

An Experimental Evaluation of Task Assignment in Spatial Crowdsourcing

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ABSTRACT

Recently, with the rapid development of mobile devices and the crowdsourcing platforms, the spatial crowdsourcing has attracted much attention from the database community. Specifically, spatial crowdsourcing refers to sending a location-based request to workers according to their positions, and workers need to physically move to specified locations to conduct tasks. Many works have studied task assignment problems in spatial crowdsourcing, however, their problem settings are different from each other. Thus, it is hard to compare the performances of existing algorithms on task assignment in spatial crowdsourcing. In this paper, we present a comprehensive experimental comparison of most existing algorithms on task assignment in spatial crowdsourcing. Specifically, we first give general definitions about spatial workers and spatial tasks based on definitions in the existing works such that the existing algorithms can be applied on the same synthetic and real data sets. Then, we provide a uniform implementation for all the tested algorithms of task assignment problems in spatial crowdsourcing (open sourced). Finally, based on the results on both synthetic and real data sets, we discuss the strengths and weaknesses of tested algorithms, which can guide future research on the same area and practical implementations of spatial crowdsourcing systems.

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1. INTRODUCTION

With the ubiquity of smart devices equipped with various sensors (e.g., GPS) and the convenience of wireless mobile networks (e.g., 5G), nowadays people can easily participate in *spatial tasks* requiring to be conducted at specified locations that are close to their current locations, such as taking photos/videos [6], delivering packages [7], and/or reporting waiting times of hot restaurants [4]. As a result, a new framework, namely *spatial crowdsourcing* [21], which enables *spatial workers* to conduct spatial tasks, has emerged in both academia (e.g., the database community) and industry (e.g., Uber[8]). In spatial crowdsourcing systems (e.g., gMission [10, 5]

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and MediaQ [23]), the active workers can only conduct spatial tasks close enough to them such that they can physically move to the required locations before the deadlines of tasks. Therefore, studying and designing effective strategies for helping workers to conduct spatial tasks to maximize the overall *utility* (defined in Section 2) of systems is the major goal of the existing studies in spatial crowdsourcing [21, 22, 29, 16, 25, 12, 13, 18, 27, 19].

In a spatial crowdsourcing platforms, spatial tasks are keeping on arriving and being completed, and workers are free to join or leave. In addition, the platforms have no information about the future arrival tasks and workers. In general, there are two modes to assign workers to tasks: 1) batch-based mode [21, 29, 12, 19], where the platforms periodically assign the available workers to the opening tasks in the current timestamps; 2) online mode [16, 25], where the platforms immediately assign suitable tasks to the worker when he/she joins in the platform (In platforms with more workers than tasks, when a new task is created, the system will assign the most suitable worker to it). Specifically, we illustrate the spatial crowdsourcing with the following examples:

Example 1. (*Car-hailing Services*) *Car-hailing services allow riders to post their travel requests to the system, then suitable cabs will be dispatched to them based on the locations of riders and cabs. Many industrial applications (e.g., Uber [8] and DiDi Chuxing [3]) provide car-hailing services. In car-hailing systems, a cab and a travel request can be treated as a worker and a task, respectively. Car-hailing systems usually try to match a travel request with a closest cab such that the travelling distance for the cab to pick up the rider is minimized and the waiting time of the rider is also minimized. The existing car-hailing systems can either work on batch-based mode (i.e., assigning available cabs to travel requests every 2 seconds) or online mode (i.e., assigning the most suitable cab to the travel request immediately when it appears). Thus, task assignment in car-hailing services can be modeled as a spatial crowdsourcing problem.*

Example 2. (*Mobile Audit Services*) *Mobile audit services allow companies to create their location-specific in-store audit projects, which can be reporting the on-shelf status of commodities, checking the prices of goods inside stores, and surveying the thinking of shoppers towards particular products. Then, shoppers with Mobile audit Apps (e.g., Field Agent [4]) installed (noted as agent) will be assigned to proper tasks (e.g., closest tasks) and contribute their efforts. Since the agents are not totally correct, some quality control mechanisms (e.g. Majority Voting [22]) are used to aggregate the answers from different agents for the same task such that the returned answers are credible. With the returned answers, the business companies can analyze the almost real-time results and react quickly. The mobile audit system also can process the tasks*

on batch-based mode or online mode, which can also be modeled as a task assignment problem in spatial crowdsourcing.

To handle the task assignment problems in spatial crowdsourcing, existing studies proposed various algorithms to overcome the dynamics of the spatial tasks and workers, and to address problems with different utility definitions. For example, in [21, 22, 29, 16, 25, 30] the utility of the spatial crowdsourcing system is defined as the number of finished task while in [13] it is defined as the reliability and diversity of finished tasks. However, no existing work has compared the algorithms tailored for different settings in spatial crowdsourcing, thus the results in different works cannot be compared directly and it is difficult for users to know which algorithm to apply in the real applications.

In this paper, we provide a fair comparison study over the existing algorithms under a general spatial crowdsourcing definition to show their pros and cons. Currently, there is no highly customizable spatial crowdsourcing platforms to run comparison experiments for all the existing spatial crowdsourcing algorithms. We utilize an open source simulation tool to generate data sets either following given distributions (e.g., Normal distribution, Zipf distribution, Skewed distribution and Uniform distribution) or based on real spatial/temporal data sets (e.g., Gowalla and Twitter), which can help to compare algorithms with different parameters more accurately. In addition, we set up a common experiment setting for all the existing notable methods, and show the performances of the methods on important spatial crowdsourcing metrics, such as running time, numbers of finished tasks, and average moving distance. As a result, our uniform implementation [2, 1] can avoid the “noises” from implementation skills (e.g., Java v.s. C++), settings and metrics, which enable us to report the true contributions of algorithms.

To summarize, we try to make the following contributions:

- We propose a general definition for task assignment in spatial crowdsourcing in Section 2, which can be a footstone for the future studies in this area.
- We provide uniform baseline implementations for the most notable algorithms in both batch-based and online mode. These implementations adopt common basic operations and offer a benchmark for comparing with future studies in this area.
- We propose an objective and sufficient experimental evaluation and test the performances of the most notable algorithms over extensive benchmarks in Section 5.
- We discuss the advantages and disadvantages of two task assignment modes (batch-based mode and online mode) based on the results of our experimental evaluation in Section 5.3.

Section 3 and Section 4 introduce existing algorithms in batch-based mode and online mode respectively. Section 6 concludes this paper.

2. PROBLEM DEFINITION

In this section, we give a general definition of task assignment in spatial crowdsourcing, which is based on the definitions in existing studies [21, 22, 16, 13].

Definition 1. (Dynamic Moving Workers) Let $W = \{w_1, w_2, \dots, w_n\}$ be a set of n workers. Each worker w_i ($1 \leq i \leq n$) is located at position $l_i(p)$ at timestamp p , can move with velocity v_i , specifies a square working area with side length a_i , and has a reliability value $r_i \in [0, 1]$ and a capacity value c_i . ■

In Definition 1, worker w_i can move dynamically with speed v_i in any direction, and at each timestamp p , he/she is located at location $l_i(p)$. He/she prefers to conduct the tasks within his/her square working area centering at the spatial place $l_i(p)$ with side length of a_i . Based on the historical performance of each worker, we can estimate his/her reliability values $r_i \in [0, 1]$, which indicates the probability that he/she can correctly finish the assigned task. Moreover, each worker may accept at most c_i tasks at the same time and conduct them one by one. In spatial crowdsourcing systems, a worker w_i can be either available or busy. Here being available means the worker can be assigned with more tasks while being busy indicates the number of assigned tasks to worker w_i reaches the his/her capacity c_i and no more tasks can be assigned unless he/she finishes or rejects some assigned tasks.

Definition 2. (Spatial Tasks) Let $T = \{t_1, t_2, \dots, t_m\}$ be a set of time-constrained spatial tasks. Each task t_j ($1 \leq j \leq m$) is published at timestamp s_j , locate at a specific location l_j , and is associated with a deadline e_j . To guarantee the quality, task t_j may require b_j answers and specify a required quality level q_j . ■

Usually, a task requester creates a time-constrained spatial task t_j at timestamp s_j , which requires workers to physically reach a specific location l_j before its deadline e_j . In order to tackle the intrinsic error rate (unreliability) of workers, different accuracy control techniques are used in existing studies [13, 22, 15, 20]. Without loss of generality and for the ease of presentation, in this paper, we consider the spatial tasks with binary (Yes/No) choices and use Majority Voting [22] to aggregate the answers from different workers such that the expected quality scores of tasks are satisfied. (To avoid draws, we can require b_j to be an odd number.) For example, to check the stock status of a particular product (e.g., Coke Cola) in a store, the question of a spatial crowdsourcing task can be “Whether the coke cola in the store has enough stock?” and the answer could be “Yes” or “No”. Specifically, for a task t_j with b_j answers, we report the majority answer choice (selected by no less than $\frac{b_j+1}{2}$ workers) as the final result for task t_j . Let the set W_j be the workers that answer task t_j . We can compute the expected accuracy of a task as follows:

$$\Pr(W_j) = \sum_{x=\frac{b_j+1}{2}}^{b_j} \sum_{W_j^x} \left(\prod_{w_i \in W_j^x} r_{ij} \prod_{w_i \in W_j - W_j^x} (1 - r_{ij}) \right), \quad (1)$$

where W_j^x indicates the subsets with exact x workers out of the worker set W_j who answered task t_j . Particularly, $\Pr(W_j)$ can represent the probability that the final answer of task t_j is correct.

Definition 3. (Assignment Instance Set) At timestamp p , an *assignment instance set*, denoted by I_p , is a set of worker-and-task assignment pairs in the form $\langle w_i, t_j \rangle$, where a spatial task t_j is assigned to a worker w_i while satisfying the constraints of workers and tasks. The utility of worker-and-task pair $\langle w_i, t_j \rangle$ is noted as $U(w_i, t_j)$. ■

Here, each worker-and-task pair $\langle w_i, t_j \rangle$ in I_p indicates the required location l_j of task t_j is in the working area of worker w_i and he/she can reach l_j before its arrival deadline e_j . Moreover, the capacity constraint of worker w_i is satisfied, which means the number of assigned tasks for worker w_i is not larger than his/her capacity c_i . Assigning worker w_i to task t_j has utility $U(w_i, t_j)$, which can be defined in different forms. For example, in [21], it is simply defined as $U(w_i, t_j) = 1$, which means only the number of assigned tasks is concerned.

