

# Authentication via Multi-Service Tickets in the *Kuperee* Server

(Extended Abstract)

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**Abstract.** The subject of this paper is the authentication services as found in the *Kuperee*<sup>3</sup> server. The authentication protocol is based on the Zheng-Seberry public key cryptosystem, and makes use of the distinct features of the cryptosystem. Although couched in the terminology of Kerberos, the protocol has subtle features, such as the *binding* together of two entities by a third entity, leading to the need of equal co-operation by the two entities in order to complete the authentication procedure. Another important feature is the use of a *multi-service* ticket to access multiple services offered by different servers. This removes the need of the Client to consult the Trusted Authority each time it needs a service from a Server. In addition, this allows an increased level of parallelism in which several Servers may be concurrently executing applications on behalf of a single Client. The scheme is also extendible to cover a more global scenario in which several realms exist, each under the care of a trusted authority. Finally, the algorithms that implement the scheme are presented in terms of the underlying cryptosystem. Although the scheme currently employs a public key cryptosystem, future developments of the server may combine private key cryptosystems to enhance performance.

## 1 Introduction

In the last two decades an explosion of interest have been shown in the use of cryptographic techniques to provide some solutions to the problems of information security. Previously, the study of these techniques was confined only to within the military and intelligence communities, with the primary non-government application being in the banking sector. However, more recently these techniques have been widely recognized and appreciated as being crucial to security and they have been incorporated into the more general computing and information systems environments. Specialized architectures providing for specific security services have found realization within the client-server paradigm.

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<sup>3</sup> *Kuperee* is a mythical enormous black kangaroo in the Dreamtime Myths of the Australian Aboriginal people. It moves at a high speed, and leaves havoc and terror wherever it goes.

The two types of servers that have emerged corresponding to the two approaches in cryptographic techniques are *Authentication Servers*, which embody private-key cryptosystems, and *Certification Servers*, which rely on public-key cryptosystems. Both types of servers provide for services relating to the secrecy of communications and interactions between entities, and for the authentication of one entity by another. The development of these servers represent the bridging stage from systems with little integrated security features to systems with security as one of their major design considerations. With most of the secure systems being expensive and less compatible with existing systems, the notion of a bridging server that provide for secrecy and authentication is an attractive one.

In the past few years a number of systems for authentication services have been developed, among others the *Kerberos* authentication service [1, 2, 3] within Project Athena at MIT [4], *SPX* [5, 6] as part of the DEC's Distributed Systems Security Architecture (DSSA) [6] and *Sesame* [7, 8, 9] within ECMA's standard for security framework.

Kerberos adopts the private (shared) key approach, and is a trusted third-party authentication service developed from the Needham-Schroeder protocol [10] which has subsequently been improved and shown to be reliable [11, 12]. The Kerberos authentication service provides a trusted intermediary between a *User* or *Client* that requires services from a *Server*. It authenticates the User or Client by way of a shared private key, and it provides a way for the Server to authenticate the User or Client when it request the services of the Server.

Due to the use of private key cryptography, the Kerberos authentication service requires a key to be shared between the User or Client and the trusted authorities in the system, namely the *Key Distribution Center* (KDC) and the *Ticket Granting Server* (TGS) [3]. This, however, requires a great amount of trust to be placed on the implementation of the trusted authorities, since their compromise results in possible masquerade by the attacker of the User or Client whose private key are stored with these trusted authorities [13].

In this paper we discuss the authentication service provided by the *Kuperee* server. The authentication protocol is based on the Zheng-Seberry public key cryptosystem [14], and makes use of the distinct features of the cryptosystem. In general, the use of a public key cryptosystem provides an advantage in terms of the trust level expected from a server [15]. That is, a server based on a public key cryptosystem would hold certified public keys of Users and/or Clients, and thus the compromise of the server does not lead to the compromise of the corresponding secret keys.

Although couched in the terminology of Kerberos, *Kuperee* has a number of subtle features, such as the *binding* together of two entities by a third entity, leading to the need of equal co-operation by the two entities in order to complete the authentication procedure. That is, a Ticket Granting Server has the ability to bind together a Client and the Server that is providing the Client with some services. In this case the Server cannot proceed without the cooperation of the Client in the form of the client submitting a cryptographic *authenticator* to the

server. The authenticator in this case is not an enciphered piece of information (as in Kerberos), but rather it is a cryptographic component that contributes to the successful authentication by the Server. This paper also focuses on a feature of the scheme in which one *multi-service* ticket can be used by a Client to access multiple Servers, thereby reducing the need of the Client to continually prompt the TGS for service tickets. This allows an increased level of parallelism in which several Servers may be concurrently executing applications on behalf of a single Client. The scheme is also extendible to cover a more global scenario in which several realms exist, each under the care of a Trusted Authority.

Although we initially model our approach on Kerberos and employ its language in our discussions, we by no means limit ourselves to the use of the underlying cryptosystem following the steps of Kerberos. The underlying public key cryptosystem has more to offer and future developments of Kuperee will address more efficient ways to achieve authentication than currently presented in this paper. Efforts such as in *SPX* [5] clearly show that better performance and security may be achieved by combining suitable implementations of both public key and private key cryptosystems.

In the next section (Section 2) for the sake of clarity we briefly summarize the Kerberos authentication service (version 5) as described in [3]. Readers unfamiliar with Kerberos are directed to [1, 3] for more details on its implementation. In Section 3 we present our approach using the public key cryptosystem of [14]. This is continued in Section 4 by the description of our method to generate a multi-service ticket for multiple services. The algorithms that implement our approach are then given in Section 5. The flexibility of our approach is further illustrated in Section 6 by inter-realm authentication in a hierarchically organized realms or domains, each managed by a TGS. Section 7 briefly discusses the security level achieved by our solution, while the paper is finally closed in Section 8 by some concluding remarks.

