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Prox-RBAC: A Proximity-based Spatially Aware RBAC
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Prox-RBAC: A Proximity-based Spatially Aware RBAC

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ABSTRACT

As mobile computing devices are becoming increasingly dominant in enterprise and government organizations, the need for fine-grained access control in these environments continues to grow. Specifically, advanced forms of access control can be deployed to ensure authorized users can access sensitive resources only when in trusted locations. One technique that has been proposed is to augment role-based access control (RBAC) with spatial constraints. In such a system, an authorized user must be in a designated location in order to exercise the privileges associated with a role. In this work, we extend spatially aware RBAC systems by defining the notion of *proximity-based* RBAC. In our approach, access control decisions are not based solely on the requesting user's location. Instead, we also consider the location of other users in the system. For instance, a policy in a government application could prevent access to a sensitive document if any civilians are present. We introduce our spatial model and the notion of proximity constraints. We define the syntax and semantics for the Prox-RBAC language, which can be used to specify these policy constraints. We introduce our enforcement architecture, including the protocols and algorithms for enforcing Prox-RBAC policies, and give a proof of functional correctness. Finally, we describe our work toward a Prox-RBAC prototype and present an informal security analysis.

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1. INTRODUCTION

Role-based access control (RBAC) has been widely adopted as a way to streamline the maintenance of access control policies. As the deployment of mobile devices in these settings has increased, researchers have explored techniques for augmenting RBAC with contextual information. Perhaps the most common extension of RBAC is to incorporate the location constraints [9, 17, 14, 1, 20]. A common form of restriction is to constrain the use of roles to specific geographic locations. Suppose for example that an organization has a role *Manager* and this role is constrained to the location *Office*. A user wishing to use this role must not only have the authorization to use this role, but also be in his office when using the role. Consequently, the user would be prevented from using the role and the permissions granted to the role from other locations.

A major limitation of current approaches to spatially aware RBAC is that they focus only on the location of the user issuing the role usage request. However in many real situations whether a user can use a role and access the resources for which access is granted to the role may depend on the presence or absence of other users. As an example, consider a government agency with data classified at multiple levels of security. One policy could prohibit access to a sensitive document if there are any civilians (*i.e.*, non-governmental employees) present. Another could require the presence of a supervisor when a document is signed. Yet another could require that the subject is alone (*e.g.,* "for your eyes only" restrictions).

In this paper, we address the problem of specifying and enforcing a novel class of location constraints, referred to as *proximity-based* location constraints, for RBAC for both static and mobile environments. That is, we want to make decisions about granting access to roles by also taking into account the location of other users, possibly considering the proximity of those users to the requesting subject. Incorporating contextual factors in mobile environments is challenging, as these environments are inherently dynamic. As such, it is important to consider how to monitor and react to changes in users' locations. This challenge can be described as enforcing *continuity of usage* constraints. Our approach is to adopt the policy language semantics of the UCON$_{ABC}$ family of access control models [25, 18]. This family of models defines a number of semantic structures that enable the specification of contextual access control policies.

To illustrate the integration of continuity of usage with proximity-based constraints, consider the movement of a user from one protected region to another. For this user, it would be desirable to preserve the existing permissions in use if possible. However, the movement may involve entering a region in which a spatial role is not permitted to be used. Consequently, the movement would trigger a policy re-evaluation, revoking permissions as needed. In addition, the movement may impact another user by violating a

condition of the latter's policy constraints. Another challenge is to bind the user to the device making the request, as well as the location. That is, it would be undesirable for the user to download sensitive data to a device, then proceed to allow another user to leave with the device (and the data).

To address these challenges, we propose Prox-RBAC, which consists of a model, policy language, and enforcement architecture for specifying and enforcing proximity-based location constraints. In Prox-RBAC, administrators can write policies that specify either the presence or absence of other users within a protected area. Prox-RBAC also makes a distinction between policies that require authorization only a single time prior to access and policies that specify conditions that must continue to hold for as long as the permission is used. Finally, Prox-RBAC is backward compatible; that is, Prox-RBAC can specify existing spatially aware RBAC policies, as well as traditional RBAC. Thus, the contributions of this work can be summarized as follows.

- We introduce the notion of proximity constraints and provide a formal definition of these constraints.
- We specify the syntax and semantics of Prox-RBAC, a language for expressing proximity constraints in a spatial RBAC system.
- We propose the integration of proximity constraints with continuity of usage within the context of a constrained indoor space model.
- We define an enforcement architecture, including the specification of a cryptographic protocol and algorithms for Prox-RBAC.

2. BACKGROUND

Prox-RBAC builds on the GEO-RBAC spatially aware RBAC model. In addition, we use the UCON$_{ABC}$ family of models to define the semantics of the Prox-RBAC language. In this section, we provide a brief summary of these existing works.

2.1 GEO-RBAC

Prox-RBAC is defined as an extension of GEO-RBAC, a spatially aware RBAC model. In GEO-RBAC, traditional RBAC roles are augmented to incorporate the subject's location. Policies can use these *spatial roles* in defining fine-grained access control permissions. For instance, policies using the spatial role $< Manager, Room\ 513 >$ would require that the user activate the $Manager$ role (assuming the user is authorized) and be physically present in room 513. Consequently, a subject using the role $Manager$ would be denied access if the request is made from another location.

A key feature of GEO-RBAC that we use in Prox-RBAC is the differentiation of *role enabling* and *role activation*. A spatial role is automatically enabled if the user is authorized to activate the role and the user is physically present in the requisite location. However, an enabled role does not explicitly grant any privileges. Instead, the user must activate the role in order to exercise the associated permissions. This differentiation allows for mutually exclusive roles and hierarchical roles to be defined on the same space. It is the user's specific action the determines the role applied.

2.2 UCON$_{ABC}$

UCON$_{ABC}$ is a family of access control models that can be used to formalize the behavior of a system in terms of authorizations (A), obligations (B), and conditions (C), that must be satisfied either before (pre), during (on), or after (post) an access occurs. For instance, UCON$_{\text{preA}}$ can be used to formalize an access control system that requires authorizing the subject before the access is granted. With each type of model, there are multiple variations (*e.g.,* UCON$_{\text{preA}_0}$, UCON$_{\text{preA}_1}$, and UCON$_{\text{preA}_3}$). For a full description of these details, we refer the reader to the UCON$_{ABC}$ paper [25, 18].

Specifying a policy in UCON$_{ABC}$ can be done by declaring the functions, relations, and other mathematical structures, and then defining the implication that must hold if the access is granted. As an example, consider a traditional RBAC system, where $\mathcal{S}$, $\mathcal{O}$, $\mathcal{A}$ and $\mathcal{R}$ denote the sets of subjects, objects, actions, and roles, respectively. A permission is an ordered pair (o, a) for $o \in \mathcal{O}, a \in \mathcal{A}$. Subjects are mapped to active roles via the $ActiveRoles$ function, while $PermittedRoles$ maps permissions with the roles that are to be granted access. As $ActiveRoles$ are user-specific, we also declare $ATT(\mathcal{S}) = \{ActiveRoles\}$, where $ATT(\mathcal{S})$ specifies the set of attributes that are associated with subjects.

To specify that a subject s is authorized to perform action a on object o, UCON$_{\text{preA}_0}$ uses an invariant $allowed(s, o, a) \Rightarrow P$, where P denotes a necessary condition for authorization. For instance, in RBAC, the necessary condition is that the requester has an active role ($\exists role \in ActiveRoles(s)$) that is granted the desired permission ($\exists role' \in PermittedRoles(o, a), role \geq role'$). The following example illustrates how UCON$_{\text{preA}_0}$ can specify traditional RBAC policies.

$< role, act, obj >$ – UCON$_{\text{preA}_0}$:
$Perms = \{(o, a) \mid o \in \mathcal{O}, a \in \mathcal{A}\}$
$ActiveRoles : \mathcal{S} \rightarrow 2^{\mathcal{R}}$
$PermittedRoles : Perms \rightarrow 2^{\mathcal{R}}$
$ATT(\mathcal{S}) = \{ActiveRoles\}$
$allowed(s, o, a) \Rightarrow \exists role \in ActiveRoles(s),$ $\exists role' \in PermittedRoles(o, a), role \geq role'$

To enforce that certain conditions continue to hold as the access occurs (*i.e.*, continuity of usage constraints), UCON$_{ABC}$ defines additional primitive formalisms. First, $preCON$ declares a set of conditions that are evaluated, while $getPreCON(s, o, a)$ specifies proposition built on these conditions. Then $preConChecked$ can be used in the necessary proposition in the $allowed(s, o, a) \Rightarrow P$ implication. For instance, if the subject must be over the age of 18 or accompanied by an adult, we could specify this portion of the policy as:

$preCON = \{Over18(s), Accompanied(s)\}$
$getPreCON(s, o, a) = Over18(s) \vee Accompanied(s)$
$allowed(s, o, a) \Rightarrow preConChecked(getPreCON(s, o, a))$

For on-going conditions (*i.e.*, UCON$_{\text{onC}}$), similar structures exist (*i.e.*, $onCON$ and $getOnCON(s, o, a)$). Specifying permission revocation is similar to the $allowed(s, o, a)$ invariant. Specifically, $stopped(s, o, a) \Leftarrow \neg onConChecked(getOnCON(s, o, a))$ declares that the access must be stopped once the on-going required condition is no longer true.

