Privacy-preserving Proof-of-Location With Security Against Geo-tampering

Mamunur Akand, Reihaneh Safavi-Naini, Marc Kneppers, Matthieu Giraud, and Pascal Lafourcade

Abstract—A Proof-of-Location (POL) system is used to issue a proof-of-location token (pol) to a user who has been present at a location ℓoc, such that it can be later presented to a verifier to assure the presence of the user at ℓoc. Basic POL security requirements are *unforgeability* of pol, and its *non-transferability* (a pol issued to user u_1 cannot be used by u_2). An additional important property of POL systems is *user privacy* against the issuers and verifiers. We make two contributions. First, we formalize the POL security and privacy properties, and construct the first system providing provable security and privacy against the issuer and the verifier, both. Second, we introduce a *geo-tampering attack* that completely breaks POL system security, by simply changing the location of a pol issuing node. The attack applies to portable infrastructure nodes that are not continually monitored. We propose an algorithm that is used by a pol issuer to provide a location integrity "proof", that will be embedded in a pol to protect against this attack. The proof relies on a novel application of Euclidean Distance Matrices. We implemented our POL on an off-the-shelf Android smartphone to show the practicality of the proposed algorithms.

Index Terms—Proof-of-Location, Distance bounding, Geo-tampering.

1 Introduction

A Proof-of-Location (POL) system issues *proof-of-location tokens* that can be carried by the user and later presented to, and verified by, the verifiers. POL systems [1], [2], [3] rely on a *trusted location infrastructure* that reliably determines the location of the claimant, using a set of *location infrastructure nodes* that cover the area of interest, and issue a proof-of-location token, pol, to a user who has "proved" their presence at a claimed location ℓoc. The issued token can be later used to prove to a (trusted) *verifier* that the user has been at ℓoc. A pol can be seen as a credential that can be used together with other credentials of the user to provide refined access control [4], [5] and supply chain management [6].

A pol can be with respect to a specific *geo-coordinate* that is obtained from a Global Positioning System (GPS), or act as a certification for the *proximity* of the prover to the *issuer*, which has a known (to the infrastructure) location. POL systems usually use the latter approach because of the unavailability and unreliability of GPS signals indoors, as well as a range of known attacks on the GPS systems [7], [8][1].

The only known method of verifying closeness to the issuer with provable cryptographic security, is by using Distance Bounding (DB) protocols [9], [10], [11] that use well designed challenge-and-responses to allow the (untrusted) prover to prove their proximity (being within a distance bound B) to a (trusted) verifier. Systems that use Radio Signal Strength [12] or Time of Flight [13], [14] for estimating proximity are not reliable and allow the distance to be shortened [15].

State of DB-based POL systems. We focus on POL systems that use DB protocols [16], [17], [18]. Such systems must provably provide a number of security properties including unforgeability, non-transferability and privacy. Existing POL systems however have two major limitations. Firstly, there is no known protocol that provides privacy in the sense that the pol issuer and pol verifier cannot learn the identity of the user, or be able to link multiple pols and trace the user. To generate a pol, the issuer (i) uses a DB protocol to verify a user u's position with respect to issuer's location that is assumed known and trusted, and (ii) digitally signs this location information. To provide non-transferability, the prover's identity must be included in the pol. This however results in full traceability of a user, both while interacting with the pol issuer and also while presenting the pol to a verifier. The only POL system that considers user privacy against the issuer and the verifier is due to Gambs et al. [17]. This POL uses a public key DB protocol [19] that does not provide adequate security level for POL applications. More specifically, secure DB protocols must protect against three main attacks, distance fraud, Mafia fraud and Terrorist fraud [10]. Although in some applications some of these properties can be tolerated, for secure POL systems, all these properties are required. The protocol in [19] was shown to be insecure against distance fraud and terrorist fraud attack [20], which renders the POL system in [17], insecure. It is worth noting that the construction of this POL system is not modular, and critically depends on the structure of its underlying DB protocol. Thus, *there is no known construction of private POL system.* A second important limitation of the works in this area is that security of POL systems is only argued informally. POL systems can be seen as anonymous credential systems that require formal cryptographic model

- *M. Akand and R. Safavi-Naini are with University of Calgary, Canada. E-mail: {mdmamunurrashid.akan, rei} @ucalgary.ca*
- *M. Kneppers is with Telus Communications, Canada. E-mail: marc.kneppers @telus.com*
- *M. Giraud and P. Lafourcade are with University Clermont Auvergne, France. E-mail: {matthieu.giraud, pascal.lafourcade} @uca.fr*

1. One can always consider a combination of the two to improve accuracy if reliable GPS signal is available

and analysis similar to other credential systems such as [21], [22], [23]. A formal model and analysis will form the foundation of essential properties such as ensuring that *pol* issuing infrastructure has not been tampered with, that we consider in this paper, as well as new properties such as combining multiple credentials to achieve high level properties.

Our contribution.

Our goal in this paper is to lay a solid foundation for design and analysis of POL systems, and design a secure POL system with provable security using a trusted location infrastructure. We then relax the trust assumption on the *the location of infrastructure nodes* and consider the case that some of the infrastructure nodes are *displaced by the attacker*. Such a physical displacement is a real threat for small and unprotected infrastructure nodes, and as will be shown in Section 4 can completely compromise security of the system. We show how such an attack can be efficiently detected, and extend POL systems to provide security in this extended model. In the following we outline our contributions that are to, *(i)* formalize security and privacy of POL systems, and construct a POL system that provably achieves these properties, assuming an infrastructure that has assured location for the infrastructure nodes; *(ii)* define geo-tampering attack and show its devastating effect on the security of POL systems and propose an efficient and effective approach to providing "proof" of infrastructure integrity, and show that the *pol* can be extended to include this extra infrastructure integrity information, while maintaining its provable security guarantee; and *(iii)* implement our cryptographic algorithm and infrastructure integrity generation algorithms, to show feasibility of our solution in practice. More details below.

(i) Security model and construction. We use a game-based approach to define two security properties, *unforgeability* and *non-transferability*, and an indistinguishability based approach to define *user full anonymity* in its interaction with the issuer and the verifier. We assume there is an identity issuer that stores sufficient amount of secret information that can be used to "open" transcripts of the user's interactions with the issuer and the verifier, if needed, and hence providing the required accountability.

The POL construction requires a DB protocol that (a) provides anonymity for the (DB) prover against the (DB) verifier, and (b) includes sufficient information in the DB protocol transcript that can be used in the *pol* to make it non-transferable. We construct such a DB, use it to construct a POL, and prove its security and privacy in our proposed model. To our knowledge none of the existing anonymous DB protocols [24], [25], [26], [27] satisfy both properties simultaneously.

(ii) Geo-tampering attacks and protection. In geo-tampering attack the hardware and the software of the access point will remain untouched, and all cryptographic protocols are run flawlessly[2]. The attacker however physically moves one or more access points. Figure 1 is an illustration of the attack:

2. Modern WiFi access points come with built-in encryption scheme such as WPA/WPA2 and are considered secure if a strong enough password or paraphrase is used. Therefore, attacker's ability to move the AP does not necessarily mean that they can break into the AP.

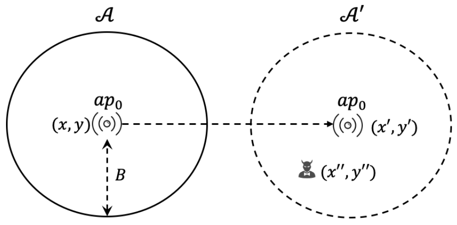


Fig. 1. A *geo-tampering* attacker moves ap_0 from (x, y) to (x', y'). This enables the attacker located at (x'', y'') in $\mathcal{A}'$ to claim locations in $\mathcal{A}$.

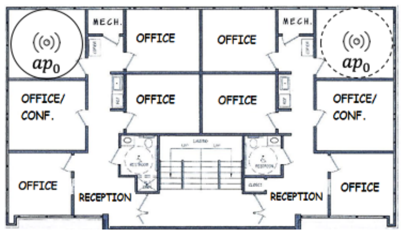


Fig. 2. ap_0 in the office on the top left is moved to the office on the top right. Alice can obtain a proof of being in the former office, while being in the latter.

the attacker moves ap_0 to a geo-coordinate (x', y'). This results in the set of "close-by" points $\mathcal{A}$ to be replaced by $\mathcal{A}'$, allowing the attacker (located at (x'', y'') to claim a location in $\mathcal{A}$. The attack is feasible because of the prevalence of small access points that are increasingly used as infrastructure nodes. The attack can stay undetected until, for example, when a *proof-of-location (pol)* issued to an honest user is not verified as expected. Fig. 2 shows an example of this attack in a typical setting, where an employee can obtain a proof-of-location without being in their designated office.

To detect the attack, an infrastructure node must perform a real-time integrity checking algorithm to provide verifiable information about its location. We sometimes informally refer to this information as "proof" of infrastructure integrity. In Section 4 we show that generating such information naively, for example by using trilateration, requires introduction of many additional infrastructure nodes. We then propose a novel method of achieving location integrity information by using geo-location of "neighboring" nodes, that are reachable from *pol* issuing node through (possibly) multiple hops. We construct an initial Euclidean Distance Matrix (EDM) (see Section 4.1) that records the pairwise physical (point-to-point straight line) distances among the nodes in the infrastructure. This matrix is then used to verify the "proof of integrity" of a *pol* issuing node, by comparing the real-time measured pairwise distances of neighbor nodes of the *pol* issuer, with the corresponding recorded values. The effectiveness of the approach is due to the fact that *all* physical distances between nodes in the neighbourhood are used, while trilateration based approaches rely on the distances of the neighbouring nodes to the issuing node, only.

(iii) Implementation and experiments.

a. Implementation. We give a proof-of-concept implementation of our proposed POL system using the Idemix Java library[3] for an off-the-shelf android smart-phone. The library is developed by IBM Security Research and is widely used for anonymous credentials. We use the library to implement the cryptographic components of the protocol including commitment, zero-knowledge proof and CL-signatures (see Section 2 for a description on these primitives), in three different security (RSA modulus length for CL-signature) settings.

b. Geo-tampering detection: We implement our detection algorithm to verify its correct detection of tampering for spars neighborhoods. We show that our approach can detect geo-tampering attack with reasonable "accuracy", that is defined as the minimum amount of movement of an access point before tampering is detected (see section 5). Our experiments clearly show effectiveness and superiority of using distance information of neighboring nodes, compared to trilateration which only uses the distances of the neighboring node to the issuing node.

Organization. Section 2 gives the system setting and definitions of proof-of-location schemes and their security properties. Our proof-of-location construction is in Section 3. Section 4 introduces geo-tampering attack on proof-of-location schemes, and presents an extended proof-of-location scheme proven to be secure against this attack. Section 5 details our experiments. We discuss related work in Section 6 and conclude the paper in Section 7. The supplemental material includes the security proofs.

2 Model and Definitions

2.1 Cryptographic Primitives

The following cryptographic primitives are used in our proof-of-location scheme.

Commitment. Commitment is a two-party protocol between a committer and a receiver. A commitment scheme ($\mathbb{C}$) has two stages - *Commitment* stage and *Reveal* stage. In the *Commitment* stage, the committer, for a value x produces a *commitment c*, and in the *Reveal* stage, opens the commitment to a value x'. A commitment protocol is *perfectly hiding* if the receiver cannot learn anything about the committed value x after the *Commitment* stage, and *perfectly binding* if in the *Reveal* stage, the committer can open the commitment only to the committed value $x(x' = x)$. The formal definitions of these properties can be found in [28]. A property can be satisfied against an unbounded adversary, resulting in statistical security, or a polynomially bounded adversary, resulting in computational security.