## 2 Kerberos authentication service

In the Kerberos authentication system [1, 3] the entities that interact with the authentication service are called *principals*. The term can be used for Users, Clients or Servers. Commonly, a user directs a Client (eg. a program) on a machine to request a service provided by a Server on a remote machine. The Server itself is usually a process on the remote machine, and different services are usually taken to be available on differing remote machines. Kerberos employs two types of credentials to achieve authentications, namely the *tickets* of the form

$$\{s, c, addr, timestamp, lifetime, K_{s,c}\}$$

and the *authenticators* of the form

$$\{c, addr, timestamp\}$$

which is enciphered using a key common to the issuer and the recipient. Here the ticket consists of the Server and Client identities, followed by the Client's network

address, a unique timestamp, the lifetime of the ticket and finally by the common key to be shared between the Server and the Client [1]. In this example, the ticket contains the key  $K_{s,c}$  shared between the Client  $c$  and the Server  $s$ . The Server is trusted to generate such shared keys and when the ticket is to be given to a Client  $c$  then it must be enciphered using the Client's key  $K_c$ . In the remainder of the paper we will employ the notation used for Kerberos in [1, 3] with respect to the encipherment/decipherment operation. That is, the operation " $\{\}_K$ " means that the contents within the braces " $\{\}$ " are enciphered/deciphered using the key  $K$  (Section 5 gives the precise algorithms for the encipherment/decipherment operations).

In brief, the interactions within the authentication service consists of the Client requesting the Key Distribution Center (KDC) for a *ticket-granting ticket* to be submitted by the Client to the Ticket Granting Server (TGS). The TGS then issues the Client with a *service ticket* which has a shorter lifetime compared to the ticket-granting ticket. The service ticket is then used by the Client to request the services of the Server which is mentioned in the ticket. These two stages are also referred to as the credential-initialization and client-server authentication protocols respectively in [13].

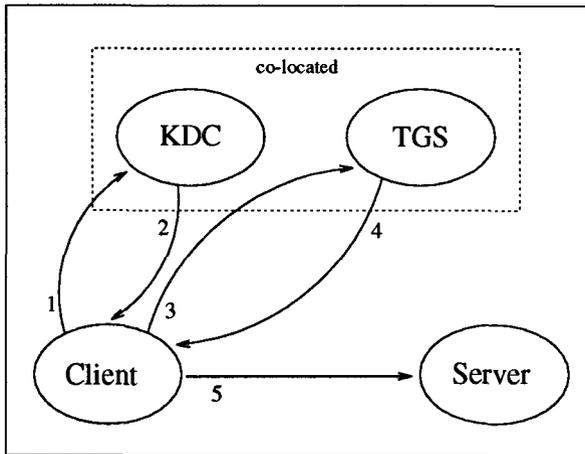


Fig. 1. Obtaining a service ticket (after [3])

The actions of the Kerberos authentication service following the description of [3] is given in the following (Figure 1).

1. Client  $\rightarrow$  KDC:  $c, tgs$
2. KDC  $\rightarrow$  Client:  $\{K_{c,tgs}\}_{K_c}, \{T_{c,tgs}\}_{K_{tgs}}$
3. Client  $\rightarrow$  TGS:  $\{A_c\}_{K_{c,tgs}}, \{T_{c,tgs}\}_{K_{tgs}}, s$
4. TGS  $\rightarrow$  Client:  $\{K_{c,s}\}_{K_{c,tgs}}, \{T_{c,s}\}_{K_s}$
5. Client  $\rightarrow$  Server:  $\{A_c\}_{K_{c,s}}, \{T_{c,s}\}_{K_s}$

## 6. Server $\rightarrow$ Client: $\{timestamp + 1\}_{K_{c,s}}$

In step 1 the Client  $c$  requests the Key Distribution Center (KDC) for an initial ticket and credentials to be presented to the Ticket Granting Server (TGS).

In step 2 the KDC generates a *session* key  $K_{c,tgs}$  that will be shared between the Client and the TGS. A copy of this key is enciphered using the Client's key  $K_c$  to guarantee that the Client can obtain it securely. The ticket-granting ticket  $T_{c,tgs}$  to be presented to the TGS by the Client already contains a copy of the session key  $K_{c,tgs}$ . Hence, both the Client and the TGS can later communicate securely using this session key shared between them. Note that the ticket is enciphered using the TGS's private key  $K_{tgs}$  known only to the KDC and the TGS.

In step 3 the Client then creates an authenticator  $A_c$  to be read only by the TGS (hence enciphered using  $K_{c,tgs}$ ) and presents it to the TGS together with the ticket  $\{T_{c,tgs}\}_{K_{tgs}}$  which the Client obtained from the KDC.

On receiving the authenticator and ticket-granting ticket from the Client, the TGS deciphers and authenticates the ticket (step 4). The TGS then generates another session key  $K_{c,s}$  to be shared between the Client  $c$  and the Server  $s$ . The TGS also creates a service ticket destined for the Server. This ticket  $T_{c,s}$  contains a copy of the new session key, and its lifetime is shorter than the lifetime of the initial ticket  $T_{c,tgs}$ . The TGS knows the private key of every Server  $s$ , and ticket is made exclusively for the eyes of the Server by enciphering it using  $K_s$ . A copy of the session key  $K_{c,s}$  (hidden by enciphering it using  $K_{c,tgs}$ ) accompanies the ticket to the Client.

In step 5, the Client enciphers the authenticator  $A_c$  using the session key  $K_{c,s}$  which it will share with the Server  $s$ . This is then sent to the Server  $s$  together with the ticket obtained from the TGS. The Client may request the Server to prove its identity which can be achieved by the Server incrementing the timestamp value by one, and enciphering the result using the session key shared between the Server and the Client (step 6).