3. THE PROX-RBAC LANGUAGE

In this section we present the syntax and semantics of our proximity constraint language. After a short preliminary subsection to introduce some notation, we describe our space model, which is a key element in the definition of the proximity constraint model. We then briefly introduce our spatial role model, followed by the introduction of the three main constructs of our proximity constraint model. Such introduction is followed by the definition of the syntax and semantics of the proximity constraint model.

3.1 Preliminaries

The core Prox-RBAC model, which underlies our language, uses a number of primitives that are similar to existing spatially aware RBAC models. As in traditional RBAC, we have $Subjects$ ($\mathcal{S}$) that can request permission to perform $Actions$ ($\mathcal{A}$) on $Objects$ ($\mathcal{O}$). Let $Roles$ ($\mathcal{R}$) denote the set of roles in the system. When $s \in \mathcal{S}$ requests the privilege to perform $a \in \mathcal{A}$ on $o \in \mathcal{O}$, s must activate a role $r \in \mathcal{R}$ to which the requested permission is granted.

3.2 Space Model

The first challenge in defining our model is to specify how space is modeled. We adopt a spatial model that subdivides generic spaces into regions based on security classifications. We consider the reference space $\top$ to be a region that is divided into a set of **protected areas** (PA). A PA is a physically bounded region of space, accessible through a limited number of **entry points**, which consists of a physical barrier that requires authorization. Each PA can be arbitrarily large and we place no restrictions on the internal structure. For instance, a PA could consist of a single room or an entire floor that is made up of distinct but unlocked rooms. In the latter case, the subject's presence in a particular room is irrelevant to the security questions, and we model the floor in its entirety as a PA. An entry point is a one-way walking device which connects one PA to another PA. Should the passage be in both directions, two distinct entry points are needed, one for each direction.

Figure 1 demonstrates a number of characteristics of our space. The PAs are distinguished by shading and lines filling the area. The red dots indicate the entry points and are labeled as the guard device $e_{i,j}$ controlling passage from pa_i to pa_j. Observe that rooms 103A and 103B are both part of pa_2, thus indicating that PAs do not necessarily have a one-to-one correspondence to the features of the space. In addition, suite 100A defines pa_3 and consists of the entire space shaded with gray, which includes rooms 101, 102, 103A, and 103B. Similarly, pa_5 covers the entire floor. This illustrates that PAs can be defined hierarchically. Finally, pa_O defines the $outdoor$ space.

To represent this constrained space we define an indoor space model [16, 15]. Indoor space models present distinguishing features which perfectly match the requirements posed by our scenario. A major feature is that those spaces are cellular (or symbolic), *i.e.*, they consist of a finite set of named cells or symbolic coordinates (*e.g.*, rooms 103A and 103B) [3]. Moreover, indoor spaces may present complex topologies. Among the various topologies that one can specify, the most relevant are the connectivity between the indoor and outdoor spaces, as well as connectivity between cells (*i.e.*, PAs). We choose to define the indoor space model as the tuple $(\mathcal{P}, \mathcal{E}, G, H)$ where $\mathcal{P}$ is the set of PAs, $\mathcal{E}$ the set of entry points, G the connectivity topology referred to as *accessibility graph*, and H the hierarchy of PAs. This space model allows us to introduce the notion of accessibility graph for a specific subject, defining the subspace in which the subject is authorized to move.

3.2.1 Hierarchy of PAs

As noted above, our model incorporates the notion of hierarchy of PAs. For instance, access to the first floor of a building may be restricted to a set of users; in addition, access to room 105 may be further restricted to an individual user. As such, when the user is in room 105, the permissions associated with the first floor should still be granted.

To model this hierarchy, we introduce the partial order $\sqsubseteq$ between PAs such that $pa_i \sqsubseteq pa_j$ (*i.e.*, pa_i is-part-of pa_j) means: i) any subject present in pa_i is also present in pa_j; ii) pa_i can be only entered if the subject is present in pa_j; iii) if pa_i is part of both pa_j and pa_k then either $pa_k \sqsubseteq pa_j$ or $pa_j \sqsubseteq pa_k$.[1] Note that the meaning of the partial order relation is not simply of spatial containment. That motivates the second condition which explicitly requires the two PAs to be connected through an entry point. For instance, consider a room ($Room$ 204) whose only entrance is a private stairwell from a room on the first floor; since this room is not reachable from any other part of the second floor, $Room$ 204 $\not\sqsubseteq$ $Floor$ 2. The third condition states that the partial order takes the form of a tree where the root is the reference space and the leaves are the PAs which do not contain further PAs. Note that, as $\sqsubseteq$ is a partial order, if $pa_i \sqsubseteq pa_j$ it cannot happen that $pa_j \sqsubseteq pa_i$, for $i \neq j$. Therefore, the number of subjects in pa_j is equal or greater than the sum of the subjects in the children of pa_j. This partial order leads naturally to the notion of **type**; for instance, if pa_i is of the $room$ type and pa_j is the $floor$ type, it is possible that $pa_i \sqsubseteq pa_j$, but it cannot happen that $pa_j \sqsubseteq pa_i$. In addition, we write $s \in_l pa$ to express the user's location at the finest granularity. That is, if $s \in_l pa_i$, then $\nexists pa_j$ with $pa_j \sqsubseteq pa_i$ and $i \neq j$ such that $s \in_l pa_j$. Figure 2(b) illustrates the hierarchy corresponding to Figure 1.

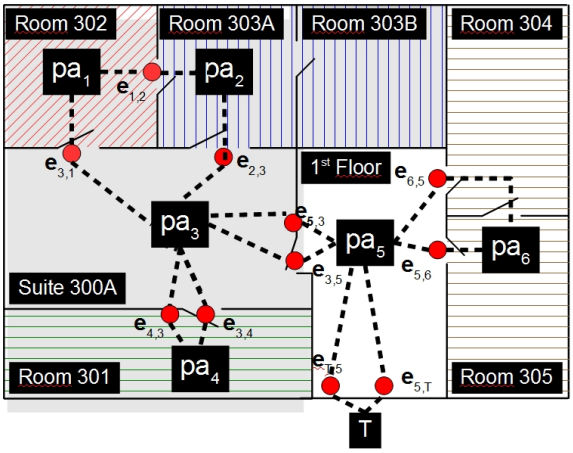


Figure 1: Reference space with PAs marked

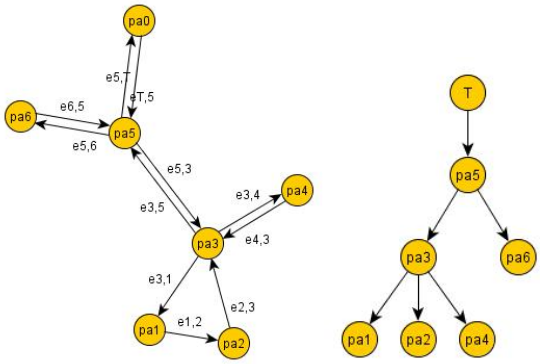
3.2.2 Accessibility graph

The accessibility graph represents the relationship of connectivity among PAs through a directed multigraph (multidigraph). Figure 2 shows the accessibility graph for the space in Figure 1. The accessibility graph consists of a set V of vertices each representing either the outdoor space or a PA, and a multiset $A \subseteq V \times V$ of edges, one for each entry point connecting one PA to another PA. The direction of edges reflects the direction of entrypoints. Edges are labelled with the corresponding entrypoints, *i.e.*, $e_{i,j}$ (or $e^k_{i,j}$, for some $k > 0$ in case of multiple entry points from pa_i to pa_j). If there is a path between the two vertex representing pa_i and pa_j respectively, we say that pa_j is reachable from pa_i. If the path consists of a unique edge then pa_j is directly reachable. *Main entrance* and *main exit* are the vertices that are directly reachable from pa_O and from which pa_O can be directly reached, respectively. The graph G is assumed to connected. Moreover, for the accessibility graph to be consistent with the hierarchy of PA, the following properties must hold.