We use a commitment scheme proposed by Damagard and Fujisaki [28]. For a security parameter λ, in $\mathbb{C}.\mathtt{KeyGen}$, a public key $PK_c = (n, g, h)$ is generated, where n is a special RSA modulus, $h \leftarrow QR_n, g \leftarrow \langle h \rangle$, where $\langle h \rangle$ is the group generated by h, QR_n denoting quadratic residue modulo n. The commitment $com = \mathbb{C}.\mathtt{Commit}(x, r)$ for a string x uses a random string $r \in \mathbb{Z}_n$ and is computed as $com = g^x \times h^r \mod n$. In the reveal stage, the committer reveals the values x, r. The receiver can verify $com = \mathbb{C}.\mathtt{Commit}(x, r)$. This commitment scheme is *statistically hiding*, and *computationally binding* assuming factoring is a hard problem.

3. www.zurich.ibm.com/idemix

Zero-knowledge proof of knowledge. Zero-knowledge proof of knowledge ($\mathbb{ZKPoK}$) is a protocol between a *prover* and a *verifier*, in which the prover convinces the verifier that they possess a certain quantity w that satisfies some polynomial-time computable relation R, without revealing any information about w. We use Camenisch and Stadler's [29] representation of proofs of knowledge of discrete logarithms, and proofs of the validity of statements about discrete logarithms. For example, $\mathbb{ZKPoK}\{(\alpha, \beta, \gamma) : y = g^\alpha h^\beta \wedge \tilde{y} = \tilde{g}^\alpha \tilde{h}^\gamma\}$ expresses a Zero-Knowledge Proof of Knowledge of integers α, β and γ s.t. $y = g^\alpha h^\beta$ and $\tilde{y} = \tilde{g}^\alpha \tilde{h}^\gamma$ are true, where $y, g, h, \tilde{y}, \tilde{g}$ and $\tilde{h}$ are elements of some groups $G = \langle g \rangle = \langle h \rangle$ and $\tilde{G} = \langle \tilde{g} \rangle = \langle \tilde{h} \rangle$. By convention, the Greek letters denote quantities the knowledge of which is being proved, while all other parameters are known to the verifier.

We also use Camenisch and Lysianskaya's digital signature scheme (CL-signature scheme [30]) that provides existential unforgeability, and a public key encryption scheme that provides indistinguishability under chosen ciphertext (IND-CCA) attack [31]. Backgrounds and notations for these primitives are in the supplemental material, in Appendix **??**.

2.2 Proof-of-Location

System model and entities. As shown in Fig. 3, we consider four types of entities in the system: *i) Users*, *ii) Infrastructure nodes* that issue *pol* to registered users, *iii) Verifiers* who can verify a *pol* that is presented by a registered user, and *iv) a trusted authority* who sets up the system parameters. The system works as follows.

User requests a proof-of-location (*pol*) from an infrastructure node. $\mathcal{U}$ denotes the set of users in the system. *Infrastructure* consists of a set of access points $\mathcal{AP} = \{ap_0, ..., ap_n\}$ that can issue *pol*s to the users. Infrastructure also includes a database server $DBase$ that stores the initial location information of these access points. *Verifiers* need to verify a user's past location information (e.g. to provide service to them). $\mathcal{V}$ denotes the set of verifiers in the system. *Trusted Authority (TA)* generates public parameters of the system and the keys, and registers the users.

Users, access points and verifiers are the *participants* in the system. Each participant has a public key that is issued by the TA, and a geo-location $\ell oc = (x, y) \in \mathbb{R} \times \mathbb{R}$ in a well defined coordinate system, with distances measured as planar Euclidean distance. The distance function $d(\ell oc_1, \ell oc_2)$ returns the distance between two locations ℓoc_1 and ℓoc_2. Given a distance threshold B, two participants located at $(\ell oc_1, \ell oc_2)$ are said to be *close-by* if $d(\ell oc_1, \ell oc_2) \leq B$, and *far-away* otherwise.

Clock. We assume nodes in the infrastructure and the verifier use a UTC (Universal Time Coordinate) to loosely synchronize their local clocks. UTC may not reach all the system entities at the same time due to atmospheric pressure, network(s) transmission time and software overhead in local OS [32]. We use interval timestamp to capture the uncertainty over measuring time using UTC. An issuer will use interval timestamp to specify the time interval of issuing a *pol*, and the verifier check their local interval time to check validity of the time information. The format of an

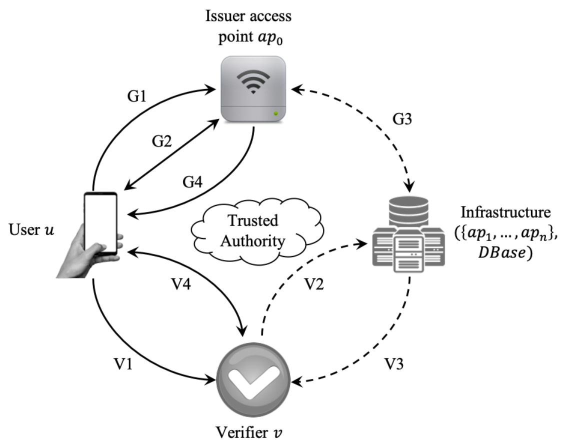

Issuer access point ap_0
G1
G2
G3
G4
User u
Trusted Authority
Infrastructure ($\{ap_1, ..., ap_n\}$, $DBase$)
V1
V2
V3
V4
Verifier v

Fig. 3. Proposed proof-of-location system model. Trusted authority provides secret and public keys to the system entities. pol generation steps are: $G1$: user makes a pol request to ap_0; $G2$: ap_0 runs a DB protocol with u; G3: ap_0 generates proof of its own location integrity by communicating with neighboring APs; and G4: ap_0 issues the pol to the user. pol verification stage: V1: user presents the pol to a verifier; V2,V3: Verifier requests for and receives ap_0's neighborhood data from the server $DBase$; V4: ap_0 verifies location integrity and signature on the pol, runs a zero knowledge proof of knowledge protocol with the user to authenticate it. G3, V2 and V3 are for protection against geo-tampering - see Section 4.

interval timestamp t is $[t_1, t_2], t_2 > t_1$. The interval width is source-dependent - may vary from one entity to another. We will see in Section 4 that the infrastructure nodes also use interval timestamp to show the time of generation of "proof" of location integrity.

Trust assumptions. Users are dishonest; they can claim wrong location, or attempt to forge or transfer a proof-of-location. APs and the verifiers are honest-but curious and can attempt to link pols and users to infer location movement trajectories.

Each AP has a location loc that is stored in a database $DBase$. The location of a user is with respect to the location of the access point that issues the pol. When a user u requests a proof of location from an access point ap_0, the ap_0 runs a DB protocol with the user, which if successful guarantees that u is *close-by*. In its basic form, pol is the ap_0's digital signature on the statement "$[u]$ is within distance B from ℓoc_{ap_0}", ℓoc_{ap_0} being the location of ap_0. This information is captured in the transcript of the DB protocol.

User privacy is an important requirement of POL systems. This requires the users to use *pseudonyms*, to request pol. We use $[u]$ to denote this pseudonym that will be used to anonymously authenticate the user u. In the following, we first describe our computational model, *assuming the infrastructure nodes have correct location.*

Adversary (Computational). An adversary can corrupt a subset of participants $\mathcal{X}^* \subset \mathcal{U} \cup \mathcal{AP} \cup \mathcal{V}$. For each security property, the adversary has a defined goal, which is reflected as restrictions of $\mathcal{X}^*$; in *unforgeability* and *non-transferability*, $\mathcal{X}^* \subset \mathcal{U}$ and in *anonymity* $\mathcal{X}^* \subset \mathcal{AP} \cup \mathcal{V}$. We note that corrupting a participant refers to the adversary gaining full control on the participant's code.

In Section 4 we consider a *physical attacker* that tampers with physical location of infrastructure nodes.

Definition 1 (Proof-Of-Location Scheme POL). For a security parameter λ, a proof-of-location scheme (POL) is defined by a tuple $(\texttt{POLInit}, \texttt{POLJoin}, \texttt{POLGen}, \texttt{POLVer})$. $\texttt{POLInit}(1^\lambda)$ generates the public and private parameters of the system (run by TA). `POLJoin` is an interactive protocol between user and TA, where TA registers a new user in the system and generates credentials for them. `POLGen` is an interactive protocol between a user $u \in \mathcal{U}$ and an access point $ap \in \mathcal{AP}$, that proceeds in two stages: i) `POLGen.DB`: a distance bounding protocol is run between u and ap_0, where ap_0 verifies if $d(\ell oc_{ap_0}, \ell oc_u) \leq B$, where B is the distance bound. ii) `POLGen.issue`: ap_0 issues a proof-of-location (pol) to the user u, which is ap_0's signature on a statement "$[u]$ is within distance B from ℓoc_{ap_0}", ℓoc_{ap_0} being ap_0's location. `POLVer` is an interactive protocol between a user $u \in \mathcal{U}$ and a *verifier* $v \in \mathcal{V}$. User u presents a proof-of-location pol to the *verifier* v. If the *verifier* is convinced that pol was issued by a valid issuer to the presenter of the proof, it outputs 1 (accept); otherwise it outputs 0 (reject).

POL Correctness. If all parties follow the protocols correctly, i.e. key generation and `POLJoin` are correctly executed, `POLGen` protocol is performed between an access point ap_0 that has trusted code and trusted location, and a close-by honest user u, the proof-of-location pol issued by the ap_0 and held by u, will be successfully verified by the *verifier* that runs `POLVer` protocol with u.

Proving security of cryptographic systems uses two main approaches, game-based and simulation based. While simulation based approach gives a more holistic view of security and allow composition of the proofs, we will use game-based approach because (i) security of distance bounding protocols that form a sub-protocol of our POL system has been studied using game based approach, and (ii) AP geo-tampering attack is an attack on physical location of APs and more amenable to modeling and analysis using game-based security. Simulation based models that include "physical" properties have been considered in [33]. However, no simulation-based model has been proposed for proximity verification.

In game-based approach the game is defined between the adversary and the challenger. The challenger initializes the system and provides oracle access to different parts of the system. The adversary's power is modelled by the set of their oracle accesses. We assume the adversary has the access to the following types of oracle queries.

1) $Corrupt(\mathcal{X}^*)$: An adversary can send a $Corrupt(\mathcal{X}^*)$ query to the challenger, asking to corrupt a subset of participants $\mathcal{X}^* \subset \mathcal{U} \cup \mathcal{AP} \cup \mathcal{V}$. The challenger returns the secret credentials of all participants in $\mathcal{X}^* \subset \mathcal{U} \cup \mathcal{AP} \cup \mathcal{V}$ to the adversary. Also, the codes and locations of these participants are set according to the adversary's instruction. The list $CorruptList$ stores the identities of the corrupted participants.
2) $POLGen(ap_0, u)$: The adversary selects an access point $ap_0 \in \mathcal{AP}$ and a user $u \in \mathcal{U}$, and makes an oracle query $POLGen(ap_0, u)$. The challenger runs the protocol `POLGen` as access point ap_0 with user u, and returns

either a proof-of-location pol, or $\perp$. If pol is returned, the tuple (pol, u) is appended to the list $GenList$.