## 3 Public key approach

In this section we propose an approach based on public key cryptography. Our approach is founded on the public key cryptosystem of [14], and some of its constructs that are necessary for the current discussion will be presented in the following. The algorithms that implement the cryptosystem are deferred until Section 5 in order to simplify discussion.

In the public key cryptosystem of [14] a secret key is chosen randomly and uniformly from the integers in  $[1, p-1]$ , where the prime  $p$  is public and is used to generate the multiplicative group  $GF(p)^*$  of the finite field  $GF(p)$ . The generator of this multiplicative group is denoted as  $g$  and it is a publicly known value. This usage of  $g$  and  $p$  is inspired by notable works of [16] and [17]. The corresponding public key is then produced by using the secret key as the exponent of  $g$  modulo  $p$ . In the remainder of this paper all exponentiations are assumed to be done over the underlying groups.

For the current usage of the cryptosystem, assume that the secret and public key pairs of the principals are as follows. The KDC has the pair  $(X_{kdc}, Y_{kdc} \equiv g^{X_{kdc}})$ , the Client has  $(x_c, y_c \equiv g^{x_c})$ , the TGS has  $(X_{tgs}, Y_{tgs} \equiv g^{X_{tgs}})$ , while the Server has  $(X_s, Y_s \equiv g^{X_s})$ . The keys  $Y_{kdc}$ ,  $y_c$ ,  $Y_{tgs}$  and  $Y_s$  are known to the public as in other systems based on public key cryptography.

Each session secret and public key pair is denoted by  $(k, K \equiv g^k)$ , and their subscripts indicates which principals employ the key pair. Hence, the pair  $(k_{c,tgs}, K_{c,tgs})$  is used for interactions between the Client and the TGS. In our case the tickets to be employed do not contain any keys, hence their form are:

$$\{s, c, addr, timestamp, lifetime\}$$

### 3.1 Getting an initial ticket

1. Client  $\rightarrow$  KDC:  $c, tgs$
2. KDC  $\rightarrow$  Client:  $K_{c,tgs}, C_{c,tgs}$

The KDC first generates the session key pair  $(k_{c,tgs}, K_{c,tgs})$  to be used between the Client and the TGS.

The cryptogram  $C_{c,tgs}$  is the ticket-granting ticket  $T_{c,tgs}$  being enciphered as:

$$C_{c,tgs} \equiv \{T_{c,tgs}\}_{r_{c,tgs}}$$

where

$$r_{c,tgs} \equiv (y_c Y_{tgs})^{X_{kdc} + k_{c,tgs}} \quad (1)$$

3. Client  $\rightarrow$  TGS:  $A_{c,tgs}, K_{c,tgs}, C_{c,tgs}, s$

On receiving the enciphered ticket  $C_{c,tgs}$  together with its accompanying session public key  $K_{c,tgs}$  the Client computes a *Authenticator*  $A_{c,tgs}$ :

$$A_{c,tgs} \equiv (Y_{kdc} K_{c,tgs})^{x_c} \quad (2)$$

The authenticator, the received session public key and enciphered ticket-granting ticket, and the identity of the destination Server  $s$  are then delivered to the TGS.

The TGS employs the session public key  $K_{c,tgs}$  to compute its *Decryptor*  $D_{tgs,c}$  as:

$$D_{tgs,c} \equiv (Y_{kdc} K_{c,tgs})^{X_{tgs}} \quad (3)$$

This is then used to recreate the key  $r_{c,tgs}$  that was used by the KDC to encipher the ticket:

$$r_{c,tgs} \equiv A_{c,tgs} D_{tgs,c}$$

The resulting key  $r_{c,tgs}$  is then used to recover the ticket  $T_{c,tgs}$ .

### 3.2 Getting a service ticket

In order to obtain the services of the Server the Client must obtain a service ticket from the TGS to be presented to the Server. We continue the procedure in the following steps.

#### 4. TGS $\rightarrow$ Client: $K_{c,s}, C_{c,s}$

In order to encipher the service ticket  $T_{c,s}$  the TGS must generate the session key pair  $(k_{c,s}, K_{c,s})$  which is used as follows:

$$C_{c,s} \equiv \{T_{c,s} || k_{c,s}\}_{r_{c,s}}$$

where

$$r_{c,s} \equiv (y_c Y_s)^{X_{tgs} + k_{c,s}}$$

resulting in the cryptogram  $C_{c,s}$ .

The cryptogram  $C_{c,s}$  and the session public key  $K_{c,s}$  are then delivered to the Client.

#### 5. Client $\rightarrow$ Server: $A_{c,s}, K_{c,s}, C_{c,s}$

As when dealing with the TGS, the Client must compute the authenticator  $A_{c,s}$  indicating its desire to use the service provided by the Server:

$$A_{c,s} \equiv (Y_{tgs} K_{c,s})^{x_c}$$

This authenticator, the received session public key and enciphered service ticket are then presented to the Server whenever the Client requires the service.

On first being presented with the (enciphered) service ticket, the Server must compute its corresponding decryptor

$$D_{s,c} \equiv (Y_{tgs} K_{c,s})^{X_s}$$

The Server is then able to recreate the session key  $r_{c,s}$  as:

$$r_{c,s} \equiv A_{c,s} D_{s,c}$$

to be used to obtain  $\{T_{c,s} || k_{c,s}\}$ .

#### 6. Server $\rightarrow$ Client: $\{timestamp + 1\}_{r_{s,c}}$

If required, the Server may respond to the Client's request of proving the Server's identity. This can be done by the Server reusing the key  $k_{c,s}$  that was enciphered together with the service ticket  $T_{c,s}$ . The key is reused to create  $r_{s,c}$  as:

$$r_{s,c} \equiv (y_c)^{X_s + k_{c,s}}$$

to encipher  $\{timestamp + 1\}$ .