Properties (Accessibility Graph)

- Every PA must be directly reachable from either the parent or sibling in the hierarchy of PA. This follows from the fact

[1]To simplify the model, in our context, PAs can only overlap if one is wholly contained within the other. However, one could extend the model to allow overlapping PAs, at the cost of increased complexity of the hierarchical processing.



(a) Accessibility graph (b) Hierarchy of PAs

Figure 2: Accessibility graph and hierarchy of PAs for Figure 1

that a PA can be only entered if the subject is present in the parent PA.

- The main entrances must correspond to the PAs at the highest level in the hierarchy of PA. This follows from the fact that otherwise a PA could be entered from a PA which is different from the parent or sibling, against the definition of hierarchy of PAs.

- The graph also does not contains loops (*i.e.*, edges do not start from and end to the same vertex).

3.2.3 Accessibility graph for a subject

Intuitively, the entrance of a subject into a PA corresponds to the transition from one vertex to an adjacent vertex in the accessibility graph. Key to our definition of the security system is the authentication and confirmation of passage. That is, enforcement of Prox-RBAC requires a physical barrier separating PAs, as well as deployment of a technology that ensures only authorized personnel can pass. Detecting such a movement requires the subject's presence at an entry point. However, we must also have a way to detect that the subject did, in fact, pass through the entry point, rather than doubling back into the current space. As we will describe in Section 4.4, ensuring the trustworthiness of position is a challenging issue in deployment of spatially aware RBAC systems.

Besides passage confirmation, the other aspect of concern that we consider here regards the authentication of passage. Subjects, in general, are not allowed to enter every PA. We denote with $AuthPA(s)$ the set of PAs that the subject s is authorized to enter. For this set to be consistently defined, every PA in the set must be reachable from the outdoor space and, vice versa, the outdoor space must be reachable from any PA in the set. It can be shown that these requirements are met if the following conditions are satisfied.

Properties (Authorized PAs)

- If $pa \in AuthPA(s)$, then the parent of pa must also be in $AuthPA(s)$.

- If $pa \in AuthPA(s)$ and pa is only reachable from one or more siblings in the hierarchy, then all these siblings must also be in $AuthPA(s)$.

The subgraph with vertices that are the authorized PAs and edges that are the subset of edges which connect the authorized PAs is itself an accessibility graph, namely it represents the *accessibility graph of the subject*. Therefore, because every PA of the set can be reached through the parent or a sibling, when the subject is at an entry point $e_{i,j}$, the system can refer to the accessibility graph of the subject to determine whether the subject is authorized to enter the target PA.

3.3 Spatial Roles

As in GEO-RBAC, we augment traditional roles with geographic information. Specifically, a **spatial role** is the tuple $< r, pa >$, where $r \in \mathcal{R}$ and $pa \in \mathcal{P} \cup \{\top\}$, where $\top$ denotes the reference space. A spatial role $< r, pa >$ is **enabled** for the subject s if s has activated the traditional role r, and, in addition, one of these two conditions is satisfied: a) $s \in_l pa$; ii) $s \in_l pa_i$ and $pa_i \sqsubseteq pa$. Note that if subject s has been assigned role $< r, pa >$ with $pa \in \mathcal{P}$, then s must be authorized to enter pa, *i.e.*, $pa \in AuthPA(s)$, otherwise the role would have never been enabled. The spatial role is then **activated** if the user wishes to exercise the privileges associated with the role. If user s has activated role $< r, pa >$, we write $< r, pa > \in ActiveRoles(s)$.

While role activation in Prox-RBAC seems intuitive, subtle challenges arise when users are permitted to maintain contintuous access across PA boundaries. To be precise, consider a user who moves from pa_i to pa_j and what should happen to $< r, pa_i > \in ActiveRoles(s)$. In order to streamline the user experience, Prox-RBAC keeps the roles active, but updates the location from pa_i to pa_j. That is, if $< r, pa_i > \in ActiveRoles(s)$ prior to the transition, then $< r, pa_j > \in ActiveRoles(s)$ after. Additionally, if $s \notin pa_i$ after the transition (*i.e.*, $pa_j \not\sqsubseteq pa_i$), then $< r, pa_j > \notin ActiveRoles(s)$. One exception to this automatic activation of $< r, pa_j >$ occurs when mutually exclusive roles are defined. Specifically, if $< r, pa_j >$ would conflict with another *activated* role $< r', pa_j >$, then both are deactivated in the transition.[2]

Although it would be desirable to treat the movement as atomic, we find this insufficient to provide strong location guarantees. For instance, a user could initiate the movement with an entry point, then wait for several seconds before actually passing through the doorway. Thus, our access control policies must account for the time between authorization and the actual passage between the PAs. As such, the transition triggers a **movement event**, during which the user's location is identified as $s \in_l pa_k$, where pa_k is the **least common ancestor**, the smallest PA that contains both the old and new PAs. That is, $pa_i \sqsubseteq pa_k$, $pa_j \sqsubseteq pa_k$, and either $pa_i \not\sqsubseteq pa_l$ or $pa_j \not\sqsubseteq pa_l$ for any $pa_l \in Children(pa_k)$, where $Children(pa_k)$ is defined by the hierarchy of PAs. In addition, permissions currently in use will be revoked during the movement event only if the permission is not granted for $< r, pa_j >$ and $pa_j \not\sqsubseteq pa_i$. Otherwise, the permissions are retained.

3.4 Continuous Proximity Constraints

A **proximity constraint** is a security requirement that is satisfied by the location of other users. If the constraint must be continuously evaluated for the duration of the user's access session, then we call the constraint **continuous**. Proximity constraints are built from three primitive constructs: relative constraint clauses, continuity of usage constraints, and timeouts. Relative constraint clauses define the static presence or absence conditions that must be met. However, mobile environments are inherently dynamic. As such, the latter two constructs are necessary to ensure the relative constraint clause is enforced properly as the environment changes.

A **relative constraint clause** specifies the proximity requirement of other users in the spatial environment. These clauses can be described as either **presence constraints** or **absence constraints**.

[2]The deactivation does not occur if $< r, pa_j >$ would conflict with a role $< r', pa_j >$ that is enabled but not currently activated.

To formulate these conditions, we adopt an intuitive syntax that can be illustrated as follows:

$$at\_most\ 0\ civilian\ in\ Room\ 105$$

The basic structure consists of an optional cardinality qualifier (*e.g.,* at_most or at_least), a nonnegative integer specifying the number of subjects, a role (*e.g.,* $civilian$), and a spatial relationship (*e.g.,* $in\ Room\ 105$). The spatial relationship consists of two parts: a topological relation and a logical location descriptor that identifies a PA. Let $\mathcal{R}_T$ denote the set of topological relations. In our initial approach, we will only consider a small set of relations, namely $\mathcal{R}_T = \{in, out, adj\}$. The location descriptor can be absolute, as was the case here, or it can take the form of $this.type$. In this latter structure, the $type$ specifies a level in the hierarchy of PAs, while $this$ dictates that the location of the subject fulfilling the role in the clause must match that of the requester. For instance, let v_i denote $Room\ 105$, v_j denote $Room\ 100$, and v_k denote $Floor\ 1$. Assume the requester is in $Room\ 105$ and his supervisor is in $Room\ 100$. Since $v_i \sqsubseteq v_k$ and $v_j \sqsubseteq v_k$, the following relative constraint clause would be satisfied:

$$at\_least\ 1\ supervisor\ in\ this.floor$$

Some operations may require a significant duration. For instance, reading a sensitive document may take several minutes or hours. Furthermore, it may be necessary to ensure the relative constraint holds for the entire duration of the permitted session. To declare whether the constraint must be checked only at the beginning of the session or must hold for the duration, we introduce into our language **continuity of usage qualifiers**, called $when$ and $while$, respectively. Their use is illustrated as follows:

$$while\ (\ at\_most\ 0\ civilian\ in\ Room\ 105\ )$$

A **when constraint** is evaluated at the access request time; if the constraint is satisfied, the permission is granted. A **while constraint** is repeatedly checked and the permission is granted until the constraint is violated. The frequency of the check is a system-wide parameter that is dependent on the deployment scenario. That is, specifying this parameter requires considering issues such as network latency, size of the spatial environment, number and mobility of users.