3) $POLGenIssue(ap_0, u)$: The adversary selects an access point $ap_0 \in \mathcal{AP}$ and a user $u \in \mathcal{U}$, and makes an oracle query $POLGenIssue$ (ap_0, u). The challenger runs only the second stage of protocol `POLGen`, i.e., `POLGen.issue`, as access point ap_0 with user u, and returns a proof-of-location pol. The tuple (pol, u) is appended to a list $IssueList$.
4) $POLVer(v, u, pol)$: The adversary selects a verifier $v \in \mathcal{V}$ and a user $u \in \mathcal{U}$, and makes an oracle query $POLVer(v, u, pol)$ for a proof-of-location pol. The challenger runs the protocol `POLVer` as *verifier* v with user u on proof-of-location pol, and returns either 1 or 0. If 1 is returned, the tuple (pol, u) is appended to a list $VerList$.

We first define a general POL game and then show how it can be used to define each property.

Definition 2 (POL Game). For a security parameter λ, we define the following game between a challenger and an adversary.

1) *Initialize:* The challenger runs $\texttt{POLInit}(1^\lambda)$ and publishes the public parameters of the system. The challenger also initializes empty lists $CorruptList$, $GenList$, $IssueList$ and $VerList$.
2) *Generate participants:* The challenger generates a set of m users ($\mathcal{U}$), a set of n access points ($\mathcal{AP}$), and a set oof q verifiers ($\mathcal{V}$). The credentials (i.e., public/private key pairs) are generated for all the verifiers and access points. The locations of these participants are set arbitrarily. Then the challenger runs `POLJoin` for all the users. The challenger publishes the list $\mathcal{U}, \mathcal{AP}$ and $\mathcal{V}$ (i.e., the public credentials as well as location of each participant).
3) Queries: Adversary makes queries to oracles $Corrupt(\mathcal{X}^*)$, $POLGen(ap_0, u)$, $POLGenIssue(ap_0, u)$ and $POLVer(v, u, pol)$.
4) Adversary's output: The adversary outputs a proof-of-location pol_A.

The properties for POL are defined based on the POL Game. Conditions to win the game however vary depending on the property. We define three POL properties: unforgeability, non-transferability and anonymity. The following definition were motivated in Section 1, and *assume integrity of the access points' locations (access points are always assumed to correctly perform the computation).*

Property 1 (POL Unforgeability). Consider a POL scheme POL and a POL Game with the following restrictions: the adversary can only corrupt users, i.e., $\mathcal{X}^* \subset \mathcal{U}$ in the $\texttt{Corrupt}(\mathcal{X}^*)$ query. An adversary succeeds in the game, if there exists an entry $(pol, .) \in VerList$, s.t., $pol = pol_A$, and any of the following two holds: i) There does not exist an entry $(pol, .) \in GenList$ s.t. $pol = pol_A$, and there does not exist an entry $(pol, .) \in IssueList$ s.t. $pol = pol_A$; ii) There exists an entry $(pol, .) \in GenList$ s.t. $pol = pol_A$, and $d(\ell oc_{ap_0}, \ell oc_u) > B$. A proof-of-location scheme POL provides unforgeability, if the advantage of the adversary in succeeding in the above game, denoted by Adv_{UF}, is negligible.

Property 2 (POL Non-transferability). Consider a proof-of-location scheme POL and a POL Game with the following restriction: the adversary can only corrupt users, i.e., $\mathcal{X}^* \subset \mathcal{U}$ in the $\texttt{Corrupt}(\mathcal{X}^*)$ query. An adversary succeeds in the game, if there exists an entry $(pol, u) \in VerList$, s.t., $pol = pol_A$, and any of the following two holds: i) There exists an entry $(pol, u') \in GenList$ s.t. $pol = pol_A$, and $u' \neq u$; ii) There exists an entry $(pol, u') \in IssueList$ s.t. $pol = pol_A$, and $u' \neq u$. A proof-of-location scheme POL provides non-transferability if the advantage of the adversary in succeeding in the above game, denoted by Adv_{NT}, is negligible.

Property 3 (POL Anonymity). Consider a proof-of-location scheme POL and a POL Game, with the restriction that the adversary can only corrupt access points and *verifier*s, i.e., $\mathcal{X}^* \subset \mathcal{AP} \cup \mathcal{V}$ in the $Corrupt(\mathcal{X}^*)$ query. POL Anonymity is twofold.

1) *Anonymity with respect to the access point*: We remove step 4 in the POL game, and add the following steps. *i)* The adversary chooses a pair of users $(u_0, u_1) \in \mathcal{U}$, an access point $ap \in \mathcal{AP}$, and sends its choice of the participants to the challenger. However, the pair of users chosen by the adversary must be either both *close-by* the access point ap, or both being *far-away* from ap (otherwise, the adversary can win the game by simply looking at the output of the oracle in the following step). *ii*) The challenger randomly selects a bit $b_{ap} \leftarrow \{0, 1\}$, and simulates $POLGen(ap, u_{b_{ap}})$ oracle. The oracle returns either $\perp$ or a proof-of-location pol, which is forwarded to the adversary. In addition, the transcript of the protocol execution (i.e., in this case, all the messages exchanged between $(ap, u_{b_{ap}})$ in the `POLGen` protocol) is also sent to the adversary. *iii*) The adversary outputs a bit $\hat{b_{ap}} \in \{0, 1\}$.
2) *Anonymity with respect to verifier*: The game is the same as above, with the following modifications in the additional steps: *i)* the pair of users $(u_0, u_1) \in \mathcal{U}$ that are chosen by the adversary must be both *close-by* the access point ap (otherwise the game cannot proceed to pol verification stage), and *ii)* the challenger first simulates $POLGen(ap, u_{b_v})$ oracle, where b_v is a random bit picked by challenger, and then simulates $POLVer(v, u_{b_v}, pol)$ oracle, where $v \in \mathcal{V}$ is chosen by the adversary, and pol is the proof-of-location resulted from $POLGen$ query. The adversary's final output is a bit $\hat{b_v} \in \{0, 1\}$.

Adversary's advantage in winning the game is expressed as a tuple $(Adv^{ap}_{AN}, Adv^{v}_{AN})$, where, $Adv^{ap}_{AN} = |Pr[\hat{b_{ap}} = b_{ap}] - \frac{1}{2}|$ and $Adv^{v}_{AN} = |Pr[\hat{b_v} = b_v] - \frac{1}{2}|$. The proof-of-location scheme POL achieves anonymity with respect to the access point ap if Adv^{ap}_{AN} is negligible, and the *verifier* v if Adv^{v}_{AN} is negligible.

Note that anonymity with respect to ap implies anonymity with respect to the location infrastructure as this is the only part of the infrastructure that interacts with the user, and transcripts of different POL sessions are statistically independent. Following similar arguments, anonymity w.r.t v implies anonymity with respect to the set of verifiers in the system, $\mathcal{V}$.

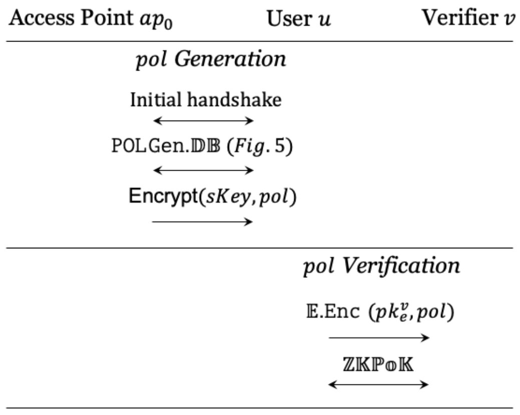


Fig. 4. An overview of pol generation (POLGen) and pol verification (POLVer) protocols in POLA scheme. Here $pol = \langle sig, msg \rangle, sig \leftarrow \mathbb{DS}.\texttt{Sig}(sk_s^{ap_0}, msg), msg = \langle com, pk_s^{ap_0}, \ell oc_{ap_0}, t \rangle$. See Fig. 5 for $com, sKey$ generation.

3 POLA: Proof-of-Location with Issuer and Verifier Anonymity

POLA is a proof-of-location scheme with anonymity against the issuer and the verifier. We assume each access point has a registered keypair (sk_s^{ap}, pk_s^{ap}) of the digital signature scheme $\mathbb{DS}$ that provides security against existential forgery. The public verifying key pk_s^{ap} is known by all the verifiers in the system. Also, each access point (respectively each verifier) has registered keypair (sk_e^{ap}, pk_e^{ap}) (resp. (sk_e^v, pk_e^v) for verifier) of the encryption scheme $\mathbb{E}$ that provides CCA security. The public encryption keys (pk_e^{ap}, pk_e^v) are known by all the registered users in the system. Fig. 4 gives an overview of pol generation and pol verification protocols in POLA scheme. Details of the scheme follows.

Initialization (POLInit).

TA calls $\mathbb{DS}.\texttt{KeyGen}(1^k)$ to generate (sk_s^{TA}, pk_s^{TA}), a private/public key pair of the digital signature scheme.

User registration (POLJoin).

Upon receiving join request from a user with identity u, TA generates a random binary string as the user's long term secret s_u. TA digitally signs s_u to generate the certificate $cert_u = \mathbb{DS}.\texttt{Sig}(sk_s^{TA}, s_u)$ and provides the private credential $(s_u, cert_u)$ to the user.

Proof-of-location generation (POLGen).

Access point discovery and initial handshake. APs can be discovered in several ways by the user. One way is that APs advertise their capability of providing proof-of-locations through periodically transmitted beacons, and user scans for available APs and identify them [34]. Once the public key of a *close-by* access point is known, the user performs an initial handshake with the access point (i.e., user requesting a pol and AP acknowledging the request), and proceeds to the distance bounding stage.

Distance bounding between u and ap_0 (POLGen.DB). The user and the access point start the distance bounding protocol as shown in Figure 5. The protocol has three phases. Let λ be the security parameter.

