

# Context-aware Dynamic Access Control for Pervasive Applications\*

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## Abstract

*As computing technology becomes more pervasive and mobile services are deployed, applications will need flexible access control mechanisms. Unlike traditional approaches for access control, access decisions for these applications will depend on the combination of the required credentials of users and the context and state of the system. In this paper, we extend the role-based access control model to provide dynamic context-aware access control for pervasive applications. The operation of the presented model is illustrated.*

*Keywords: security, access control, context-aware, pervasive computing, role based.*

## 1 Introduction

Pervasive computing and communication technologies are rapidly weaving themselves into the fabrics of everyday life and have the potential for fundamentally redefining the way we interact with information, each other, and the world around us. The proliferation of smart gadgets, mobile devices, PDAs and sensors has enabled the construction of pervasive computing environments, transforming regular physical spaces into intelligent spaces [4]. Such intelligent spaces provide services and resources that users can access and interact with via personal portable devices such as a PDA using short-range wireless communications such as Bluetooth or IEEE 802.11. The resulting anytime-anywhere access infrastructures is enabling a new generation of applications that can leverage this pervasive information Grid to continuously manage, adapt and optimize. One example of such an application is the Aware Home project at Georgia

Institute of Technology [7]. Sensors in the home can capture, process and store a variety of information about its residents and their activities, enabling the Aware Home application to detect and respond to events in the room. Another application is the Intelligent Room project at MIT. In this application, computers are embedded in a room so that people can interact with computers the way they do with other people, using speech, gesture, movement and context [9]. Other applications are described in [2, 6]. Such pervasive applications are characterized by continuous pervasive access to information, resources and services and ad hoc, dynamic interactions between participating entities, and lead to significant research challenges.

One key challenge in pervasive applications is managing security and access control. Access Control List (ACL) is a very commonly used access control mechanism. In this approach, permission to access resources or services is moderated by checking for membership in the access control list associated with each object. However, this strategy is inadequate for pervasive applications as it does not consider context information. In a pervasive environment, users are mobile and typically access resources (information, services, sensors, etc.) using mobile devices. As a result the context of a user (i.e. location, time, system resources, network state, network security configuration, etc.) is highly dynamic, and granting a user access without taking the user's current context into account can compromise security as the user's access privileges not only depend on "who the user is" but also on "where the user is" and "what is the user's state and the state of the user's environment". As a result, even an authorized user can damage the system as the system may have different security requirements within different contexts. Traditional access control mechanisms such as access control list break down in such environments and a fine-grained access control mechanism that changes the privilege of a user dynamically based on context information is required.

Although a lot of work has been done in the area of access control, most of this work is user-centric, where only

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credentials of the user are considered when granting access permission. Relatively little research has been done to combine context information with credentials while making access control decisions. The existing research however does not address pervasive applications where context is dynamic and a user's privileges must continuously adapt based on the context.

This paper presents a dynamic context-aware access control mechanism that dynamically grants and adapts permissions to users according to current context. The proposed mechanism extends the role based access control (RBAC) model [1], while retaining its advantages (i.e. ability to define and manage complex security policies). The model dynamically adjusts *Role Assignments* and *Permission Assignments* based on context information. In our approach, each user is assigned a role subset (by the authority service) from the entire role set. Similarly the resource has permission subsets for each role that will access the resource. During a secure interaction, state machines are maintained by delegated access control agents at the subject (*Role State Machine*) to navigate the role subset, and the object (*Permission State Machine*) to navigate the permission subset for each active role. The state machine consists of state variables (role, permission), which encode its state, and commands, which transform its state. These state machines define the currently active role and its assigned permissions and navigate the role/permission subsets to react to changes in the context.

The rest of this paper is organized as follows: Section 2 presents background and related work. Section 3 outlines a motivating application. Section 4 presents the proposed dynamic context-aware access control model. Section 5 presents a short discussion about the model and its implementation. Section 6 concludes the paper.