The Client can recreate the key  $r_{s,c}$  as:

$$r_{s,c} \equiv (K_{c,s} Y_s)^{x_c}$$

which is then used to recover and check  $\{timestamp + 1\}$ .

## 4 Multi-service ticket

One interesting feature in Kuperee deriving from its usage of the public key cryptosystem of [14] is its ability to present Clients with one service-ticket which can be used with several Servers (Figure 2) This removes the need of the Client to consult the TGS each time it needs a service from a Server. In addition, this allows an increased level of parallelism in which several Servers may be concurrently executing applications on behalf of a single Client. The level of dependence of the Client on the TGS is also reduced since such multi-service tickets maybe given a longer life-time, hence reducing the impact on the system when the TGS is temporarily unavailable.

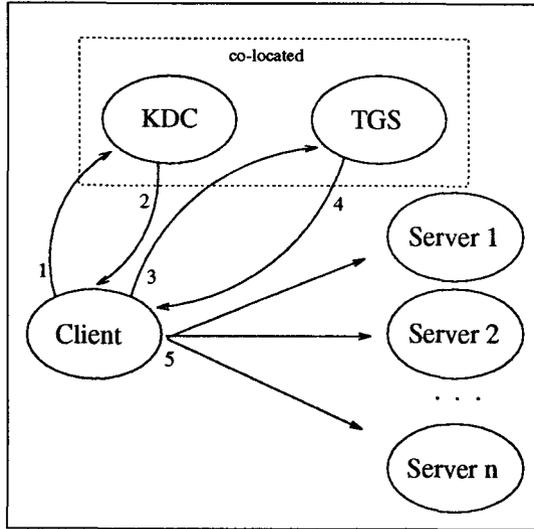


Fig. 2. Obtaining a multi-service ticket

In this section the creation and use of the multi-service tickets is discussed. First, the TGS must be notified by the Client about the  $q$  Servers  $s_1, s_2, \dots, s_q$  that the Client wishes to access. We can repeat the last two steps (ie. steps 4 and 5) as follows:

**M3.** Client  $\rightarrow$  TGS:  $A_{c,tgs}, K_{c,tgs}, C_{c,tgs}, m = (s_1, s_2, \dots, s_q)$

**M4.** TGS  $\rightarrow$  Client:  $K_{c,m}, C_{c,m} (R_{c,s_1}, R_{c,s_2}, \dots, R_{c,s_q})$

The TGS prepares the service ticket  $T_{c,m}$ , generates the key pair  $(k_{c,m}, K_{c,m})$  and enciphers the ticket into  $C_{c,m}$ :

$$C_{c,m} \equiv \{T_{c,m} || k_{c,m}\}_{r_{c,m}}$$

where

$$r_{c,m} \equiv (y_c Y_{s_1} Y_{s_2} \dots Y_{s_q})^{X_{tgs} + k_{c,m}}$$

The TGS must also compute  $q$  number of *selectors*  $R_{c,s_1}, R_{c,s_2}, \dots, R_{c,s_q}$  which will be used by the Client to choose among the  $q$  specified Servers  $s_1, s_2, \dots, s_q$ . These selectors are computed as:

$$\begin{aligned} R_{c,s_1} &= (Y_{s_2} Y_{s_3} \dots Y_{s_q})^{X_{tgs} + k_{c,m}} \\ R_{c,s_2} &= (Y_{s_1} Y_{s_3} \dots Y_{s_q})^{X_{tgs} + k_{c,m}} \\ &\vdots \\ R_{c,s_q} &= (Y_{s_1} Y_{s_2} \dots Y_{s_{q-1}})^{X_{tgs} + k_{c,m}} \end{aligned}$$

The cryptogram  $C_{c,m}$ , the session public key  $K_{c,m}$  and the selectors are then delivered to the client.

**M5.** Client  $\rightarrow$  Server  $s_v$ :  $A_{c,m}, K_{c,m}, C_{c,m}, R_{c,s_v}$

As in the single-service case, the Client must compute its authenticator to be delivered to the Server. Thus,

$$A_{c,m} \equiv (Y_{tgs} K_{c,m})^{x_c}$$

However, in this multi-service case, the Client must select the Server from which it requires service. Assuming that the Client requires service from Server  $s_v$  ( $1 \leq v \leq q$ ), then the Client must employ the selector  $R_{c,s_v}$ .

This authenticator  $A_{c,m}$ , the received session public key  $K_{c,m}$ , the enciphered service ticket  $C_{c,m}$  and the selector  $R_{c,s_v}$  must then be presented to the Server  $s_v$ .

On first being presented with the (enciphered) service ticket, the Server  $s_v$  must compute its corresponding decryptor

$$D_{m,c} \equiv (Y_{tgs} K_{c,m})^{X_{s_v}}$$

The Server is then able to recreate the enciphering key  $r_{c,m}$  as:

$$r_{c,m} \equiv A_{c,m} D_{m,c} R_{c,s_v}$$

to be used to decipher the service ticket  $C_{c,m}$ .

## 5 Algorithms

As described briefly in Section 3, our approach is based on the public key cryptosystem of [14]. In this section we provide further notations for the cryptosystem and present the algorithm for the encipherment and decipherment of tickets based on a modified version of the original cryptosystem of [14]. The algorithms expresses only the encipherment (decipherment) of the plaintext (ciphertext) tickets, and do not incorporate the steps taken by the KDC, Client, TGS and the Server. Hence, the reader is encouraged to read them in conjunction with the steps provided in Sections 3.2 and 3.1.

