Incentivizing WiFi-Based Multilateration Location Verification

Mingzhe Li, *Student Member, IEEE*, Wei Wang, *Member, IEEE*, Jin Zhang, *Member, IEEE*, and Qian Zhang, *Fellow, IEEE*

***Abstract*—Due to the proliferation of WiFi devices and the high verification precision, researchers have shown interests in WiFi-based multilateration location verification (WMLV), where multiple WiFi APs (also known as verifiers) verify the location information claimed by a prover. However, it is a high expenditure for any single location-based service provider to deploy densely covered WiFi facilities. Incentivizing independent WiFi owners to corporately verify location information is thus a feasible solution to this plight, yet none of the previous research has taken this into consideration. To this point, we design a double auction-based incentive mechanism for WMLV, which motivates the participation of both provers and verifiers. More importantly, we consider practical situations, where the provers have various verification precision requirements, and different number of verifiers are required by different provers. The proposed double auction mechanism achieves desirable economical properties, including *truthfulness, individual rationality, computational efficiency, budget balance,* and *nonnegative social welfare.* The desired properties are validated through both theoretical analysis and extensive simulations.**

***Index Terms*—Double auction mechanism, incentive mechanisms, location verification, WiFi-based multilateration location verification (WMLV).**

I. Introduction

IN CURRENT wireless networks, location-based techniques and services are ubiquitous. The verification of *whether* a user is present at a certain location range (also known as location verification) is the nub in many location-based applications (e.g., Foursquare [6], Yelp [9], Pokémon Go [7], and Uber [8]) and has attracted considerable research interest in recent years (e.g., [20], [21], [30]). Location verification is of great significance, as the location information of users is often required in location-based systems. Therefore, it is possible for a user to *spoof or falsify* the claimed location information and further *disrupt the system functionalities* [31].

WiFi-based multilateration location verification (WMLV) (e.g., [10], [26], [28]) has recently drawn much attention from researchers due to its high verification precision and the popularization of WiFi facility. WMLV consists of mainly three entities: 1) *prover*, who claims and wishes to prove its location (e.g., the user in a location-based application); 2) *verifier*, the WiFi AP that helps provers verify their location claims; and 3) *platform*, the service provider, who helps verifiers and provers to collect and judge the verification results. The term *multilateration* means that multiple verifiers verify one location claim in a collaborative way.

Despite of the potential of WMLV, its adoption gets hindered due to the enormous expenditure to deploy extensively covered WiFi APs [1], [2], especially when the WiFi devices are deployed by *single* location-based service provider (e.g., Foursquare). An alternative way to address this plight is to leverage the WiFi APs owned by different WiFi owners (e.g., a store, a library, etc.) to verify locations. However, individual WiFi AP owner may be reluctant to join the location verification since participating as a verifier usually consumes extra resources and expenditure. Therefore, it is necessary to design incentive mechanisms to stimulate WiFi owners to participate in the system, as the success of WMLV strongly relies on the number of WiFi devices.

As a consequence, we consider the incentive mechanism design for the WMLV system. Auction is an efficient method to design incentive mechanisms, and a number of auction-based incentive mechanisms have been proposed for various systems (e.g., [15], [16], [29]). However, none of the previous research has designed auction mechanisms for location verification systems. More importantly, the auction-based incentive mechanism design for WMLV has the following challenges.

The first challenge is that the design of the auction mechanism for WMLV is different from many classical auction mechanisms, where, solely the bids are considered (e.g., [16]). In the auction design for WMLV, the precision and the number of verifiers requirements are two extra essential attributes that should be satisfied for every winner. In practical WMLV,

Manuscript received February 26, 2021; revised June 11, 2021; accepted June 29, 2021. Date of publication July 13, 2021; date of current version February 4, 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 61701216; in part by the Shenzhen Science, Technology and Innovation Commission Basic Research Project under Grant JCYJ20180507181527806; in part by the Guangdong Provincial Key Laboratory under Grant 2020B121201001; in part by the "Guangdong Innovative and Entrepreneurial Research Team Program" under Grant 2016ZT06G587; and in part by the "Shenzhen Sci-Tech Fund" under Grant KYTDPT20181011104007. *(Corresponding authors: Wei Wang; Jin Zhang; Qian Zhang.)*

Mingzhe Li is with the Department of Computer Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China, and also with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Hong Kong (e-mail: mlibn@cse.ust.hk).

Wei Wang and Qian Zhang are with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Hong Kong (e-mail: weiwa@cse.ust.hk; qianzh@cse.ust.hk).

Jin Zhang is with the Guangdong Provincial Key Laboratory of Brain-Inspired Intelligent Computation, Department of Computer Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China (e-mail: zhangj4@sustech.edu.cn).

Digital Object Identifier 10.1109/JIOT.2021.3096820

the verification precision requirements are necessary. it represents the range around the claimed location that the verifiers should verify (e.g., verify whether a prover is in a small cafe (higher precision), or a big shopping mall (lower precision)). In addition, a reliable WMLV requires multiple verifiers to verify one location claim. The requirement of multiple verifiers is mainly for improving the verification precision and detecting misbehaving verifiers.

Moreover, the precision model of WMLV is different from those models in the previous quality-aware auction mechanisms (e.g., [27]), which further increases the difficulty for defining the precision model and designing the WMLV-based auction. Last but not least, it is challenging to design an auction that satisfies many nice economic properties simultaneously (i.e., truthfulness, individual rationality, computational efficiency, budget balance, and nonnegative social welfare), especially when the auction design in WMLV should also consider the precision and the number of verifiers' requirements.

Therefore, we propose INTIMATION, which incentivizes the participation in WMLV. Specifically, INTIMATION is based on double auction [22], which involves auctions and stimulates the participation among both verifiers and provers. More importantly, we take the *precision requirement* as well as the *number of verifiers requirement* into considerations. Based on that, we design a practical double auction-based mechanism supporting *multiple provers and verifiers*.

We summarize our contributions as follows.

1) We are the first, to the best of our knowledge, to investigate incentive mechanisms for location verification. As an essential step, we consider the precision and number of verifiers' requirements in our auction design and based on which we formally define a practical precision model for WMLV.
2) The proposed double auction mechanism bears many desirable properties, including truthfulness, individual rationality, computational efficiency, budget balance, as well as nonnegative social welfare.
3) We conducted extensive simulations using different data sets and compared the proposed double auction mechanism with other baseline methods. Simulation results show that the proposed mechanism produces nonnegative social welfare and platform balance. Moreover, it achieves noticeable computational time savings.

II. Background and Motivation

In this section, we further elaborate the background of location verification and WMLV, as well as the motivation of our article.

A. Location-Based System and Location Verification

In a location-based system, users discover their locations and share them with a server. The server then performs operations based on the location information and returns data/services to the users. The users can generally benefit from being at a specific location in a location-based system. For instance, location-based service providers, such as Foursquare [6] and Yelp [9] offer some rewards (such as gift vouchers) to users who frequently check-in at specific locations. However, the benefit for appearing at a location could stimulate people to falsely claim that they are in a place where they are not. Moreover, today's location-based systems generally obtain users' locations directly via GPS, making it possible for a user to manipulate the location and report fake location information. For example, it is observed that a significant percentage of Foursquare check-ins are fake and submitted by dishonest users to obtain benefit, which could be detrimental to other users' interests and impair the whole system [34]. As a consequence, location verification becomes a necessary second line-of-defence against such misbehaviour in many location-based systems [24].

A location verification system is different from a localization system (e.g., GPS) in the following two main aspects. First, some a-priori information (e.g., a claimed location) is provided in a location verification system, whereas such information is not required in a localization system. Second, the output of a location verification system is a binary decision, whereas the output is an estimated location in a localization system. However, location verification and localization can be complementary to each other. For example, the claimed location requested in location verification is usually provided by GPS, and a location verification system can detect errors in the GPS or detect location manipulations.

B. WiFi-Based Multilateration Location Verification

Many existing works have explored approaches of using wireless infrastructure (e.g., WiFi APs) collaboratively verify users' locations (e.g., [10], [26], [28]), named WMLV. Fig. 1 illustrates the basic model of verifying the location information for one location in WMLV. A *prover* in WMLV is the mobile device, which generates location claims to prove its presence at certain location. A *verifier* is the WiFi AP in proximity with the prover and is willing to create a location proof to verify the presence for the prover upon receiving its location claim. In addition, a *platform* (e.g., service provider) is required for a WMLV system to coordinate the provers and verifiers, collecting and validating the verification results. The location verification process can be basically categorized into RTT-based (round trip time) and RSS-based (received signal strength). In RTT-based location verification [11], the verifier exchanges messages with the prover through wireless communication. Based on the RTT, the verifier calculates a distance bound which it reckons the prover is within. Similarly, the verifier deduces the distance bound based on the RSS in RSS-based location verification [32]. In this article, we mainly focus on the RTT-based model.

As shown in Fig. 1(a), it is generally required for multiple verifiers to verify one location claim, representing the term "multilateration." Multilateration could provide high location verification precision. For example, if one verifier verifies that a prover is within a radius of 50 m from it [Fig. 1(b)], then with four verifiers could they verify that a prover is within the intersection of all four circles [Fig. 1(a), the dashed are], which is more precise than with one verifier.

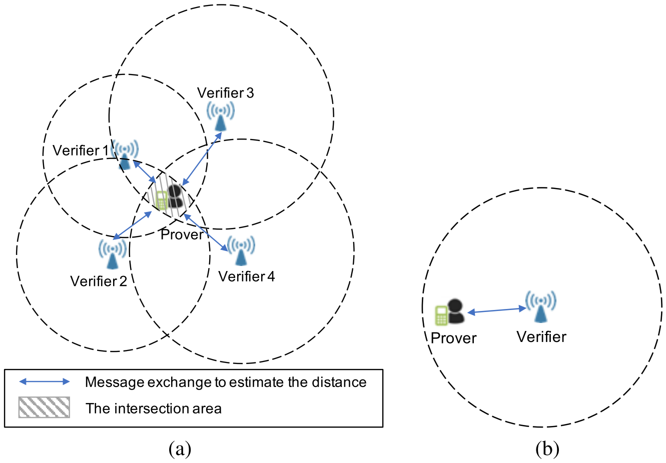


Fig. 1. Basic model for WiFi-based location verification (without illustrating the platform). (a) Illustration for WMLV. (b) Location verification with one verifier.