## 2 Background and Related Work

Role based access control (RBAC) [10, 1] is an alternative to traditional discretionary (DAC) and mandatory access control (MAC). In RBAC, users are assigned roles and roles are assigned permissions. A principle motivation behind RBAC is the ability to specify and enforce enterprise specific security policies in a way that maps naturally to an organization's structure. As user/role associations change more frequently than role/permission associations, in most organizations, RBAC results in reduced administrative costs as compared to associating users directly with permissions. It can be shown that the cost of administrating RBAC is proportional to  $U+P$  while the cost of associating users directly with permissions is proportional to  $U * P$ , where  $U$  is the number of individuals in a role and  $P$  is the number of permissions required by the role. Sandhu et al [10, 1] define a comprehensive framework for RBAC models which

are characterized as follows:

- $RBAC_0$  : the basic model with users associated with roles and roles associated with permissions.
- $RBAC_1$  :  $RBAC_0$  with role hierarchies.
- $RBAC_2$  :  $RBAC_1$  with constraints on user/role, role/role, and/or role/permission associations.

Recently RBAC was found to be the most attractive solution for providing security features in different distributed computing infrastructure [10]. Although the RBAC models vary from very simple to pretty complex, they all share the same basic structure of subject, role and privilege. Other factors such as relationship, time and location, which may be part of an access decision, are not considered in making access control decision in these models. In this paper, we extend  $RBAC_0$  to provide context-aware access control mechanisms for pervasive applications.

Giuri and Iglío [3] have proposed a role-based access control model that provides special mechanisms for the definition of content-based access control policies. By extending the notion of permission, they have allowed for the specification of security policies in which the permission of an object may depend on the content of the object itself. For example, in a health-care organization, the physician is only allowed to access and modify patient records related to his or her patient.

Woo and Lam [11] designed a distributed authorization service using their Generalized Access Control Language (GACL). In their design, they use the notion of system load as the determining factor in certain access control decisions, so that, for example, certain programs can only be executed when there is enough system capacity available.

Finally, Michael J. Covington et al [8, 7] have proposed the Generalized Role Based Access Control (GRBAC) model. In this model, they extend the traditional RBAC by applying the roles to all the entities in a system. (In RBAC, the role concept is only used for subjects). By defining three types of roles, i.e., Subject roles, Environment roles, and Object roles, GRBAC uses context-information as a factor in making access decisions.

All of the research efforts described above take additional factors into consideration when make access control decision. However, both Giuri, Iglío and Woo, Lam don't consider context information as a key factor in their access control mechanism. In GRBAC, the definition of environment roles allows the model to partially address problem we described, but it may not be feasible in practice because the potential large amount of environment roles make the system hard to maintain. Also, by defining too many roles in the system, it loses the advantage that RBAC provides.

### 3 Access Control Challenges for Pervasive Applications

To illustrate the motivation of our research, let us discuss an example application that will be enabled by a pervasive computing infrastructure in a smart building of a university, as illustrated in Figure 1. The building has many rooms including faculty offices, administration offices, conference rooms, classrooms and laboratories. Sensors in the building can capture, process and store a variety of information about the building, the users and their activities. Pervasive applications in such an environment allow faculty, staff, students and administrators to access resources/information from any locations at anytime while inside this building using mobile devices (PDAs) and wireless networks. While user credentials are still the basis for all the access control decisions, user's context information and application state should also be considered. For example, a student can only control the audio/video equipment in a classroom if she/he is scheduled to present in that class at that time by the faculty in charge. Similarly the payroll server should not be allowed to access if its load is above 80% or if the access is over an insecure link. In such applications, privileges assigned to the user will change as context changes. If the user is accessing the resource while the user's context information is changing (say the moves from a secure network link to an insecure link), specific access control mechanisms are needed to ensure that system/application security and consistency are maintained without decreasing flexibility.

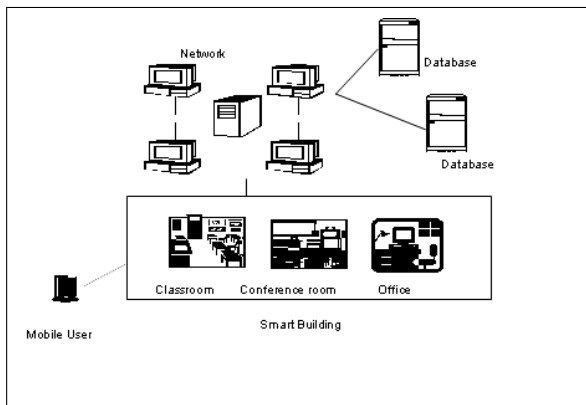


Figure 1. Smart Building Application

The examples above embody many of the key ideas of the research presented in this paper. To maintain system security for such a pervasive application, we have to dynamically adapt access permissions granted to users as context information for the session changes. Context information here includes environment of the user such as location, time that the user access the resource and system information such as CPU usage and network bandwidth. The traditional