## 5.1 Notation

The following notation is taken directly from [14]. The cryptosystem of [14] employs a  $n$ -bit prime  $p$  (public) and a generator  $g$  (public) of the multiplicative group  $GF(p)^*$  of the finite field  $GF(p)$ . Here  $n$  is a security parameter which is greater than 512 bits, while the prime  $p$  must be chosen such that  $p - 1$  has a large prime factor. Concatenation of strings are denoted using the “||” symbol and the bit-wise XOR operations of two strings is symbolized using “ $\oplus$ ”. The notation  $w_{[i..j]}$  ( $i \leq j$ ) is used to indicate the substring obtained by taking the bits of string  $w$  from the  $i$ -th bit ( $w_i$ ) to the  $j$ -th bit ( $w_j$ ).

The action of choosing an element  $x$  randomly and uniformly from set  $S$  is denoted by  $x \in_R S$ .  $G$  is a cryptographically strong pseudo-random string generator based on the difficulty of computing discrete logarithms in finite fields [14].  $G$  stretches an  $n$ -bit input string into an output string whose length can be an arbitrary polynomial in  $n$ . This generator produces  $O(\log n)$  bits output at each exponentiation. All messages to be encrypted are chosen from the set  $\Sigma^{P(n)}$ , where  $P(n)$  is an arbitrary polynomial with  $P(n) \geq n$  and where padding can be used for messages of length less than  $n$  bits. The polynomial  $\ell = \ell(n)$  specifies the length of tags. The function  $h$  is a one-way hash function compressing input strings into  $\ell$ -bit output strings. In the remainder of this paper all exponentiations are assumed to be done over the underlying groups. The reader is directed to [14] for a comprehensive discussion on the constructs of the family of cryptosystems.

## 5.2 Getting initial and service tickets

In the process of getting an initial ticket the Client asks the KDC to prepare the ticket to be submitted by the Client to the TGS. The KDC first performs  $k_{c,tgs} \in_R [1, p - 1]$  followed by the calculation  $K_{c,tgs} \equiv g^{k_{c,tgs}}$ . The KDC then enciphers the ticket  $T_{c,tgs}$  using the key  $r_{c,tgs}$  by invoking *Encipher* (Algorithm 1) with the input parameters  $(p, g, r_{c,tgs}, T_{c,tgs})$  resulting in the output  $C_{c,tgs}$ .

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### Algorithm 1 *Encipher*( $p, g, r, T$ )

1.  $z = G(r)_{[1..(P(n)+\ell(n))]}$ .
2.  $t = h(T \oplus r)$ .
3.  $m = (T || t)$ .
4.  $C = z \oplus m$ .
5. output ( $C$ ).

end

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The KDC then sends the resulting ciphertext  $C_{c,tgs}$  and the session public key  $K_{c,tgs}$  to the Client who proceeds to compute  $A_{c,tgs}$ . These values are then submitted by the Client to the TGS who tries to decipher  $C_{c,tgs}$ . This is done by the

TGS first computing  $D_{tgs,c}$  and using it and the received values as input to *Decipher* (Algorithm 2). That is, the TGS inputs  $(p, g, A_{c,tgs}, K_{c,tgs}, C_{c,tgs}, D_{tgs,c})$  and receives the output  $T_{c,tgs}$ .

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**Algorithm 2** *Decipher* $(p, g, A, K, C, D)$

1.  $r' = A D$ .
2.  $z' = G(r')_{[1 \dots (P(n)+\ell(n))]}$ .
3.  $m = z' \oplus C$ .
4.  $T' = m_{[1 \dots P(n)]}$ .
5.  $t' = m_{[(P(n)+1) \dots (P(n)+\ell(n))]}$ .
6. if  $h(T' \oplus r') = t'$  then
  - output  $(T')$
  - else
  - output  $(\emptyset)$ .

**end**

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The same procedure is followed by the TGS in enciphering the ticket to be submitted by the Client to the Server. The minor difference in this case is that the TGS appends a response key  $k_{c,s}$  (ie. the secret half of the session key) to the ticket  $T_{c,s}$ . This addition does not affect the algorithms and their security in any way. Hence, the TGS invokes *Encipher* (Algorithm 1) with the input parameters  $(p, g, r_{c,s}, (T_{c,s} || k_{c,s}))$  resulting in the output  $C_{c,s}$ . The Server deciphers  $C_{c,s}$  into  $(T_{c,s} || k_{c,s})$  using *Decipher* (Algorithm 2) with input values  $(p, g, A_{c,s}, K_{c,s}, C_{c,s}, D_{s,c})$ .

## 6 Hierarchical inter-realm authentication

The integration of security into distributed systems has introduced the need to manage the information pertaining to the security functions in the distributed system. The most common and important need is that of providing a method to manage cryptographic keys of the components in the distributed system. One approach that may be adopted is that of organizing the components into a hierarchy consisting of a number of domains or realms, each being managed by an independent trusted authority (eg. TGS). This approach has the advantage of the localized distribution of new keys, hence reducing the replication of keys across the entire distributed system.

Within the context of our discussion a domain or realm can consist of Clients, Servers, a local managing TGS and of other TGSs that manage their own realms. In this manner, the components are organized into a hierarchy based on the TGSs, with each TGS managing a certain number of Clients, Servers and other

TGSs. A Client within a realm may request service from a Server in the same domain in the manner previously discussed. However, it is also natural for a Client to request service from a “foreign” Server which is located in a different realm on another part of the hierarchy. In this section we address inter-realm authentication together with some accompanying issues. Our approach is general enough to be applicable to a number of areas, one being the X.500 Directory Services [18].