1) Initialization Phase: u chooses three random strings $\alpha, \beta, sKey$ each of length λ, where α is used to generate a

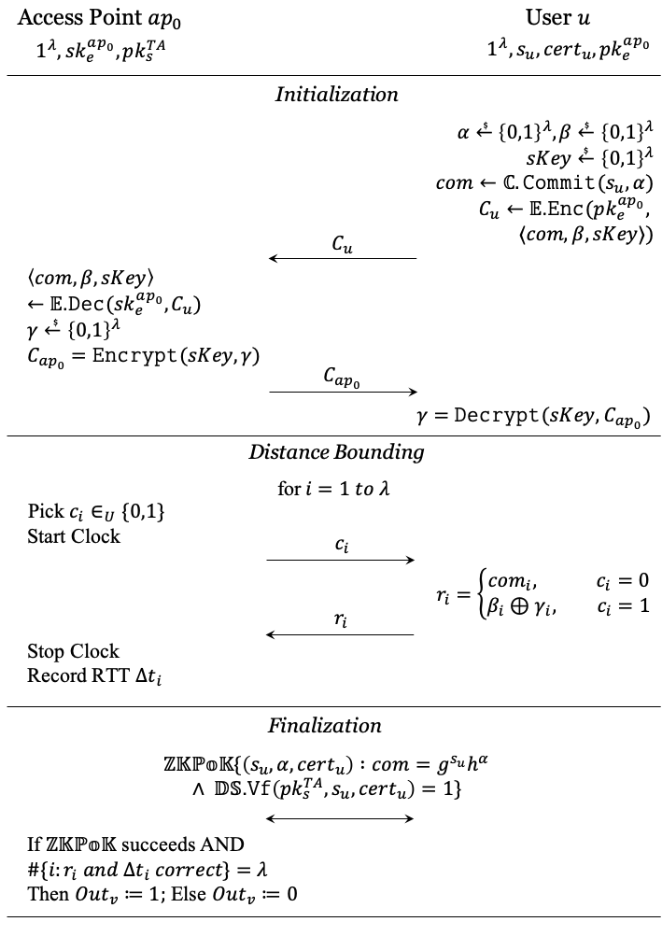

Access Point ap_0
User u
$1^\lambda, sk_e^{ap_0}, pk_s^{TA}$
$1^\lambda, s_u, cert_u, pk_e^{ap_0}$
Initialization
$\alpha \xleftarrow{\$} \{0,1\}^\lambda, \beta \xleftarrow{\$} \{0,1\}^\lambda$
$sKey \xleftarrow{\$} \{0,1\}^\lambda$
$com \leftarrow \mathbb{C}.\texttt{Commit}(s_u, \alpha)$
$C_u \leftarrow \mathbb{E}.\texttt{Enc}(pk_e^{ap_0}, \langle com, \beta, sKey \rangle)$
C_u
$\langle com, \beta, sKey \rangle \leftarrow \mathbb{E}.\texttt{Dec}(sk_e^{ap_0}, C_u)$
$\gamma \xleftarrow{\$} \{0,1\}^\lambda$
$C_{ap_0} = \texttt{Encrypt}(sKey, \gamma)$
C_{ap_0}
$\gamma = \texttt{Decrypt}(sKey, C_{ap_0})$
Distance Bounding
for $i = 1$ *to* λ
Pick $c_i \in_U \{0,1\}$
Start Clock
c_i
$r_i = \begin{cases} com_i, & c_i = 0 \\ \beta_i \oplus \gamma_i, & c_i = 1 \end{cases}$
r_i
Stop Clock
Record RTT Δt_i
Finalization
$\mathbb{ZKPoK}\{(s_u, \alpha, cert_u) : com = g^{s_u} h^\alpha \wedge \mathbb{DS}.\texttt{Vf}(pk_s^{TA}, s_u, cert_u) = 1\}$
If $\mathbb{ZKPoK}$ succeeds AND
$\#\{i : r_i$ *and* Δt_i *correct*$\} = \lambda$
Then $Out_v \coloneqq 1$; Else $Out_v \coloneqq 0$

Fig. 5. The distance bounding protocol (POLGen.DB) in POLA scheme between user u and access point ap_0.

commitment on s_u, $com = \mathbb{C}.\texttt{Commit}(s_u, \alpha)$. $sKey$ is a session key for encrypting (i.e., AES symmetric key encryption) subsequent messages sent by ap_0 to the user. User encrypts $\langle com, \beta, sKey \rangle$ using ap_0's public key $pk_e^{ap_0}$ and the result C_u is sent to ap_0, who decrypts C_u using $sk_e^{ap_0}$ and obtains $\langle com, \beta, sKey \rangle$. ap_0 chooses a random string γ of length λ, encrypts using $sKey$, and sends to u, who decrypts it to obtain γ. The values com, β and γ will be used by the user in responding to ap_0's challenges in the distance bounding phase.

2) Distance Bounding Phase: This phase has λ rounds. In the i-th round of this phase $(1 \leq i \leq \lambda)$, ap_0 sends a uniformly chosen random bit c_i to u. User immediately replies with com_i (if $c_i = 0$) or $\beta_i \oplus \gamma_i$ (if $c_i = 1$). Here x_i represents the i-th bit of the binary string x of length λ. The round trip time Δt_i for the challenge-response is measured and stored by ap_0.

3) Finalization Phase: This stage starts with a zero-knowledge proof of knowledge protocol between user and access point, where the user proves that com is a valid commitment of a value s_u that is certified by the TA. We follow the protocol proposed by Camenisch and Lysyanskaya ([30], Sec 6.2, Fig. 2), which is a zero knowledge proof of knowledge of the values $(s_u, \alpha, cert_u)$ such that $com = g^{s_u} h^\alpha \mod \gamma$ and $\mathbb{DS}.\texttt{Vf}(pk_s^{TA}, s_u, cert_u) = 1$. If the zero-knowledge proof of knowledge protocol succeeds,

ap_0 checks the user's responses from distance bounding phase. If the estimated round trip times are within bound (for distance bound B) and responses are correct in all the rounds, then ap_0 outputs 1, otherwise 0.

Issuing proof-of-location (`POLGen.Issue`*).* If distance bounding protocol succeeds and outputs 1, ap_0 generates a signature on the message msg, described below, using signing key $sk_s^{ap_0}$ of the digital signature scheme, and concatenate msg to this signature to output proof-of-location pol. The message msg is,

$$msg = \langle com, pk_s^{ap_0}, \ell oc_{ap_0}, t\rangle$$

where, ℓoc_{ap_0} is the location of ap_0, t is the interval timestamp at the issuer. pol is encrypted using $sKey$ and sent to the user.

$ap_0 \to u : \texttt{Encrypt}(sKey, pol), pol = \langle sig, msg\rangle, sig \leftarrow \mathbb{DS}.\texttt{Sig}(sk_s^{ap_0}, msg)$

Proof-of-location verification (`POLVer`**).**

User u presents pol to the *verifier* v, encrypted with the *verifier*'s public key pk_e^v. The *verifier* rejects the claim (outputs 0) if, after decrypting the values, $\mathbb{DS}.\texttt{Vf}(pk_s^{ap_0}, sig, msg) = 0$. If the issuer's signature is verified, the verifier v runs the $\mathbb{ZKPoK}$ protocol in [30] (similar to the finalization phase of `POLGen.DB`). Verifier rejects the claim if the protocol fails (outputs 0), otherwise v is convinced that u knows the secret s_u used to generate the commitment com and that this secret has been certified by the TA, and accepts the claim (outputs 1).

Discussion. In POLA, issuing a proof of location requires the issuer to run a DB protocol. To provide anonymity for the POL system, one can use an existing *anonymous* DB protocol [24], [25], [26], [27]. This however will not be sufficient because, during the verification phase, the generated pol should be linkable to the identity credential $[u]$ of the prover. These protocols do not provide this additional property. We will prove that while two pols that are issued to the same user in two distinct sessions, remain unlinkable, each individually will be linkable to the credential of the user. Our proposed anonymous DB protocol `POLGen.DB` satisfies these properties.

3.1 Security Analysis

Correctness of POLA can be straightforwardly shown. For security, we first show that the DB protocol between u and ap_0 is secure against distance fraud, distance hijacking, mafia fraud and terrorist fraud attack (See the supplemental material, Appendix **??** for attack descriptions). We use this to prove security of the protocol in Theorem 1.

Theorem 1. Let $\mathbb{E}$ be a IND-CCA secure encryption scheme, $\mathbb{C}$ be a computationally binding and computationally hiding commitment scheme, $\mathbb{DS}$ be a digital signature scheme secure against existential forgery and the protocol $\mathbb{ZKPoK}$ is sound and zero knowledge proof of knowledge of the values $(s_u, \alpha, cert_u)$. Then,

a) The distance bounding protocol (`POLGen.DB` in Fig. 5) in POLA between a user u and an access point ap_0, is secure against distance fraud, distance hijacking, mafia fraud and terrorist fraud attack.
b) If `POLGen.DB` in POLA is secure against above four types of attacks, then POLA is unforgeable.
c) Assuming the user is not willing to share their secret credential, POLA provides non-transferability.
d) POLA is anonymous with respect to both the issuer access point and the verifier.

Proof is in the supplemental material, Appendix **??**.

4 Geo-tampering attack on POL systems

Consider a POL system in Section 2 with a location infrastructure $\mathcal{AP}$ consisting of n access points $\{ap_0, ap_1, ..., ap_{n-1}\}$, each associated with a location ℓoc_{ap_i} $(i = 0, ..., n-1)$. The initial location map $LocMap = \{(ap_0, \ell oc_{ap_0}), ..., (ap_{n-1}, \ell oc_{ap_{n-1}})\}$ of the APs is stored in $DBase$.

In geo-tampering attack, an access point will have intact hardware and software but its location has been modified. Let ℓoc_{ap_0} be the geo-coordinate of an access point ap_0 in $LocMap$, and $\ell oc'_{ap_0}$ be its modified geo-coordinate. The distance bounding protocol will accept the claim of a user within $Circ(\ell oc'_{ap_0}, B)$, a circle of radius B around the location $\ell oc'_{ap_0}$, and issue a pol using its stored location ℓoc_{ap_0}. This is effectively forging a pol for a location that the user is not in.

One can use an approach such as trilateration to determine the location of the proof issuing AP, and compare it with the corresponding value that is stored in $LocMap$. This is Geo-tampering detection using *location determination*.

Geo-tampering detection using *location determination*. Assume there are three access points (ap_1, ap_2, ap_3), all with trusted location (e.g. physically secured devices) that are at the line-of-sight distance of ap_0. Assuming synchronized clocks, ap_0 sends a radio signal to ap_1, ap_2, ap_3, who record their signal arrival time, and send it to ap_0 who can use the received values to estimate the distances $d(ap_0, ap_i), i = 1, 2, 3$ using the travel time, the (constant) speed of radio signal. Using these, and the geo-coordinates of ap_1, ap_2, ap_3, one can find an estimate for the geo-coordinate of ap_0, using a trilateration algorithm (such as the one proposed in [35]). The new computed location of ap_0 will have some error because of inaccuracy of distance measurement, that is called *trilateration error*. A *geo-tampering* will be detected if the distance between the initial stored value of the ap_0's location in $LocMap$, and its new estimate exceeds a chosen *trilateration error*.

Drawback of *location determination* based approach. Trilateration requires at least three access points with trusted locations, that are at the line of sight distance (reach of radio signal) of the pol issuing AP. These requirements can be fulfilled by providing many APs with trusted location (e.g. physically protected areas) which makes the infrastructure nodes expensive for many applications.

4.1 Our approach

We propose a novel approach to detect geo-location tampering that does not require determining the location of pol issuing AP, but relies on detecting the change in the AP's relative position to its neighbors. Here the notion of "neighbor" can be defined in a flexible way, and is not restricted to nodes that are at the line-of-sight of the issuing AP. We define the neighborhood of ap_0 to be the set of all APs that are "reachable" from ap_0, where reachability means existence of a path consisting of edges that each correspond to a line of sight communication. That is, a message sent from ap_0 will reach all the nodes in the neighborhood of ap_0, possibly through multiple "hops". We assume a subset of APs in the ap_0's neighborhood have not been displaced and have correct (original) locations. We however *do not require these nodes with correct locations, to be identifiable*.

Definition 3 (Neighborhood N_{ap_0}). Let $G = [\mathcal{V}, \mathcal{E}]$ be an undirected graph where each vertex $v \in \mathcal{V}$ represents an AP in the infrastructure of the proof-of-location system, and an edge $e \in \mathcal{E}$ between two APs represents the two being at the line-of-sight of each other. A neighbourhood of ap_0 is a connected component of graph G that includes ap_0. If $N_{ap_0} = \{ap_1^0, ap_2^0, .., ap_{n-1}^0\}$ is the neighborhood of ap_0, then for each $ap_i^0 \in N_{ap_0}$, there is a path from ap_0.