WMLV can efficiently help location-based systems to prevent users from tampering with their locations, thereby ensuring the accuracy of users' reported locations and improving system security. Moreover, existing works show that the cost for implementing WMLV is low (e.g., [19], [24], [28]). Users can easily control their heterogeneous WiFi APs by installing software on laptops or mobile phones [19]. The development cost of an app on mobile devices is affordable for a location-based service provider such as Foursquare. As a fact, WMLV is easier to implement than other location verification methods (such as radar based), as no additional hardware is required. Therefore, WMLV becomes very promising in location-based applications. However, without an incentive mechanism, the dissemination of WMLV will be full of difficulties, as we will discuss next.

C. Motivation

Many previous studies in location verification (e.g., [30]) made the assumptions that the WiFi APs are deployed by single location-based service provider, such as Foursquare or Yelp. However, the widely deployed WiFi APs usually cost vast amount of expenditure for a location-based service provider and, hence, becomes a potential obstruction that impedes the implementation of WMLV systems. For example, a commercial WiFi AP typically covers around 50-m indoors, to cover a single shopping mall thus costs more than tens of thousands of dollars for just one-time expense [2]. Therefore, requiring a single location-based service provider to widely deploy WiFi causes a heavy burden for any service provider (e.g., Foursquare and Yelp).

Due to the rapid development of WiFi technology, there are WiFi devices with dense coverage belonging to different owners (e.g., shopping malls, stores, restaurants, etc.) Thereby, leveraging WiFi APs owned by independent individuals to perform location verification is a feasible solution. For instance, different stores use their own WiFi devices to verify locations for mobile phone users. However, the location verification process will conduct extra cost for WiFi owners, such as time cost and power cost [24]. As a result, a rational WiFi owner may refuse to *voluntarily* participate in the location verification process.

Motivated by the aforementioned problem, we propose to design an incentive mechanism for WMLV. Specifically, since there are extra costs for a verifier to perform location verifications, it is necessary to reward the verifier. This will incentivize more validators to participate in the system. Since the verifier helps the prover verify its location, it is reasonable for the entity being helped (i.e., prover) to reward the verifier. Additionally, when the location of the prover is verified, the prover will also get some benefits (e.g., coupons). Therefore, when the pay is less than the gain, a rational prover will also be willing to participate (e.g., the prover will get a U.S. $5 coupon, it may be willing to pay U.S. $1 to the verifiers). When more verifiers and provers participate, more locations will be correctly verified, which is also beneficial to the location-based service providers. Conversely, when verifiers are not rewarded, they may have no incentive to participate. As a result, the prover cannot pass the location verification and will lose benefits (e.g., coupons). The service provider will also suffer losses due to lack of user participation.

Double auction is an incentive mechanism suitable for motivating both buyers and sellers to participate, so it is more in line with the WMLV scenario. The auction scheme is user-centric, through a reasonable auction mechanism design, buyers' and sellers' utility can be maximized, and the platform will also have nonnegative profits. This is a win-win-win for the prover, verifier, and platform. In WMLV-based auction, the verifier is the seller, the prover is the buyer, and the service provider (e.g., Foursquare) can be the auctioneer. Verifiers and provers can act as users under location-based service, who may also use other functionalities provided by the service besides the auction. The auction algorithm is easy to implement. Service providers can deploy auction as a component to the location verification system (e.g., Foursquare adds auction as a new feature to its location verification software). Users can easily participate in the auction through the mobile device apps. In addition, the auction process is automatically controlled by the algorithm. Moreover, service providers can get more profits through auctions. Therefore, the auction is very economical and lightweight. Auction is also easy to understand and operate. Users only need to submit their real bid (price generated in mind) to the auction system, everything else can be automatically executed by the auction algorithm, the winners will be finally selected and rewarded. We hope that with the incentive mechanism could the location verification system have a broader adoption.

III. System Model and Economic Properties

In this section, we overview the basic model of our system, and introduce the precision model and the desirable economic properties.

A. System Overview

We consider a WMLV system consisting of a platform, a set of provers who want their locations to be verified, denoted as $\mathcal{P} = \{p_1, \ldots, p_N\}$, and a set of verifiers who

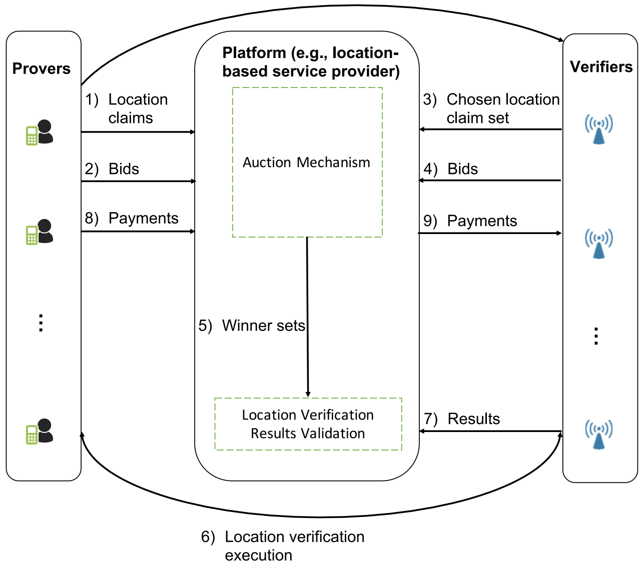


Fig. 2. Basic framework of INTIMATION.

verify the locations claimed by the provers, denoted as $\mathcal{W} = \{w_1, \ldots, w_M\}$. This architecture is similar to many location verification systems (e.g., [20], [28]). The basic workflow of INTIMATION can be divided into two phases. The first is the auction phase, where the platform serves as an auctioneer, the provers are payers (also known as buyers) and the verifiers are payees (also known as sellers). During the auction, the platform runs the auction mechanism to decide the winning provers/verifiers and the payments. The second phase is location verification results validation. After the winning provers and verifiers perform location verification, the platform charges the payments from the qualified provers and grants rewards to the qualified verifiers after validating the verification results. Our core design lies in the auction mechanism; meanwhile, we conduct extra designs for validating the location verification results and, therefore, charging/granting the right money for the winners who conduct qualified location verification. The framework of INTIMATION is given in Fig. 2, and we describe its workflow as follows.

During the auction, each prover p_j reports its location claim LC_j to the platform, containing the location needed to be verified l_j, the location verification precision requirement Q_j, and the number of verifiers requirement K_j. Meanwhile, it broadcast another claim BC_j, including Q_j and K_j to its nearby verifiers (step 1). In addition, the prover reports to the platform a bid a_j, representing the amount it is willing to pay if its location claim gets proved (step 2). After receiving the location claims, each verifier sends to the platform the set of location claims that it wants to prove (step 3), along with a bid vector $\mathbf{b}_i$, meaning its bidding prices for verifying them (step 4). Based on the received bids, the precision, and the number of verifiers requirements, the platform determines the winning provers, the winning verifiers, as well as the payment z_j^p charged from every winning prover and the payment z_i^w paid to each winning verifier (step 5).

The location verification process is then conducted among the winning provers and winning verifiers (step 6), and the location verification results are then reported to the platform from the verifiers (step 7). The platform verifies whether the location verification results are qualified (i.e., satisfy the precision and the number of verifiers requirements) and charges the payments from those provers who receive qualified location verification (step 8) and pays the rewards to the verifiers who conduct qualified location verification (step 9). Note that the payments are determined in auction yet charged/paid in steps 8 and 9, and those winning provers/verifiers who fail to give qualified location verification results will not get charged/paid.

B. Definition of Parameters and Attributes

Location Claim: The location claim that is reported to the platform is denoted as $LC_j = \ <l_j, Q_j, K_j>$, while the one that is broadcasted to nearby verifiers is denoted as $BC_j = \ <Q_j, K_j>$. The design that LC_j and BC_j are different is for preventing verifiers from falsifying the location verification results, the detailed explanation is in Section V-C. l_j stands for the location of p_j that needs to be verified. $Q_j \in [0, 1)$ represents the location verification precision requirement for a location claim, where a higher Q_j means a more precise location verification result is required (e.g., verify whether p_j is within a few square meters around l_j), whereas a lower Q_j means a more imprecise verification result. $Q_j = 0$ indicates that the verification result only shows whether p_j is within the WiFi transmission range around l_j. The choice of the Q_j value depends on specific scenarios (e.g., verify the presence in a small cafe, or a big supermarket). K_j stands for the number of verifiers requirement for LC_j, which should be at least 3 for multilateration. Multiple verifiers generally produce precise verification results [e.g., Fig. 1(a)]. Moreover, it reduces the chance for a malicious verifier to falsify the verification result [11], for example, we can easily detect the misbehavior for a malicious verifier if it verifies that a prover is around location A whereas other verifiers show that the prover is around location B.

Bids: Each prover p_j has a valuation v_j for its location to be verified, which is a private information that known only to the prover itself. The bid a_j is thus a declared valuation of p_j and could be different from the true valuation v_j. Similarly, for each verifier w_i, there is a corresponding private cost vector $\mathbf{c}_i = (c_{i1}, \ldots, c_{iN})$. c_{ij} represents the cost of performing location verification for p_j, and $c_{ij} = 0$ if w_i does not perform location verification for p_j. The bid vector $\mathbf{b}_i = (b_{i1}, \ldots, b_{iN})$ represents the declared cost of w_i. We assume that for the same verifier w_i, c_{ij} (resp. b_{ij}) is the same for verifying any location claims and, therefore, is equal to either 0 or c_i (resp. b_i). This is a reasonable assumption since for a WiFi AP (i.e., verifier), the costs for verifying different location claims are similar through WiFi communications.

Noting that in this article, we only consider the continuous cost for performing location verification. The one-time expenditure for implementing the WMLV system and the cost during the auction are ignored. This is a common assumption widely used in many auction works (e.g., [15]–[17]). This assumption is reasonable because, first, the one-time cost of implementation and the cost during the auction is not very large, as mentioned earlier (Section II-B and II-C); second, the one-time cost will decrease and vanish compared to the continuous cost during the verification.

