
Scheme-II entails the following constraints on the rewarded points to an informer \( i \) and a receiver \( r \), which incentivize them to report truthful information:

\[
q < p \tag{7}
\]
\[
X_r + S_r + p \cdot E_r \leq B_r \tag{8}
\]
\[
R_r \leq B_r \tag{9}
\]
\[
R_r < X_r + S_r + p \cdot E_r \tag{10}
\]
\[
X_r + S_r + q \cdot E_r < R_r \tag{11}
\]

To prevent an actor from reporting untruthful information within a day, we work as in Scheme-I, but disregarding the devaluation of points. Furthermore, let \( S_i(D) \) be the total points up to day \( D \) an informer \( i \) can receive, and let \( E_i^k \) be the bonus of the \( k \)-th report. Then:

\[
S_i(D) = \left( \sum_{k=1}^{R_i} \varepsilon^{k-1} \right) S_i + \sum_{k=1}^{R_i} \theta \cdot E_i^k \tag{12}
\]

where \( \theta \) equals \( p \) (resp. \( q \), if \( i \) is truthful (resp. untruthful). If after a certain number of days, a repeated misbehavior (untruthful reporting) is observed by some informer \( i \), then his/her aggregated points are reset to zero.

We now turn to the sustainability of the overall virtual credit (point) system. Assume that \( Z \) is the number of reported available parking spaces, \( U \) is the number of successful parking actions, and \( F \) is the number of unsuccessful parking actions, within a period. Assume also that \( S_0 \) is the aggregated amount of initial points distributed to new actors, within the same period. Then, it turns out that the quantity

\[
(S_i + p \cdot E_i) \cdot Z + X_r \cdot U + R_r \cdot F + S_0
\]

is the expected maximum amount of points distributed by the system to the actors, in this period. Assuming that \( I \) is the number of encrypted parking availability information, which the actors have received and bought within a period, it turns out that \( I \cdot B_r \) is the maximum amount of points that are contributed to the system by the actors within this period. Consequently, the rewarding points from the system to the actors within this period should be at most equal to the points that the parking houses and the actors contribute to the system. This implies that Scheme-II entails the following constraint for the sustainability of its point system:

\[
B_r \cdot I + \sum_{j=1}^{n} P_j \geq (S_i + p \cdot E_i) \cdot Z + X_r \cdot U + R_r \cdot F + S_0 \tag{13}
\]

The second sustainability constraint is similar to Relation (5) in Scheme-I, while Scheme-II enforces also Relation (6) from Scheme-I to prevent malicious actors from having the opportunity to redeem points earned by massive untruthful reports within the day. The following theorem proves the desired properties for Scheme-II.

Theorem 2: Scheme-II is truthful and budget feasible.

Proof (sketch). We start with truthfulness. The system should firstly give the actors incentives to report their actions and, secondly, make them provide truthful information. Relation (2), which also holds in Scheme-II, entails that for any informer \( i \), reporting the availability of a parking space is more profitable. For any receiver \( r \), reporting is also beneficial since s/he consumes \( B_r \) > 0 points to get the parking availability information and only gets some partial refund for providing reports.

By Relation (7), it is clear for an informer \( i \) that reporting truthful information is more profitable than reporting untruthful. Relation (12) guarantees that overaccumulation of points is not possible. If an informer \( i \) makes untruthful reports, then, as it was already explained in the proof of Theorem 1, s/he cannot aggregate enough points to redeem them on parking houses. If an actor provides repeated false reports, then after a certain point of time the points of this actor will be reset to zero and this actor will not receive any points for any of his/her next reports. Thus, an informer has an incentive to act truthfully both in the short and in the long term.

A receiver \( r \), on the other hand, spends \( B_r \) points in order to receive parking availability information and then either manages to park or not. Relations (8) and (9) indicate that the points that \( r \) spends are always at least equal to those that s/he gains after reporting his/her actions, so s/he also has no incentive to report untruthful actions related to some “bought” parking information from the system. Finally, Relations (10) and (11) indicate that, regardless of whether \( r \)’s parking action was successful or not, reporting truthfully his/her actions is more profitable. In overall we conclude that, for all cases, every actor has an incentive to report truthfully her parking actions to the system.

We now turn to the budget feasibility. The system collects points from parking houses and from receivers of parking availability information, and distributes points for reports of parking actions by actors. Relation (13) ensures the system’s availability of points. Relation (5) ensures that the points provided by a parking house to the system are at least equal to those returned to it. Hence, Scheme-II is budget feasible. ■

C. Comparison with related work

Crowdsourced-based parking systems highly depend on user (actor in our context) participation. Thus, efficient mechanisms able to increase user participation are of major importance. However, some of the earliest parking systems such as SpotAngels [10], OpenSpot [7] and PrimoSpot [2] understated user recruitment and the adopted incentivization/rewarding schemes were in a premature form. Specifically, in the first version of PrimoSpot no incentivization schemes have been developed for reporting parking spaces (or spots) availability. Furthermore, Google’s OpenSpot rewarding mechanism had symbolic meaning and did not correspond to tangible bonuses.