For a neighbourhood N_{ap_0}, we define an Euclidean Distance Matrix (EDM [36]) $D_{N_{ap_0}}$ as follows.

Let $|N_{ap_0}| = n$ (Neighborhood includes ap_0). $D_{N_{ap_0}}$ is a $n \times n$ matrix, with rows and columns labelled by $ap_i^0 \in N_{ap_0}$ and $D(i,j)$ is the length of the straight line connecting ap_i^0 and ap_j^0. This matrix can be constructed by knowing the exact coordinates of the nodes (that can be found in $LocMap$ stored in $DBase$) and calculating the Euclidean distance between them. The geo-tampering detection algorithm has two steps: (i) construct $D'_{N_{ap_0}}$, a real-time estimate of the matrix $D_{N_{ap_0}}$, and (ii) compare the entries of the two matrices, and use a decision algorithm to detect tampering. An overview of each step is given below. Full details and algorithms are in Sec. 4.3.

(i) Constructing $D'_{N_{ap_0}}$ is through making real-time distance measurements between each pair of nodes in N_{ap_0}. The distance measurement will be by recording the arrival time of a radio signal that is sent by one node associated to an edge, and received by the second node of that edge. Note that this measurement can be performed for only nodes that are in the radio distance of each other. Thus only the entries of $D'_{N_{ap_0}}$ that correspond to nodes that are at radio-distance of each other can be measured (possibly with some error). The entries of $D'_{N_{ap_0}}$ that can not be measured can be "reconstructed" using *distance recovery* algorithm [36]. This recovery is due to the geometric properties of distances of neighboring nodes and is available to any distance matrix. The error that is introduced in this reconstruction depends on the error in the distance measurements using radio signal, and the number of entries that cannot be found through the radio signal measurement.

(ii) Given $D_{N_{ap_0}}$ and its estimation $D'_{N_{ap_0}}$, one can use various decision algorithms to detect tampering. We use a simple threshold algorithm which requires the corresponding entries of the two matrices to be within distance Δ of each other. That is, $|D_{N_{ap_0}}(i,j) - D'_{N_{ap_0}}(i,j)| \leq \Delta, \;\; (i,j) \in \{0,..,n-1\}$.

Notice that small values of Δ implies reduced advantage for the attacker, in terms of its ability to displace the access points. Δ is called the *Geo-tampering detection threshold*, defined bellow.

Definition 4 (Geo-tampering threshold Δ). For a geo-tampering detection algorithm, Δ is the maximum distance by which the geo-tampering attacker is able to move an access point from its original location, without getting detected.

Δ is determined by (i) error in distance measurement between access points in the neighborhood, and (ii) error in reconstructing the entries in $D'_{N_{ap_0}}$ that could not be measured. Hence, for our detection algorithm, Δ is a tuple (Δ_M, Δ_R); Δ_M is the distance measurement error, and Δ_R is the distance reconstruction error.

The rest of this section provides details of our approach in geo-tampering detection, and the construction of POLA$^+$, an extension of POLA with protection against geo-tampering.

4.2 POLA$^+$: Protection against geo-tampering

Protection against geo-tampering requires the pol issuer to perform a real-time integrity checking algorithm to provide location integrity proof information. Let $LocIntInfo(ap_0)$ denote the location integrity information ("proof") that must be provided by the issuing AP ap_0 to convince the POL system that ℓoc_{ap_0} is correct.

We require the following properties for $LocIntInfo(ap_0)$.

(P1) It must be generated at the time of issuing pol to the user.

(P2) It must convince the POL system that the geo-location of ap_0 with respect to $LocMap$ is correct.

These requirements allow a modular approach to the construction of a POL system that provides security against tampering of the infrastructure node locations, based on a secure POL system that requires trusted location for the infrastructure nodes. Theorem 2 below extends Theorem 1 (POLA security) such that geo-tampering with the location of APs can be tolerated.

Theorem 2. Let $LocIntInfo(ap_0)$ satisfy P2 (have sufficient information to convince the verifier about the integrity of ap_0's geo-location). By generating and including $LocIntInfo(ap_0)$ at the time of generating pol (and thus satisfying P1), and including it in pol as shown below:

$$pol \leftarrow \langle sig, msg \rangle, sig \leftarrow \mathbb{DS}.\mathtt{Sig}(sk_s^{ap_0}, msg)$$

$$msg = \langle com, pk_s^{ap_0}, \ell oc_{ap_0}, t, LocIntInfo(ap_0) \rangle$$

we obtain a POL system that satisfies POL security properties, i.e., unforgeability (property 1), non-transferability (property 2) and anonymity (property 3), while providing security against *geo-tampering attack*.

Proof is in the supplemental material, Appendix **??**.

4.3 LocIntInfo(ap$_0$) Generation and Verification

Protection against geo-tampering is achieved by, (i) LocIntInfo(ap$_0$) Generation: at the time of pol generation, ap_0 constructs $D'_{N_{ap_0}}$, a real-time estimate of the matrix $D_{N_{ap_0}}$, and appends $D'_{N_{ap_0}}$ to the msg before digitally signing it to form the pol with the ap_0's location integrity information $LocIntInfo(ap_0)$, and (ii) LocIntInfo(ap$_0$) Verification: at the time of pol verification, verifier compares the entries of the two matrices, and uses a decision algorithm to detect tampering.

4.3.1 LocIntInfo(ap$_0$) Generation

Construction of $D'_{N_{ap_0}}$ requires real-time distance measurement between each pair of nodes in N_{ap_0}, that are at each other's line-of-sight. Any entry in $D'_{N_{ap_0}}$ corresponding to a pair of nodes that are not at LOS, will be left empty.

Measuring distance between two line-of-sight APs. Since both APs correctly follow the prescribed computation by the protocol (even if they are geo-tampered), we do not require cryptographically secure distance measurement techniques such as distance bounding. One can use distance measurement techniques that are commonly used in wireless sensor networks, including Time of Flight (TOF) or Time of Arrival (TOA), for this purpose. We use TOA as it uses a one-way signal for time measurement and has less communication overhead.

Algorithm GenLocIntInfo (Fig. 7) is used to estimate the distance between ap, ap' (an edge in $D'_{N_{ap_0}}$). In brief, ap sends a signed message to ap' that includes the sending time t_s. ap' verifies the signature, and if valid computes the distance between the two as $d'(ap, ap') = (t_r - t_s - \delta_p) \times c$, where t_r is the arrival time of the message, c is the speed of light and δ_p is the computation delay of the sender (digital signature). The computation delays are assumed publicly known.

TOA distance measurement can be affected by clock drift between two access points. To reduce the clock drift techniques such as those proposed in "PinPoint" [37] can be used to improve distance measurement accuracy. In PinPoint, multiple rounds of timestamp exchange between the two access points is used to estimate and remove the difference in the two clock readings. PinPoint provides an average accuracy of 4.18 feet, with a standard deviation of 4.4 in a complex indoor environment.

Selecting Effective Neighborhood. In practice, only a selected subset of the actual neighborhood N_{ap_0} may be used in generating location integrity information. This subset is selected such that the performance of the geo-tampering detection algorithm is improved in terms of geo-tampering threshold Δ. Also, to improve computation time of the location integrity information, it is important to select access points that have shorter path-lengths to issuer ap_0. Below we define effective neighborhood for ap_0.

Definition 5 (Effective Neighborhood EN_{ap_0}). An effective neighborhood EN_{ap_0} of access point ap_0 is a subset of ap_0's neighborhood N_{ap_0} and includes ap_0. This is a connected subgraph of N_{ap_0} (see Def. 3 for N_{ap_0}). EN_{ap_0} includes all the nodes that are used to form ap_0's location integrity information $LocIntInfo(ap_0)$.

By "connected subgraph of N_{ap_0}", we mean a subgraph of the connected component N_{ap_0}, such that each pair of vertices in it are connected by a path.

The distance matrix formed by EN_{ap_0} is $D_{EN_{ap_0}}$. As will be shown in theorem 4, the geo-tampering attack is detected with high probability if at least three untampered access points are present in the effective neighborhood. Therefore, when the risk of nodes being displaced in a system is higher (such as applications where APs are placed in public places), it will require having a larger effective neighborhood – that will increases the chance of having at least three untampered APs in the effective neighborhood.

Effective Neighbourhood Selection. An effective neighborhood selection algorithm will first choose *the size of the effective neighbourhood, m,* and then select an effective neighborhood of that size. The effective neighborhood size will depend on the estimated probability of neighbourhood nodes being moved by an adversary, with higher probabilities corresponding to larger size of m. Choosing the value of m will depend on other factors including the required security guarantee of the system and will not be further studied here. For a given value of m, the effective neighbourhood will be a set of size at least m nodes, each connected to ap_0 through a path. The choice of the set will affect (i) the geo-tampering error threshold Δ, and (ii) the delay in the generation of location integrity proof, determined by the node with the longest path to ap_0 (assuming equal transmission time on each link). In the following we consider the problem of selecting a set that minimizes Δ, and show that it reduces to the hard problem of finding a *clique* of size k in an undirected graph (see below). Selecting a set that takes both objectives of reducing Δ and maximum path length will be an extension of this work.

Minimizing Δ for a size m Neighborhood . Finding an effective neighborhood of size m that minimizes Δ implies minimizing the EDM reconstruction error, which in turn implies minimizing the number of missing elements in the matrix $D_{EN_{ap_0}}$, therefore maximizing the number of edges in the effective neighborhood EN_{ap_0}. Now, finding an effective neighborhood of size m with maximum number of edges, is NP-hard, as stated in the following theorem.

Theorem 3. Finding an effective neighborhood of ap_0 of size m that has maximum number of edges, is NP-hard.

Proof:

A clique is a subset of vertices in an undirected graph such that every two vertices are connected by an edge, forming a complete subgraph. The k-clique problem is stated as follows: *given an undirected graph G, find a clique of size k, where k is the number of vertices.* The k-clique problem has been shown to be NP-complete [38].

Finding ap_0's effective neighborhood of size m that maximizes number of edges, can be stated as follows: "Given a neighbourhood of ap_0 consisting of all nodes that are connected through a path to ap_0, find a subset of size m, each connected to ap_0, where the number of edges is maximum."

Assume there is a polynomial time algorithm that solves the above neighborhood selection problem. This algorithm can also find a subgraph of size m vertices that include ap_0, and includes all edges. That is, it will find a clique of size m that includes ap_0, if there exists one. Now it is easy to see that by repeating the algorithm for each vertex of the graph, one obtains an efficient algorithm that finds a clique of size m in the graph. This is a contradiction to the NP-completeness of k-clique problem. □

Our approach to selecting effective neighborhood of size m. For our experiment we consider a heuristic approach (Algorithm in Fig. 6) that works as follows. Let M be a $n \times n$ matrix of all APs in the neighborhood of ap_0, including ap_0. In M, each element $M(i,j)$ can take value in $\{0,1\}$, 1 denoting the event that real-time distance measurement is possible between (ap_i, ap_j), and 0 denoting the opposite - a missing element, and must be reconstructed. We sort the APs in N_{ap_0} according to the number of missing elements involved with the AP. The algorithm sorts the APs in N_{ap_0} according to the number of zeros in the row/column of M indexed by the APs. Finally, given the required effective neighborhood size m, simply select the first $(m-1)$ APs (excluding ap_0) from the sorted list in ascending order, such that there is a path from ap_0 to each of these APs. In order to find if two nodes are connected (i.e, if there is a path between these nodes) in an undirected graph, one can simply use a graph traversal algorithm such as Depth-First-Search as shown in [39]. Note that the issuing AP ap_0 is by default included in the effective neighborhood.