Winners and Payments: We define a vector $\mathbf{S}_{\mathcal{P}} = (s_1^p, \ldots, s_N^p) \in \{0, 1\}^{1\times N}$ to represent whether the provers are winners, where $s_j^p = 1$ means that p_j is the winner and $s_j^p = 0$ otherwise. Similarly, a matrix $\mathbf{S}_{\mathcal{W}} = [s_{ij}^w] \in \{0, 1\}^{M\times N}$ is denoted for the verifiers, in which $s_{ij}^w = 1$ means that w_i is the winner for verifying p_j's location claim and $s_{ij}^w = 0$ otherwise. In addition, the reward for each verifier is denoted as $z_i^w = \sum_{j:s_{ij}^w=1} z_{ij}^w$, meaning that the payment $z_{ij}^w = 0$ if w_i loses for verifying p_j's location claim (i.e., $s_{ij}^w = 0$).

Utility: In the auction, the utility is typically defined as one's incoming minus its cost [17], [18], [29]. Therefore, we define the prover's and verifier's utility, as well as the platform's utility (a.k.a platform profit) in Definitions 1–3.

For a prover, its incoming is the benefit (e.g., coupons) it will get when its location claim is verified, its cost is the payment charged by the platform and will be later payed to the verifiers.

Definition 1 (Prover's Utility): A prover p_j's utility is defined as its valuation to its location claim v_j minus the payment charged from it z_j^p, if it is the winner; or its utility is 0 otherwise

$$u_j^p = \begin{cases} v_j - z_j^p, & \text{if } s_j^p = 1 \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

For a verifier, its incoming is the reward for performing location verification, while its cost is the energy and time cost for performing location verification. Because a verifier can verify location claims for multiple provers, the verifier's utility is thus as follows.

Definition 2 (Verifier's Utility): A verifier w_i's utility is defined as the overall rewards it receives minus the costs it generates through the location claim verifications, if it is the winner for verifying at least one prover; or its utility is 0 otherwise

$$u_i^w = \begin{cases} \sum_{j:s_{ij}^w=1}\left(z_{ij}^w - c_{ij}\right), & \text{if } \sum_{j:p_j\in\mathcal{P}} s_{ij}^w \geq 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $\sum j : p_j \in \mathcal{P} s_{ij}^w \geq 1$ means the verifier w_i is selected as a winner for verifying as least one prover.

The platform (auctioneer, here could be the location-based service provider), on the one hand, earns money by charging the payments from each winning prover. One the other hand, it costs money by paying rewards to each winning verifier. Therefore, its net revenue (utility) is defined as:

Definition 3 (Platform's Utility): The utility of the platform (auctioneer) is defined as the total payments charged from all the winning provers minus the overall rewards paid to all the winning verifiers

$$u_0 = \sum_{j:s_j^p=1} z_j^p - \sum_{i,j:s_{ij}^w=1} z_{ij}^w. \tag{3}$$

The platform's utility is also considered as the profit that a platform can earn during the auction, which is a widely adopted assumption. This definition is reasonable due to similar reasons as before. First, the one-time cost for implementing the auction algorithm is low (see Section II-C). Second, the one-time cost will vanish compared to the continuous profit earned during the auction. Therefore, if the platform's utility is guaranteed to be nonnegative (i.e., budget balance), the platform will always be profitable in the near future.

The social welfare of a system is usually defined as the sum of all the entities' utilities. Therefore, based on Definitions 1–3, we define the social welfare of the WMLV system in Definition 4.

Definition 4 (Social Welfare): The social welfare of the WMLV system is defined as the sum of the platform's utility, all verifiers' and provers' utilities

$$\begin{aligned} u_s &= u_0 + \sum_{j:p_j\in\mathcal{P}} u_j^p + \sum_{i:w_i\in\mathcal{W}} u_i^w \\ &= \sum_{j:s_j^p=1} v_j - \sum_{i,j:s_{ij}^w=1} c_{ij}. \end{aligned} \tag{4}$$

Noting that when prover p_j and verifier w_i report the true bid $a_j = v_j$ and $b_{ij} = c_{ij}$, the social welfare is also equal to

$$u_s = \sum_{j:s_j^p=1} a_j - \sum_{i,j:s_{ij}^w=1} b_{ij}. \tag{5}$$

C. Precision Model

The uniqueness of our system is that, in addition to the bids, the precision requirements should also be considered during the auction. The precision model should be meticulously designed, as there is a precision requirement Q_j for every prover p_j in the WMLV system. In real cases, an verification error $\Delta d_{ij} \in (0, R_t]$ will occur when a verifier w_i performs the location verification for a prover p_j. $\Delta d_{ij} = d'_{ij} - d_{ij}$ represents the difference between the measured distance (also known as distance bound) d'_{ij} and the real distance d_{ij} from prover to verifier. The error is produced mainly due to the message calculation delay during the message exchange, as mentioned in Section II-B. The error is larger than 0 since the WiFi signal is transmitted in the speed of light and, thus, the measured distance cannot be shorter than the real distance. The error cannot be larger than the WiFi transmission range R_t since the verifier has no chance to receive any messages beyond the transmission range. Here, we assume the WiFi transmission range to be uniform for simplicity.

Based on error Δd_{ij}, we model the location verification precision that a verifier w_i conducts for a prover p_j as $q_{ij} \in [0, 1)$, where

$$q_{ij} = 1 - \frac{\Delta d_{ij}}{R_t}. \tag{6}$$

Based on q_{ij}, the overall location verification precision $\bar{q}_j \in [0, 1)$ for a prover p_j is defined as the average precision among the verifiers who verify the location for prover p_j

$$\bar{q}_j = \frac{\sum_{i:w_i\in\mathcal{W}_j} q_{ij}}{\left|\mathcal{W}_j\right|} = 1 - \frac{\sum_{i:w_i\in\mathcal{W}_j} \Delta d_{ij}}{R_t \cdot \left|\mathcal{W}_j\right|} \tag{7}$$

TABLE I
MAJOR NOTATIONS

Notation	Description
p_j and w_i	Prover j and verifier i
LC_j and BC_j	Location claim sent to the platform and broadcasted to the verifiers
Q_j and K_j	Precision requirement and number of verifiers requirement of prover j
a_j and v_j	Declared and true valuation of prover j
$\mathbf{b}_i$ and $\mathbf{c}_i$	Declared and true cost vector of verifier i
z_j^p	Payment charged from prover j
z_i^w	Overall reward paid to verifier i
z_{ij}^w	Reward paid to verifier i for verifying prover j
$\mathbf{S}_{\mathcal{P}}$	Winning prover vector
$\mathbf{S}_{\mathcal{W}}$	Winning verifier matrix
q_{ij}	Estimated precision that a verifier i provides to a prover j
N and M	Number of provers and verifiers

in which $\mathcal{W}_j$ means the set of verifiers to verify the location for prover p_j.

Justifications of the Precision Model: Our defined precision model is reasonable because when each verifier verifies the location with a high precision (i.e., less distance error Δd_{ij}), the final precision should also be high. In addition, from (7), we can see that $\bar{q}_j$ is related to not only the number of verifiers but also which set of verifiers is chosen. This precision parameter should be thoughtfully considered in our auction mechanism design since only when $\bar{q}_j \geq Q_j$, could the verifiers in $\mathcal{W}_j$ have the chance to become the final winners of the auction.

The precision q_{ij} used in our auction is a predicted value, which is a similar setting as previous quality-aware auction mechanisms in other areas (e.g., [27]). However, different from the previous work, q_{ij} is estimated by the platform in our design. This is a more practical design since the platform manages the locations of all the WiFi APs and the provers, and can conduct more precise estimations. The major notations are summarized in Table I.

D. Desirable Economic Properties

There are several desirable economic properties that a nice auction should possess. Serving as the auctioneer, one significant functionality of the location verification platform is to determine prices that are fair to all provers and verifiers. A core concern about an auction is that some provers or verifiers may gain a higher utility by dishonest behavior, making the mechanism vulnerable to malicious price manipulation. We list the desirable economic properties in the following.

1) *Truthfulness:* An auction is truthful if for each buyer (resp. seller), it cannot increase its utility by bidding a value deviating from its true valuation (resp. cost), no matter what others bid.
2) *Individual Rationality:* An auction is individually rational if for each buyer (resp. seller), its utility is nonnegative when reporting its true valuation (resp. cost).
3) *Budget Balance:* An auction is budget balanced if by the end of the auction, the auctioneer's utility is nonnegative.
4) *Computational Efficiency:* An auction mechanism is computationally efficient if it can be executed within polynomial time.

The buyers in our article are the provers, while the verifiers act as sellers. We will design an auction mechanism that satisfies all of the above properties.

Among these four properties, truthfulness is the most significant property in the auction theory. Myerson proved in [23] that an auction is truthful if it satisfies *monotonicity* and charges each bidder the corresponding *critical value*. An auction is monotonic that for any buyer (resp. seller), if it wins the auction by bidding a value, it can still win the auction by bidding a higher (resp. lower) value. The critical value for a buyer (resp. seller) is the maximum (resp. minimum) value, such that the buyer (resp. seller) would lose the auction if it bids lower (resp. higher) than this value.

IV. Auction Design

In this section, we present the problem formulation of our auction, explain the details of the proposed auction mechanism, and describe the location verification results validation process.

A. Problem Formulation

The outcome of an auction heavily relies on its objective properties. In this work, we intend to design a double auction that maximizes the social welfare while guaranteeing the precision and number of verifiers requirements. In particular, we state the social welfare maximization (SWM) problem as follows:

$$\max \quad \sum_{j:p_j\in\mathcal{P}} a_j s_j^p - \sum_{i:w_i\in\mathcal{W},j:p_j\in\mathcal{P}} b_{ij} s_{ij}^w$$

$$\text{subject to:} \quad \frac{\sum_{i:w_i\in\mathcal{W}} q_{ij} s_{ij}^w}{\sum_{i:w_i\in\mathcal{W}} s_{ij}^w} \geq Q_j s_j^p \quad \forall j \in [1, N] \tag{8}$$

$$\sum_{i:w_i\in\mathcal{W}} s_{ij}^w \geq K_j s_j^p \quad \forall j \in [1, N] \tag{9}$$

$$s_{ij}^w \leq r_{ij} \quad \forall i \in [1, M] \quad \forall j \in [1, N] \tag{10}$$

$$s_{ij}^w, s_j^p \in \{0, 1\} \quad \forall i \in [1, M] \quad \forall j \in [1, N]. \tag{11}$$

The objective function aims to maximize the social welfare, which is exactly the social welfare defined in Definition 4. The constraints (8) and (9) represent, respectively, the precision requirement and the number of verifiers requirement must be satisfied for each winning prover. In constraint (10), we denote a reaching matrix $\mathbf{R} = [r_{ij}] \in \{0, 1\}^{M\times N}$, where r_{ij} represents whether a verifier w_i can reach a prover p_j and perform location verification for it

$$r_{ij} = \begin{cases} 1, & \text{if } 0 \leq d_{ij} \leq R_t \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

Constraint (10) thus specifies the condition that only a verifier w_i who chooses to prove the location claim for a prover p_j can be selected by that prover.