RBAC models [1] do not directly address the requirements of such an application. In the RBAC model, the user is assigned a subset of roles when the user begins a session. This subset of roles are then used to access resources. During a session, although roles can be activated or deactivated based on constraints such as role conflict or prerequisite roles, the user's access privilege is not changed based on context information. Recently, Michael J. Covington et al have proposed the GRBAC model [8] that used context to provide access control for Aware Home applications. However, the definition of environment role is not feasible for pervasive applications as described in the previous section.

### 4 Dynamic Role Based Access Control Model

Dynamic Role Based Access Control model (DRBAC) addresses the dynamic access control requirement of applications in pervasive environments. It extends the traditional Role Base Access Control (RBAC) model to use dynamic context information while making access control decision. Specifically, DRBAC addresses two key requirements motivated by the application in Section 3: (1) A user's access privileges must change when the user's context changes. (2) A resource must adjust its access permission when its system information (e.g., network bandwidth, CPU usage, memory usage) changes. In this section, we first formally define DRBAC and then describe its operation.

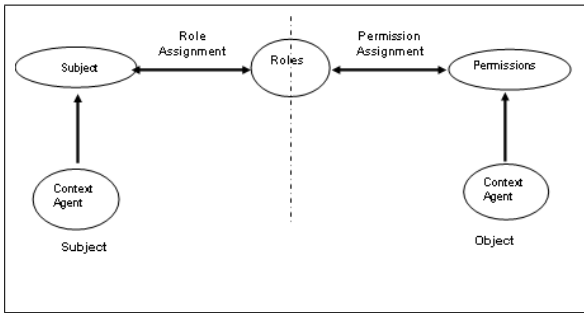
#### 4.1 DRBAC Definition

The DRBAC definition is based on the RBAC formalism presented in [5]. DRBAC has the following components:

- **USERS.** A user is an entity whose access is being controlled. USERS represents a set of users.
- **ROLES.** A role is a job function within the context of an organization with some associated semantics regarding the authority and responsibility conferred on the user assigned to the role. ROLES represents a set of roles.
- **PERMS.** A permission is an approval to access one or more RBAC protected resources. PERMS represents a set of permissions.
- **ENVS.** ENVS represent the set of context information in the system. We use an authorized "Context Agent" to collect context information in our system.
- **SESSIONS.** A session is a set of interactions between subjects and objects. A user is assigned a set of roles during each session. The active role will be changed dynamically among the assigned roles for each interaction. SESSIONS represents a set of sessions.

- UA. UA is the mapping that assigns a role to a user. In the session, each user is assigned a set of roles, the context information is used to decide which role is active. The user will access the resource with the active role.
- PA. PA is the mapping that assign permissions to a role. Every role that has privilege to access the resource is assigned a set of permissions, and the context information is used to decide which permission is active for that role.

The model is illustrated in Figure 2. In the approach, a Central Authority (CA) maintains the overall role hierarchy. When the user logs on the system, based on the user's capability, a subset of the role hierarchy is assigned to the user for each session. Then the CA sets up an agent for that user and delegates the user's right to that agent. The agent will monitor the environment status of the user and dynamically change the active role of the user. Every resource maintains a set of permission hierarchies for each potential role that will access the resource. The resource maintains its environment and dynamically adjusts the permissions for each role. We summarize the above discussions below:



**Figure 2. Dynamic Access Control Model**

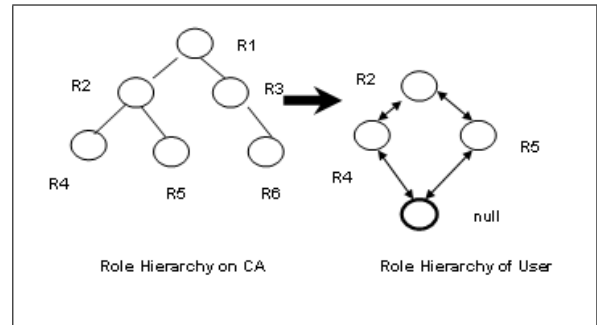
DRBAC Definition:

- *USERS, ROLES, PERMS, ENVS and SESSIONS* (users, roles, permissions, environments and sessions, respectively).
- *ACT\_ROLE and ACT\_PERMISSION* (active role and active permission respectively).
- $UA \subseteq USERS \times ROLES$ , a many-to-many mapping user-to-role assignment relation.
- $PA \subseteq PERMS \times ROLES$ , a many-to-many mapping permission-to-role assignment relation.
- *Assigned\_roles* ( $u:USERS, e:ENVS$ )  $\rightarrow 2^{ROLES}$ , the mapping of user  $u$  onto a set of roles.

- *Assigned\_permissions* ( $r:ROLES, e:ENVS$ )  $\rightarrow 2^{PERMS}$ , the mapping of role  $r$  onto a set of permissions.
- *User\_sessions* ( $u:USERS$ )  $\rightarrow 2^{SESSIONS}$ , the mapping of user  $u$  onto a set of sessions.
- *Session\_roles* ( $s:SESSIONS$ )  $\rightarrow 2^{ROLES}$ , the mapping of session  $s$  onto a set of roles. Formally:  $session\_roles(s_i) \subseteq \{r \in ROLES \mid (session\_roles(s_i), r) \in UA\}$
- $RH \subseteq ROLES \times ROLES$  is a partial order on *ROLES* called the inheritance relation, written as  $\geq$ , where  $r_1 \geq r_2$  only if all *PERMS* of  $r_2$  are also *PERMS* of  $r_1$ , and all users of  $r_1$  are also users of  $r_2$ .
- $PH \subseteq PERMS \times PERMS$  is a partial order on *PERMS* called the inheritance relation, written as  $\geq$ , where  $p_1 \geq p_2$  only if all permissions of  $p_2$  are also permissions of  $p_1$ , and all roles of  $p_1$  are also roles of  $p_2$ .

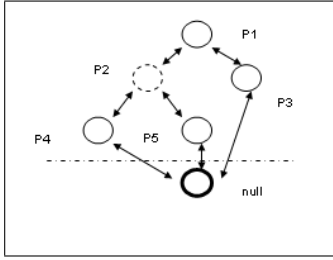
## 4.2 DRBAC Explained

In DRBAC, each user is assigned a role subset from the entire role set. Similarly, each resource will assign a permission subset from the entire permission set to each role which has a privilege to access the resource. Figure 3 illustrates the relationship between the role hierarchy maintained at the Central Authority (CA) and the role hierarchy assigned to a particular user. It can be seen that the role hierarchy a user is a subset of the overall role hierarchy.



**Figure 3. Role Hierarchy State Machine**

State machines maintain the role subset for each user and the permission subset for each role. A state machine consists of state variables, which encode its state, and events, which transform its state. In DRBAC, there is a Role State Machine for each user, and a Permission State Machine for each role. The role and permission are used as state variables respectively. The Context Agent collects context information and generates pre-defined events to trigger transitions in the state machines. A permission state machine is illustrated in Figure 4.

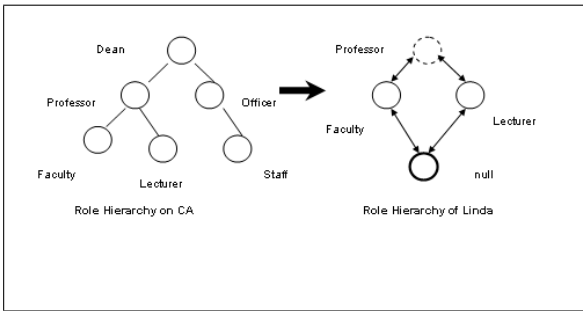


**Figure 4. Permission Hierarchy State Machine**

A null permission implies no permission. A transition is defined as  $T(\text{Initial State}, \text{Destination State})$ . So  $T(P1, P2)$  represents the transition from  $P1$  to  $P2$  and  $T(P2, P1)$  represents the transition from  $P2$  to  $P1$ . The Role State Machine is similar to the Permission State Machine.