In many cases, the desired security guarantees may require satisfying multiple relative constraints. To allow for such cases, we permit the use of two basic logical connectives: $\vee$ (logical or) and $\wedge$ (logical and). These logical connectives can be used to join relative constraint clauses or continuity of usage constraints. Parentheses may be used to specify precedence; otherwise, the clauses are enforced left-to-right. As an example, assume that c_1 is a $while$ constraint dictating that no civilians are present. In addition, either a supervisor or accountant must initially be present (c_2 or c_3). The following constraints are equivalent in expressing this requirement:

$$while\ (\ c_1\ )\ \wedge\ (\ when\ (\ c_2\ )\ \vee\ when\ (\ c_3\ )\ )$$
$$while\ (\ c_1\ )\ \wedge\ when\ (\ c_2\ \vee\ c_3\ )$$

One critical issue in enforcing continuity of usage constraints is how to react once a $while$ constraint no longer holds. In one scenario, the permission could be suspended until the condition is once again satisfied. In others, it may be acceptable to allow some leeway, wherein the permission is still granted for a short duration of time, even though the condition is technically being violated. For instance, consider a proximity constraint that specifies a supervisor must be present to read an accounting record. Due to a shift change, one supervisor leaves the room before the next arrives. However, the break is short enough that it is acceptable to allow the subject to retain the permission during their absences.

In some cases, it is acceptable for proximity constraints to be violated for a brief duration. For instance, if the policy specifies the presence of a supervisor, it would be undesirable for the employee to lose permissions while the supervisor leaves for a short break. Consequently, every proximity constraint that includes at least one $while$ clause must end with a **timeout constraint**, which takes the following form:

$$while\ (\ clause\ )\ timeout\ t$$

Here, $t \in \mathbb{N}_0$ specifies the maximum amount of time for which the permission is granted once the $while$ constraint fails. While the simplest approach is to use a single time unit for all timeout constraints, a straightforward augmentation of our language could allow t to specify the units, as well. If $t = 0$, then the permission is immediately revoked. If the condition is once again satisfied before the time limit has been reached, the permission is automatically extended as if the condition held for the entire duration.

3.5 Prox-RBAC Syntax

To formalize this syntax,[3] let $\mathcal{C}$ denote the set of basic relative constraint clauses with no Boolean connectives. Formally, we can write $c =< q, n, r, r_t, p >$, where q is a cardinality qualifier, $n \in \mathbb{N}_0$, $r \in \mathcal{R}$, $r_t \in \mathcal{R}_T$, and $p \in \mathcal{P}$. $\mathcal{C}^*$, then, denotes the set of clauses that can be constructed from a Boolean formula of basic clauses. This produces the following grammar for constraint clauses:

$$\begin{array}{lll} C & ::- & C \vee C \\ & | & C \wedge C \\ & | & Q\ n\ role\ topo\ pa \\ Q & ::- & at\_most\ |\ at\_least\ |\ \epsilon \end{array}$$

Now, let $\mathcal{W}$ denote the set of continuity of usage constraints. That is, $while\ (\ c\ ) \in \mathcal{W}$ and $when\ (\ c\ ) \in \mathcal{W}$ if $c \in \mathcal{C}^*$. Given that timeouts can only apply to $while$ constraints, we create a distinguished set $\mathcal{W}_{while} \subseteq \mathcal{W}$ that consists exclusively of the constraints $while\ (\ c\ )$, where $c \in \mathcal{C}^*$. As before, let $\mathcal{W}^*$ denote the set of Boolean conjunctions and disjunctions that can be formed from any combination of continuity of usage constraints.[4] This leads to the following rules:

$$\begin{array}{lll} W & ::- & W \vee W \\ & | & W \wedge W \\ & | & when\ (\ C\ ) \\ & | & while\ (\ C\ ) \end{array}$$

Finally, let $\mathcal{T}$ denote the set of timeouts written as $timeout\ t$, where t denotes a finite unit of time, and let $\epsilon \in \mathcal{T}$. We write $\Phi = (\mathcal{W}^* \times T) \cup \{\perp\}$ to denote the set of all possible proximity constraints, where $\perp$ denotes the absence of a proximity constraint, which allows for traditional spatially aware policies.

3.6 Prox-RBAC Policies and Semantics

A Prox-RBAC **policy** is a tuple of the form $< sr, a, o, \varphi >$, where $sr \in \mathcal{R} \times \{\mathcal{P} \cup \{\top\}\}$, $a \in \mathcal{A}$, $o \in \mathcal{O}$, and $\varphi \in \Phi$. In this section, we present the formal semantics for Prox-RBAC

[3]For the sake of simplicity, we omit from our grammars any parentheses that can be used to indicate Boolean formulas. We feel that including them in the specification needlessly complicates the discussion and distracts the reader from the most relevant topics.

[4]Observe that negations are not necessary in our language. First, negations would only be applicable in joining relative constraint clauses (*i.e.*, statements such as $not\ while\ (\ c\ )$ would be awkward). Second, the at_most and at_least qualifiers are clear opposites when the numbers are adjusted accordingly (*e.g.,* $at\_most\ 0$ is the negation of $at\_least\ 1$). Thus, our language can express negations without introducing an explicit Boolean operator.

in terms of the UCON$_{ABC}$ family of core models. Prox-RBAC employs $UCON_{AC}$ semantics, as we require authorizations (A) and conditions (C), but not obligations (B). In all of the semantic specifications below, $\geq$ can denote either the dominance relation on the partially ordered set of roles $\mathcal{R}$ or the traditional inequality on integers. The notation 2^S refers to the power set of the set S.

We start with the simplest case, in which $\varphi = \bot$. That is, there is no proximity constraint enforced, and the policy indicates a spatially aware RBAC role as defined in existing works. We can write these semantics formally as a UCON$_{\text{preA}_0}$ policy.

$< role, act, obj, \bot >$ – UCON$_{\text{preA}_0}$:

$role =< r, pa >, r \in \mathcal{R}, pa \in \mathcal{P}$
$Perms = \{(o, a) | o \in \mathcal{O}, a \in \mathcal{A}\}$
$ActiveRoles : \mathcal{S} \rightarrow 2^{\mathcal{R}}$
$EnabledRoles : \mathcal{P} \rightarrow 2^{\mathcal{R}}$
$PermittedRoles : Perms \rightarrow 2^{\mathcal{R}}$
$ATT(\mathcal{S}) = \{ActiveRoles\}$

$allowed(s, o, a) \Rightarrow \exists\, r \in EnabledRoles(pa),$
$s \in_l pa \wedge r \in ActiveRoles(s) \wedge$
$\exists\, r' \in PermittedRoles(o, a), r \geq r'$

These semantics state that, if s is allowed to perform a on o, there must be a traditional RBAC role r that is enabled by entering pa, s is physically present there, and s has activated the role. In addition, r must dominate r', which is a traditional RBAC role that is permitted to perform a on o. Obviously, it may be the case that $r = r'$. However, when hierarchical roles are created, $r \geq r'$ implies that activating r inherits all of the permissions associated with r'. As this is UCON$_{\text{preA}_0}$, this policy is checked only once prior to granting access. Finally, note that the same semantics can be applied for traditional RBAC policies, which can be expressed with $pa = \top$, indicating that role activation can occur anywhere. Thus, Prox-RBAC semantics are flexible enough to accommodate more traditional policies.

To define the semantics for $when$ and $while$ constraints, we must define a number of helper functions, which are listed in Figure 3. $TopoSat$ defines the conditions under which topological relations are satisfied. Observe that in and out are not simply satisfied by containment. Instead, Prox-RBAC considers the PA describing the subject's location at the finest granularity. As an illustration, recall the example in Section 3.2.1 in which $Room\ 204 \not\sqsubseteq Floor\ 2$; if $s \in_l Room\ 204$, then $TopoSat(s, in, Floor\ 2)$ returns false. adj, on the other hand, does not consider the finest granularity of the user's location. Instead, adj is satisfied if the subject is in a PA that is immediately reachable from the PA under consideration (or vice versa); furthermore, neither PA can be a parent of the other. $TopoSat$ is used in the context of the Sat function, which determines if a constraint has been satisfied.