Now we give the formal definition of the task assignment in general spatial crowdsourcing (TA-GSC) problem as follows:

Table 1: Symbols and Descriptions

Symbol	Description
W	a set of dynamically moving workers
T	a set of time-constrained spatial tasks
$l_i(p)$	the position of worker w_i at timestamp p
a_i	the side length of the working area of worker w_i
v_i	the moving velocity of worker w_i
r_i	the reliability value of worker w_i
c_i	the capacity of worker w_i
s_j	the timestamp of creating task t_j
e_j	the deadline of arriving at the location of task t_j
l_j	the position of task t_j
b_j	the number of required answers of task t_j
q_j	the required quality level of task t_j
$\langle w_i, t_j \rangle$	the worker-and-task assignment pair
$U(w_i, t_j)$	the utility value of the worker-and-task assignment pair $\langle w_i, t_j \rangle$

Definition 4. (TA-GSC Problem) Given a set of dynamic moving workers W and a set of spatial tasks T , the TA-GSC problem is to find a task assignment instance set I to maximize the total utility $\sum_{\langle w_i, t_j \rangle \in I} U(w_i, t_j)$ such that the following constraints are satisfied:

- Working Area Constraint: worker w_i can only be assigned to tasks located within his/her working area;
- Deadline Constraint: worker w_i can only be assigned to tasks that he/she can arrive at before their deadlines;
- Capacity Constraint: at any time, worker w_i can be assigned with at most c_i tasks;

Under this definition, we tested the notable existing algorithms to solve the task assignment problems in general spatial crowdsourcing. Figure 1 shows a taxonomy of the tested algorithms. We present them one-by-one in the following two sections.

Table 1 summarizes the commonly used symbols.

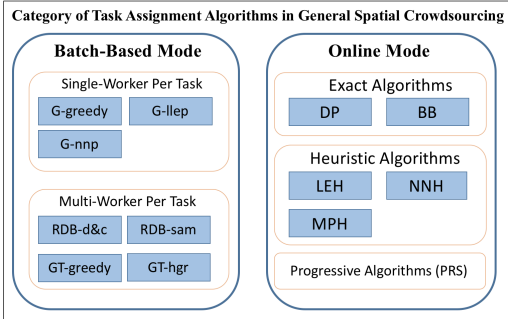


Figure 1: Taxonomy of Task Assignment Algorithms for General Spatial Crowdsourcing.

3. ALGORITHMS IN BATCH-BASED MODE

In this section, we introduce the typical batch-based algorithms for TA-GSC problems, which periodically assign the “current” available workers to unfinished spatial tasks. The general framework of batch-based algorithm for TA-GSC problems is shown in Algorithm 1. In each iteration of the framework, it uses the batch-based algorithms to match the available workers to unfinished tasks, then notifies the workers to conduct their assigned tasks.

From the perspective of the number of required answers of each task, the batch-based algorithms can be categorized into two groups: 1) Single-worker per task algorithms, where each task needs one worker to answer; 2) Multi-worker per task algorithms, where each task needs more than one worker to answer. The batch problem in each iteration of Algorithm 1 (lines 2 - 8) of the first group algorithms can be reduced to the maximum flow problem while that is