In Trucentive [6] the authors proved that the developed incentivization scheme is both truthful and budget feasible. However, although acting truthfully maximizes user’s reward, a malicious user can still benefit from the system. In particular, the system does not prevent malicious users from performing consecutive misreports in order to aggregate the required number of points and redeem them in future parking reservations.
Also, Trucentive, in contrast to our schemes, does not care for points circulation, i.e., does not prevent overaccumulation of points without being devaluated.

As for ParkBid’s rewarding scheme [8], SocialPARK’s incentivization schemes appear more effective considering user participation. Incentives are given each time an informer reports parking availability, regardless of whether the parking space is later “sold”, whereas in ParkBid the informers, called bidders, are rewarded only in case the reported parking space is eventually “bought” by a user. The absence of even a small reward makes the system less attractive and may discourage informers from reporting the observed available parking spaces, especially in the case where the probability of the reported parking space to be exploitable is low.

IV. EXPERIMENTAL RESULTS

To validate our theoretical framework, we developed (in Python) a Discrete Event Simulator based on observed behavior of the actors. We created 100 actors, both truthful and untruthful, and 20 parking spaces, initialized as free or occupied. The main attributes of actors are the following: truthfulness, number of parking reports, unparking reports, and number of reported parking spaces which are used by another actor. To realistically represent the participation of actors in both Schemes, we carried out a simulation for: (i) Different ratios of truthful and untruthful actors: the typical case of 50% truthful and 50% untruthful, and the harder (for the system) case of 30% truthful and 70% untruthful. (ii) Different values of $p$ (probability that a receiver parks on a parking space reported by an informer) in \{0.15, 0.3, 0.5, 0.7\}, to reflect different types of parking space availability in urban environments (smaller values represent busy areas with limited availability). We also set $q = p/10$ (recall that $q < p$).

A. Experimental results for Scheme-I

In our experiments we set $S_t = X_r = 1$, and let $E_t$ vary with $p$ so that $p \cdot E_t = 2$, in order to avoid overaccumulation of bonus points for large values of $p$ by truthful actors who make greater utilization of parking spaces. We start with the case of 50% truthful and 50% untruthful actors.

In Figure 1 we observe that, as $p$ increases, the points accumulated by truthful actors (T) increase, while those of untruthful actors (U) remain consistently low. This happens because, as $p$ increases, the truthfully reported available parking spaces are more likely to be used by receivers, and hence informers get more often the bonus $p \cdot E_t$. The points gained by untruthful actors remain low regardless of the increase in $p$, as parking spaces that are falsely reported as available are very unlikely ($q < p$) to be used by a receiver. Thus, an untruthful informer gets an expected additional gain of $q \cdot E_t < p \cdot E_t$. Moreover, untruthful actors who park on spaces proposed by the system without reporting their parking action, are not rewarded with $X_r$ points.

In Figure 2 we observe that for $p = 0.15$ the availability reports made by truthful and untruthful informers (RF) are about the same. As $p$ increases, the availability reports of truthful informers increase also, while those of untruthful informers decrease. This is because the lower the value of $p$, the busier the area and hence the number of occupied parking spaces (which untruthful informers falsely report as available) is larger than the truly free ones (reported by truthful informers). The higher the value of $p$, the less busy is the area and therefore the truly vacant parking spaces (reported as such by truthful informers) are larger than the occupied parking spaces (falsely reported as available by untruthful informers). Hence, utilization (i.e., number of spaces used by other actors - purple color) increases with $p$ for truthful availability reports, while it remains the same and very low for untruthful ones.

We now turn to the case of 30% truthful and 70% untruthful actors, whose results are shown in Figures 3 and 4. Despite the fact that participation of untruthful actors is much higher, the points accumulated by truthful actors are still significantly larger. Also, although for smaller values of $p$ the untruthful parking availability reports are higher than the truthful ones, the situation is reversed for larger values of $p$. Utilization of spaces provided by truthful (resp. untruthful) availability reports increases with $p$ (resp. remains very low regardless of
B. Experimental results for Scheme-II

In this scenario we set $S_i = X_r = 1$, $R_r = 6$, $B_r = 8$, and let the validation points $E_i$ vary with $p$ so that $p \cdot E_i = 5$, in order to avoid overaccumulation of bonus points for large values of $p$ by truthful actors who make greater utilization of parking spaces. Due to space limitations, we focus on the case of 30% truthful and 70% untruthful actors, whose results are shown in Figures 5 and 6 (the results for the 50%-50% case are only better). In order to examine if Scheme-II incentivizes actors to report truthfully, we count the total points each actor spends for receiving parking availability information, reporting his/her actions, or requesting a refund. We observe that even if the participation of untruthful actors is much higher than that of truthful ones, untruthful actors still spend more points than truthful ones (regardless of the value of $p$). We also observe that although for smaller values of $p$ the parking availability reports made by untruthful actors are higher than the ones made by truthful ones, their difference becomes smaller or vanishes for larger values of $p$. Utilization of spaces is similar to that in Scheme-I.

V. CONCLUSIONS

We presented two novel incentive-based schemes for the provision of truthful parking availability information in a crowdsourced parking ecosystem. Our theoretical analysis for voluntary participation of the actors and for truthfulness of the reports are also validated by our experimental evaluation.

REFERENCES