Building on these functions, we can define what it means to satisfy a relative constraint clause $c \in \mathcal{C}^*$. Recall that c can either be a simple clause ($c \in \mathcal{C}$), or it can be a complex clause that is created from disjuctions and/or conjunctions of simple clauses. That is, $c =< c_0, b_1, c_1, \ldots, b_n, c_n >$, where c_i is a simple clause and b_i is a Boolean connective. For each simple clause c_i, we have $c_i =< q, n, role, topo, pa >$. First, we apply $c_i' = Cast(c_i)$, which replaces the original pa with the PA of the correct type. Note that $Cast$ only changes c_i if pa is of the form $this.\tau$, where τ indicates a type (*e.g.*, room, suite, floor); that is, $Cast$ converts the relative pa into an absolute pa'. Now, we can apply Sat to the individual components of c_i'. This procedure describes the functionality of $EvalC$, which evaluates a simple constraint clause based on the subject's location.

Similarly, a $when$ clause $w \in \mathcal{W}^*$ consists of a Boolean combination of simple $when$ clauses, each of which contains a Boolean combination of simple relative constraint clauses. Hence, $EvalW$ evaluates each simple clause independently, then evaluates the resulting Boolean expression. Finally, $Eval$ itself operates on the full $when$ clause, evaluating the Boolean expression that is produced by evaluating each simple $when$ clause. This produces the following UCON$_{\text{preC}_0}$ semantics:

$< role, act, obj, when >$ – UCON$_{\text{preC}_0}$:

[premises from $< role, act, obj, \bot >$]
$Eval : \mathcal{W}^* \times \mathcal{P} \rightarrow \{true, false\}$
$Location : \mathcal{S} \rightarrow \mathcal{P}$
$preCON = \{Eval(when, Location(s))\}$
$getPreCON(s, o, a) = Eval(when, Location(s))$

$allowed(s, o, a) \Rightarrow$
$preConChecked(getPreCON(s, o, a)) \wedge$
$(\ \exists\, r \in EnabledRoles(pa), s \in_l pa\ \wedge r \in ActiveRoles(s) \wedge$
$\exists\, r' \in PermittedRoles(o, a), r \geq r')$

$While$ constraints with a timeout of 0 (*i.e.*, immediate revocation) are very similar to $when$ constraints, with the exception that a subset of the conditions are repeatedly checked as the permission is exercised. To model this behavior, we introduce the $WhenToBool$ function, which takes a Boolean combination of $when$ and $while$ clauses and replaces the $when$ clause with either $true$ or $false$ according to the initial evaluation. The result of this extension is the following UCON$_{\text{preC}_0\text{onC}_0}$ semantics:

$< role, act, obj, while >$ – UCON$_{\text{preC}_0\text{onC}_0}$:

[premises from $< role, act, obj, when >$]
$WhenToBool : \mathcal{W}^* \times \mathcal{P} \rightarrow \mathcal{W}^*$
$preCON = \{Eval(while, Location(s))\}$
$getPreCON(s, o, a) = Eval(while, Location(s))$
$onCON = \{Eval(WhenToBool(while), Location(s))\}$
$getOnCON(s, o, a) =$
$Eval(WhenToBool(while), Location(s))$

$allowed(s, o, a) \Rightarrow$
$preConChecked(getPreCON(s, o, a)) \wedge$
$(\exists\, r \in EnabledRoles(pa), s \in_l pa \wedge r \in ActiveRoles(s) \wedge$
$\exists\, r' \in PermittedRoles(o, a), r \geq r')$
$stopped(s, o, a) \Leftarrow$
$\neg onConChecked(getOnCON(s, o, a))$

The final type of constraint to consider is a $while$ constraint with a timeout $t > 0$. Here, we introduce $\mathcal{X}$ to denote the data structures containing expiration times for permissions. That is, $PermExp(s)$ will return $x \in \mathcal{X}$. The simplest form of x would be a 2-dimensional array $\mathcal{O} \times \mathcal{A}$, where (o, a) would store the expiration time for exercising $a \in \mathcal{A}$ on $o \in \mathcal{O}$. As such, we use the notation $x[o, a]$ for this value, though we formalize this behavior with the $FindExp$ function. The $UpdateExp$ function takes such a data structure, and updates only the $x[o, a]$ entry to be $t_c + t_e$, the sum of the current system time and the expiration time. All other entries remain unchanged.

Using these functions, we extend the UCON$_{\text{preC}_0\text{onC}_0}$ model [5] to express $while$ constraints with a $timeout$ using the following semantics. Our extension is to introduce the $onUpdate(ATT(s))$ procedure to update the subject's $PermExp$ attribute as the access occurs. During access, if the condition holds (*i.e.*, the $while$ clause is satisfied), then the expiration is updated accordingly. The permission is revoked only if the condition fails *and the current time is greater than the expiration time*.

[5] UCON$_{ABC}$ does not define an $onUpdate$ procedure for conditions, but it does for authorizations and obligations. However, we find it very straightforward to augment the model to support the same functionality for conditions.

$TopoSat : \mathcal{S} \times \mathcal{R}_T \times \mathcal{P} \rightarrow \{true, false\}$

$TopoSat(s, r_t, p) = true$ if and only if one of these hold:

$r_t = in$ and $\exists p' \in \mathcal{P}\ (s \in_l p' \wedge p' \sqsubseteq p)$

$r_t = out$ and $\exists p' \in \mathcal{P}\ (s \in_l p' \wedge p' \not\sqsubseteq p)$

$r_t = adj$ and $\exists p', p'' \in \mathcal{P}\ (s \in_l p') \wedge (p' \sqsubseteq p'') \wedge (p'' \not\sqsubseteq p) \wedge (p \not\sqsubseteq p'') \wedge ((p'', p) \in \mathcal{E} \vee (p, p'') \in \mathcal{E})$

$Sat : \mathcal{C} \rightarrow \{true, false\}$

$Sat(c) = true$ if and only if

$c =< q, n, role, topo, pa >, cmp = Inequality(q)$ and

$\exists S' \subseteq \mathcal{S}, |S'| cmp\ n$

$\forall s \in S'\ \exists role' \in ActiveRoles(s)$ such that

$(role = role' \wedge TopoSat(s, topo, pa))$

$Cast : \mathcal{C} \times \mathcal{P} \rightarrow \mathcal{C}$

[omitted for brevity, but type definition is shown]

[replaces "this" keyword according to specified PA]

$EvalC : \mathcal{C} \times \mathcal{P} \rightarrow \{true, false\}$

$EvalC(c, pa) = Sat(Cast(c, pa))$

$EvalW : \mathcal{W} \times \mathcal{P} \rightarrow \{true, false\}$

$EvalW(< w, c >, pa) =$

$BoolEval(< c'_0, b_1, c'_1, \ldots, b_n, c'_n >)$ where

$c =< c_0, b_1, c_1, \ldots, b_n, c_n >$ and

$\forall i, 0 \leq i \leq n, c'_i = EvalC(c_i, pa)$

$WhenToBool : \mathcal{W}^* \times \mathcal{P} \rightarrow \mathcal{W}^*$

$WhenToBool(< w_0, b_1, w_1, \ldots, b_n, w_n >, pa) =$

$< w'_0, b_1, w'_1, \ldots, b_m, w'_m >$, where $\forall i, 0 \leq i \leq n$

$w_i \in \mathcal{W}_{while} \Rightarrow w'_i = w_i$

$w_i \notin \mathcal{W}_{while} \Rightarrow w'_i = EvalW(w_i, pa)$

$Eval : \mathcal{W}^* \times \mathcal{P} \rightarrow \{true, false\}$

$Eval(< w_0, b_1, w_1, \ldots, b_n, w_n >, pa) =$

$BoolEval(< w'_0, b_1, w'_1, \ldots, b_m, w'_m >)$, where

$\forall i, 0 \leq i \leq n, w'_i = EvalW(w_i, pa)$

Figure 3: Helper functions for evaluating Prox-RBAC semantics

$< role, act, obj, while, time >$ – $\text{UCON}_{\text{preC}_0\text{onC}_0}$:

[premises from $< role, act, obj, when >$]

$CurentTime \in \mathbb{R}$ is the current system time

$PermExp : \mathcal{S} \rightarrow \mathcal{X}$

$UpdateExp : \mathcal{X} \times \mathcal{O} \times \mathcal{A} \times \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \mathcal{X}$

$FindExp : \mathcal{X} \times \mathcal{O} \times \mathcal{A} \rightarrow \mathbb{Z}^+$

$ATT(\mathcal{S}) = \{ActiveRoles, PermExp\}$

$onCON = \{Eval(WhenToBool(while, Location(s))),$

$CurrentTime \leq FindExp(PermExp(s), o, a)\}$

$getOnCON(s, o, a) =$

$(\ Eval(WhenToBool(while, Location(s))) \vee$

$CurrentTime \leq FindExp(PermExp(s), o, a)\ )$

$allowed(s, o, a) \Rightarrow$

$preConChecked(getPreCON(s, o, a)) \wedge$

$(\exists\ r \in EnabledRoles(pa), s \in_l pa \wedge r \in ActiveRoles(s) \wedge$