Algorithm 1: The Framework of Batch-based Algorithms

Input: A time interval Φ

Output: A set of worker-and-task assignment pairs within the time interval Φ

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1 while current time  $\varphi$  is in  $\Phi$  do
2   retrieve all the available spatial tasks to  $T$ 
3   retrieve all the available workers to  $W$ 
4   foreach  $w_i \in W$  do
5     obtain a set,  $T_i$ , of valid tasks for worker  $w_i$ 
6   use batch-based task assignment algorithms to obtain a
   good assignment set  $I$ 
7   foreach  $\langle w_i, t_j \rangle \in I$  do
8     inform worker  $w_i$  to conduct task  $t_j$ 

```

NP-hard for the second group of algorithms. We introduce them one-by-one in the rest of this section.

3.1 Single-Worker Per Task algorithms

For single-worker per task algorithms introduced in this section, the utility function of assigning worker w_i to task t_j is defined as $U(w_i, t_j) = 1$, which indicates the algorithms wants to maximize the assigned number of tasks. Then, the TA-GSC problem in each batch/iteration can be reduced to the maximum flow problem. We first represent the reduction of the maximum flow problem when each task only needs one worker to answer, then introduce the single-worker per task algorithms.

3.1.1 Reduction to Maximum Flow Problem

When each task needs only one worker, the problem to maximize the number of assigned tasks in each batch/iteration can be reduced to the maximum flow problem. For a set of available workers W and a set of available tasks T , we can create a flow network graph $G = (V, E)$ with V as the set of vertices, and E as the set of edges. The set V contains $|W| + |T| + 2$ vertices. Each worker w_i maps to a vertex w_i and each task t_j maps to a vertex t_j in graph G . In addition, we create a src vertex and a $dest$ vertex. We first connect src vertex and every worker vertex w_i and set the capacity for each of these edges as the capacity c_i of worker w_i since each worker can buffer at most c_i tasks. Each task vertex t_j is linked to the $dest$ vertex and the capacity is set to 1, as each task only needs one worker to perform. What is more, as each worker w_i can only accept the tasks located inside their working areas a_i , for every worker vertex w_i we add edges to all the tasks vertices that the corresponding tasks are inside the spatial working area a_i , and set the capacity of each edge to 1.

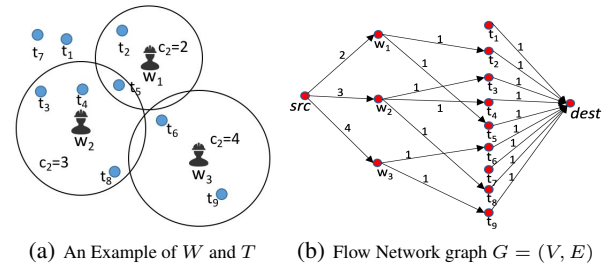


Figure 2: An Example of the Reduction of Maximum Flow Problem.

Figure 2 illustrates an example of this reduction. In Figure 2(a), each worker w_i has a capacity value c_i and a round working area around him/her. At the same time, Figure 2(b) shows the reduced maximum flow network graph. One link from worker vertex w_i

to task vertex t_j exists only when the task t_j is located inside the working area a_i of worker w_i . For example, worker vertex w_3 is connected to task vertex t_6 as task t_6 locates inside the working area of worker w_3 .

With the reduction of the maximum flow problem, existing maximum flow algorithms can be used to solve these task assignment problem for each batch/iteration. The Ford-Fulkerson algorithm [24] is one well-known algorithm to compute the maximum flow. The idea behind Ford-Fulkerson algorithm is that it starts sending flow from the source vertex to the destination vertex, as long as there is a path between the two with available capacity. Note that, greedily applying the Ford-Fulkerson algorithm for each batch in Algorithm 1 (denoted as **G-greedy**) does not necessarily result in a globally optimal answer for the entire time span Φ [21]. Two heuristic algorithms are designed to improve the results obtained by **G-greedy**.

3.1.2 Least Location Entropy Priority Algorithm

Least location entropy priority algorithm (**G-llep**) [21] gives higher priority to the tasks located in worker-sparse areas (areas with low workers densities). The intuition of this algorithm is that for a task located in worker-sparse areas, it is less likely that the task can have a potential worker to select in future timestamps. In other words, if a task located in worker-dense area is not assigned to any workers at the current timestamp, it has a higher possibility to be assigned to some other worker in the future timestamps compared with tasks in worker-sparse areas.

The algorithm utilizes *location entropy* [14] to measure the total number of workers in a location as well as the relative proportion of their future visits to that location. A location with high location entropy indicates many workers visit that location with equal proportions. In other words, for a given location, if only a small number of workers often visit it, its location entropy is low.

For a given location l , let O_l be the set of visits to it, W_l be the set of distinct workers that visited l , and $O_{w,l}$ be the set of visits belonging to worker w . Note that, here one visit of worker w_i to a location l means worker w_i appears around location l with distance $dis(w_i, l) \leq a_i$. Then, the location entropy for l is calculated as follows:

$$Entropy(l) = - \sum_{w \in W_l} P_l(w) \cdot \log P_l(w), \quad (2)$$

where $P_l(w) = \frac{|O_{w,l}|}{|O_l|}$ is the fraction of total visits to l made by worker w . The location entropies will be updated every batch and one visit of worker w_i to location l here means the worker's working area covers location l at the moment when the batch process starts. According to the suggestions in [21], we can discretize the whole spatial space into a grid with small cells (e.g., 30 meters \times 30 meters), then just update the location entropy of each cell (when the working area of worker w_i overlaps with a cell in one batch, we count that as a visit of worker w_i to the cell) and use each cell's location entropy as that of the tasks located in the cell.

For each location l , the entropy of it can be treated as its cost value, then the optimization goal of this algorithm is to assign as many tasks as possible with minimum total cost associated to the assigned tasks in each timestamp, which can be reduced to the minimum-cost maximum flow problem [9]. To solve the minimum-cost maximum flow problem, one of the well-known techniques [9] is to first find the maximum flow in the network, then use linear programming method to minimize the total cost of the flow. Let $G_p = (V, E)$ be the flow network graph for timestamp p . For each edge $(u, v) \in E$, the capacity is $c(u, v) > 0$, the flow $f(u, v) \geq 0$, and the cost is $a(u, v) \geq 0$. The cost of sending the flow $f(u, v)$ is $f(u, v) \cdot a(u, v)$. Denote the maximum flow sent from src vertex

to $dest$ vertex as f_{max} , then the linear programming to minimize the total cost can be represented as below:

$$\begin{aligned} & \text{minimize} && \sum_{(u,v) \in E} f(u,v) \cdot a(u,v) \\ & \text{s.t.} && f(u,v) \leq c(u,v), \\ & && f(u,v) = -f(v,u), \\ & && \sum_{w \in V} f(u,w) = 0 \text{ for all } u \neq src, dest \\ & && \sum_{w \in V} f(src,w) = f_{max} \text{ and } \sum_{w \in V} f(w,dest) = f_{max} \end{aligned}$$

G-llep maximizes the number of assigned tasks first, then minimizes the total cost guaranteeing that the total number of assigned tasks is maximized.

3.1.3 Nearest Neighbor Priority Algorithm

Nearest neighbor priority algorithm (**G-nnp**) [21] first maximizes the number of assigned tasks first, then minimizes the total moving distance of workers. The intuition of **G-nnp** is that if the moving distances can be reduced, workers can finish their assigned tasks faster as the moving distances are shorter, then the overall number of finished tasks can be potentially improved.

In **G-nnp**, the *travel cost* $d(w, t)$ of worker w to task t is defined as the Euclidean distance between them. In the network flow graph, each edge between a worker vertex and a task vertex is associated with a weight equaling the travel cost of the worker to the task. Then the problem turns into the minimum-cost maximum flow problem and the technique in Section 3.1.2 with a different cost function can be applied to it.

3.2 Multi-Worker Per Task Algorithms

In real systems, workers may make mistakes or submit wrong answers deliberately such that the received answers are not totally reliable. To guarantee the reliability of tasks, existing works assign more than one worker to the same task (Multi-worker per task), then aggregate the answers from workers to obtain a reliable final answer for each task. In the rest part of this section, we introduce three multi-worker per task algorithms.

3.2.1 Sampling-Based Algorithm

The sampling algorithm (**RDB-sam**) is proposed to solve reliable diversity based spatial crowdsourcing problem (**RDB-SC**) [13], which tries to maximize the minimum reliability score of tasks. **RDB-SC** is proved to be NP-hard, thus not tractable. **RDB-sam**, as an approximation algorithm, can achieve a worker-and-task assignment strategy with high reliable-and-diversity score on the fly. We generally introduce the algorithm as follows. The algorithm first estimates the number of sample size k , where each sample is a possible assignment instance set (Definition 3). Then, it randomly generates k samples and reports the one with the highest reliability score as the final result.

RDB-sam provides a method to estimate a sample size K such that the "best" sample among the K samples can achieve a (ϵ, δ) -bound, which means the "best" sample is within top ϵ of the entire population with probability δ . For a given batch **TA-GSC** problem, **RDB-sam** conducts a binary search within $\left(\frac{p \cdot M \cdot e^{-1+p}}{1-p+e \cdot p}, M \right]$, such that \hat{K} is the smallest K value such that $Pr\{X \leq (1-\epsilon) \cdot N\} \leq 1-\delta$ (variable X be the rank of the largest sample, S_K , in the entire population and N is the size of the entire population), where $p = \prod_{j=1}^n \frac{1}{deg(w_j)}$, $M = (1-\epsilon) \cdot N$, and e is the base of the natural logarithm.