From the formulation above, we can see that the SWM problem is a nonlinear 0-1 programming problem, which is generally an NP-hard problem that takes exponentially long

Algorithm 1 DA-WMLV Winner Selection

Input:
$a_j, K_j, Q_j, b_i, q_{ij}, \mathcal{P}, \mathcal{W}, \mathbf{R}$;
Output:
$\mathbf{S}_{\mathcal{P}}, \mathbf{S}_{\mathcal{W}}, \bar{a}^*, b^*$;
1: **for** each $j : p_j \in \mathcal{P}$ **do**
2: $\quad \bar{a}_j \leftarrow a_j/K_j$;
3: **end for**
4: sort p_j and w_i from highest to lowest based on $\bar{a}_j$ and b_i, respectively;
5: **for** each $j : p_j \in \mathcal{P}$ **do**
6: $\quad \mathcal{T} \leftarrow \{(\bar{a}_j, b_i) | \bar{a}_j \geq b_i, \bar{a}_{j+1} < b_i\}$;
7: **end for**
8: **for** each $(\bar{a}_j, b_i) \in \mathcal{T}$ **do**
9: $\quad \mathbf{S}_{\mathcal{P}}^{\bar{a}_j} \leftarrow [s_{p_j}^{\bar{a}_j}] \in [0]^{1\times N}, \mathbf{S}_{\mathcal{W}}^{b_i} \leftarrow [s_{w_{ij}}^{b_i}] \in [0]^{M\times N}$
10: $\quad \mathcal{P}^{\bar{a}_j} \leftarrow$ provers with bids $> \bar{a}_j$;
11: $\quad \mathcal{W}^{b_i} \leftarrow$ verifiers with bids $< b_i$;
12: $\quad$ **for** each $p_j \in \mathcal{P}^{\bar{a}_j}$ **do**
13: $\quad\quad \mathcal{W}\simeq_{p_j} \leftarrow \{w_i | w_i \in \mathcal{W}^{b_i}$, w_i with the top K_j highest q_{ij}, w_i with $r_{ij} = 1\}$;
14: $\quad\quad$ **if** $|\mathcal{W}\simeq_{p_j}| = K_j$ and $\frac{\sum_{i:w_i\in\mathcal{W}\simeq_{p_j}} q_{ij}}{|\mathcal{W}\simeq_{p_j}|} \geq Q_j$ **then**
15: $\quad\quad\quad s_{p_j}^{\bar{a}_j} \leftarrow 1$;
16: $\quad\quad\quad$ **for** $i : w_i \in \mathcal{W}\simeq_{p_j}$ **do**
17: $\quad\quad\quad\quad s_{w_{ij}}^{b_i} \leftarrow 1$;
18: $\quad\quad\quad$ **end for**
19: $\quad\quad$ **end if**
20: $\quad$ **end for**
21: **end for**
22: $\mathbf{S}_{\mathcal{P}}, \mathbf{S}_{\mathcal{W}} \leftarrow \arg\max_{\mathbf{S}_{\mathcal{P}}^{\bar{a}_j}, \mathbf{S}_{\mathcal{W}}^{b_i}} (u_s)$;
23: $(\bar{a}^*, b^*) \leftarrow \arg\max_{(\bar{a}_j, b_i):\mathbf{S}_{\mathcal{P}}^{\bar{a}_j}, \mathbf{S}_{\mathcal{W}}^{b_i}} (u_s)$;
24: **return** $\mathbf{S}_{\mathcal{P}}, \mathbf{S}_{\mathcal{W}}, \bar{a}^*, b^*$;

time to solve [14]. Usually, solving a problem that takes exponentially long time is impractical and unreasonable for a real auction system, especially for a large-sized problem instance. Therefore, we propose to design a computational efficient double auction and aim to ensure nonnegative social welfare, instead.

B. Proposed Auction Mechanism

We present our double auction mechanism for WMLV (DA-WMLV) that is truthful, individually rational, budget-balanced, computationally efficient, and ensuring nonnegative social welfare. DA-WMLV consists of two phases: 1) *Winner Selection* and 2) *Payment Determination*, we will explain them in detail.

Winner Selection: In the winner selection phase (Algorithm 1), the algorithm first sorts the provers and verifiers from highest to lowest based on the unit bid $\bar{a}_j = a_j/K_j$ and the bidding price b_i, respectively, (lines 1–4). Even though each verifier has multiple b_{ij}, we choose one b_{ij} as the bid b_i since they are the same (mentioned in Section III-B). Next, it finds all bid pairs $(\bar{a}_j, b_i)$ that $\bar{a}_j \geq b_i$ and $\bar{a}_{j+1} < b_i$, all those bid pairs compose a set $\mathcal{T}$ (lines 5–7). Then, for each bid pair in $\mathcal{T}$, the algorithm puts all provers with unit bid $> \bar{a}_j$ into a set $\mathcal{P}^{\bar{a}_j}$ and puts all verifiers with bidding price $< b_i$ into set $\mathcal{W}^{b_i}$ (lines 8–11). For each prover in $\mathcal{P}^{\bar{a}_j}$, the algorithm chooses K_j verifiers who are in $\mathcal{W}^{b_i}$ and can verify its location claim with the top K_j verification precision (lines 12 and 13). If both the precision requirement and the requirement on the number of verifiers are satisfied for a prover p_j in $\mathcal{P}^{\bar{a}_j}$, the prover along with the selected verifiers are set to be the preparatory winners and the corresponding elements are set to be 1 in the preparatory winning prover vector $\mathbf{S}_{\mathcal{P}}^{\bar{a}_j}$ and the preparatory winning verifier matrix $\mathbf{S}_{\mathcal{W}}^{b_i}$ (lines 14–19). Finally, it chooses the winning provers and verifiers who achieve the highest social welfare as the final winners, the corresponding winning bid pair is denoted as $(\bar{a}^*, b^*)$ (lines 22 and 23).

Algorithm 2 DA-WMLV Payment Determination

Input:
$\mathbf{S}_{\mathcal{P}}, \mathbf{S}_{\mathcal{W}}, K_j, \bar{a}^*, b^*$;
Output:
z_j^p, z_i^w;
1: **for** each j:$s_j^p = 1$ **do**
2: $\quad z_j^p \leftarrow \bar{a}^* \cdot K_j$;
3: **end for**
4: **for** each i: $\sum_{j\,:\,p_j\in\mathcal{P}} s_{ij}^w \geq 1$ **do**
5: $\quad z_i^w \leftarrow \sum_{j:s_{ij}^w=1} b^*$;
6: **end for**
7: **return** z_j^p, z_i^w;

Payment Determination: Our payment determination (Algorithm 2) is inspired by the idea of the uniform pricing in auctions. After deciding the winning bid pair $(\bar{a}^*, b^*)$, the payment charged from each winning prover is determined as

$$z_j^p = \bar{a}^* \cdot K_j \tag{13}$$

and the reward paid to each winning verifier is denoted as

$$z_i^w = \sum_{j:s_{ij}^w=1} b^*. \tag{14}$$

C. Analysis of the DA-WMLV Mechanism

In this section, we prove several desirable properties of our DA-WMLV.

We first prove the truthfulness of DA-WMLV through Theorems 1–3.

Theorem 1: The proposed DA-WMLV is truthful for any prover p_j.

Proof: We prove this theorem by showing that DA-WMLV satisfies the proteries of monotonicity and critical value for any prover p_j.

1) *Monotonicity:* In Algorithm 1, provers are sorted based on their bids, and only the prover whose bid is larger than the winning bid can be the winner. Therefore, it is clear that if a prover p_j wins by bidding a_j, it will

also win the auction by bidding any $a'_j > a_j$. Thus, monotonicity is achieved.

2) *Critical Value:* Algorithm 2 in fact charges every winning prover the infimum of its bid, which can make it a winner. If its bid is lower than the value, it will lose. Therefore, critical value is achieved.

As proved in [23], these two properties make an auction truthful. Therefore, the proposed DA-WMLV is truthful for any prover p_j. ■

Theorem 2: The proposed DA-WMLV is truthful for any verifier w_i.

Proof: We prove this theorem by showing that, for any verifier w_i, DA-WMLV satisfies the proterties of monotonicity and critical value.

1) *Monotonicity:* Similar to Theorem 1, verifiers are sorted based on their bids in Algorithm 1, and only the verifier whose bid is lower than the winning bid can be the winner. Therefore, it is clear that if a verifier w_i wins by bidding b_{ij}, it will also win the auction by bidding any $b'_{ij} < b_{ij}$. Thus, monotonicity is achieved.

2) *Critical Value:* Similar to Theorem 1, Algorithm 2 pays every winning verifier the supremum of its bid, that can make it a winner. If its bid is larger than the value, it will lose. Therefore, critical value is achieved.

Combined with these two properties, the proposed DA-WMLV is truthful for any verifier w_i. ■

Theorem 3: The proposed DA-WMLV is truthful.

Proof: Combining Theorems 1 and 2, we can prove that our DA-WMLV is truthful for both provers and verifiers, i.e., each prover p_j maximizes its utility by bidding v_j, and each verifier w_i maximizes its utility by bidding c_{ij}. ■

We then prove other desirable properties that our mechanism can achieve in the following theorems.

Theorem 4: The proposed DA-WMLV is individual rational.

Proof: In DA-WMLV, according to Definitions 1 and 2, losers receive zero utilities. Moreover, only the provers (resp. verifiers) whose unit bids (resp. bids) are higher (resp. lower) than $\bar{a}^*$ (resp. b^*) have the chance to become winners, and charged (resp. paid) the payment according to (13) [resp. (14)]. Therefore, it is guaranteed that all provers and verifiers receive nonnegative utilities and, thus, the proposed DA-WMLV is individual rational. ■

Theorem 5: The proposed DA-WMLV is budget balanced.