$\exists\ r' \in PermittedRoles(o, a), r \geq r')$

$onUpdate(PermExp(s)) : PermExp(s) =$

$UpdateExp(PermExp(s), o, a, t, time)$ if

$Eval(WhenToBool(while, Location(s)))$

$stopped(s, o, a) \Leftarrow$

$\neg onConChecked(getOnCON(s, o, a))$

4. IMPLEMENTATION

As a proof of concept, we have implemented a Prox-RBAC prototype. Our architectural design couples a centralized authorization server with a distributed, asynchronous clients. These clients can be either stationary (*e.g.,* workstations) or mobile devices (*e.g.,* laptops). In either case, accessing sensitive data requires providing a high-integrity proof of location that is generated with the help of a fixed-location device, such as an near-field communication (NFC) or magnetic stripe reader. In addition, passage through an entry point must be monitored and controlled by a fixed-location device that reports the user's location change to the centralized server. In this section, we describe the principals of our enforcement architecture, our multi-factor authentication protocol and algorithm for requesting access to a protected resource, and a description of our implementation features. We then use these definitions to present the sketch of a formal proof of correctness.

4.1 Principals

Our Prox-RBAC prototype is built on interaction between four principals. First, the *Authorization Server (AS)* is the centralized server that acts as the policy decision point (PDP). The *AS* maintains a mapping of all users' locations, represented at the finest-granularity PA that applies. The *AS* also maintains all access control policies. Next, the *User* refers to the human user requesting access. Each user (subject) s will have an identifier id_s, a password pwd_s[6], and a proximity-connection device that is used for generating the proof of location. This portable device will have a secret value $sv(s)$, as well as a certificate, signed by the *AS*, that contains data required to perform an interactive zero-knowledge proof-of-knowledge protocol that demonstrates possession of $sv(s)$.

The user performs the access control protocol using a *Client*, which is a trusted computing device for accessing sensitive data. The client acts as the policy enforcement point (PEP), revoking privileges when requested by the *AS*. As clients may be mobile, they are identified solely by an identifier and denoted c_i. Each client has a network connection to communicate with the *AS* and is equipped with a trusted computing component (TCC), such as a TPM, that can bind keys to applications. That is, the application requesting access to a protected resource will have a public-private key pair, denoted $pk(c_i)$ and $sk(c_i)$ respectively, and a certificate $Cert(c_i)$ signed by *AS*. For simplicity, we assume the presence of a trusted path for the user to enter a password. Additionally, we assume unauthorized software is prevented from accessing sensitive data, and remote attestation techniques are used to ensure that the software on the client matches a pre-approved configuration.

A *Location Device (LD)* is a fixed-location reader distributed in a PA. These devices are used to authenticate the location of the user at the time of an access request. Since these devices have fixed locations, each is denoted $ld_{i,j}$ to indicate the j^{th} location device in pa_i. Each *LD* employs a proximity-based communication technology and possesses a certificate $Cert(ld_{i,j})$ that is signed by the *AS*. These certificates contain coordinates $cdt(ld_{i,j})$, as well as data that allows *AS* to retrieve $sv(ld_{i,j})$, a secret value stored on $ld_{i,j}$. For example, this data could be an encrypted version of $sv(ld_{i,j})$, where only *AS* has the corresponding key. In order to bind the user and client to the location, the client and *LD* must have a physical connection. For instance, the *LD* could be integrated in a laptop base station that is built into a desk.[7]

4.2 Access Request

Our access request protocol is built on a number of cryptographic primitives. First, let (Gen,Enc,Dec) denote both public key and symmetric key encryption schemes. In both cases, $k \leftarrow \mathsf{Gen}(1^n)$

[6]Other user authentication mechanisms, such as public key certificates, could also be used in place of a password.

[7]One could argue that the physical connection between the client and *LD* obviates the need for the proximity-based communication device that the user carries. However, the device would be a small persistent device that the user employs for entrance to secured areas and other activities, as well. As such, the device is simply used to provide an additional layer of authentication.

$\mathsf{Read}(s, o, r, c_i, ld_{j,k})$ – Subject s activates role r and requests $read$ privilege on object o, using client c_i at location device $ld_{j,k}$.		
(1)	$s \leftrightarrow ld_{j,k}$	$\mathsf{Prove}(sv(s))$
(2)	$s \rightarrow c_i$	id_s, pwd_s, r
(3)	$c_i \rightarrow ld_{j,k}$	$\mathsf{Sign}_{sk(c_i)}(id_s), Cert(c_i)$
	$[ld_{j,k}]$	$h := \mathsf{H}(n \| id_s \| T \| pk(c_i) \| sv(ld_{j,k}))$
(4)	$ld_{j,k} \rightarrow c_i$	$c \leftarrow \mathsf{Commit}(h)$
(5)	$c_i \rightarrow AS$	$\mathsf{Sign}_{sk(c_i)}(c), Cert(c_i)$
(6)	$c_i \leftrightarrow AS$	$\mathsf{Auth}(id_s, pwd_s, r)$
	$[AS]$	$\mathcal{K} \leftarrow \mathsf{Gen}(1^n)$
(7)	$AS \rightarrow c_i$	$\mathsf{Enc}_{pk(c_i)}(\mathcal{K})$, $\mathsf{Enc}_{\mathcal{K}}(\mathsf{Sign}_{sk(AS)}(c, pk(c_i))$
(8)	$c_i \rightarrow ld_{j,k}$	$\mathsf{Sign}_{sk(AS)}(c, pk(c_i))$
	$[ld_{j,k}]$	$\mathcal{K}' \leftarrow \mathsf{Gen}(1^n)$
(9)	$ld_{j,k} \rightarrow c_i$	$Cert(ld_{j,k})$, $\mathsf{Enc}_{pk(AS)}(\mathcal{K}')$, $\mathsf{Enc}_{\mathcal{K}'}(\mathsf{Open}(c, h))$
(10)	$c_i \rightarrow AS$	$o, Cert(ld_{j,k})$, $\mathsf{Enc}_{pk(AS)}(\mathcal{K}')$, $\mathsf{Enc}_{\mathcal{K}'}(\mathsf{Open}(c, h))$
(11)	$AS \rightarrow c_i$	$\mathsf{Enc}_{\mathcal{K}}(\hat{o})$

Figure 4: Protocol for requesting read access

denotes a probabilistic key generation algorithm and $m := \mathsf{Dec}_k(c)$ denotes the decryption of ciphertext c using the key k. In the public key case, $c \leftarrow \mathsf{Enc}_k(m)$ is an IND-CPA-secure encryption (which is probabilistic), while $c := \mathsf{Enc}_k(m)$ denotes (t, ϵ)-secure (deterministic) symmetric key encryption. While this reuse is a slight abuse of notation, it should be obvious to the reader which scheme is used, as we denote public key pairs as $pk(\cdot)$ and $sk(\cdot)$ and a symmetric key as $\mathcal{K}$.

Similarly, (Gen,Sign,Verify) denotes an unforgeable signature scheme where $k \leftarrow \mathsf{Gen}(1^n)$ denotes a probabilistic key generation algorithm, $s := \mathsf{Sign}_{sk(x)}(m)$ indicates the signature s to be the message m signed with the secret key of x, and $v := \mathsf{Verify}_{pk(x)}(s, m)$ produces either $true$ or $false$ by verifying s is the signature of m, using the public key of x. Let H denote a collision-resistant cryptographic hash function such that $h := \mathsf{H}(m)$ denotes the hash of a message m.

Finally, let (Commit,Open) denote a non-interactive commitment scheme that is both perfectly hiding and computationally binding. $c \leftarrow \mathsf{Commit}(s)$ refers to the probabilistic generation of the public commitment c for the secret value s, while $\mathsf{Open}(c, s)$ denotes the process of revealing of the parameters of the commitment. Let $\mathsf{Prove}(sv(p))$ denote an interactive zero-knowledge proof-of-knowledge protocol in which the prover p demonstrates knowledge of a secret value sv. Finally, $\mathsf{Auth}(id_s, pwd_s, r)$ denotes an authentication protocol in which the user provides password pwd_s to prove the claim to identity id_s, and r indicates a requested role.