3.2.2 Divide-and-Conquer Based Algorithm

When each task needs more than one worker to conduct, the complexity of algorithms for TA-GSC problems will increase dramatically with the increase of the number of tasks and workers. To improve the efficiency, the divide-and-conquer based (RDB-d&c) algorithm [13] keeps dividing the whole problem instance into several subproblem instances, solves the subproblems instances, then merge the results of subproblem instances, which creates a trade-off between efficiency and effectiveness.

Since a worker may exist in more than one subproblems and RDB-d&c solves each subproblem without coordinating with other subproblems, the total assigned tasks of a worker may exceed his/her capacity of tasks. To satisfy the capacity constraint, RDB-d&c first estimates the cost of replacing the worker in each subproblem, then it greedily substitutes the worker having lower replacing cost with the “best” available worker in the current situation. Here, the “best” available worker is the worker who can most improve the overall utility and is not fully assigned with tasks. If conflicts between subproblems happens frequently, the time cost of reconciling conflicts will be enlarged and the running time will increase.

3.2.3 Heuristic-Enhanced Greedy Algorithm

Heuristic-Enhanced Greedy Algorithm (GT-hgr) [22] assumes only when the aggregate reputation score $ARS(t_i)$ of a task t_i is higher than its required quality level q_j , task t_j is treated as a finished task. For a given task t_j and its assigned workers W_j , its aggregate reputation score ($ARS(t_i)$) is the probability that at least $\frac{|W_j|+1}{2}$ workers perform the task t correctly, which can be calculated with Equation (1).

The utility function $U(w_i, t_j)$ of GT-hgr is defined as follows:

$$U(w_i, t_j) = \begin{cases} \frac{1}{|W_j|}, & ARS(t_j) \geq q_j \\ 0, & ARS(t_j) < q_j \end{cases} \quad (3)$$

where $|W_j|$ is the number of workers assigned to task t_j . The idea of this definition is that only when the required quality level q_j of task t_j is satisfied, the system utility can increase 1 (i.e., $\sum_{w_i \in W_j} U(w_i, t_j) = 1$, when $ARS(t_j) \geq q_j$). In addition, TA-GSC problem is proved NP-hard with the utility defined as Equation 3 by reducing from *maximum 3-dimensional matching problem* (M3M) [26].

GT-hgr utilizes three heuristics to improve the result of a basic greedy algorithm (GT-greedy), which greedily assign a task to one correct match until no further tasks can be assigned. Here one correct match is a task-and-workers pair $\langle t_j, W_j \rangle$ whose aggregate reputation score $ARS(W_j)$ is not less than the required quality level q_j of task t_j . The first heuristic is filtering heuristic, which can reduce the size of correct matches by pruning the dominated correct matches. For two correct matches $\langle t_j, W_j \rangle$ and $\langle t_j, W'_j \rangle$, if $W_j \subseteq W'_j$, match $\langle t_j, W_j \rangle$ dominates $\langle t_j, W'_j \rangle$. The second heuristic is least worker assigned heuristic, which associates a higher priority for matches with fewer workers. The last heuristic is least aggregate distance heuristic, which prefers the match with smaller summation of moving distances of the workers in that match.

4. ALGORITHMS IN ONLINE MODE

In the online mode, the servers do not trace the locations of workers and just recommend a task plan for each worker when he/she is querying the suitable tasks, which indicates a route for the worker to go and conduct as many tasks as possible by the way [16, 17]. The utility function for the online mode algorithms discussed in this section is simply defined as $U(w_i, t_j) = 1$.

Algorithm 2: The Framework of Online Algorithms

Input: An available worker w_i

Output: A set of suitable tasks for worker w_i to conduct

- 1 Obtain a set of valid tasks for worker w_i
- 2 Use online task assignment algorithms to obtain a set, T_i , with the most number of suitable tasks for worker w_i
- 3 Notify worker w_i to conduct tasks in T_j

The framework of the TA-GSC algorithms in online mode is shown in Algorithm 2. One example is shown in Figure 3 [16], where the worker is located at (6, 5) and five tasks A to E are located at five different locations with their deadlines. The result of this example is that the worker can finish at most four tasks following the order $A \rightarrow E \rightarrow C \rightarrow D$.

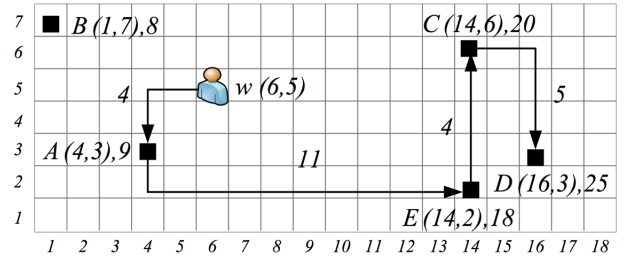


Figure 3: Running example of MTS.

The TA-GSC problem in online mode can be reduced from a specialized version of Traveling Salesman Problem (TSP) called sTSP, which is a NP-hard problem [16]. Exact algorithms, such as *dynamic programming algorithm* and *branch-and-bound algorithm* [16], can solve the problem for each single worker exactly. However, for the entire time period, exact algorithms still achieve only approximated results. In addition, to improve the efficiency, some heuristic algorithms and progressive algorithms are proposed [16, 17]. In the rest of this section, we will briefly introduce them.

4.1 Exact Algorithms

As the server in online mode tries to provide the longest tasks sequence for each worker such that he/she can conduct as many tasks as possible. Although this problem is proved NP-hard, the dynamic programming algorithm and the branch-and-bound algorithm [16] can solve small scale problems.

4.1.1 Dynamic Programming Algorithm

The dynamic programming algorithm (DP) [16] iteratively expands the sets of tasks in the ascending order of set sizes, and ignores the order of task sequence but examines the sets of tasks. Given a worker w , and a set of tasks T , let $opt(T, j)$ be the maximum number of tasks that worker w can complete under the constraints of tasks and starts from the current locations of w and ends at the tasks t_j , and R be the corresponding task sequence to achieve the optimum value. In addition, they denote the second-to-last task in R as task t_x . Then, the recurrent formula is given as below

$$opt(T, t_j) = \begin{cases} 1, & \text{if } |T| = 1 \\ \max_{t_i \in T, t_i \neq t_j} \{opt(T - \{t_j\}, t_x) + \delta_{xj}\}, & \text{otherwise} \end{cases} \quad (4)$$

$$\delta_{xj} = \begin{cases} 1, & \text{if } t_x \text{ can be finished after connecting } t_j \text{ in the end of } R' \\ 0, & \text{otherwise} \end{cases}$$

where R' is a task sequence without task t_j . With the recurrent formula in Equation 4, the algorithm can be implemented based on existing dynamic programming framework.

To further reduce the running time of the dynamic programming algorithm, the Apriori principle [31] can be utilized to remove the invalid sets such that the problem space can be smaller. The observation is that if a task set is invalid, then all of its supersets must be invalid. When exploring the task sets, if one invalid task set is founded, all its supersets can be safely removed. However, when most of the task sets are valid, the optimization strategy may not be effective as the cost of generating candidate sets may surpass the benefits from removing invalid task sets.

4.1.2 Branch-and-Bound Algorithm

The branch-and-bound algorithm (BB) [16] searches the whole problem space with pruning and directing. The search space of branch-and-bound algorithm can be represented as a tree, then the algorithm conducts a depth-first search with effective directing and pruning. Specifically, for each node, the algorithm expands it to a set of candidate task nodes. One observation is that a node's candidate task set in the search tree is the subset of its parent's candidate task set, which can improve the speed of expanding nodes. With the candidate task set of node r , the algorithm can estimate the upper bound ub_r of the maximum task sequence along the node r in the search tree in the equation below

$$ub_r = level(r) + |cand_r| \quad (5)$$

where $level(r)$ indicates the level of node r in the search tree, and $|cand_r|$ represents the size of the candidate task set of node r . Then the algorithm can safely prune the branch of node r when its upper bound ub_r is smaller than the best current known solution $curMax$. To determine the best searching order, the algorithm sorts the current searching branches by their upper bounds (ub) or lower bounds (lb), which can be estimated with approximation algorithms in Section 4.2. In addition, if the upper bound of a node r is less than the lower bound of any other node, the node r can be safely pruned.

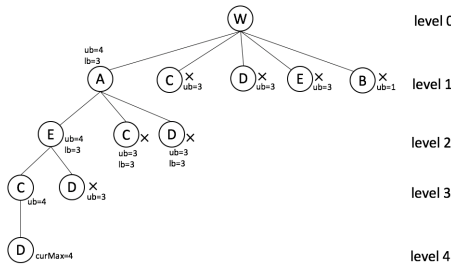


Figure 4: An overview of branch-and-bound algorithm.

Figure 4 displays an overview of the branch-and-bound algorithm of solving the example shown in Figure 3. On level 1, the five nodes are ordered by their upper bounds and node B can be pruned as its upper bound is less than the lower bound of node A. Then after visiting node D on level 4, the algorithm finds the current best known result $curMax = 4$. When $curMax = 4$, the algorithm prunes all other nodes as their upper bounds are all less than 4.

4.2 Heuristic Algorithms

Exact algorithms give the exact result for each single worker's request but not the entire time period, and their time complexities and memory consumption increase exponentially as the number of tasks grows such that they are not efficient enough for real-world

applications. In this section, we briefly introduce three heuristics to return results to the workers quickly [16].