Proof: According to the payment determination algorithm, the final payment charged for a winning prover p_j is $z_j^p = \bar{a}^* \cdot K_j$, and the reward paid to the corresponding winning verifiers in column j of the matrix $\mathbf{S}_{\mathcal{W}}$ is $b^* \cdot K_j$. Moreover, we have $\bar{a}^* \geq b^*$ according to the winner selection algorithm. Therefore, for all the winning provers and verifiers, the platform still receives nonnegative utility and, thus, the proposed DA-WMLV is budget-balanced. ■

Theorem 6: The proposed DA-WMLV is computational efficient, with the computational complexity of $min(O(N^2M), O(NM^2))$.

Proof: According to the winner selection algorithm, sorting the provers and verifiers takes at most $O(N^2) + O(M^2)$. Finding all bid pairs $(\bar{a}_j, b_i)$ takes $min(O(N), O(M))$. Selecting winning provers and verifiers in each bid pair $(\bar{a}_j, b_i)$ spends at most $O(MN)$. Deciding the final winners takes $min(O(N), O(M))$. The payment determination takes $O(N) + O(M)$. The overall computational complexity for DA-WMLV is thus $min(O(N^2M), O(NM^2))$. ■

Theorem 7: The proposed DA-WMLV guarantees nonnegative social welfare.

Proof: Based on Theorems 4 and 5, we know that each prover, each verifier and the platform all have nonnegative utilities. Combining the social welfare definition (Definition 4), it is clear that the social welfare of our proposed mechanism is ensured to be nonnegative. ■

D. WMLV Results Validation

The payment will be charged (resp. paid) from (resp. to) the winners who have qualified location verification results, as described in Section III-A. Specifically, the verifiers send the estimated distance d'_{ij} to the platform after the location verification. The platform then validates the results for each prover based on (7), such that if the actual final location verification precision $\tilde{q}_j$ satisfies the prover's precision requirement Q_j, the corresponding winning prover (resp. verifiers) will be charged (resp. paid).

Noting that, in our design, each verifier only receives the claim BC_j not containing the location information of the prover, as mentioned in Section III-B. This design is mainly for the falsification-resistant purpose. Because if a verifier knows the location of a prover, it is able to falsify the measured distance and report a fake location verification result to swindle out more reward.

V. Evaluation

In this section, we introduce the baseline methods, simulation settings, as well as simulation results of the performance evaluation about the proposed INTIMATION framework.

A. Baseline Methods

In our evaluation of the incentive mechanism, the first baseline method is an *SW-Max* approach, which solves the SWM problem in Section IV-A directly. Since directly solving the SWM problem cannot guarantee truthfulness among bidders, we therefore assume that the provers and verifiers are all truthful in the *SW-Max* mechanism, and hence the mechanism could *achieve the maximum social welfare*. However, although the *SW-Max* approach can achieve the maximum social welfare, solving it takes a long time. The results will be shown in Section V-C.

Since there is no relevant research on designing auctions for location verification systems, the second baseline method we choose is a relatively *Straightforward* auction mechanism. This straightforward mechanism achieves all the mentioned desirable properties in our paper except budget balance. During the winner selection, it first sorts the provers based on a weight $\text{weight}_j = (1/Q_j) \cdot (a_j/K_j)$, representing the amount of bid to pay when each witness provides unit precision. Then, for each prover p_j from the highest

TABLE II
PARAMETER SETTINGS

Setting	M	N	a_j	b_{ij}	K_j	Q_j	q_{ij}
1	[50, 130]	20	[30, 50]	[5, 10]	[4, 6]	[0.8, 0.95]	[0.8, 0.95]
2	90	[10, 30]	[30, 50]	[5, 10]	[4, 6]	[0.8, 0.95]	[0.8, 0.95]

weight to the lowest weight, the algorithm chooses K_j verifiers with the top K_j largest q_{ij}/b_i (the chosen verifiers compose a set $S'^{p_j}_{\mathcal{W}}$, the K_{j+1}th largest weight is denoted as $q_{K_{j+1}j}/b_{K_{j+1}}$). The prover p_j and the selected verifiers in $S'^{p_j}_{\mathcal{W}}$ are set to be winners if: 1) the Q_j requirement is satisfied; 2) there are no less than $K_j + 1$ optional verifiers; and 3) the social welfare for p_j is nonnegative (i.e., $a_j - \sum_{i:w_i \in S'^{p_j}_{\mathcal{W}}} b_i \geq 0$). Finally, the straightforward algorithm will delete the winning prover with the lowest weight ($weight_{lowest}$) along with its verifiers from the winner set. In payment determination, the expenditure for winning prover p_j is $weight_{lowest} \cdot (Q_j \cdot K_j)$, and the reward for winning verifier w_i is $[q_{ij}/(q_{K_{j+1}j}/b_{K_{j+1}})]$.

B. Simulation Settings

We conducted simulations based on different data sets. The main data set (data set I) we used for our performance evaluation is a UJIIndoorLoc data set that consists of WiFi AP locations covering three buildings (around $100,000m^2$) of Universitat Jaume I [3]. The two alternative data sets we used are a Tampere University data set (data set II) that contains WiFi AP locations covering one building (around 10 000 mx^2) [3], and a New York City WiFi AP data set [4] (data set III) (we sampled an area with 1 000 000 m^2 in this data set). Data set I and II are indoor data sets, whereas data set III is in outdoor setting.

The parameter settings in our simulation are given in Table II. Our parameter setting is similar to several related works [16], [27]. Also noting that the range of each parameter can be chosen differently from those used here. However, the results of using different reasonable setups are similar to the results shown in this article. Therefore, we only show the representative results for the above setup. Specifically, parameters a_j, b_{ij}, Q_j, and q_{ij} are sampled uniformly at random from the intervals given in Table II. K_j is an integer variable that uniformly distributed in the intervals given in Table II. In setting 1, we fix the number of provers as 20 and vary the number of verifiers from 50 to 130, whereas we fix the number of verifiers as 90 and change the number of provers from 10 to 30 in setting 2. In addition, the WiFi transmission range R_t is set to be 50-m indoors (i.e., data set I and II) and 100-m outdoors (i.e., data set III), for simulating the real case [5].

C. Simulation Results

Based on data set I, we evaluate the performance in terms of social welfare, platform utility, and running time of our proposed auction mechanism. In addition, we evaluate satisfactory rate of our INTIMATION framework. Finally, we conduct the same evaluations based on data sets II and III. The main simulation results are illustrated as follows.

TABLE III
WINNING RATE IN SETTING 1

# of verifiers	50	70	90	110	130
Winning rate	0.715	0.776	0.800	0.809	0.830

TABLE IV
WINNING RATE IN SETTING 2

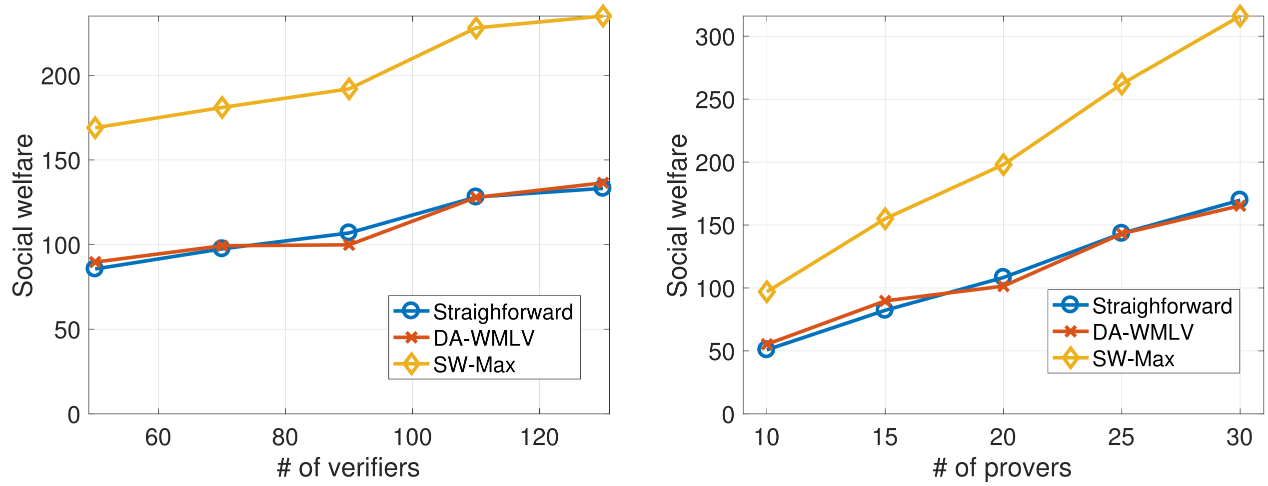
# of provers	10	15	20	25	30
Winning rate	0.819	0.797	0.800	0.778	0.777

Social Welfare: In Fig. 3(a) and (b), we compare the social welfare generated by our DA-WMLV with those of the two baseline methods in Settings 1 and 2, respectively. These two figures show that DA-WMLV generates similar social welfare compared to the Straightforward mechanism, and the social welfare is nonnegative for both of the two mechanisms. The *SW-Max* solution achieves maximum social welfare, yet it cannot guarantee truthfulness property and has huge computational overhead (will be illustrated later), and thus is an impractical method.

Platform Utility: We evaluate the platform utility of DA-WMLV by comparing it with the Straightforward method. The results are shown in Fig. 4(a) and (b). We can see that DA-WMLV always guarantees nonnegative platform utility and, thereby, it is budget-balanced. However, the Straightforward mechanism has no such a guarantee.