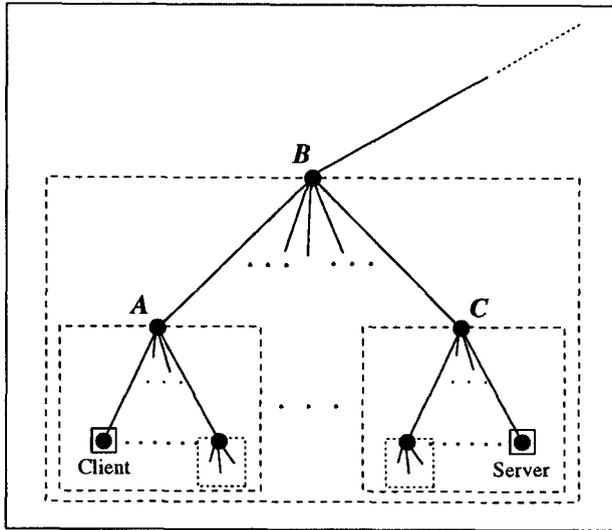


Fig. 3. A hierarchy of TGSs

In our usage, a hierarchy is assumed to be a directed acyclic graph and each node in the hierarchy is assumed to have only one parent node. An example of such a hierarchy that will be used in the following discussions is given in Figure 3. In Figure 3 the Client is located in the domain or realm under the jurisdiction of the TGS A. The Client requires the service provided by a Server which is located within the realm of TGS C. In this case the TGS A must enroll the aid of its parent TGS B to forward the Client’s request to TGS node C. Two general arrangements of the keys of the nodes in the hierarchy will be considered in the following. Note that the terms “TGS” and “node” will be used interchangeably to simplify discussion. In our example, we assume that the TGSs A, B and C have the key pairs  $(X_{tgsa}, Y_{tgsa})$ ,  $(X_{tgsb}, Y_{tgsb})$  and  $(X_{tgs c}, Y_{tgs c})$  respectively.

### 6.1 Localized keys

One possible arrangement of keys in the hierarchy is based on their maintenance on a per realm basis. That is, in this arrangement a TGS node holds the public

key of only its parent node and all its children nodes. This arrangement is similar to the arrangement of directories in [19]. Using Figure 3 as an example, TGS node  $B$  has the public key of its parent and of TGS nodes  $A$  and  $C$ . However,  $B$  does not have the public keys of the descendants of TGS nodes  $A$  and  $C$ . In this situation the TGS node  $A$  must refer the Client to node  $A$ 's parent, namely node  $B$ . The node  $B$ , not knowing the public key of the Server must then refer the Client to  $B$ 's child node  $C$ . Since node  $C$  is the trusted authority of the realm in which the Server resides, node  $C$  knows the public key of the Server and thus can forward the Client's request to the Server. These steps are shown in the following (Figure 4). Note that in essence, the Client must interact with every TGS node between its own TGS node ( $A$ ) and the common ancestor node ( $B$ ), and between the common ancestor node and the destination's TGS node ( $C$ ). The deeper the Client is located in the hierarchy from the common ancestor, the more interactions it has to perform in order to reach the destination.

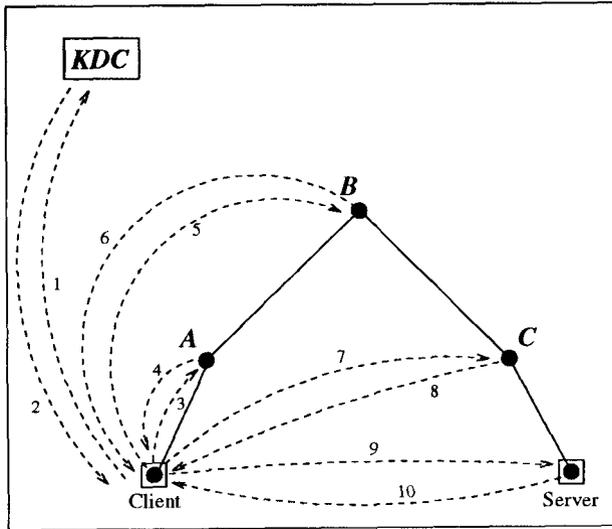


Fig. 4. Authentication with localized keys

1. Client  $\rightarrow$  KDC:  $c, tgsa$
2. KDC  $\rightarrow$  Client:  $K_{c,tgsa}, C_{c,tgsa}$
3. Client  $\rightarrow$  TGS  $A$ :  $A_{c,tgsa}, K_{c,tgsa}, C_{c,tgsa}, s$
4. TGS  $A$   $\rightarrow$  Client:  $K_{c,tgsb}, C_{c,tgsb}$
5. Client  $\rightarrow$  TGS  $B$ :  $A_{c,tgsb}, K_{c,tgsb}, C_{c,tgsb}, s$
6. TGS  $B$   $\rightarrow$  Client:  $K_{c,tgsc}, C_{c,tgsc}$
7. Client  $\rightarrow$  TGS  $C$ :  $A_{c,tgsc}, K_{c,tgsc}, C_{c,tgsc}, s$
8. TGS  $C$   $\rightarrow$  Client:  $K_{c,s}, C_{c,s}$
9. Client  $\rightarrow$  Server:  $A_{c,s}, K_{c,s}, C_{c,s}$
10. Server  $\rightarrow$  Client:  $\{timestamp + 1\}_{r,s,c}$

## 6.2 Globalized keys

Another possible arrangement of keys in the hierarchy is a more globalized one, in which a node knows not only the public key of all its descendant nodes, but also the public key of all its ancestor nodes (bearing in mind that a node only has one parent). Here a node does not have the public keys of any of its sibling nodes nor that of their descendants. Although such a configuration is costly in terms of the number of messages to be delivered when a node generates a new public key, the gains occur during the interaction with nodes located in other realms. Note that in our approach the public keys are not distributed in a fully globalized manner. That is, since a node does not have the public keys of its siblings, it must request the aid of its parent when dealing with such siblings. However, the steps used in our approach can be modified in a straight-forward manner to suit cases in which a node has a copy of the public key of every other node in the hierarchy.