Least expiration time heuristic (LEH). The LEH constructs a task sequence by greedily appending the task with the least expiration time to the end of current task sequence. It first orders the tasks by their expiration time, then check each task on the ascending order of their expiration time. If one task can be conducted by the worker, which means the worker can arrive at the location of the task before its deadline, then the algorithm adds the task to the end of the current task sequence. Finally, the task sequence is sent to workers to conduct one by one.

Nearest neighbor heuristic (NNH). The NNH utilizes the spatial proximity between tasks through keeping selecting the nearest valid task to the last added task in the current task sequence, where the valid task means the worker can arrive at its location before its deadline. The heuristic greedily adds more tasks to the end to the task sequence until no more tasks can be selected, then it returns the task sequence to the worker who is querying the available tasks.

Most promising heuristic (MPH). The MPH is a heuristic for the branch-and-bound algorithm in Section 4.1.2 to choose the most promising branches when it is exploring the search tree, where the most promising branch for each level can be the branch having the nodes with the highest upper bound at that level. In addition, MPH just reports the first found candidate task sequence.

As the heuristic algorithms run fast, on real-world application, the system can run the three heuristic algorithms at the same time, noted as Heuristic Algorithm (HA), and just reports the best result to improve the utility of the final result but without harming the user experience of workers.

4.3 Progressive Algorithms

The idea of progressive algorithms (PRS) is to report a small number of spatial tasks to a worker quickly at the beginning, and then to keep incrementally building the rest of the task sequence off-line and report the newly added tasks to the worker before he/she finishes all the tasks already reported to them. Under this framework, one progressive algorithm can use approximation algorithms to response one worker very fast at the beginning, then utilizes one exact algorithm to progressively construct the rest task sequence.

The advantage of progressive algorithms is that they can response a worker faster than exact algorithms and report more accurate results than heuristic ones. On the other hand, the potential tasks for a worker may be promoted to other workers when they are conducting the initial tasks, and they cannot see the entire task sequence at the beginning which may lead to a worse user experience compared to that of the other online algorithms.

5. EXPERIMENTAL STUDY

5.1 Experiments Setup

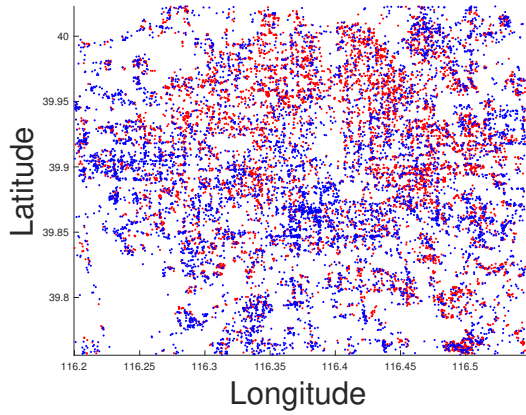
Data Sets. We use both real and synthetic data to test task assignment methods in batch-based mode and online mode.

For real data set, we utilize the data provided by DiDi Chuxing [3]. Specifically, the real data set includes the temporal locations of taxis and orders, which is retrieved from the time period between 7:30 am and 8:30 am in a normal day in the urban area of Beijing (with latitude from 39.7558° to 40.0229° and longitude from 116.1996° to 116.5457°). There are more than 10,000 orders and 13,000 taxis in the data set. Figure 5 shows the distribution of 7K sampled taxis and orders, where the locations of orders and taxis are represented by red and blue points, respectively. Note that, when drawing Figure 5, we added a random disturbance to each location of taxis and orders for privacy protection. For simplicity,

Table 2: Algorithms Comparison

Algorithms	Time Complexity	Assignment Mode	Maximizing Goal	Randomization
MaxFlow Greedy (G-greedy) [21]	$O(E \max f)$	Batch-based	the number of assigned tasks	Deterministic
MaxFlow with least location entropy priority (G-llep) [21]	$O(E \max f)$	Batch-based	the number of assigned tasks	Heuristic
MaxFlow with nearest neighbor priority (G-nnp) [21]	$O(E \max f)$	Batch-based	the number of assigned tasks	Heuristic
Trustworthy greedy (GT-greedy) [22]	-	Batch-based	the number of correct matches	Randomized
Heuristic-enhanced greedy (GT-hgr) [22]	-	Batch-based	the number of correct matches	Heuristic
Divide and conquer (RDB-d&c) [13]	$O(m \cdot n^2)$	Batch-based	the minimum reliability	Heuristic
Sampling (RDB-sam) [13]	-	Batch-based	the minimum reliability	Randomized
Dynamic programming (DP) [16]	$O(n \cdot m^2 \cdot 2^m)$	Online	the number of scheduled tasks	Deterministic
Brach and bound (BB)[16]	$O(n \cdot m!)$	Online	the number of scheduled tasks	Deterministic
Heuristic ensemble algorithm (HA) [16]	$O(n \cdot \log(m))$	Online	the number of scheduled tasks	Heuristic
Progressive algorithm (PRS) [16]	-	Online	the number of scheduled tasks	Heuristic

we first linearly map locations from DiDi Chuxing into a $[0, 1]^2$ data space. Then, we use the taxi records to initialize locations and timestamps of workers, and utilize the order records to set up the required locations and creation timestamps of spatial tasks. In the experiments, we treat every ϕ seconds as a time slot (i.e., the temporal unit in the experiments).

**Figure 5: Real data distribution (orders:red points, taxis:blue points).**

For synthetic data, we generate locations of workers and tasks in a 2D data space $[0, 1]^2$ following Uniform (UNIF), Gaussian (GAUS), Skewed (SKEW), as different distributions may affect the validation relationships of worker-and-task pairs (i.e., satisfying working area constraint and deadline constraint). For Uniform distribution, we uniformly generate the locations of tasks in the 2D data space. For Gaussian distribution, we generate the locations of tasks/workers in a Gaussian cluster (with mean μ and variance σ^2). Similarly, we also generate the tasks/workers with the Skewed distribution through locating 90% of them into Λ Gaussian clusters (with mean of 0.5, variance of 0.05^2 and randomly chosen centers), and distributing the rest workers/tasks uniformly in the 2D data space. We present the illustrations of the distributions with different parameters in Appendix A of our technical report [11]. For each synthetic dataset, we generate 50 time slots.

To simulate the synthetic data and the other properties of real data, we use a toolbox, SCAWG [28], to generate data records for each time slot. For both real and synthetic data sets, we simulate the working ranges each worker as squares whose centers are at the locations of workers, and the length of sides of the squares are generated with Gaussian distribution within range $[a^-, a^+]$ [21, 29]. In addition, we set the velocity of each worker as v . When the workers are idle, they move randomly within their working areas. Each worker will locate at the position of his/her latest task after finishing it. For the count of required answers to each task and the capacity of each worker, we generate them following the Gaussian distribu-

Table 3: Experiments Settings

Parameters	Values
number of tasks, m	7.5K , 10K, 12.5K, 15K, 17.5K
number of workers, n	7.5K , 10K, 12.5K, 15K, 17.5K
task duration range, $[rt^-, rt^+]$	[1, 2], [2, 3], [3, 4], [4, 5]
required answers range, $[b^-, b^+]$	[1, 3], [3, 5], [5, 7], [7, 9]
capacity range, $[c^-, c^+]$	[2, 3], [3, 4], [4, 5], [5, 6]
required quality level range, $[q^-, q^+]$	[0.65, 0.7], [0.75, 0.8], [0.8, 0.85], [0.85, 0.9]
reliability range, $[r^-, r^+]$	[0.65, 0.7], [0.75, 0.8], [0.8, 0.85], [0.85, 0.9]
side length range, $[a^-, a^+]$	[0.05, 0.1], [0.1, 0.15], [0.15, 0.2], [0.2, 0.25]
worker velocity, v	0.01, 0.05, 0.1, 0.15
time slot length, ϕ	30, 60, 120 , 180
mean of Gaussian distribution, μ	0.1, 0.3, 0.5 , 0.7, 0.9
variance of Gaussian distribution, σ^2	0.01 ² , 0.03 ² , 0.05² , 0.07 ² , 0.1 ²
number of Gaussian distributed clusters in the skewed distribution, Λ	1, 3, 5, 7

tions within the range $[b^-, b^+]$ and the range $[c^-, c^+]$, respectively [21, 29]. Meanwhile, for the required confidence of each task and the reliability of each worker, we produce them following the Gaussian distributions within the range $[q^-, q^+]$ and the range $[r^-, r^+]$, respectively [22]. For temporal constraints on tasks, we also generate the deadlines for tasks according to the range $[rt^-, rt^+]$ of the duration of tasks with Gaussian distribution [12, 13, 16]. Here, for Gaussian distributions, we linearly map data samples within $[-1, 1]$ of a Gaussian distribution $\mathcal{N}(0, 0.2^2)$ to the target ranges. **Evaluation Metrics.** To evaluate the efficiency and effectiveness of the tested approaches, we report the most important metrics for spatial crowdsourcing systems as follows:

- *Average moving distance of each worker (AvgMD).* For workers, they want to accomplish maximum number of tasks with minimum moving distance. Then, higher average moving distance of each worker may harm the benefit of workers, which should be avoided. Thus, algorithms achieving results with lower AvgMDs are better.
- *Number of fully assigned tasks (NFT).* For the spatial crowdsourcing platforms, they want to fully assign as many tasks as possible, which can reflect their effectiveness. Here, one fully assigned task means it is assigned with the required number of workers. Higher NFT is better.
- *Number of confidently assigned tasks (NCT).* Only when the expected accuracy (calculated with Equation 1) of the assigned workers W_j of task t_j is higher than the required quality level q_j , task t_j is considered as a confidently assigned task. When the total number of tasks is fixed, algorithms achieving higher NCTs are better.
- *Running time (RT).* The running time represents the total execution time of the tested algorithm for resolving a given TA-GSC problem. Lower RT is better.

Tested Approaches. Table 3 depicts our experimental settings, where the default values of parameters are in bold font. In each

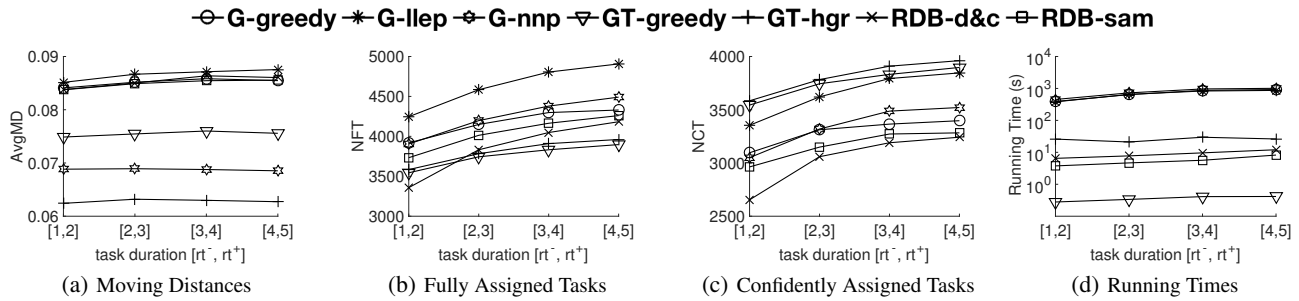


Figure 6: Effects of Task Duration rt (Batch-based Mode, Real).

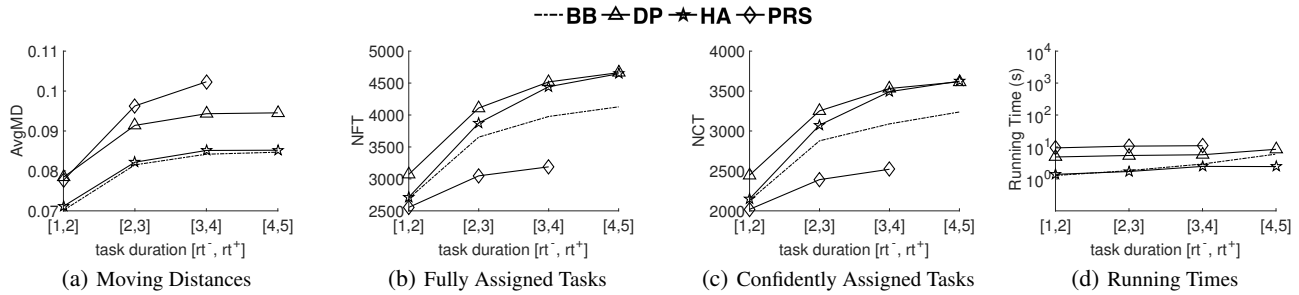


Figure 7: Effects of Task Duration rt (Online Mode, Real).