### 4.3 DRBAC Operation

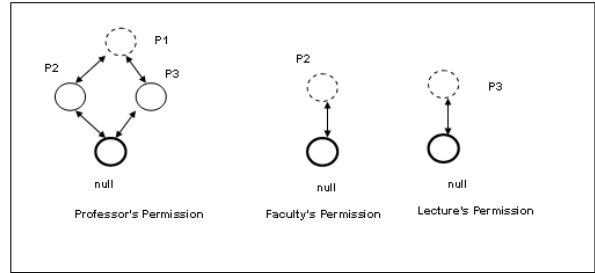
The operation of DRBAC is illustrated using the example presented in Section 3. In this example, when Professor  $B$  logs on the system in her office with a PDA, the central authority assigns her a subset of roles, for example, *Professor*, *Lecturer* and *Faculty*, based on her credentials. Then the central authority also sets up an access control agent on her PDA, which maintains the role state machine. Events issued by the context agent will trigger transitions between the roles in the role state machine. Now, consider a security policy that defines  $B$ 's active role as *Professor* when she is in the office (see Figure 5, where the dashed circle is the active role), and defines the transition as: *Change role from Professor to Faculty when professor B leaves her office*.



**Figure 5. Role Hierarchy for the Smart Building**

When professor  $B$  accesses the resource in her office, the active role *Professor* is used. The resource maintains the permission state machines as shown in Figure 6. The figure shows that each of the roles, *Professor*, *Faculty* and *Lecturer*, have their own permission state machines. The

dashed circle represents the current active permission for each role. The *null* means the role does not have permission to access the resource. Similar to the role state machine, the context agent at the resource will trigger transitions in the permission state machine. In this example, we assume that the active permission of the role *professor* is  $P1$  while the system load of the resource is low.  $P1$  means both read and write privilege. The security policy for the resource may define a permission transition for role *professor* as: *Transit permission from  $P1$  to  $P2$  when the system load is high*. The permission  $P2$  means only read privilege.



**Figure 6. Permission Hierarchy for the Resource**

Based on the situations defined above, we can describe some scenarios to illustrate dynamic access control.

- When professor  $B$  moves out of her office, the context agent will send an event to the access control agent on her PDA. This event will trigger a transition in the role state machine, changing her active role to *Faculty*. As a result, professor  $B$  will not be able to write to resource once she leaves her office as role *Faculty* only has the permission  $P2$  or null.
- When professor  $B$  accesses the resource in her office, her active role is *professor*, which has both read and write privilege on the resource as long as the system load of the resource is low. If the system load becomes critically high, the resource permission state machine will change the active permission for professor  $B$ 's role *professor* to  $P2$  and she will lose the privilege to write the resource.

From the scenarios described above, we see that DRBAC can enhance the security of the pervasive applications. The DRBAC mechanism implemented in this application guarantees that professor  $B$ 's privilege to access the resource will be changed dynamically when the context changes. Using context information to change the user's privileges prevents resources from being incorrectly used.

## 5 Discussion

The major strength of DRBAC model is its ability to make access control decisions dynamically based on the context information. This property is particularly useful for applications in pervasive computing environments. However, implementing DRBAC can increase the complexity of an application. The overhead of DRBAC is experimentally evaluated in [12]. To successfully implement DRBAC in the real applications, the following issues should be considered:

- As we use the context information while granting access privilege, we must guarantee the security of the context information. Compromised context information can cause a system to make incorrect access control decisions and can compromise the security of the applications.
- In the DRBAC model, the active role of the user and the active permission of the role can change dynamically. It is possible that in some situations the active role of the user changes but the user has already been granted permissions to access the resource based on a previously assigned role. Mechanisms are required to maintain consistency in such a situation.
- Because the DRBAC role state machine will run on the user's device (PDA, mobile phone), the resource consumption of the mobile terminal will increase. However, users will typically have fewer than ten roles assigned to them. Given the increasing power of mobile devices, maintaining a state machine with less than ten states should have little if any effect on performance.

## 6 Conclusion

In this paper, we presented the Dynamic Role Based Access Control (DRBAC) model that provides context aware access control for pervasive applications. DRBAC extends the role based access control (RBAC) model and dynamically adjusts *Role Assignments* and *Permission Assignments* based on context information. The operation of the model was illustrated using a sample application scenario. Compared to traditional access control mechanisms, the DRBAC model can provide improved security for pervasive applications. However, access control alone is not sufficient and DRBAC must be combined with feasible authentication mechanisms to secure pervasive applications in the real world.

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