Returning to our scenario where a Client requires the services offered by a foreign Server, the TGS in the Client's realm has more flexibility in issuing the enciphered ticket. Hence, with a TGS node knowing the public keys of all its ancestors, the node can find a common ancestor between itself and the TGS who manages the realm in which the Server resides. Looking back at Figure 3, the TGS node *A* (managing the Client's realm) and the TGS node *C* (managing the Server's realm) have a common ancestor (parent) in the TGS node *B*.

In this case, the TGS node *A* must prepare the enciphered ticket to be decipherable by the common ancestor (node *B*). This common ancestor node *B* must then locate the desired Server and re-encipher the ticket in such a way that it is decipherable by the Server with the necessary approval of the TGS within the Server's realm. That is, the ticket must be decipherable by the Server with the approval of the TGS node *C* in the form of node *C* sending a decryptor for the ticket to the Server. Note that only TGS *A* and *C* are involved with the common ancestor *B*, even though both TGSs *A* and *C* may have many other ancestors between them and TGS *B* respectively. Hence, in such a globalized key approach only a maximum of three TGSs (*A*, *B* and *C*) are invoked independent of the depth of the two TGS nodes (*A* and *C*) from their common ancestor (*B*). This scenario is expressed in the following steps (Figure 5).

1. Client  $\rightarrow$  KDC:  $c, tgsa$
2. KDC  $\rightarrow$  Client:  $K_{c,tgsa}, C_{c,tgsa}$
3. Client  $\rightarrow$  TGS *A*:  $A_{c,tgsa}, K_{c,tgsa}, C_{c,tgsa}, s$
4. TGS *A*  $\rightarrow$  TGS *B*:  $K_{c,tgsb}, C_{c,tgsb}$

Here

$$C_{c,tgsb} \equiv \{T_{c,tgsb}\}_{r_{c,tgsb}}$$

where

$$r_{c,tgsb} \equiv (y_c Y_{tgsb})^{X_{tgsa} + k_{c,tgsb}}$$

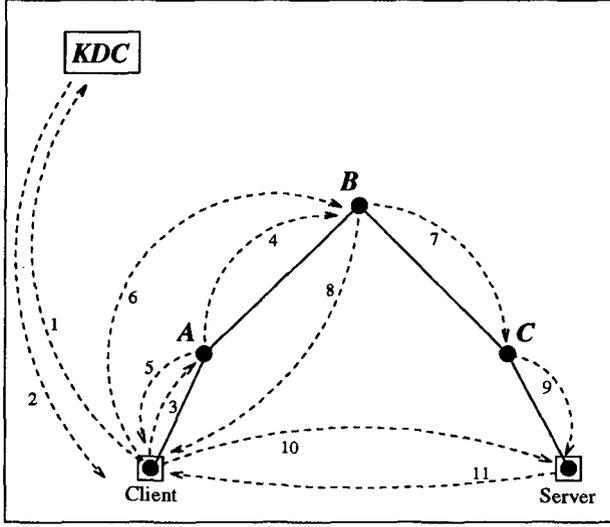


Fig. 5. Authentication with globalized keys

5. TGS  $A \rightarrow$  Client:  $K_{c,tgsb}$
6. Client  $\rightarrow$  TGS  $B$ :  $A_{c,tgsa}$   
where

$$A_{c,tgsa} \equiv (Y_{tgsa} K_{c,tgsb})^{x_c}$$

7. TGS  $B \rightarrow$  TGS  $C$ :  $K_{c,tgscs}$ ,  $C_{c,tgscs}$   
The TGS  $B$  computes

$$D_{tgsb,tgsa} \equiv (Y_{tgsa} K_{c,tgsb})^{X_{tgsb}}$$

and recreates the key

$$r_{c,tgsb} \equiv A_{c,tgsa} D_{tgsb,tgsa}$$

in order to decipher  $C_{c,tgsb}$  into  $T_{c,tgsb}$ .

TGS  $B$  then renames the ticket into  $T_{c,tgscs}$  and enciphers it as

$$C_{c,tgscs} \equiv \{T_{c,tgscs} || k_{c,tgscs}\}_{r_{c,tgscs}}$$

where

$$r_{c,tgscs} \equiv (y_c Y_{tgsb} Y_s)^{X_{tgsb} + k_{c,tgscs}}$$

8. TGS  $B \rightarrow$  Client:  $K_{c,tgscs}$
9. TGS  $C \rightarrow$  Server:  $K_{c,tgscs}$ ,  $C_{c,tgscs}$ ,  $D_{tgsb,tgsb}$   
where

$$D_{tgsb,tgsb} \equiv (Y_{tgsb} K_{c,tgscs})^{X_{tgsb}}$$

10. Client  $\rightarrow$  Server:  $A_{c,tgsb}$   
 where

$$A_{c,tgsb} \equiv (Y_{tgsb} K_{c,tgscs})^{x_c}$$

The Server then computes

$$D_{s,tgsb} \equiv (Y_{tgsb} K_{c,tgscs})^{x_s}$$

and recreates the key

$$r_{c,tgscs} \equiv A_{c,tgsb} D_{tgsb,tgsb} D_{s,tgsb}$$

in order to decipher  $C_{c,tgscs}$  into  $\{T_{c,tgscs} || k_{c,tgscs}\}$

11. Server  $\rightarrow$  Client:  $\{timestamp + 1\}_{r_{s,c}}$

## 7 Security achieved

One of the primary motivating reasons for employing the cryptosystem of [14] is its strength against chosen ciphertext attacks [20]. In such an attack the attacker has access to the deciphering algorithm and can feed the algorithm with any input ciphertext in order to obtain its corresponding original plaintext. From these matching instances the attacker can then obtain information to finally cryptanalyze and break a given ciphertext.

The cryptosystem is promising because it has been show in [14] to be secure, not only against chosen ciphertext attacks, but further against *adaptively* chosen ciphertext attacks. In this type of attacks the attacker is permitted to select the input ciphertext which are *correlated* to the target ciphertext. Hence, the attacker continues to have access to the enciphering algorithm even after the attacker has the target ciphertext. Clearly, the attacker is not permitted to feed the target ciphertext into the deciphering algorithm.