set of experiments, we vary one parameter, while setting other parameters to their default values. For each experiment, we report the measured metrics of all tested approaches, which includes the algorithms for batch-based mode: maximum flow based greedy algorithm (G-greedy), maximum flow with least location entropy priority heuristic algorithm (G-llep), maximum flow with nearest neighbor priority heuristic algorithm (G-nnp), greedy algorithm for trustworthy query (GT-greedy), heuristic-en-hanced greedy algorithm for trustworthy query (GT-hgr), sampling-based algorithm (RDB-sam) and divide-and-conquer-based algorithm (RDB-d&c), and the algorithms in online mode: dynamic programming algorithm (DP), branch-and-bound algorithm (BB), heuristic ensemble algorithm (HA, here we run three heuristic algorithms, LEH, NNH and MPH, introduced in Section 4.2 and report the best result of the results of them) and progress algorithm (PRS). Table 2 summarizes all the tested algorithms, where E is the number of valid worker-and-task pairs, $\max |f|$ is the size of the maximum flow, m is the number of tasks and n is the number of workers.

All our experiments were run on an Intel Xeon X5675 CPU @3.07 GHZ with 32 GB RAM in Python. The source code to generate the testing data sets and implementations of tested algorithms can be found on our GitHub repositories [2, 1].

5.2 Experimental Results

5.2.1 Experiments on Real Data

In this subsection, we show the results on the real data set and vary the range of task durations rt , the range $[a^-, a^+]$ of the side length workers' working areas, the range $[q^-, q^+]$ of tasks' required quality levels, the range $[r^-, r^+]$ of workers' reliabilities, the range $[b^-, b^+]$ of tasks' required answers, the range $[c^-, c^+]$ of workers' capacities, the velocity v of workers and the length of the time slot ϕ .

Effect of the range, $[rt^-, rt^+]$, of tasks' durations. We show the effect of the range, $[rt^-, rt^+]$, of tasks' durations on the performances of tested approaches through varying $[rt^-, rt^+]$ from [1, 2] to [4, 5] (the unit is time slot).

Figure 6 illustrates the results of batch-based algorithms. In Figure 6(a), AvgMDs of the results of batch-based algorithms almost do not change when tasks' durations increase, because in each batch workers are assigned with tasks whose numbers reach their capacities in the real data set (tasks and workers are well mixed as shown in Figure 5). G-llep causes workers to move the longest average distances, as it prefers to assign workers to tasks positioned at farther locations but with lower location entropies. GT-greedy and GT-hgr only assign correct matches (one correct match is a task-and-workers pair $\langle t_j, W_j \rangle$ whose expected accuracy $Pr(W_j)$ is not less than the required quality level q_j of task t_j), thus the two algorithms will use limited workers to confidently finish fewer tasks. As a result, the AvgMDs of results of GT-greedy and GT-hgr are small. As for G-nnp, it assigns workers to their nearest tasks, thus AvgMDs of its results are smaller than GT-greedy but higher than GT-hgr. G-greedy, RDB-d&c and RDB-sam tend to assign as many worker-and-task pairs as possible thus have high AvgMDs. In Figure 6(b), when the tasks' durations increase, all the batch-based approaches can fully assign more tasks, as each task will last for more batches such that more workers will be available for it. G-llep can fully assign the most number of tasks, which shows the effectiveness of its least location entropy priority strategy. G-greedy and G-nnp can fully assign fewer tasks than G-llep but more tasks than other batch-based algorithms. GT-greedy and GT-hgr can fully assign fewer tasks than other algorithms, as they just assign correct matches. In addition, RDB-d&c and RDB-sam can fully assign more tasks than GT-greedy and GT-hgr but fewer than other batch-based algorithms. When we consider the quality of assigned workers to tasks as shown in Figure 6(c), GT-greedy and GT-hgr can confidently assign most tasks than other algorithms, as they are proposed to handle the quality issues of tasks. The other batch-based algorithms keep their ranks in Figure 6(b). Note that many fully assigned tasks are in fact not confidently assigned. In Figure 6(d), when the tasks' durations increase, all the batch-based algorithms need more time to resolve the problems, because the average number of tasks in each batch increases, which leads to the problem space increases. G-greedy, G-llep and G-nnp use more time than other batch-based algorithms, because they all need to invoke

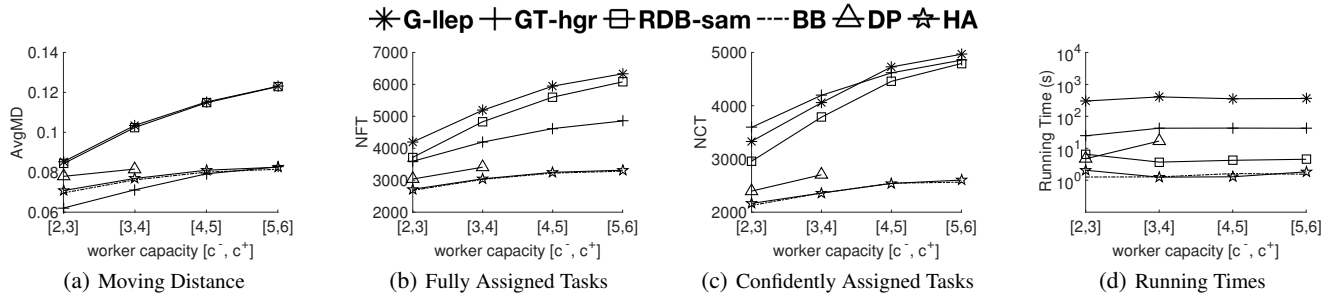


Figure 8: Effects of Worker Capacity c (Real).

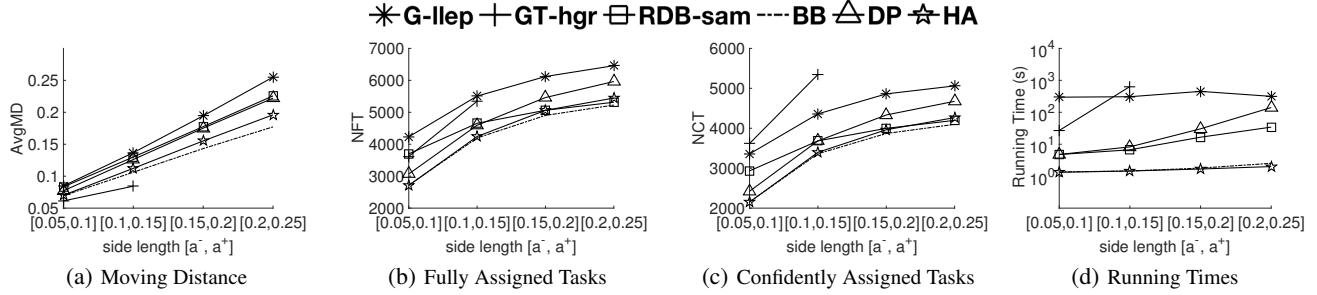


Figure 9: Effects of Range of Side Length of Worker Working Area a (Real).

the time-consuming Ford-Fulkerson algorithm or its variants. GT-greedy runs fastest among the batch-based algorithms. As RDB-sam just quickly sample worker-and-task pairs, it runs fast but still slower than GT-greedy. RDB-d&c is slower than RDB-sam but faster than GT-hgr.

Figure 7 shows the results of online algorithms. In Figure 7(a), when tasks' durations increase, AvgMDs of results of online algorithms will increase, because workers can arrive at tasks located at farther locations leading to that online algorithms schedule workers to farther tasks. PRS achieves results with the highest AvgMDs. PRS first assigns one task to each worker then use BB to plan other valid tasks. In the first step of PRS, some tasks may already be fully assigned with workers. Then in the second step of PRS, workers may be scheduled with farther tasks compared with using DP or BB directly. HA will result in larger AvgMDs than BB but smaller AvgMDs than other tested online algorithms. In Figure 7(b), when the tasks' durations increase, similarly, all the tested online approaches also can fully assign more tasks. PRS fully assigns the least tasks among online algorithms while DP fully assigns the most tasks. Similar ranking of results achieved by the tested online approaches can be observed when the quality levels of tasks are considered, as shown in Figure 7(c). However, the number of confidently assigned tasks is less than the number of fully assigned tasks for all the results achieved by the tested online algorithms. In Figure 7(d), when the tasks durations increase, all the tested online algorithms consume more time to achieve results. HA and PRS are the fastest and slowest approaches among the tested online algorithms, respectively. In addition, BB is faster than DP.

To compare the algorithms in batch-based mode and online mode together, we select three algorithms performing well from each category and place the results of them in the same figures to compare clearly. Specifically, we select G-llep, GT-hgr and RDB-sam from algorithms in batch-based mode, and select BB, DP and HA from algorithms in online mode. In the following discussion, we just show the results of the six selected algorithms.

Effect of the range, $[c^-, c^+]$, of workers' capacities. Figure 8 shows the effect of the range of workers' capacities on the performances of tested approaches through varying $[c^-, c^+]$ from [2, 3] to [5, 6]. As the running time of DP increases dramatically, we

do not report the results of DP when $[c^-, c^+]$ is [4, 5] and [5, 6]. When the capacities of workers increase, each worker may need to move longer to finish more tasks as shown in Figure 8(a). However, we find G-llep in fact sacrifices the efficiency of moving distances to fully assign more tasks. When some tasks are located in far positions with low location entropies, G-llep will assign these tasks with higher priorities such that AvgMD will increase. In addition, we find AvgMDs of the results of batch-based algorithms, except for GT-hgr, are higher than that of online algorithms. The reason is that online algorithms schedule the assigned tasks for each worker with the minimum total travel cost. NFTs of the tested algorithms are shown in Figure 8(b). When the capacities of workers increase, NFTs of the tested algorithm increase. Moreover, batch-based algorithms can fully assign more tasks than online algorithms. For NCTs shown in Figure 8(c), batch-based algorithms can also confidently assign more tasks than online algorithms. NCTs of GT-hgr are higher than that of G-llep when the worker capacities are lower than 4. However, when the worker capacities are higher than 4, G-llep can confidently assign more tasks than GT-hgr. The reason is that although G-llep does not consider the expected quality of the fully assigned tasks, when NFT of G-llep is high enough, NCT of G-llep can beat that of GT-hgr, the one particularly designed to focus on the quality of tasks. For the running times of the tested approaches as shown in Figure 8(d), DP is the slowest when worker capacities are higher than 4. BB and HA are faster than batch-based algorithms. G-llep is slower than GT-hgr, as G-llep needs to keep updating the entropies of many positions.

Effect of the range, $[a^-, a^+]$, of the side length of workers' working areas. When workers' working areas get larger, there will be more available tasks located in the working area of each worker leading to the number of valid worker-and-task pairs increases. As the running time of GT-hgr increases dramatically when workers' working areas get larger, we do not report the results of GT-hgr when $[a^-, a^+]$ is [0.15, 0.2] and [0.2, 0.25].

In Figure 9(a), as the working areas get larger, AvgMDs of the results achieved by all the tested approaches increase obviously, because the worker can reach tasks located further. In Figure 9(b), all the tested approaches can fully assign more tasks when the range of side length of working areas a increases, as each task can be

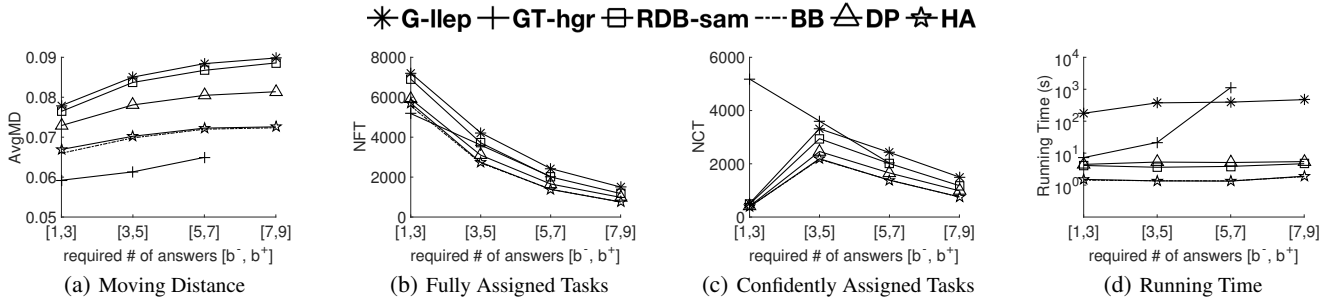


Figure 10: Effects of Required Answer Count b (Real).