Figure 4 shows our basic access protocol. It is initiated by a subject $s \in \mathcal{S}$ to request $read$ permission on object $o \in \mathcal{O}$, while using role $r \in \mathcal{R}$. The request is made using client c_i at location $ld_{j,k}$. The protocol starts by s using his proximity device to prove knowledge of $sv(s)$ to $ld_{j,k}$ and entering id_s, pwd_s, and r into the client via a trusted path. The client presents a signed version of id_s to $ld_{j,k}$ via the physical connection, and $ld_{j,k}$ responds with a commitment c, binding id_s to c_i at timestamp T with a nonce n. Note that only $ld_{j,k}$ is able to open this commitment. c_i signs the commitment, sending the result to the *AS*. The *AS* and c_i then enter an authentication protocol that confirms the identity of id_s and his authorization to enter r.

Assuming the authentication of s is successful, the *AS* returns a signed version of the commitment c, encrypted in a manner that is only readable by c_i. c_i decrypts the signed commitment, and forwards the result to $ld_{j,k}$, who confirms the signature of the *AS* (thus indicating that the *AS* received the commitment intact). $ld_{j,k}$ opens the commitment and encrypts the result with the public key of the *AS*. c_i forwards the encrypted packet and the name of the object o requested, and the *AS* returns the encrypted object with a key bound to c_i. Note that, while this protocol describes $read$ actions, it is straightforward to extend it to handle $write$ actions.

4.3 Algorithms

Policy evaluation occurs after step 10 of the access control protocol in Figure 4. The **Request** algorithm, defined below, attempts to activate the spatial role based on the user's location. If the activation is successful, the policies are evaluated and the on-going conditions (in the case of $while$ constraints) are determined. Assuming the initial conditions are satisfied, the algorithm returns approval and the object is sent in step 11 of the protocol.

Request(s, o, c_i, a, r)
Input: s: the requesting subject; o: the requested object; c_i: the client; a: the requested action
Output: $approved$ or $denied$
1. **if** $Activate(s, r, Location(s)) = failure$ **then return** $denied$
2. $satisfied \leftarrow EvalPolicies(s, Policies[o][a])$
3. **if** $satisfied = \emptyset$ **then return** $denied$
4. $ongoing \leftarrow \emptyset$
5. **foreach** $p = < sr, a, o, \phi > \in satisfied$
6. $\quad ongoing \leftarrow ongoing \cup WhenToBool(p, Location(s))$
7. $Ongoing(s) = Ongoing(s) \cup \{< o, c_i, ongoing >\}$
8. **return** $approve$

The policy evaluation procedure is defined in the **EvalPolicies** algorithm. The *AS* identifies the relevant policies for the object and action, determines if the user has an activated role that satisfies the policy, then proceeds to evaluate the proximity constraints. The algorithm returns the set of policies that are satisfied, as these policies may have on-going conditions (*i.e.*, $while$ clauses) that must be continuously enforced.

EvalPolicies$(s, P(o, a))$
Input: s: the requesting subject; $P(o, a)$: the set of matching policies
Output: $satisfied$: the set of policies that have been satisfied
1. **foreach** $p = < sr, a, o, \varphi > \in P(o, a), sr = < r_p, pa_p >$
2. $\quad permitted \leftarrow false$
3. $\quad$ **foreach** $role = < r_s, pa_s >$ **in** $ActiveRoles(s)$
4. $\quad\quad$ **if** $r_s \geq r_p$ **and** $pa_s \sqsubseteq pa_p$ **then**
5. $\quad\quad\quad permitted \leftarrow true$
6. $\quad$ **if** $permitted = true$ **then**
7. $\quad\quad$ **foreach** w clause in φ
8. $\quad\quad\quad$ **foreach** $constraint$ in w
9. $\quad\quad\quad\quad$ evaluate $constraint$ based on location information
10. $\quad\quad\quad$ evaluate w clause based on $constraint$ satisfaction
10. $\quad\quad$ **if** w is satisfied satisfied **then**
11. $\quad\quad\quad satisfied \leftarrow satisfied \cup \{p\}$
12. **return** $satisfied$

The constraint evaluation is a straightforward evaluation based on the location information maintained by *AS* and the specified topological relation. For instance, consider the constraint

$$when\ at\ least\ 1\ Supervisor\ in\ Room\ 105$$

The *AS* simply checks to see if there is at least one person in Room 105 who has Supervisor as an active role. If the constraint instead specified

$$when\ at\ least\ 1\ Supervisor\ in\ Floor\ 1$$

then the *AS* would compute the sum of all users with an active Supervisor role who are present anywhere on the first floor. If the constraint uses the $this$ keyword, the algorithm traverses the parent hierarchy to find the correct PA based on the user's PA. Hence, the policy evaluation has a linear complexity based on identifying the PAs that are relevant to the constraint.

4.4 Prototype Implementation

We have developed a proof-of-concept prototype of Prox-RBAC to measure the performance of the cryptographic protocols and the enforcement algorithms. To instantiave the Prove construct, we employed the Feige-Fiat-Shamir identification protocol [11], which uses a zero-knowledge proof, and we use a Pedersen commitment [19] for the Commit and Open primitives. For Auth, we simply used a salted hash of a password. We used SHA-256, AES-256, 1024-bit RSA, and SHA-1 with DSA for the Hash, Enc_k, $\mathsf{Enc}_{pk(c)}$, and Sign_k primitives, respectively. We implemented our prototype in Java 1.6.0_20, relying on standard cryptographic implementations when possible. For the Pedersen commitment and the Feige-Fiat-Shamir protocols, we used a custom implementation that employed the BigInteger class. Our test machine consisted of a 2.26GHz Intel® Core™ 2 Duo CPU with 3GB of 667MHz memory, running on Ubuntu 10.04 ("Lucid Lynx") with version 2.6.32 of the Linux kernel. Based on 500 iterations, the most expensive of the cryptographic operations are the Pedersen commitment (average of 17.7 ms to generate and 20.2 ms to confirm) and RSA (5.7 ms to encrypt, but 30.2 ms to decrypt). Other than the DSA signature (9.8 ms average), all other computations required less than 1 ms on average to complete. The average time for the complete Read protocol (including the policy evaluation algorithms) was approximately 89.4 ms.

Moving toward a practical deployment with location sensing is more challenging. We have performed preliminary work toward using an Advanced Card Systems (ACS) NFC reader, model ACR 122 to communicate with a Nokia 6131 NFC-enabled cell phone. Communication between the ACR 122 and the Nokia 6131 uses the peer-to-peer extension to the Java JSR 257 Contactless Communication API. Our software employs the NFCIP library[8], which uses the Java smartcardio libraries. One difficulty we had with this implementation is that the BigInteger class does not exist in the Java ME distribution. Consequently, deploying a protocol such as the Feige-Fiat-Shamir scheme requires developing one's own solution for large integers. However, based on our experiments, we observe that the average computation time for generating the Feige-Fiat-Shamir proof is less than the amount of time to perform the AES encryption in the protocol. Thus, such a deployment is feasible.

The final challenge in developing a practical implementation of Prox-RBAC is enforcement of the one-way movement through entry points. In our current prototype, we use the NFC phone to connect to a reader that would (in a real deployment) control the lock to a door. To confirm passage, the user would have to use the NFC phone to connect to a reader on the other side of the door. Clearly, this approach is inelegant, and a more desirable solution would include other forms of sensing to detect the user's movement. In addition, our prototype does not include proximity-based communication between the client (*i.e.*, a laptop) and the entry. For completeness and to prevent data leakage, the entry points should be equipped with a means to detect when a laptop is leaving the PA and revoking permissions as necessary.

4.5 Functional Correctness

In this section, we use the protocol and algorithm specifications to demonstrate that our prototype correctly enforces the Prox-RBAC semantics as defined. Due to space constraints, we will only offer sketches of proofs and leave full consideration for the full version of the paper.

Lemma 1: The access protocol defined in Figure 4 prevents unauthorized access under the Dolev-Yao adversarial model.

[8]Available download at http://code.google.com/p/nfcip-java/.

Proof: As all sensitive data is encrypted, eavesdroppers only observe signed data (preventing unauthorized modification), the object being requested, or the one-time use commitment. If the adversary modifies either of the latter two pieces of data, the user and/or the *AS* would detect the corruption. Furthermore, modifying the object requested would not give the user access to unauthorized data. Thus, only authorized access is allowed. □

Lemma 2: The policy evaluation algorithms correctly enforce $when$ and $while$ constraints.