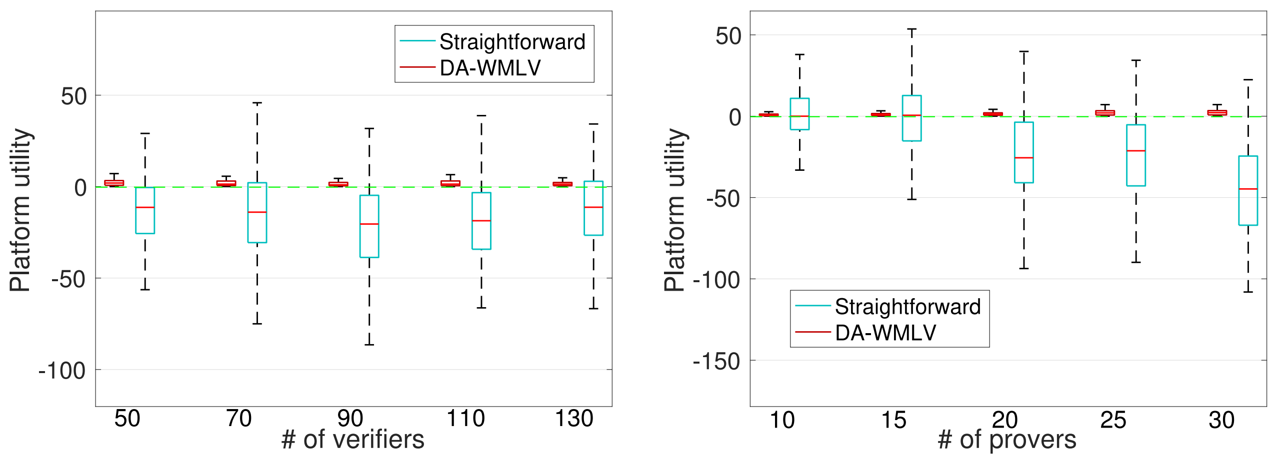
Winning Rate: We also evaluate the probability for the provers to be selected as winners. Results are shown in Tables III and IV. Under both settings, the winning rate is relatively high, meaning most of the provers can be selected as winners. More importantly, as widely assumed in existing auction-based works, the user's utility is 0 (meaning its gain and cost are both 0, see Section III-B) if it loses in the auction. This is because the time and energy costs are mainly generated when the winners perform the location verification *after* the auction. While the cost during the auction is usually considered as negligible. Therefore, even if a user is not selected as a winner, its cost is negligible since it will not perform the location verification.

Running Time: Next, we compare the running time of DA-WMLV with the *SW-Max* method. The results illustrated in Fig. 5(a) and (b) show that solving the *SW-Max* requires exponentially long time, as mentioned in Sections IV-A and V-A. Therefore, even though the *SW-Max* approach can achieve the optimal social welfare, it is not scalable in practice. Whereas, DA-WMLV is executed in polynomial time and the running time of DA-WMLV is 4 orders of magnitude less than that of *SW-Max* on average, which shows that DA-WMLV is scalable and practical.



(a) (b)

Fig. 3. Social welfare in data set I. (a) Setting 1. (b) Setting 2.



(a) (b)

Fig. 4. Platform utility in data set I. (a) Setting 1. (b) Setting 2.

Satisfactory Rate: During the auction, the precision provided by each verifier q_{ij} is predicted by the platform. However, it may not be the same with the actual precision $\tilde{q}_{ij}$ conducted by each verifier during the location verification. Therefore, we evaluate the satisfactory rate Pr for INTIMATION, representing the number of real satisfactory provers during the location verification divided by the number of winning provers in the auction.

In this evaluation, we assume that the actual precision $\tilde{q}_{ij}$ obeys normal distribution $N(q_{ij}, \sigma^2)$, and we change σ from 0.01 to 0.05 to see the satisfactory rate results. M and N are fixed as 90 and 20, respectively.

The results are shown in Table V, from which we can see that most of the satisfactory rate is higher than 0.9, and even when $\sigma = 0.05$, the satisfactory rate is still high. Note that $\sigma = 0.05$ means more than 99.7% estimated precision results deviate less than 0.15 precision value from the actual precision, which is a reasonable scenario. The satisfactory rate decreases with the increasing variance since that with the variance increasing, the platform prediction accuracy decreases, leading to a decreasing satisfactory rate.

TABLE V
SATISFACTORY RATE

σ	0.01	0.02	0.03	0.04	0.05
Pr	0.976	0.946	0.932	0.917	0.893

Evaluations on Alternative Data Sets: We also conducted simulations on data sets II and III, and only show the results of social welfare and platform utility due to the space limitation. From the results in Figs. 6 and 7, we can observe that DA-WMLV conducts similar performance no matter how the data set changes. This represents that DA-WMLV is insensitive to data set changing and can be applied in various scenarios (e.g., both indoor and outdoor, both broad area and narrow area).

VI. RELATED WORK

With the development of wireless communication technology such as WiFi, researchers has proposed many WiFi-based location verification frameworks. Saroiu and Wolman [25] proposed a location verification mechanism, where users and wireless APs exchange their signed public keys to create location proofs. VeriPlace [20] is a

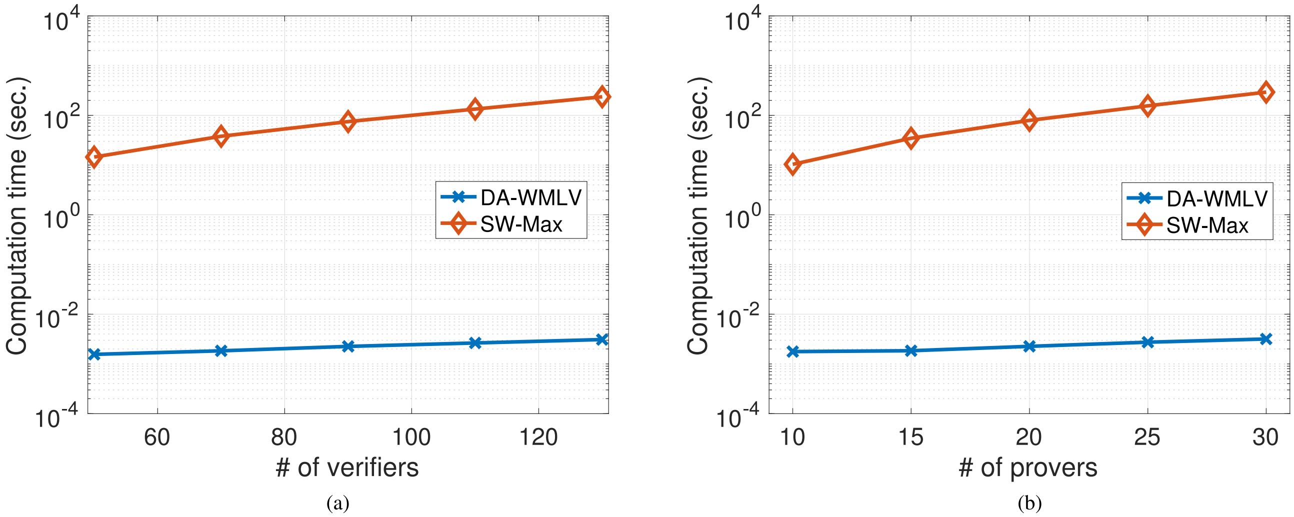


Fig. 5. Running time in data set I. (a) Setting 1. (b) Setting 2.

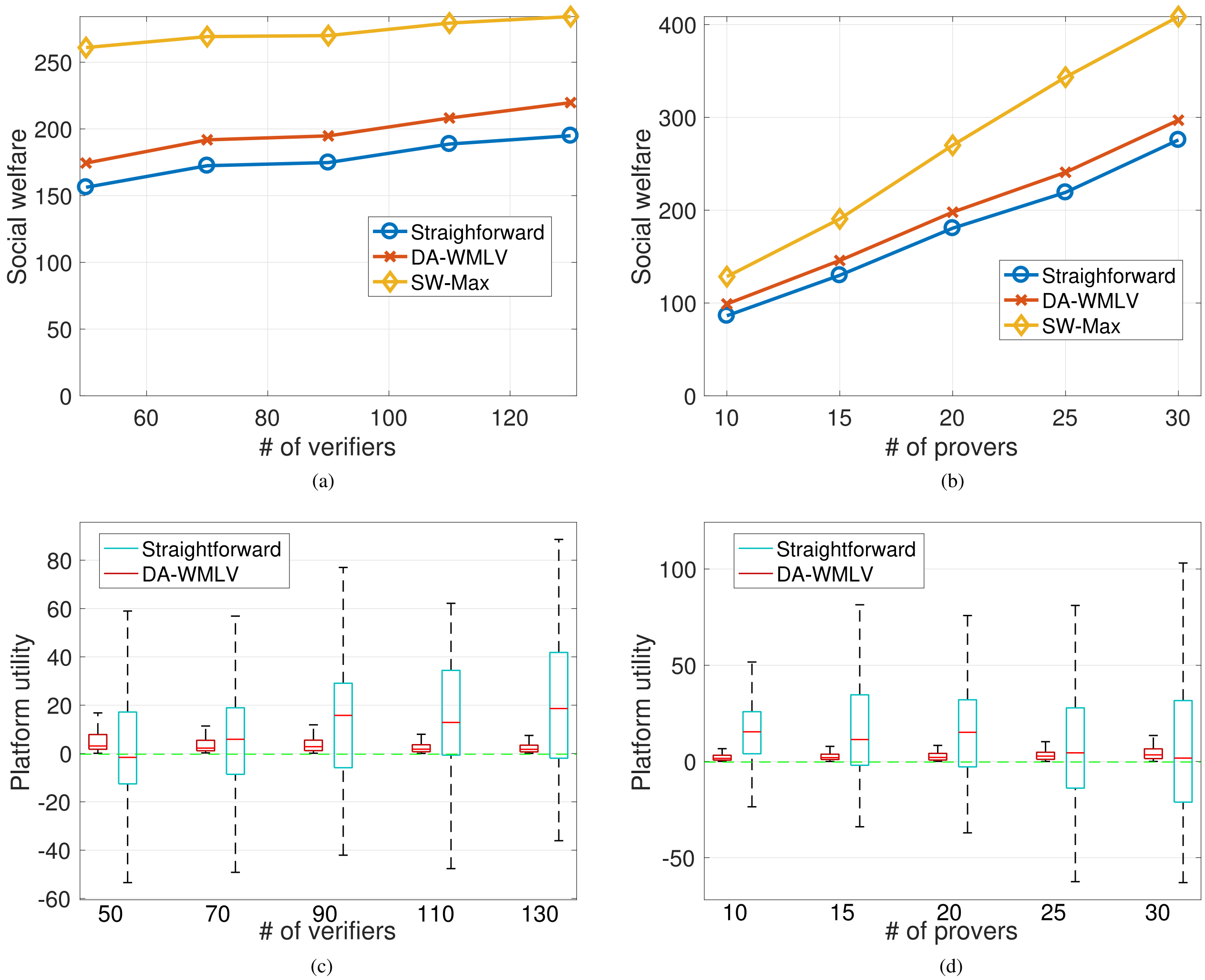


Fig. 6. Performance evaluation in data set II. (a) Social welfare in Setting 1. (b) Social welfare in Setting 2. (c) Platform utility in Setting 1. (d) Platform utility in Setting 2.