Generating location integrity information. The nodes in the chosen effective neighborhood set of ap_0 measure the pairwise distances among themselves, and send the results back to ap_0. A path from ap_i to ap_j is a finite sequence of edges between ap_i and ap_j. Algorithm GenLocIntInfo (Fig. 7) uses TOA technique to generate $D'_{EN_{ap_0}}$. We define Adj_{ap} as the adjacent list of ap, that is the list containing all access points in radio range of ap. An edge between two APs (ap_i, ap_j) is denoted by $\{ap_i, ap_j\}$.

(Step 1) ap_0 determines its neighborhood using $LocMap$, then selects its effective neighborhood EN_{ap_0} by running algorithm in Fig. 6. A distance matrix $D'_{N_{ap_0}}$ is initiated with all zero entries. Then ap_0 generates and broadcasts a signed location integrity request Req, that contains a sequence number $ReqID$, `Requester` and `Sender` name (both set as ap_0), the effective neighborhood list `ENList` (set as EN_{ap_0}), adjacent list `SenderAdjList` (set as Adj_{ap_0}), and the time of sending this message `SenderTime` (set as ap_0's local time t_{ap_0}).

(Step 2) Access point ap_i receives Req, records the receive time (`ReceiverTime`) and checks if itself and the `Sender` both are members of `ENList`. If so, it computes the length of the edge between them (`EdgeLength`) using `ReceiverTime`, `SenderTime` and sender processing delay δ_p. Then it computes a path P back to the Requester, and transmits a signed response Res containing `Destination` (set as `Requester`), `Responder` (set as ap_i), `Path` (set as P), `Edge` (set as $\{\texttt{Sender}, \texttt{Responder}\}$) and `EdgeLength`.

ap_i also rebroadcasts the message Req so that it will reach all the member of effective neighborhood of ap_0. However, instead of using blind flooding (i.e., each node broadcast the message whenever it receives it) which would waste wireless resource considerably, we use the "Self-pruning" method in [40]. Following this method, ap_i checks

```
Input: $ap_0$'s neighborhood $N_{ap_0}$ of size $n$, location map $LocMap$, required size of effective neighborhood: $m$
Output: Effective neighborhood $EN_{ap_0}$ of size $m$
1: Include issuer AP $ap_0$ to the effective neighborhood $EN_{ap_0}$.
2: Create a $n \times n$ matrix $M$, for neighborhood $N_{ap_0}$, with rows and columns labelled by $ap_i \in N_{ap_0}$. Each element $M(i,j)$ will take value in $\{0,1\}$. $0$ denotes an edge between $ap_i, ap_j$, and $1$ denotes absence of the edge.
3: Count the number of zeros in each column (or row) of $M$, and assign this number to the AP that labels this column (or row, respectively).
4: Excluding $ap_0$, sort the APs in $N_{ap_0}$ according to the assigned number (i.e., count of zeros).
5: Select the first $(m-1)$ APs in ascending order, such that there is a path from $ap_0$ to each of these APs. Add these APs to $EN_{ap_0}$.
6: return $EN_{ap_0}$.
```

Fig. 6. Effective neighborhood selection algorithm.

if all its adjacent nodes have already received Req. If so, it refrains from re-broadcasting Req. Otherwise, it resets `Sender` as ap_i, `SenderAdjList` as its own adjacent list, `SenderTime` as its own local clock time, then signs and forwards the modified Req.

(Step 3) ap_0 receives Res, it updates the element in $D'_{N_{ap_0}}$ corresponding to the `Edge` in Res and discards future Res with same `Edge` value. If all the elements in $D'_{EN_{ap_0}}$ are updated (excluding the elements that corresponds to absence of an edge), ap_0 outputs location integrity data that includes $EN_{ap_0}, D'_{EN_{ap_0}}$ and the algorithm completion time t_{int}.

4.3.2 LocIntInfo(ap_0) Verification

Verifier, upon receiving $LocIntInfo(ap_0)$ as part of the *pol* from a user, runs algorithm VerLocIntInfo (Fig. 8). Basically this algorithm reconstructs any missing element in $D'_{EN_{ap_0}}$, then compares the entries of the two matrices $(D_{EN_{ap_0}}, D'_{EN_{ap_0}})$, and uses a decision algorithm to detect tampering.

Reconstructing missing entries. The distance matrix $D'_{EN_{ap_0}}$ is an EDM. As noted earlier, the real-time distance measurements using Algorithm GenLocIntInfo (Fig. 7) may not obtain all the distances and corresponding entries in $D'_{EN_{ap_0}}$ will be missing. EDM geometric constraints allow recovery of missing distances.

We used the algorithm "Alternating Descent" in [36] (see the supplemental material, Appendix **??**) that can complete an EDM with high success probability when the number of missing elements in the matrix is bounded.

Comparing the two matrices. Once all distances of $D'_{EN_{ap_0}}$ that correspond to the stored distances of $D_{EN_{ap_0}}$ are recovered, a matching algorithm is used to decide if the effective neighborhood of ap_0 has been tampered with. Note $D'_{EN_{ap_0}}$ does not match $D_{EN_{ap_0}}$ could be because of changes in one or more node in the neighborhood. The matching algorithm in our experiments is by simply comparing every pair of

```
Input: $LocMap$ containing system AP locations, sender processing delay $\delta_p$ for TOA, Effective neighborhood size $m$
Output: Location integrity data $LocIntInfo(ap_0)$
1: Issuing AP $ap_0$ does the following:
    i. Determines its neighborhood $N_{ap_0}$ from $LocMap$.
    ii. Selects effective neighborhood $EN_{ap_0}$ of size $m$ by running Algorithm in Fig. 6.
    iii. Initializes an empty $m \times m$ distance matrix $D'_{N_{ap_0}}$. Elements in this matrix that correspond to absence of an edge
         between the APs indexing the element, are set as 0, representing a missing element.
    iv. Selects a unique sequence number $ReqID$ for the message it is going to broadcast. Sets $\texttt{Requester} =$
        $ap_0, \texttt{Sender} = ap_0, \texttt{ENList} = EN_{ap_0}, \texttt{SenderAdjList} = Adj_{ap_0}, \texttt{SenderTime} = t_{ap_0}$. Then broadcast a request:
        $Req = \langle m, \mathbb{DS}.\texttt{Sig}(sk_s^{ap_0}, m)\rangle, \quad m = \langle ReqID, \texttt{Requester}, \texttt{Sender}, \texttt{ENList}, \texttt{SenderAdjList}, \texttt{SenderTime}\rangle$
2: $ap_i$ that receives a message $Req$, records the reception time ReceiverTime, and does the following:
    i. If $ap_i \in EN_{ap_0}$ and Sender $\in EN_{ap_0}$, then computes $\texttt{EdgeLength} = (\texttt{ReceiverTime} - \texttt{SenderTime} - \delta_p) \times c$.
       Then computes $\texttt{Path} = P$ to Requester, sets $\texttt{Destination} = \texttt{Requester}, \texttt{Responder} = ap_i, \texttt{Edge} =$
       $\{\texttt{Sender}, \texttt{Responder}\}$, selects a unique sequence number $ResID$, and transmits following response: $Res =$
       $\langle m', \mathbb{DS}.\texttt{Sig}(sk_s^{ap_i}, m')\rangle, \quad m' = \langle ResID, ReqID, \texttt{Responder}, \texttt{Destination}, \texttt{Path}, \texttt{Edge}, \texttt{EdgeLength}\rangle$. This
       response will be forwarded along the path $P$ to $ap_0$.
    ii. Computes own adjacent list $Adj_{ap_i}$. If $Adj_{ap_i} - \texttt{SenderAdjList} - \{\texttt{Sender}\}$ is empty, sets $\texttt{Sender} =$
        $ap_i, \texttt{SenderAdjList} = Adj_{ap_i}, \texttt{SenderTime} = t_{ap_i}$. Then forwards the modified request: $Req =$
        $\langle m, \mathbb{DS}.\texttt{Sig}(sk_s^{ap_i}, m)\rangle, \quad m = \langle \texttt{ReqID}, \texttt{Requester}, \texttt{Sender}, \texttt{ENList}, \texttt{SenderAdjList}, \texttt{SenderTime}\rangle$
3: $ap_0$ receives a response $Res$, and does the following:
    i. Extracts Edge from $Res$. If it has not already received a $Res$ containing same Edge, updates the element in $D'_{N_{ap_0}}$
       indexed by APs in the Edge.
    iii. If all the elements of $D'_{N_{ap_0}}$ (excluding the ones that were initially set as 0) are updated, or a predefined
         waiting period has passed (in which case the elements that were not updated are set as 0), $ap_0$ outputs
         $LocIntInfo(ap_0) = \langle EN_{ap_0}, D'_{EN_{ap_0}}, t_{int}\rangle$, $t_{int}$ is the timestamp of the algorithm completion, at $ap_0$.
```

Fig. 7. GenLocIntInfo: Location integrity information generation algorithm

```
Input: $LocIntInfo(ap_0)$, $LocMap$, geo-tampering detection threshold $\Delta = (\Delta_M, \Delta_R)$. $\Delta_M$: distance measurement error, $\Delta_R$: distance recovery error
Output: $Out = \{0, 1\}$
1: Extract the distance matrix $D'_{EN_{ap_0}}$ and effective neighborhood $EN_{ap_0}$ from $LocIntInfo(ap_0)$.
2: If $D'_{EN_{ap_0}}$ has missing elements, let $\mathcal{M}$ be the set of missing elements. Apply the Alternating Descent on $D'_{EN_{ap_0}}$ to recover distances in $\mathcal{M}$.
3: Use $LocMap$ and $EN_{ap_0}$ to compute the distance matrix $D_{EN_{ap_0}}$.
4: For each $D_{N_{ap_0}}(i,j) \in \mathcal{M}$, check if $|D_{N_{ap_0}}(i,j) - D'_{N_{ap_0}}(i,j)| \leq \Delta_R$.
5: For each $D_{N_{ap_0}}(i,j) \notin \mathcal{M}$, check if $|D_{N_{ap_0}}(i,j) - D'_{N_{ap_0}}(i,j)| \leq \Delta_M$.
6: If all the checks succeed, $Out \leftarrow 1$, otherwise $Out \leftarrow 0$
7: return $Out$
```

Fig. 8. VerLocIntInfo: Location integrity information verification algorithm.

corresponding distances in $D_{EN_{ap_0}}$ and $D'_{EN_{ap_0}}$, and detect a change if the difference is larger than geo-tampering detection threshold Δ. As noted earlier, this value is the tuple of EDM recovery error, and the distance measurement error.

Theorem 4 states that location integrity data satisfies P2.

Theorem 4 (Sufficiency of $LocIntInfo(ap_0)$). Assuming *Alternating Descent* can complete EDM with high success probability, and at least three untampered node are present in the effective neighborhood of ap_0, $LocIntInfo(ap_0)$ generated by algorithm GenLocIntInfo satisfies P2 with high probability: convinces the POL system that the geo-location of ap_0 with respect to $LocMap$ is correct.

Proof is in the supplemental material, Appendix **??**.

4.4 Putting it together: Constructing POLA$^+$

This section puts all the parts together and extends our proposed proof-of-location scheme POLA to construct POLA$^+$ that provides security against geo-tampering attack.