Proof: The **EvalPolicies** algorithm includes a procedure for evaluating the initial conditions, corresponding to the $when$ constraints. The algorithm returns the set of satisfied policies, which are then added to the user's $Ongoing$ list. This list identifies the $while$ constraints that must continuously be evaluated. If an $Ongoing$ constraint is no longer satisfied, the list entry contains the object and client used; the *AS* uses this information to send a revocation request to the client. □

5. RELATED WORK

Role-based access control (RBAC) [21] is a popular technique for maintaining and administering access privileges in an organization. One of the advantages of RBAC is its ability to incorporate hierarchies into the model [22, 23]. Building on the core RBAC model, researchers have proposed extensions that integrate contextual factors [6, 8]. These extensions include temporal and spatial constraints [9, 14, 1, 9, 20, 4, 2, 7, 5]. Our work can be viewed as an extension of the latter category, in which spatial information is considered as part of the access control request. However, our work has a significantly different focus than these works.

Specifically, models for spatial RBAC systems, such as those just identified, are based solely on the location of the user making the request. The presence or absence of other users in the reference space is irrelevant in those models. In contrast, our focus is to define proximity constraints that are based on the user's location *in relation to other users in the system*. This work is the first to focus on the specification of these relative constraints and the challenges of their enforcement.

Two works are close in aim as our own. Team-based access control using contexts (C-TMAC) [12], like our own, incorporates both RBAC and the location of multiple users. However, in C-TMAC, the system only considers locations of users who are on the same team as the requesting user, rather than all users. Furthermore, C-TMAC does not specifically focus on location, but rather the more generic notion of context (of which location is one aspect). As such, C-TMAC does not consider the challenges of location validation and does not define a policy language. A different interpretation of proximity has previously been explored in the context of access control. Specifically, the proximity-based access control (PBAC) model [10, 13] considers the requesting user's proximity to a computer. For instance, if a temporary emergency medical center is created during a disaster response, then a doctor who is in the immediate vicinity would be granted access. In other words, PBAC can be viewed as considering *absolute proximity*, as the computer typically has a static location. Our work, in contrast, considers *relative proximity* based on the locations of other users, who are assumed to be continually moving.

One area of study that may appear similar to our own is the question of nearest neighbor queries. For instance, Yang *et al.* [24] have proposed techniques for k-nearest neighbor queries within an indoor environment. These queries are based on a minimal walking distance metric. Although Prox-RBAC also considers the location of other users, we do not use a uniform metric. That is, our spatial

model abstracts the distance between protected regions of varying sizes. One interesting extension of Prox-RBAC could be to apply k-nearest neighbor queries to our spatial model, where the distance metric is the number of hops within the network of entry points.

6. CONCLUSIONS

In this work, we have extended the notion of spatially aware RBAC to incorporate proximity constraints, which specify policy requirements that are based on the locations of other users in the environment. We have introduced our spatial model, primarily consisting of an accessibility graph that is based on existing work on graph-based indoor space models. We have also defined the syntax and semantics for the Prox-RBAC language for specifying these constraints. In addition to the formalization of our model and language, we have defined an enforcement architecture, including protocols and algorithms. We have offered preliminary results that prove the architecture correctly meets the semantic definitions. We have also described our initial work toward developing a prototype Prox-RBAC system, and closed with an informal security analysis. Based on these results, we find that it is feasible to construct a usable and efficient proximity-based RBAC system.

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8. REFERENCES

[1] S. Aich, S. Sural, and A. K. Majumdar. STARBAC: Spatiotemporal role based access control. In *OTM Conferences*, 2007.

[2] V. Atluri and S. A. Chun. A geotemporal role-based authorisation system. In *International Journal of Information and Computer Security*, volume 1, pages 143–168, 2007.

[3] C. Becker and F. Dürr. On location models for ubiquitous computing. *Personal Ubiquitous Computing*, 9:20–31, January 2005.

[4] S. Chandran and J. Joshi. LoT RBAC: A location and time-based RBAC model. In *Proc. of 6th International Conference on Web Information Systems Engineering (WISE)*, pages 361–375. Springer-Verlag, 2005.

[5] L. Cirio, I. F. Cruz, and R. Tamassia. A role and attribute based access control system using semantic web technologies. In *Proc. of 2007 On the Move to Meaningful Internet Systems - Volume Part II*, OTM'07, pages 1256–1266, Berlin, Heidelberg, 2007. Springer-Verlag.

[6] M. J. Covington, W. Long, S. Srinivasan, A. K. Dev, M. Ahamad, and G. D. Abowd. Securing context-aware applications using environment roles. In *Proc. of 6th ACM Symposium on Access Control Models and Technologies (SACMAT '01)*, pages 10–20, 2001.

[7] I. F. Cruz, R. Gjomemo, B. Lin, and M. Orsini. A location aware role and attribute based access control system. In *Proc. of 16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM GIS)*, pages 84:1–84:2, New York, NY, USA, 2008. ACM.

[8] M. L. Damiani and E. Bertino. Access control and privacy in location-aware services for mobile organizations. In *7th International Conference on Mobile Data Management (MDM)*, 2006.

[9] M. L. Damiani, E. Bertino, B. Catania, and P. Perlasca. GEO-RBAC: A spatially aware RBAC. In *ACM Transactions on Information and System Security (TISSEC)*, 2007.

[10] S. M. Didar-Al-Alam, H. Mahmud, and M. A. Mottalib. Modifications in proximity based access control for multiple user support. *International Journal of Engineering Science and Technology*, 2:3603–3613, 2010.

[11] U. Feige, A. Fiat, and A. Shamir. Zero knowledge proofs of identity. In *Proc. of 19th Annual ACM Symposium on Theory of Computing (STOC)*, pages 210–217, 1987.

[12] C. K. Georgiadis, I. Mavridis, G. Pangalos, and R. K. Thomas. Flexible team-based access control using contexts. In *Proc. of 6th ACM Symposium on Access Control Models and Technologies (SACMAT)*, pages 21–27, New York, NY, USA, 2001. ACM.

[13] S. K. S. Gupta, T. Mukherjee, K. Venkatasubramanian, and T. B. Taylor. Proximity based access control in smart-emergency departments. In *Proc. of 4th Annual IEEE international Conference on Pervasive Computing and Communications Workshops (PERCOMW)*, pages 512–, Washington, DC, USA, 2006. IEEE Computer Society.

[14] F. Hansen and V. Oleschuk. SRBAC: A spatial role-based access control model for mobile systems. In *Proc. of 8th Nordic Workshop on Secure IT Systems (NORDSEC)*, pages 129–141, October 2003.

[15] C. S. Jensen, H. Lu, and B. Yang. Graph model based indoor tracking. In *10th International Conference on Mobile Data Management (MDM)*, pages 122–131, 2009.

[16] C. S. Jensen, H. Lu, and B. Yang. Indoor–a new data management frontier. *IEEE Data Eng. Bull.*, 33(2):12–17, June 2010.

[17] M. S. Kirkpatrick and E. Bertino. Enforcing spatial constraints for mobile rbac systems. In *Proc. of 15th ACM Symposium on Access Control Models and Technologies (SACMAT)*, pages 99–108, New York, NY, USA, 2010. ACM.

[18] J. Park and R. Sandhu. The UCON$_{ABC}$ usage control model. In *ACM Transactions on Information and System Security*, volume 7, pages 128–174, 2004.

[19] T. P. Pedersen. Non-interactive and information-theoretic secure verifiable secret sharing. In *Proc. of 11th Annual International Conference on Advances in Cryptology*, CRYPTO '91, pages 129–140, London, UK, 1992. Springer-Verlag.

[20] I. Ray, M. Kumar, and L. Yu. LRBAC: A location-aware role-based access control model. In *Proc. of Internation Conference on Information Systems Security (ICISS)*, pages 147–161, 2006.

[21] R. Sandhu. Role-based access control models. In *IEEE Computer*, Feb. 1996.

[22] R. Sandhu. Role hierarchies and constraints for lattice-based access controls. In *4th European Symposium on Research in Computer Security (ESORICS)*, 1996.

[23] R. Sandhu. Role activation hierarchies. In *3rd ACM Workshop on Role-Based Access*, 1998.

[24] B. Yang, H. Lu, and C. S. Jensen. Probabilistic threshold k nearest neighbor queries over moving objects in symbolic indoor space. In *Proc. of 13th International Conference on Extending Database Technology*, EDBT '10, pages 335–346, New York, NY, USA, 2010. ACM.

[25] X. Zhang, J. Park, F. Parisi-Presicce, and R. Sandhu. A logical specification for usage control. In *Proc. of 9th ACM Symposium on Access Control Models and Technologies (SACMAT)*, 2004.