location verification architecture in which wireless APs and other three different trusted entities together verify location claims in a privacy-preserving way. Hasan and Burns [13] proposed a scheme which relies on both location proofs from wireless APs and witness endorsements from Bluetooth-enabled mobile peers. In STAMP [28], the verifiers

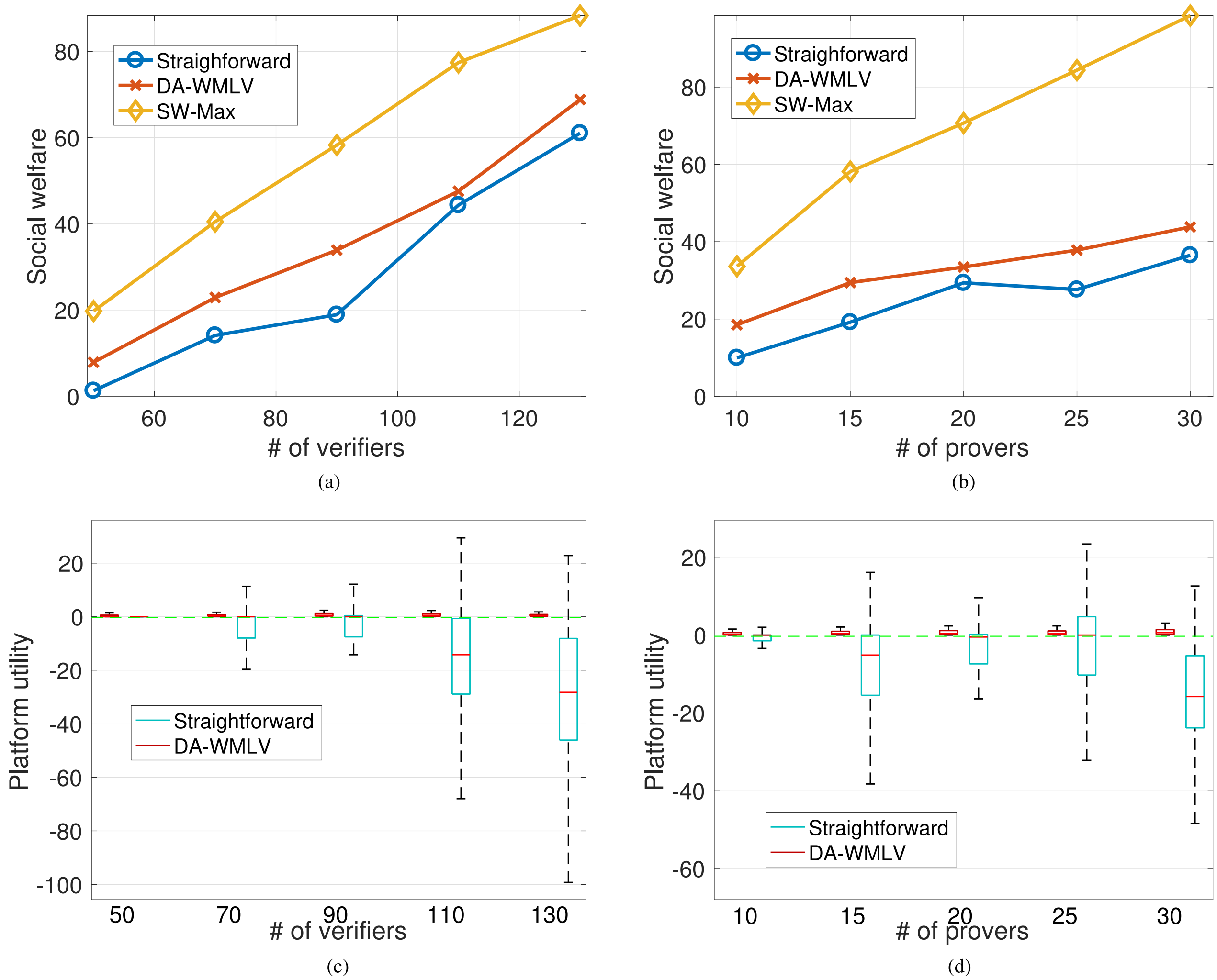


Fig. 7. Performance evaluation in data set III. (a) Social welfare in Setting 1. (b) Social welfare in Setting 2. (c) Platform utility in Setting 1. (d) Platform utility in Setting 2.

could be either mobile devices or WiFi APs, they interact with provers, a server, and a CA to generate location proofs.

Multilateration can be used to precisely verify a location claim. Quite a few researchers have studied the multilateration algorithm, such as [10], [11], and [26] whereas their concerns are generally at security issues. Most of the aforementioned works in the above two paragraphs either implicitly or explicitly adopt multilateration in their systems. However, the previous WMLV frameworks mainly focus on the location verification mechanism design, yet none of them considers incentive mechanism upon location verification.

The incentive mechanism has been exploited in widespread applications and systems (e.g., [29], [35]–[37]). A table of several incentive mechanisms in various scenarios are listed in Table VI. However, only few existing research has explored to exploit incentive mechanism in location verification systems. For example, Nosouhi *et al.* [24] proposed to reward verifiers in their location verification system. Nonetheless, there is no formal design, analysis, or evaluation of their incentive mechanism. Auction is a useful incentive mechanism which has elegant economic properties, and is easy to implement and play. Some of the previous auction-based research focused on single-sided auction (e.g., [18], [27], [38]), where either sellers or buyers submit their bids to the auctioneer and wait the auctioneer clear the market. Different from single-sided auction, double-sided auction (or double auction) is a bilateral trade in which potential buyers submit their bids and potential sellers simultaneously submit their ask prices to an auctioneer. There are also many studies on double auction (e.g., [15]–[17]). However, none of the existing auction schemes can be applied in our WMLV case. The reason is that, in classical auction schemes, only the bid decides who can be selected as winners. However, in the auction for WMLV, the precision and the number of verifiers requirements are two extra essential attributes that should be considered for selecting each winner. Therefore, our auction mechanism design is different from the others. Moreover, when considering extra requirements, it is even challenging to design an auction scheme with nice economic properties including truthfulness, individual rationality, computational efficiency, budget balance, and nonnegative social welfare.

TABLE VI
SEVERAL INCENTIVE MECHANISMS IN RELATED APPLICATIONS

Related works	Incentive mechanisms	Applications	Advantages	Disadvantages
Z. Zhou et al. [35]	Single auction	Mobile crowdsensing	Incentivize mobile users (sellers) to participate	Fail to incentivize buyers, no quality consideration
J. Lin et al. [18]	Single auction	Crowdsending	Incentivize mobile users (sellers) to participate, Sybil-proof	Fail to incentivize buyers, no quality consideration, not budget balanced
J. Wang et al. [27]	Single auction	Mobile crowdsensing	Incentivize mobile users (sellers) to participate, quality-aware	Fail to incentivize buyers, not budget balanced
R. Zhu et al. [38]	Single auction	Spectrum re-allocation	Incentivize buyers to participate, privacy-preserving	Fail to incentivize sellers, no quality consideration
B. Jedari et al. [15]	Double auction	Cache trading	Incentivize both sellers and buyers	No quality consideration
H. Jin et al. [16]	Double auction	Mobile crowdsensing	Incentivize both sellers and buyers	No quality consideration, not budget balanced
W. Jin et al. [17]	Double auction	Mobile crowdsensing	Incentivize both sellers and buyers, privacy-preserving	No quality consideration
Z. Zhou et al. [36]	Contract	Vehicular for computing	Incentivize sellers to participate	No quality consideration, complex scheme
M. R. Myerson et al. [24]	Not explained explicitly	Location verification	Incentivize verifiers to participate	Fail to incentivize provers, no quality consideration

In this article, we choose to use double auction since provers and verifiers are both independent individuals and each has its own valuation which platform does not know. Moreover, double auction incentivizes both provers and verifiers to join in the location verification, which is more reasonable than just stimulate the participation of only one side.

VII. Discussion on Location Privacy

In this section, we mainly discuss the users' location privacy in our system. We will explain that, our system can protect user privacy in normal cases and does not bring additional privacy risks.

First, as mentioned before (Section IV-D), each verifier is unknown to the location of any prover. Specifically, each verifier only receives the claim not containing the location information of the prover. This prevents the location privacy leakage from the prover to the verifier.

Second, each prover does not know the specific location of any verifier, as verifiers do not need to report their locations to anyone. However, as location verification is based on WiFi communication, the prover will inevitably know that there are verifiers around it. This is also a fact faced by most of the existing work on WiFi-based localization or location verification. In addition, we can protect the privacy of the prover and verifier through anonymization or encryption methods.

Third, the location reported to the platform can be protected via cryptographic approaches (e.g., differential privacy [12], homomorphic encryption [33], etc.). Hence, the platform will not know about the location of the provers. Actually, there are some related works on protecting user privacy in location verification. Our work, as an incentive layer, can be built on top of the existing privacy-preserving WMLV work. Our system thus does not introduce additional privacy risks during location verification.

Finally, the user privacy can be protected from the external attackers. To protect the information from being exploited by external attackers, we can also encrypt the information during the information transmission process to protect user privacy. Additionally, the users who want to participate in the system can be certificated by Certificate Authority. When participating in the system, the certificate of each user will be first checked to prevent external attacks.

VIII. Conclusion

In this article, we studied incentive mechanism design for WMLV. We taken the practical precision requirement and the number of verifiers requirement into consideration, and considered the co-existence of multiple provers and verifiers in the system. Based on those practical concerns, we formally defined the precision model in WMLV and designed a double auction-based incentive mechanism, which incentivizes both the participation of provers and verifiers. In addition, the auction mechanism satisfies nice economic properties of truthfulness, individual rationality, computational efficiency, nonnegative platform profit, as well as nonnegative social welfare. We rigorously proved the desired properties of the proposed mechanisms and validated them through extensive simulations based on different data sets.