In our mode of usage of the cryptosystem, the weakest point in the scheme is equivalent to solving instances of the discrete logarithm problem [21]. More specifically, in attempting to obtain any secret key that participated in the creation of an authenticator, a descriptor or a selector the attacker is faced with solving a discrete logarithm problem. In attempting to obtain the plaintext ticket from any given ciphertext, the attacker must break the cryptosystem.

## 8 Conclusion

In this paper we have discussed the authentication services as found in the *Kuperee*. Kuperee is based on the recent public key cryptosystem of [14], which has been shown to be secure against the adaptatively chosen ciphertext attacks. The protocol has subtle features, such as the *binding* together of two entities by a third entity, leading to the need of equal co-operation by the two entities in order to complete the authentication procedure. Furthermore, it allows a Client to use a *multi-service* ticket to access multiple services offered by different Servers.

This removes the need of the Client to consult the TGS each time it needs a service from a Server. In addition, this allows an increased level of parallelism in which several Servers may be concurrently executing applications on behalf of a single Client. Hierarchical inter-realm authentication has been illustrated by way of two protocols based on the localized and globalized arrangement of keys. In general public key cryptography provides the advantage of one-to-one secure and authentic communications between entities in the system, something which is not immediately available to approaches based on private key cryptography. Our selection of the cryptosystem of [14] is motivated not only by its high level of security, but also by the ease at which session key compositions can be created. The use of public key cryptography also has the advantage in that the trusted authorities can be implemented with less trust since they only maintain the publicly-known keys [13]. This offers considerable benefit over systems such as Kerberos which are based on private key cryptography, since in these systems the compromise of a trusted authority leads to the capture of all the private keys of entities which are held by the trusted authority. The protocols in the current work represents a step towards solutions based on the mixture of private key and public key cryptography (such as in [5]), combining the advantages of both philosophies.

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## References

1. J. G. Steiner, C. Neuman, and J. I. Schiller, "Kerberos: an authentication service for open network systems," in *Proceedings of the 1988 USENIX Winter Conference*, (Dallas, TX), pp. 191-202, 1988.
2. S. M. Bellovin and M. Merritt, "Limitations of the Kerberos authentication system," *Computer Communications Review*, vol. 20, no. 5, pp. 119-132, 1990.
3. J. T. Kohl, "The evolution of the kerberos authentication service," in *Proceedings of the Spring 1991 EurOpen Conference*, (Tromsø, Norway), 1991.
4. E. Balkovich, S. R. Lerman, and R. P. Parmelee, "Computing in higher education: The Athena experience," *Communications of the ACM*, vol. 28, pp. 1214-1224, November 1985.
5. J. J. Tardo and K. Alagappan, "SPX: Global authentication using public-key certificates," in *Proceedings of the 1991 IEEE Symposium on Research in Security and Privacy*, (Oakland, CA), pp. 232-244, IEEE Computer Society, 1991.
6. M. Gasser, A. Goldstein, C. Kaufman, and B. Lampson, "The Digital Distributed Systems Security Architecture," in *Proceedings of the 12th National Computer Security Conference*, (Baltimore, MD), pp. 305-319, NIST/NCSC, October 1989.

7. R. Cole, "A model for security in distributed systems," *Computers & Security*, vol. 9, no. 4, pp. 319-330, 1990.
8. T. A. Parker, "A secure European system for applications in a multi-vendor environment (the SESAME project)," in *Information Security: An Integrated Approach* (J. E. Ettinger, ed.), ch. 11, pp. 139-156, Chapman & Hall, 1993.
9. P. Kaijser, T. Parker, and D. Pinkas, "SESAME: The solution to security for open distributed systems," *Computer Communications*, vol. 17, no. 4, pp. 501-518, 1994.
10. R. M. Needham and M. D. Schroeder, "Using encryption for authentication in a large network of computers," *Communications of the ACM*, vol. 21, no. 12, pp. 993-999, 1978.
11. D. E. Denning and G. M. Sacco, "Timestamps in key distribution protocols," *Communications of the ACM*, vol. 24, no. 8, pp. 533-536, 1981.
12. R. M. Needham and M. D. Schroeder, "Authentication revisited," *Operating Systems Review*, vol. 21, no. 1, p. 7, 1987.
13. T. Y. C. Woo and S. S. Lam, "Authentication for distributed systems," *IEEE Computer*, vol. 25, pp. 39-52, January 1992.
14. Y. Zheng and J. Seberry, "Immunizing public key cryptosystems against chosen ciphertext attacks," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 5, pp. 715-724, 1993.
15. L. Gong, "Increasing availability and security of an authentication service," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 5, pp. 657-662, 1993.
16. W. Diffie and M. E. Hellman, "New directions in cryptography," *IEEE Transactions on Information Theory*, vol. IT-22, no. 6, pp. 644-654, 1976.
17. T. El Gamal, "A public key cryptosystem and a signature scheme based on discrete logarithms," *IEEE Transactions on Information Theory*, vol. IT-31, no. 4, pp. 469-472, 1985.
18. ISO/IEC, "Information Processing Systems - Open Systems Interconnection - The Directory - Information Model," 1989. ISO/IEC 9594-1.
19. A. D. Birrell, B. W. Lampson, R. M. Needham, and M. D. Schroeder, "A global authentication service without global trust," in *Proceedings of the 1986 IEEE Symposium on Security and Privacy*, (Oakland, CA), pp. 156-172, IEEE Computer Society, 1986.
20. J. Seberry and J. Pieprzyk, *Cryptography: An Introduction to Computer Security*. Sydney: Prentice Hall, 1989.
21. M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP Completeness*. New York: W. H. Freeman, 1979.