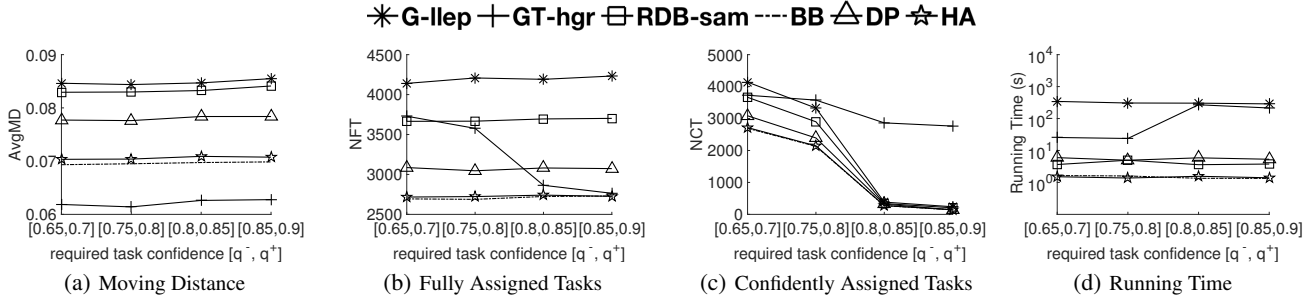


Figure 11: Effects of Required Quality Level q (Real).

reached by more workers and can be fully assigned with a higher probability. Specifically, the increasing speed of NFT of the tested online algorithms is higher than that of G-llep and RDB-sam. In Figure 9(c), GT-hgr still can achieve the highest NCT than other tested algorithms. When the range of side length of working areas reaches $[0.15, 0.2]$, online algorithms can achieve similar or even higher NCT than RDB-sam, as far workers be scheduled to farther tasks by online algorithms. In Figure 9(d), the running time of all the tested approaches increases when the range of a_i increases, as more valid worker-and-task pairs need to process. When $[a^-, a^+]$ is higher than $[0.1, 0.15]$, GT-hgr needs much more time than other tested approaches. Running time of DP increases faster than other approaches except for GT-hgr, as for each worker the computation complexity of DP is $O(m^2 \cdot 2^m)$.

Effect of the range, $[b^-, b^+]$, of the number of tasks' required answers. When the range $[b^-, b^+]$ increases, AvgMDs achieved by the tested approaches increase simultaneously shown in Figure 10(a). The reason is the worker labor does not increase, when a task t_j needs more workers, the platform will to schedule farther workers to join. For the number of finished tasks as shown in Figure 10(b), when the range $[b^-, b^+]$ increases, NFTs of all approaches decrease as the worker labor does not increase. For NCTs shown in Figure 10(c), different approaches performed quite different. When the range $[b^-, b^+]$ increases, NCTs of GT-hgr decrease monotonously, because workers are just enough for GT-hgr to fully assign fewer tasks. For other approaches not caring the correctness of the assignment, when the range $[b^-, b^+]$ is too small, like $(1, 3)$, each tasks' assigned workers will rarely satisfy its required quality level. When the range $[b^-, b^+]$ increases a little, more fully assigned tasks will become confidently assigned tasks. But when the range $[b^-, b^+]$ becomes larger, as NFTs decrease, NCTs also decrease. When each task requires more workers, all the tested algorithms need more time to achieve results, as shown in Figure 10(d). Specifically, the running time of GT-hgr increases dramatically, as for a task t_j , when more workers can be assigned to it, the number of correct matches for t_j will increase quickly.

Effect of the range, $[q^-, q^+]$, of tasks' required quality levels. When the range of tasks' required quality levels changes, only GT-hgr will be affected in all the metrics and other algorithms will only

be affected in NCTs. In Figure 11(a), the required quality levels does not affect the average moving distance of the results achieved by the tested algorithms. In Figure 11(b), GT-hgr will assign fewer workers when the range $[q^-, q^+]$ gets higher, as the number of correct matches will decrease leading to NFT of GT-hgr decreasing. In Figure 11(c), when the range of q_j increases, NCTs of all the tested approaches will decrease. We notice that although NCT of G-llep is higher than that of GT-hgr when $[q^-, q^+]$ is $[0.65, 0.7]$, GT-hgr can confidently assign more tasks when $[q^-, q^+]$ becomes larger (e.g., 0.75 to 0.9), which shows the effectiveness of the trust-worthy query. In Figure 11(d), when $[q^-, q^+]$ increases, only the running time of GT-hgr increases, as it is harder to select a correct match for each task from fewer correct matches.

Effect of the length of time slot ϕ . Figure 12 presents the effects of the length of time slot ϕ on the performances of the tested approaches by varying ϕ from 30 seconds to 180 seconds.

When the length of the time slot increases, AvgMDs of all the tested approaches increase as shown in Figure 12(a) and NFTs of them also increase as shown in Figure 12(b). The reason is that when the time slot length increases, during each time slot the number of workers will increase leading to more tasks can be fully assigned. As more tasks are fully assigned, AvgMDs of all the tested algorithms will increase. We can still observe that GT-hgr has the lowest AvgMDs as it only selects correct matches. In addition, as G-llep may give higher priorities to far tasks located in positions with low location entropies, workers may move farther to conduct tasks in the results of G-llep. For NCTs shown in Figure 12(c), all the tested algorithms can confidently assign more tasks when the time slot length increases, as more tasks are fully assigned. Specifically, when the time slot length is short (e.g., $\phi = 30$), G-llep and RDB-sam can confidently assign more tasks than GT-hgr. When the time slot length is longer than 60 seconds, GT-hgr has the highest NCTs. As GT-hgr algorithms only assign correct matches, when more workers are available, the number of correct matches will increase exponentially leading to that NCT of GT-hgr increases similarly. For the running times shown in Figure 12(d), when ϕ increases, the running times of G-llep and GT-hgr increase dramatically. Because the numbers of valid worker-and-task pairs and the correct matches increase quickly when the numbers of workers and

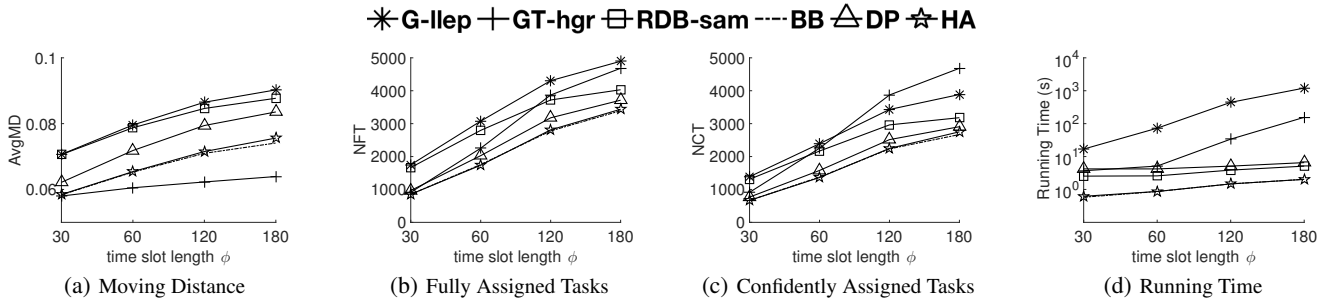


Figure 12: Effects of Time Slot Length ϕ (Real).

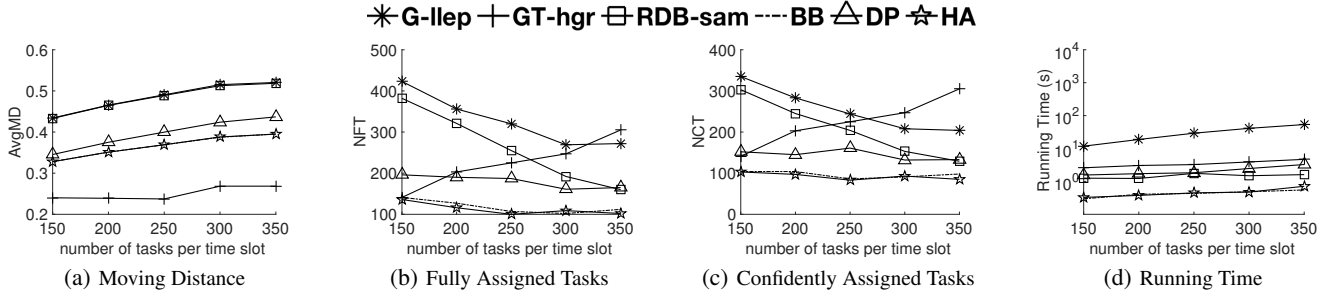


Figure 13: Effects of Number of Tasks Per Time Slot (Synthetic).

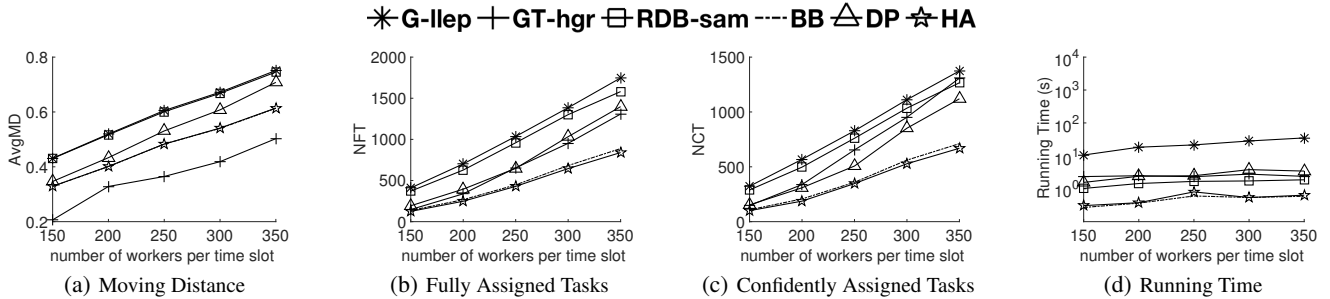


Figure 14: Effects of Number of Workers Per Time Slot (Synthetic).

tasks increase due to the increase of length of time slots.

We also conducted experiments on the real dataset with varied workers' reliabilities and workers' velocities. In addition, we also tested the algorithms when the working areas of workers are circles whose diameters are configured with a Gaussian distribution within range $[a^-, a^+]$. Due to the space limitation, we put the results in Appendix B of our technical report [11].

5.2.2 Experimental Results on Synthetic Data

In this subsection, we show the performances of tested approaches on synthetic dataset by varying the number of tasks m , and the number of workers n when the locations of workers/tasks both follow Uniform (UNIF) distribution. Due to the space limitation, we put the results about the effects of the location distributions of workers/tasks in Appendix C of our technical report [11].

Effect of the number of tasks, m . Figure 13 shows the effect of the number m of spatial tasks on the performances of tested approaches, where we vary m from 7.5K to 17.5K.

In Figure 13(a), the assigned workers of all the tested approaches will have higher average moving distances for larger m . The reason is that the approaches select tasks in perspectives different from proximity of tasks. When the number of tasks per time slot increases, they may select the most suitable tasks located further. In addition, as the GT-hgr assigns much fewer workers, the average moving distance of the results achieved by it is small. In Figure 13(b), except for GT-hgr, NFTs of the results achieved by all the tested algorithms will decrease when the number of tasks per time

slot increases. Except for GT-hgr, other tested algorithms do not concern the minimum required number of answers by each task. When the number of tasks increases, the workers are distributed to more tasks and the average number of workers for tasks will decrease, which leads to NCTs decrease. However, GT-hgr only assigns correct matches, which can guarantee that each assigned task will have a set of workers to satisfy the required number of workers. Meanwhile, when the number of tasks increases, GT-hgr will produce more correct matches as more suitable tasks are available to be selected such that NFT of GT-hgr increases. In addition, we notice that although some tasks in the results of G-llep and RDB-sam algorithms are assigned with required number of workers, their expected accuracy values may be not satisfied (their aggregation reputation scores may be smaller than their required quality levels). The reason is that G-llep and RDB-sam algorithms only assign as many worker-and-task pairs as possible without considering the required quality level. Similar results can be observed in Figure 13(c) due to the same reason. In Figure 13(d), when each time slot has more tasks, the running time of all the tested algorithms increases slightly, as more tasks need to be checked and maintained. DP runs much slower than other online algorithms.

Effect of the Number of Workers, n . Figure 14 shows the effect of the number n of spatial workers on the performances of tested approaches, where we vary n from 7.5K to 17.5K.

In Figure 14(a), when the number of workers in each time slot increases, the average moving distance of workers in the results achieved by all the tested algorithms also increases. The reason

is that when there are more workers in each time slot, the working areas of workers can cover more tasks, to conduct more tasks the AvgMDs will increase. In addition, we find that G-llep requires workers to move more to conduct tasks. The reason is G-llep gives higher priorities to the tasks created at locations with fewer workers, then more far tasks are assigned to workers. As shown in Figure 14(b), when m increases, all the tested approaches can fully assign more tasks. Online algorithms can fully assign fewer tasks than batch-based algorithms. G-llep algorithms can fully assign more tasks than other algorithms. The reason is compared to other algorithms, G-llep can finish more far tasks as explained above. RDB-sam can finish many tasks but still slightly fewer than that of G-llep. In Figure 14(c), all the approaches can achieve results with higher NCTs when there are more workers available in each time slot. Moreover, the increasing rate of NCT of GT-hgr is faster than other approaches. As GT-hgr only assigns correct matches, when more workers are available, the number of correct matches will increase exponentially leading to that NCT of GT-hgr increases similarly. In Figure 14(d), the running time of G-llep algorithms increases obviously when the number of workers per time slot increases, as the complexity of maximum flow algorithm increases linearly with respect to the number of edges of the graph, which increases super-linearly w.r.t n . BB and HA are faster than other algorithms, as BB can quickly assign enough tasks for each worker and HA just assigns tasks based on very simple heuristics (e.g., selecting next nearest neighbor). G-llep is slower than other five algorithms.