Initialization (POLInit). As in POLA in Section 3.

User registration (POLInit). As in POLA in Section 3.

Proof-of-location generation (POLGen). *Access point discovery and initial handshake.* As in POLA in Section 3.

*Distance bounding between u and ap_0 (*POLGen.DB*).* As in POLA in Section 3.

Generating location integrity data for ap_0. If POLGen.DB returns 1, ap_0 begins GenLocIntInfo algorithm (see Fig. 7) and generates $LocIntInfo(ap_0)$.

*Issuing proof-of-location (*POLGen.Issue*).* This is as in POLA, but with $LocIntInfo(ap_0)$ included in the issued proof-of-location pol.

$$pol \leftarrow \langle sig, msg\rangle, sig \leftarrow \mathbb{DS}.\texttt{Sig}(sk_s^{ap_0}, msg)$$

$$msg = \langle com, pk_s^{ap_0}, \ell oc_{ap_0}, t, LocIntInfo(ap_0)\rangle$$

$$LocIntInfo(ap_0) = \langle EN_{ap_0}, D'_{EN_{ap_0}}, t_{int}\rangle$$

Proof-of-location verification (POLVer). This is as in POLA, with following additional checking by the verifier:

- Extracts $LocIntInfo(ap_0)$ from pol, retrieves $LocMap$ from $DBase$.
- Extracts timestamps t from msg and t_{int} from $LocIntInfo(ap_0)$. Checks that t and t_{int} are at most a predefined value Γ apart from each other.
- Runs algorithm VerLocIntInfo (Fig. 8).
- If the algorithm outputs 0, verifier rejects the claim and aborts, otherwise accepts the claim.

Setting a small Γ ensures that $LocIntInfo(ap_0)$ is generated immediately before pol is issued to the user, and so P1 is satisfied. P2 is also satisfied as proved in theorem 4. Now we can derive following corollary from theorem 2 and 4.

Corollary 1. POLA$^+$ is secure against *geo-tampering*, while preserving POL security properties (property 1, 2 and 3).

5 Experiments and Evaluation

5.1 Proof-of-concept implementation of POLA

Our implementation goal is to estimate the processing time of user, issuer, and verifier. For all these we use a mobile phone (Samsung Galaxy S9) to represent the resource limitations of the user (requester) as well as the small portable base stations that represent the issuer and the verifier.

We use the Java implementation version v2.3.43 of Idemix (Identity Mixer) [41], a cryptographic protocol suite that is designed for providing anonymity for authentication, and unlinkability for transactions, using CL signature and hash functions. Idemix uses SHA-256 hash function. Idemix commitment scheme is based on the hardness of discrete logarithm (DL) problem, while the CL signature security relies on the hardness of factorization problem. To show the effect of key size (security level) on the computation time and storage, we consider three different RSA modulus sizes for the CL-signature, 1024 bits, 1536 bits and 2048 bits. For these sizes, Idemix uses appropriate group sizes for the DL problem so that the overall cryptographic security will be equivalent to that of the RSA modulus size. More details are in the Idemix specification document given as Table 2 and 3 in [42]. More specifically, Idemix uses 768 bit commitment modulus with 1024 bit RSA modulus, and 1632 bits commitment modulus with both 1536 and 2048 bit RSA modulus.

We examine the computational time and storage that are needed to run POLA with our implementation. The results that are shown in Figure 9 are based on 10 independent runs of each test. During the tests, we ensured that no other background processes were running in parallel.

In our testbed, the user, who already possesses a certificate from TA on its secret key (a CL-signature from TA on user's secret), requests for a pol to an issuer that contains a commitment on user's secret and a non-interactive zero-knowledge proof stating that user holds a valid certificate from the TA on the committed value. Issuer decides if user is within an acceptable distance and validates the zero-knowledge proof. This is the *initialization phase* in Figure 9. After the initialization phase the user and the issuer take part in generating the pol credential, which is essentially the issuer's CL-signature on user's commitment, issuer's location and time. This is *pol generation* phase in Figure 9. Finally, in *pol verification* phase, the verifier and user takes part in the verification of pol which is a non-interactive zero-knowledge proof allowing verifier to validate pol without revealing user's identity.

Initialization phase, that corresponds to user making commitment on its secret and generating zero-knowledge-proof, and issuer verifying the proof, takes $24.7, 36.3$ and 55.6 milliseconds for user, and $16.5, 24.4$ and 38.7 for issuer (for RSA modulus size of 1024, 1536 and 2048 bits, respectively). RSA modulus size comes into play when prover generates zero-knowledge proof of knowledge on its certificate (CL-signature) from TA, and when issuer verifies that proof, and thus affecting the computation time.

pol generation phase is most costly (amount of time) phase in all cases, that generates CL-signature on user attributes (location, time) and requires the user and the issuer to perform a protocol consisting of multiple rounds (see specification of Idemix [42], Section 6.1.1 for a description of the protocol). For three RSA modulus sizes (1024, 1536 and 2048 bits), the computation times for this phase are $170.4, 185.6$ and 242.9 ms for users, and $228.7, 234.7$ and 288.2 ms for the issuer. pol verification protocol at the user and verifier takes $21.8, 32, 51.1$ ms and $13.6, 22.3, 36.4$ ms, respectively.

pol size for three different RSA modulus lengths are $1840, 2087, 2391$ bytes, respectively, that are definitely acceptable considering the storage capacity of today's mobile devices.

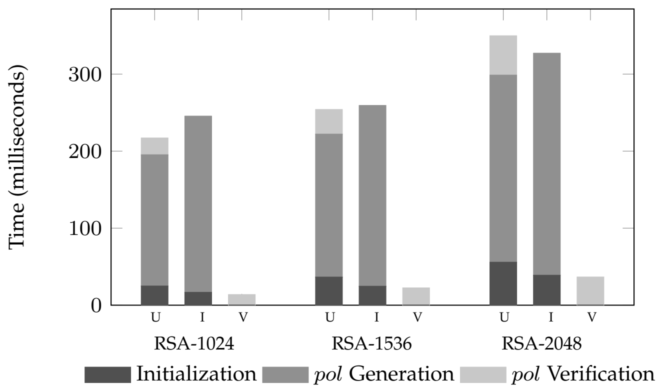


Fig. 9. Computation time of different phases of POLA for user (U), issuer (I) and verifier (V), with 1024 bits, 1536 bits and 2048 bits RSA modulus sizes for CL-signature.

5.2 *Geo-tampering* detection

The goal of this experiment is to analyze the geo-tampering detection threshold Δ (Def. 4) of our geo-tampering detection approach, and to evaluate the performance of our proposed algorithm to select effective neighborhood (Algorithm in Fig. 6) in terms of lowering this threshold. We also compare our geo-tampering detection algorithm with location determination (trilateration) based approach (see Sec. 4 for descriptions of both approaches).

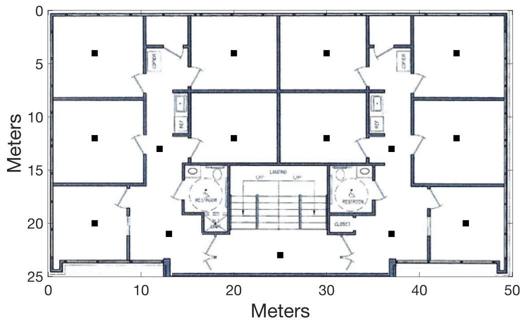


Fig. 10. Floor plan of an office building of 50×25 sq. meter area. A total of 15 access points (black squares) have been deployed at various locations in the building. In experiments, we ran each test for 15 times, to consider all fifteen possible locations as the location of the issuer AP. To ensure integrity of the experiments, we considered the worst possible (maximum) value for number of missing edges (Fig. 1) or geo-tampering threshold Δ (Fig. 11), among these 15 runs.

TABLE 1
Effective neighborhood selection: Direct Vs Proposed approach. Proposed approach significantly reduces the number of missing edges in EN_{ap_0}. When proposed approach selects an EN_{ap_0} of size 8 for coverage range of 25 meters, there are only 4 missing edges out of total possible 28 edges. Direct approach gives an EN_{ap_0} with 12 missing edges, for the same setting.

Effective neighborhood size			Coverage Range (m) 25	30	35	40	45
	4	Proposed	2(6)	0(6)	0(6)	0(6)	0(6)
		Direct	4(6)	3(6)	2(6)	1(6)	0(6)
	8	Proposed	4(28)	1(28)	0(28)	0(28)	0(28)
		Direct	12(28)	10(28)	6(28)	2(28)	0(28)
	12	Proposed	17(66)	8(66)	3(66)	1(66)	0(66)
		Direct	28(66)	18(66)	11(66)	3(66)	0(66)

Missing edges (Total edges)

We noted earlier that geo-tampering detection threshold (Δ) is the tuple of EDM Recovery Error (Δ_R) and distance measurement error (Δ_M). However, in experiments, distance measurement error is a parameter that we "choose", and observe the EDM Recovery Error for the chosen values of Δ_M. Hence when we mention geo-tampering threshold (Δ) in this section, we mean only the EDM recovery error (Δ_R).

5.2.1 Experiment Setup

We considered an indoor office environment of 50×25 square meters dimension, that deploys fifteen access points at different locations (e.g., each of the 10 rooms has one AP in it, 5 more are deployed in the passageway, see Fig. 10). We used MATLAB to simulate this environment.

Coverage range instead of line-of-sight. In indoor environment, Line-Of-Sight (LOS) is hardly achievable due to walls and other obstacles. However, unavailability of LOS does not render TOA based distance measurement techniques (which is used by our approach) impractical in indoor environment. TOA based ranging between two access points in indoor environment is practical as long as the APs are within *Coverage range* of each other. Coverage range is a distance that is related to *maximum tolerable path loss of the direct path*. A direct path cannot be detected after the Coverage range due to high attenuation and scattering of signal in indoor environment [43]. As shown in [43], in typical indoor environments (such as office, laboratory, factory), coverage range is between 25 to 60 meters.

5.2.2 Selecting effective neighborhood

We implemented Algorithm in Fig. 6, and for comparison considered a direct (baseline) approach where, given an effective neighborhood size m, a total $(m-1)$ APs are selected arbitrarily (randomly) from the available APs in the neighborhood N_{ap_0}. ap_0 is included by default, and thus completing the effective neighborhood.

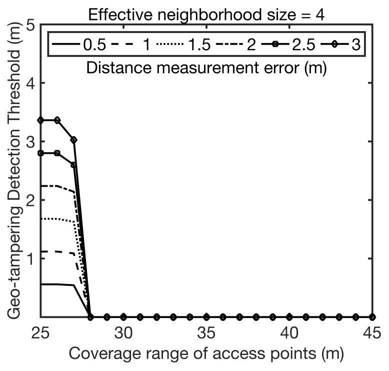
Comparison of direct and proposed approach. We compared the direct approach with the proposed approach in terms of number of missing edges in the resulting effective neighborhood EN_{ap_0}, and the comparison is shown in figure 1. We fixed the distance measurement error to 2 meters. We ran the test 15 times, each time we selected a different AP, located at different location in the building, to play the role of ap_0, and took worst possible value, that is, the highest number of missing edges in EN_{ap_0} among this 15 runs. We considered effective neighborhood size of 4, 8 and 12, for Coverage range $25, 30, 35, 40, 45$ meters, for both approaches (See Table 1).