References

[1] *What's Important in Budgeting A Wireless Network Project?*. Accessed: 2020. [Online]. Available: https://www.asd-usa.com/wireless-networks/project-budget/
[2] *Wi-Fi for Your Customers*. Accessed: 2020. [Online]. Available: http://www2.bain.com/wifi-interactive/default.asp
[3] *AmbiLoc*. Accessed: 2020. [Online]. Available: http://indoorlocplatform.uji.es/databases/all/
[4] *There Are 95 WiFi Datasets Available on Data.World*. Accessed: 2020. [Online]. Available: https://data.world/datasets/wifi
[5] (2020). *What Is the Range of a Typical Wi-Fi Network?*. [Online]. Available: https://www.lifewire.com/range-of-typical-wifi-network-816564
[6] *Foursquare*. Accessed: 2020. [Online]. Available: https://foursquare.com
[7] *Pokémon Go*. Accessed: 2020. [Online]. Available: https://pokemongolive.com
[8] *Uber*. Accessed: 2020. [Online]. Available: https://www.uber.com
[9] *Yelp*. Accessed: 2020. [Online]. Available: https://www.yelp.com
[10] S. Capkun and J.-P. Hubaux, "Secure positioning of wireless devices with application to sensor networks," in *Proc. IEEE 24th Annu. Joint Conf. Comput. Commun. Soc.*, Miami, FL, USA, 2005, pp. 1917–1928.
[11] J. T. Chiang, J. J. Haas, and Y.-C. Hu, "Secure and precise location verification using distance bounding and simultaneous multilateration," in *Proc. 2nd ACM Conf. Wireless Netw. Security*, 2009, pp. 181–192.

[12] C. Dwork, "Differential privacy: A survey of results," in *Proc. Int. Conf. Theory Appl. Models Comput.*, 2008, pp. 1–19.

[13] R. Hasan and R. C. Burns, "Where have you been? secure location provenance for mobile devices," 2011. [Online]. Available: arXiv:1107.1821.

[14] D. S. Hochba, "Approximation algorithms for NP-Hard problems," *ACM SIGACT News*, vol. 28, no. 2, pp. 40–52, 1997.

[15] B. Jedari and M. Di Francesco, "Auction-based cache trading for scalable videos in multi-provider heterogeneous networks," in *Proc. IEEE INFOCOM Conf. Comput. Commun.*, Paris, France, 2019, pp. 1864–1872.

[16] H. Jin, L. Su, and K. Nahrstedt, "CENTURION: Incentivizing multi-requester mobile crowd sensing," in *Proc. IEEE INFOCOM Conf. Comput. Commun.*, Atlanta, GA, USA, 2017, pp. 1–9.

[17] W. Jin, M. Li, L. Guoy, and L. Yang, "DPDA: A differentially private double auction scheme for mobile crowd sensing," in *Proc. IEEE Conf. Commun. Netw. Security (CNS)*, Beijing, China, 2018, pp. 1–9.

[18] J. Lin, M. Li, D. Yang, G. Xue, and J. Tang, "Sybil-proof incentive mechanisms for crowdsensing," in *Proc. IEEE INFOCOM Conf. Comput. Commun.*, Atlanta, GA, USA, 2017, pp. 1–9.

[19] X. Lin and W. He, "WiLoVe: A WiFi-coverage based location verification system in LBS," *Procedia Comput. Sci.*, vol. 34, pp. 484–491, 2014.

[20] W. Luo and U. Hengartner, "VeriPlace: A privacy-aware location proof architecture," in *Proc. 18th SIGSPATIAL Int. Conf. Adv. Geograph. Inf. Syst.*, 2010, pp. 23–32.

[21] F. Malandrino, C. Borgiattino, C. Casetti, C.-F. Chiasserini, M. Fiore, and R. Sadao, "Verification and inference of positions in vehicular networks through anonymous beaconing," *IEEE Trans. Mobile Comput.*, vol. 13, no. 10, pp. 2415–2428, Oct. 2014.

[22] R. P. McAfee, "A dominant strategy double auction," *J. Econ. Theory*, vol. 56, no. 2, pp. 434–450, 1992.

[23] R. B. Myerson, "Optimal auction design," *Math. Oper. Res.*, vol. 6, no. 1, pp. 58–73, 1981.

[24] M. R. Nosouhi, S. Yu, W. Zhou, M. Grobler, and H. Keshtiar, "Blockchain for secure location verification," *J. Parallel Distrib. Comput.*, vol. 136, pp. 40–51, Feb. 2020.

[25] S. Saroiu and A. Wolman, "Enabling new mobile applications with location proofs," in *Proc. 10th Workshop Mobile Comput. Syst. Appl.*, 2009, p. 3.

[26] N. Sastry, U. Shankar, and D. Wagner, "Secure verification of location claims," in *Proc. 2nd ACM Workshop Wireless Security*, 2003, pp. 1–10.

[27] J. Wang, J. Tang, D. Yang, E. Wang, and G. Xue, "Quality-aware and fine-grained incentive mechanisms for mobile crowdsensing," in *Proc. IEEE 36th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Nara, Japan, 2016, pp. 354–363.

[28] X. Wang, A. Pande, J. Zhu, and P. Mohapatra, "STAMP: Enabling privacy-preserving location proofs for mobile users," *IEEE/ACM Trans. Netw.*, vol. 24, no. 6, pp. 3276–3289, Dec. 2016.

[29] C. Wu, Z. Wei, F. Wu, G. Chen, and S. Tang, "Designing differentially private spectrum auction mechanisms," *Wireless Netw.*, vol. 22, no. 1, pp. 105–117, 2016.

[30] D. Wu, D. Zhu, Y. Liu, and D. Zhao, "Location verification assisted by a moving obstacle for wireless sensor networks," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 322–335, Feb. 2018.

[31] S. Yan, R. Malaney, I. Nevat, and G. W. Peters, "Location verification systems for VANETs in Rician fading channels," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5652–5664, Jul. 2016.

[32] S. Yan, G. W. Peters, I. Nevat, and R. Malaney, "Location verification systems based on received signal strength with unknown transmit power," *IEEE Commun. Lett.*, vol. 22, no. 3, pp. 650–653, Mar. 2018.

[33] L. Zhang, Y. Zheng, and R. Kantoa, "A review of homomorphic encryption and its applications," in *Proc. 9th EAI Int. Conf. Mobile Multimedia Commun.*, 2016, pp. 97–106.

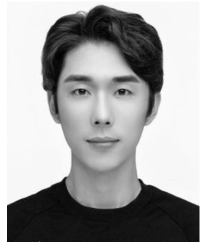
[34] Z. Zhang *et al.*, "On the validity of geosocial mobility traces," in *Proc. 12th ACM Workshop Hot Topics Netw.*, 2013, pp. 1–7.

[35] Z. Zhou, H. Liao, B. Gu, K. M. S. Huq, S. Mumtaz, and J. Rodriguez, "Robust mobile crowd sensing: When deep learning meets edge computing," *IEEE Netw.*, vol. 32, no. 4, pp. 54–60, Jul./Aug. 2018.

[36] Z. Zhou, H. Liao, X. Zhao, B. Ai, and M. Guizani, "Reliable task offloading for vehicular fog computing under information asymmetry and information uncertainty," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 8322–8335, Sep. 2019.

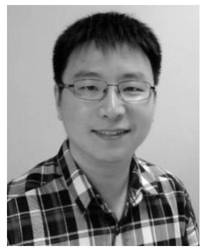
[37] R. Zhu, Z. Li, F. Wu, K. Shin, and G. Chen, "Differentially private spectrum auction with approximate revenue maximization," in *Proc. 15th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2014, pp. 185–194.

[38] R. Zhu and K. G. Shin, "Differentially private and strategy-proof spectrum auction with approximate revenue maximization," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, Hong Kong, 2015, pp. 918–926.



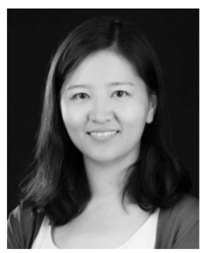
Mingzhe Li (Student Member, IEEE) received the B.E. degree in communication engineering from the Southern University of Science and Technology, Shenzhen, China, in 2016. He is currently pursuing the Ph.D. degree with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Hong Kong, and Southern University of Science and Technology.

His research interests are mainly in blockchain, network economics, and wireless communication, and networks.



Wei Wang (Member, IEEE) received the B.Eng. and M.Sc. degrees from Shanghai Jiao Tong University, Shanghai, China, in 2007 and 2010, respectively. and the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada, in 2015.

He is currently an Assistant Professor with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Hong Kong. He is also affiliated with HKUST Big Data Institute. His research interests cover the broad area of networking and distributed systems, with a special focus on big data and machine learning systems, cloud computing, and computer networks.



Jin Zhang (Member, IEEE) received the B.E. and M.E. degrees in electronic engineering from Tsinghua University, Beijing, China, in 2004 and 2006, respectively, and the Ph.D. degree in computer science from Hong Kong University of Science and Technology, Hong Kong, in 2009.

She is currently an Assistant Professor with the Department of Computer Science and Engineering, Southern University of Science and Technology, Shenzhen, China. Her research interests are mainly in mobile healthcare and wearable computing, wireless communication and networks, network economics, cognitive radio networks, and dynamic spectrum management.

Qian Zhang (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in computer science from Wuhan University, Wuhan, China, in 1994, 1996, and 1999, respectively.

She is currently a Tencent Professor of Engineering and the Chair Professor with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology (HKUST), Hong Kong, where she is also serving as the Co-Director of Huawei-HKUST innovation lab and the Director with the Digital Life Research Center. Before that, she was with Microsoft Research Asia, Beijing, China, where she was the Research Manager with the Wireless and Networking Group. She has published more than 400 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, wireless sensor networks, and overlay networking. She is the inventor of more than 50 granted international patents. Her current research interests include Internet of Things, smart health, mobile computing and sensing, wireless networking, as well as cybersecurity.

Dr. Zhang is currently serving as the Editor-in-Chief for the IEEE TRANSACTIONS ON MOBILE COMPUTING. She was a Members-at-Large of the IEEE Communications Society from 2016 to 2018. She is a Fellow of the Hong Kong Academy of Engineering Science.