5.3 Summary

With the experimental studies, we summarized one grade table that describes the pros and cons of each algorithms under different metrics. Specifically, for a set of experimental results, we grade the performance of algorithm Ψ_j on metric M_i with Equation 6 as follows:

$$G(M_i, \Psi_j) = \begin{cases} 5 \cdot \frac{V_{ij} - L_i}{U_i - L_i}, & M_i \in \{NFT, NCT\} \\ 5 \cdot (1 - \frac{V_{ij} - L_i}{U_i - L_i}), & M_i \in \{AvgMD, RT\} \end{cases} \quad (6)$$

where V_{ij} is the result value of algorithm Ψ_j on metric M_i , and U_i and L_i are the upper and lower values among all the tested algorithms on metric M_i , respectively. For example, in Figure 8(a), when $[c^-, c^+] = [2, 3]$, AvgMD of GT-hgr is the lowest, then the grade of GT-hgr on AvgMD is 5 in this set of experiments. Then, in Table 4, we report the average grades of each tested algorithms for the four metrics. Therefore, users can find a good option given a TA-GSC application.

Another important issue is about location privacy of workers. In batch-based mode, spatial crowdsourcing systems need to trace the location of workers, which may scare away some potential workers. However, in online mode, workers only need to reveal their locations when they are requesting the available tasks, which is much more acceptable for most workers.

Online algorithms usually have good efficiency, which means the spatial crowdsourcing systems can response to the worker requests quickly, which leads to a better user experience than batch-based mode. However, systems in batch-based mode also can reduce the time interval between two adjacent batches such that they can also response to the worker requests quickly.

We provide the following high-level suggestions for choosing algorithms for TA-GSC applications.

1. When the expected accuracy of tasks is important for the platforms (e.g., mobile audit services, such as Field Agent [4]), GT-greedy or GT-hgr should be selected, as they can guarantee the

Table 4: Grades of algorithms for different metrics on our data sets. The grade varies from zero to five, and a higher grade indicates that the algorithm is better at the corresponding metric. B and O stand for batch-based mode and online mode, respectively.

Algorithm	Mode	AvgMD	NFT	NCT	RT
G-greedy	B	1.6	3.6	3.1	0.5
G-llep	B	1.4	5.0	4.5	0.7
G-nnp	B	4.1	3.8	3.3	0.0
GT-greedy	B	3.1	2.3	4.8	5.0
GT-hgr	B	5.0	2.5	5.0	4.8
RDB-d&c	B	1.6	2.6	2.2	4.9
RDB-sam	B	1.7	3.2	2.7	5.0
DP	O	1.2	3.3	2.9	5.0
BB	O	2.6	1.9	1.6	5.0
HA	O	2.5	2.8	2.5	5.0
PRS	O	0.4	0.0	0.0	4.9

quality of tasks, especially for applications for tasks with high required quality levels and workers with low reliabilities. On the contrast, when the required quality levels of tasks are low, the reliabilities of workers are high or the required numbers of answers are high, the expected accuracy of tasks will be high, then there is no need to particularly care the expected quality of tasks. As a result, G-llep, RDB-sam and DP are good choices.

2. When the travel costs of workers is the key measure for the platforms (e.g., Uber [8] and DiDi Chuxing [3]), GT-hgr and G-nnp should be chosen. Moreover, GT-hgr can also guarantee the quality of tasks.
3. When the responding speed for the workers is the key issue for the platforms (e.g., car-hailing platforms, such as Uber [8]), the maximum flow based algorithms, such as G-greedy, G-llep and G-nnp, should be avoided due to their high running times.

6. CONCLUSION

In this paper, we present a comprehensive experimental comparison of most existing algorithms on task assignment in spatial crowdsourcing. Specifically, we first give some general definitions about spatial workers and spatial tasks based on definitions in the existing works studying task assignment problems in spatial crowdsourcing such that the existing algorithms can be applied on the same synthetic and real data sets. We uniformly implement tested algorithms in both batch-based and online modes. With the experimental results of the tested algorithms on synthetic and real datasets, we show the effectiveness and efficiencies of the algorithms through their performances on five important metrics. According to the experimental results, we summarize the performance of tested algorithms on synthetic and real data sets through grading, which can guide users on selecting algorithms for real applications under different situations.

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8. REFERENCES

- [1] [online] spatial crowdsourcing benchmark algorithms. <https://github.com/gmission/SpacialCrowdsourcing>, 2018.
- [2] [online] spatial crowdsourcing dataset generator. <https://github.com/gmission/SCDataGenerator>, 2018.
- [3] [online] DiDi Chuxing. <https://www.didichuxing.com>, 2018.
- [4] [online] Field Agent. <https://www.fieldagent.net>, 2018.
- [5] [online] gMission. <http://gmission.github.io>, 2018.
- [6] [online] GoogleMap Street View. <https://www.google.com/maps/views/streetview>, 2018.
- [7] [online] TaskRabbit. <http://crowdfunder.com/>, 2018.
- [8] [online] uber. <https://www.uber.com>, 2018.
- [9] R. K. Ahuja, T. L. Magnanti, and J. B. Orlin. Network flows. Technical report, DTIC Document, 1988.
- [10] Z. Chen, R. Fu, Z. Zhao, Z. Liu, L. Xia, L. Chen, P. Cheng, C. C. Cao, and Y. Tong. gmission: A general spatial crowdsourcing platform. *PVLDB*, 7(13):1629–1632, 2014.
- [11] P. Cheng, X. Jian, and L. Chen. Task assignment on spatial crowdsourcing (technical report). <http://arxiv.org/abs/1605.09675>.
- [12] P. Cheng, X. Lian, L. Chen, J. Han, and J. Zhao. Task assignment on multi-skill oriented spatial crowdsourcing. *TKDE*, 2016.
- [13] P. Cheng, X. Lian, Z. Chen, R. Fu, L. Chen, J. Han, and J. Zhao. Reliable diversity-based spatial crowdsourcing by moving workers. *PVLDB*, 8(10):1022–1033, 2015.
- [14] J. Cranshaw, E. Toch, J. Hong, A. Kittur, and N. Sadeh. Bridging the gap between physical location and online social networks. In *Proceedings of the 12th ACM international conference on Ubiquitous computing*, pages 119–128. ACM, 2010.
- [15] A. P. Dawid and A. M. Skene. Maximum likelihood estimation of observer error-rates using the em algorithm. *Applied statistics*, pages 20–28, 1979.
- [16] D. Deng, C. Shahabi, and U. Demiryurek. Maximizing the number of worker’s self-selected tasks in spatial crowdsourcing. In *Proceedings of the 21st SIGSPATIAL GIS*, pages 314–323, 2013.
- [17] D. Deng, C. Shahabi, U. Demiryurek, and L. Zhu. Task selection in spatial crowdsourcing from worker’s perspective. *GeoInformatica*, 20:529–568, 2016.
- [18] U. U. Hassan and E. Curry. A multi-armed bandit approach to online spatial task assignment. In *Ubiquitous Intelligence and Computing, 2014 IEEE 11th Intl Conf on and IEEE 11th Intl Conf on and Autonomic and Trusted Computing, and IEEE 14th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UTC-ATC-ScalCom)*, pages 212–219. IEEE, 2014.
- [19] H. Hu, Y. Zheng, Z. Bao, G. Li, J. Feng, and R. Cheng. Crowdsourced poi labelling: Location-aware result inference and task assignment. *ICDE*, 2016.
- [20] P. G. Ipeirotis, F. Provost, and J. Wang. Quality management on amazon mechanical turk. In *Proceedings of the ACM SIGKDD workshop on human computation*, pages 64–67. ACM, 2010.
- [21] L. Kazemi and C. Shahabi. Geocrowd: enabling query answering with spatial crowdsourcing. In *Proceedings of the 21st SIGSPATIAL GIS*, pages 189–198, 2012.
- [22] L. Kazemi, C. Shahabi, and L. Chen. Geotrucrowd: trustworthy query answering with spatial crowdsourcing. In *Proceedings of the 21st ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*, pages 314–323. ACM, 2013.
- [23] S. H. Kim, Y. Lu, G. Constantinou, C. Shahabi, G. Wang, and R. Zimmermann. Mediaq: mobile multimedia management system. In *Proceedings of the 5th ACM Multimedia Systems Conference*, pages 224–235. ACM, 2014.
- [24] J. Kleinberg and É. Tardos. *Algorithm design*. Pearson Education India, 2006.
- [25] Y. Li, M. L. Yiu, and W. Xu. Oriented online route recommendation for spatial crowdsourcing task workers. In *Advances in Spatial and Temporal Databases*, pages 137–156. Springer, 2015.
- [26] R. G. Michael and S. J. David. Computers and intractability: a guide to the theory of np-completeness. *WH Free. Co., San Fr*, 1979.
- [27] L. Pournajaf, L. Xiong, V. Sunderam, and S. Goryczka. Spatial task assignment for crowd sensing with cloaked locations. In *Mobile Data Management (MDM), 2014 IEEE 15th International Conference on*, volume 1, pages 73–82. IEEE, 2014.
- [28] H. To, M. Asghari, D. Deng, and C. Shahabi. Scawg: A toolbox for generating synthetic workload for spatial crowdsourcing. In *2016 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*, pages 1–6. IEEE, 2016.
- [29] H. To, C. Shahabi, and L. Kazemi. A server-assigned spatial crowdsourcing framework. *ACM Transactions on Spatial Algorithms and Systems*, 1(1):2, 2015.
- [30] Y. Tong, J. She, B. Ding, L. Wang, and L. Chen. Online mobile micro-task allocation in spatial crowdsourcing. In *Data Engineering (ICDE), 2016 IEEE 32nd International Conference on*, pages 49–60. IEEE, 2016.
- [31] M. J. Zaki. Scalable algorithms for association mining. *IEEE transactions on knowledge and data engineering*, 12(3):372–390, 2000.