Table 1 shows that our proposed selection algorithm performs better than the direct one in terms of missing edges, for all three sizes of EN_{ap_0}. For instance, when the required effective neighborhood size is 8 and the coverage range is 25 meters, proposed approach outputs an effective neighborhood with only 4 missing edges out of possible 28 edges, while the direct approach outputs an effective neighborhood with 12 missing edges. Since EDM reconstruction error is directly dependent on the number of missing elements [44], the proposed selection approach significantly reduces geo-tampering threshold Δ.

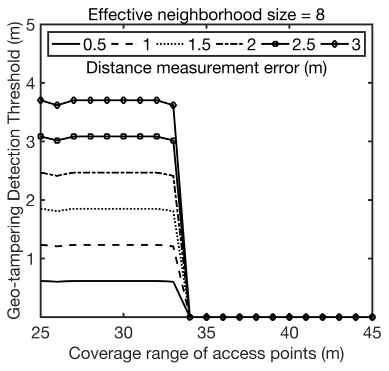
5.2.3 Trade-off between Δ and EN size.

Figure 11 shows how the value of Δ changes when we vary: (i) Size of the effective neighborhood (4, 8 and 12), (ii) Coverage range of access points (ranging from 25 to 45 meters, in 1 meter interval), and (iii) distance measurement error (0.5 to 3 meters, in 0.5 meter interval). We consider the AP layout as in Fig. 10, (i.e., 15 APs in a 50×25 sq. meters office building). We used algorithm in Fig. 6 to select the effective neighborhood in all cases. As in the last experiment, we ran each test for all 15 possible location of ap_0, and took the maximum value of Δ.

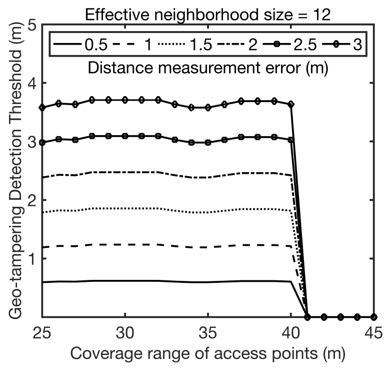
Observe that for all sizes of effective neighborhood, when the coverage range gets bigger, the geo-tampering threshold Δ approaches zero. This is due to the fact that bigger coverage range results in EDMs with very small percentage of missing elements, and consequently smaller recovery error. Also notice that smaller the effective neighborhood size, faster the Δ becomes zero in terms of coverage range. Smaller sizes of EN are therefore more suitable for applications that have devices with comparatively weaker radio strength, and/or operates in more complex indoor scenarios where coverage ranges are affected by obstacles.



(a)

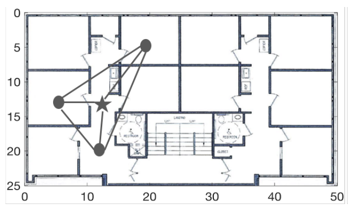


(b)

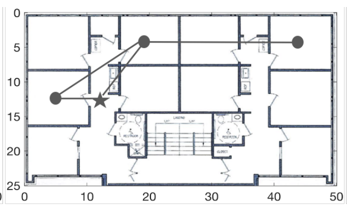


(c)

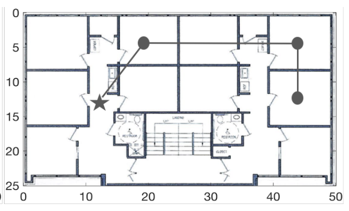
Fig. 11. Geo-tampering threshold (Δ) for varying coverage range (25 to 45 meters), distance measurement error (0.5 to 3 meters) and size of effective neighborhood (4, 8, 12). For all cases, after a certain value for coverage range of access points, Δ becomes zero. For example, in (a), this happens when coverage range increases from 27 to 28 meters. This jump to zero is due to (i) we chose the coverage range interval for our experiment as 1 meter, and (ii) number of missing edges in EN_{ap_0} is zero when coverage range is 28 meters in this case.



Scenario 1



Scenario 2



Scenario 3

	Scenario		
Approach	1	2	3
Location determination	0.58	NA	NA
Proposed	0	2.1	2.2

Δ (m)

Fig. 12. **Comparison with location determination based approach.** Star represents the issuer AP, circles represent neighboring APs, and a solid line between two APs means that these are in coverage range of each other. Location determination (Trilateration) based approach can only detect geo-tampering in Scenario 1, where all 4 APs are in each other's coverage range. Our approach is applicable in all three scenarios.

On the other hand, bigger sizes of EN are more suitable for applications that operates in less secure or public area, such as shopping malls, where the possibility of geo-tampering is higher; so bigger neighborhood will increase the chance of having at least three untampered APs in it, and thus guaranteeing the detection of geo-tampering attack (see Theorem 4).

5.2.4 *Comparison with location determination based detection.*

Figure 12 compares our approach in detecting geo-tampering attack with the location determination (trilateration) based detection approach.

We consider three scenarios. In all scenarios, we consider the presence of only 4 access points in the office building. We assume that all other access points are absent (i.e., temporarily down or were not deployed in the first place). In scenario 1, there are three access points at the coverage range the issuer AP. In scenario 2, two access points are at the coverage range of the issuer AP, and the remaining one is two hops away. In scenario 3, only one access point is at the coverage range of the issuer AP, and rests are two and three hops away, respectively.

We fixed a distance measurement error of 2 meters, and tried to compute the geo-tampering detection threshold Δ in all scenarios, for both approaches. For location determination based detection approach, the trilateration error, which is the distance between actual and trilaterated location of issuer AP, is the amount that the AP needs to be moved for a successful geo-tampering detection, and according to the definition 4, this is the geo-tampering detection threshold.

Observe that trilateration based approach is only applicable in scenario 1, where all three APs are at the coverage range of the issuing AP, and detects a geo-tampering with $\Delta = 0.58$ meters. Our approach is applicable in all three scenarios, and and detects geo-tampering with $\Delta = 0, 2.1$ and 2.2 meters, respectively.

6 Related Work

Geo-tampering attack that is introduced in this paper is complementary to the traditional attacks in localization systems such as [45], [46] where the access points remain intact and the prover's goal is to claim a different location. In secure localization systems the prover intends to change the timing of the signals such that the verifying nodes have measurements that are constrained by their physical locations that are assumed correct. For example in [45] it is shown that the prover's restriction is that they can add a single delay to all distances and this will limit the places that are possible to claim. In our setting the locations of the access points are malleable and the change, if any, must be detected in real time and by performing new distance measurements and comparing them with some base measurements. Note that this attack is increasingly possible as the number of access points gets smaller and can be easily moved/relocated. Also note that tampering with location (moving) is a much easier attack compared to breaking into such nodes and modify their codes.

A number of proof-of-location systems have been proposed to date but none of them considers location integrity of the infrastructure.

Location proof system in Javali et al. [34] utilizes CSI (Channel State Information) data extracted from packets sent by users to access points to determine their location, and a fuzzy vault technique to preserve user location privacy. However, this is vulnerable to relay attack that enables a user obtaining proof for locations that they have not been. VeriPlace [3] is another proof-of-location system that employs three different trusted third parties to provide proof-of-location to the users. However, user location verification capability of this scheme is significantly limited since the scheme can only detect location cheating when the two locations claimed by a user in consecutive proof-of-location requests are impossible in space-time domain for that individual. APPLAUS [2] is a proof-of-location system where bluetooth enabled users mutually generate proof-of-location that are uploaded on a server, that can later by queried by a *verifier* to validate a user's location claim. Periodically changing pseudonyms are used to provide user anonymity, that can introduce high storage and management overhead for the Certificate Authority. To achieve user anonymity with respect to the issuer, Nasouhi et al. [47] use a modified version of DB in [27] and encrypt the user ID to achieve POL security and privacy. They however do not provide user anonymity with respect to the *pol* verifier. Also, *pol* generation in the scheme is verifier specific; that is a user must use the public key of the verifier to encrypt their identity during the *pol* generation phase to preserve anonymity against issuer, resulting in a *pol* that can be used only by the target verifier.

Our model of POL system assumes existence of a trusted location infrastructure consisting of APs with correct locations and honest behaviour. In [2], [16], [17], [47], [48] however the *pol* is constructed by untrusted "witnesses", each consisting of a neighbouring device. These works, however, do not cryptographically model and prove security. Rather they use informal security arguments such as "trust ranking" [2], [16], [17] or incentive and penalty models [47], [48] to show security of the system.

7 Concluding Remarks

We provided a formal model and security definition for proof-of-location systems that provide privacy for the user against *pol issuer* and *verifier*, and proposed a proof-of-location system with provable properties in our model. We introduced a novel attack that targets the physical integrity of the proof issuing infrastructure, and results in forged *pol*. We showed how EDM can be effectively used to provide provable protection against this attack. Using EDM for infrastructure integrity is a novel approach and can have applications to other location systems. We also implemented our proof-of-location scheme on android smart-phones to observe computational time and storage requirement. Optimal placement of access points given the physical restrictions of indoor environments to naturally protect against geo-tampering is an interesting research direction.

Acknowledgment

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Mamunur Akand is a Ph.D. candidate in the Department of Computer Science, University of Calgary, Canada, and Dr. Reihaneh Safavi-Naini is his current supervisor. He received his Bachelor and Master in Computer Science from Islamic University of Technology, Bangladesh and University of Calgary, Canada, respectively. Akand has been working with ISPIA Lab, University of Calgary since 2014. His research interests include cryptography, information security, and location-based security and privacy.

Reihaneh Safavi-Naini holds the NSERC/Telus Industrial Research Chair and Alberta Innovates Chair in Information Security. She is the (co-) Founding Director of Institute for Security, Privacy and Information Assurance at the University of Calgary, during 2009-2019, and currently the Director of Information Security Lab in the Department of Computer Science at the University of Calgary, Canada. Before joining University of Calgary in 2007, she was a Professor of Computer Science, and the Director of Telecommunication and Information Technology Research Institute (TITR) and the Centre for Information Security, all at the University of Wollongong, Australia. She has a Ph.D. in coding theory from University of Waterloo, Canada. Her current research interests include information-theoretic security, provable cryptography, network security, and security of distributed and decentralised systems.

Marc Kneppers received his Master in Astronomy from University of Western Ontario (Western University). He has 20 years of experience in IT/networking security and was appointed a TELUS Fellow and is now the Chief Security Architect for TELUS Communications. His responsibilities include security oversight and strategy across all of TELUS' technologies and portfolios. He represents TELUS on Canadian national infrastructure forums and industry boards with membership in international security forums and vendor advisory boards.

Matthieu Giraud received his Master in Cryptography in 2016 from Universite de Bordeaux, France, and Ph.D. in 2019 from Laboratory LIMOS of University Clermont Auvergne, France, on the security of data storage in the cloud. Currently he is working as an Engineer in the cryptography department of Thales Security and Communications (Gennevilliers, France). His research interests include cryptography, mathematics, and protection of privacy. He has worked on symmetric searchable encryption schemes, particularly on their leakage.

Pascal Lafourcade obtained his Ph.D. in 2006 from ENS Cachan (laboratory LSV) on verification of cryptographic protocols in presence of algebraic properties. He spent 1 year at the ETH Zurich in David Basin group, where he worked on WSN. Then, he was associate professor at Verimag during 7 years, where he developed automatic techniques for verifying cryptographic primitives and analyzed security protocols. Currently, he holds an industrial chair on Digital Trust in Laboratory LIMOS (Team Networks and Protocols) and is associate professor at University of Auvergne (Clermont-Ferrand, France).