Using Trusted Computing to Secure Mobile Ubiquitous Environments

Adrian Leung, Po-Wah Yau and Chris J. Mitchell

Information Security Group
Royal Holloway, University of London
Egham, Surrey TW20 0EX, UK
{A.Leung,P.Yau,C.Mitchell}@rhul.ac.uk

1 Introduction

Today's users typically have a multitude of electronic devices, such as desktop and laptop computers, Personal Digital Assistants (PDAs) and mobile/cellular phones, each with the capability to communicate with one another. At the same time, wireless communication has become more affordable and pervasive, and we have seen the introduction of smaller wireless-enabled devices such as headsets and headphones. In the future, the widespread use of sensor devices for a variety of monitoring applications is expected to become commonplace.

A set of user devices is likely to use a range of, possibly incompatible, communication technologies, such as IEEE 802.3 (Ethernet), IEEE 802.11 (WLAN), Bluetooth and infrared. Regardless of the available communication methods, users and service providers will both require global Internet connectivity.

Managing such a heterogenous environment is a complex problem, and current services are singular in nature — a service is provided to a single user, and typically to only one device. The synergy of user devices is not utilised in any way, which means additional management effort for the user. However, as user devices become more capable, at least in terms of communication and computation, new approaches are needed.

The Mobile Virtual Centre of Excellence (Mobile VCE)[1] has been conducting research aimed at such future technologies, with the goal of developing novel means of providing future mobile services. The underlying goal is to help deliver ubiquitous services, by providing technology that enables content and service providers to support multimedia applications over a range of access network technologies (including ad hoc networks), each with its own capabilities for service delivery. To further enhance user experience, and to reduce the complexity for users, a new model for personal distributed computing, called a 'Personal

[1]See `www.mobilevce.com`.

Distributed Environment' (PDE) [2, 15], has been proposed. A PDE is a 'virtual network' of a user's devices, providing the tools to assist the user to manage their PDE.

Inevitably, in this new environment users are vulnerable to a variety of security threats and attacks. In order to fully realise the Mobile VCE vision, sound security solutions are crucial for the widespread adoption of PDE-based ubiquitous services. Users are becoming increasingly concerned about their online privacy [6, 7], and the potential risks (such as identity theft) of leaving any form of digital trail when making electronic transactions. Given a choice, users may prefer to remain anonymous when interacting with other entities.

Trusted Computing (TC)[2] offers a range of security functionality that can be used to help meet the objective of enhancing the security of future mobile ubiquitous environments. Trusted computing is a technology that has been developed to improve the security of computing platforms in increasingly heterogenous environments. This objective is realised through the incorporation of a hardware component, known as a Trusted Platform Module (TPM), into computing platforms. The TPM provides the 'trusted platform' with a foundation of trust (so-called 'roots of trust') as well as the basis on which a suite of TC security functionality can be built. As a result, users can gain greater assurance that the platform with which they are interacting is behaving in the expected manner [3, 45].

In this chapter, we show how trusted computing mechanisms can be used to develop services to enhance the security of a PDE, to secure the process of service discovery in a mobile ubiquitous environment, and to support anonymous watermarking for content distribution protection. While this chapter presents solutions that use trusted computing technology in the context of a PDE, the general approaches we present are likely to be of use in a more general context, such as in peer-to-peer networks [4, 5] to address the problem of Sybil Attacks.

The remainder of this chapter is organised as follows. Section 2 describes the ubiquitous environment, provides more details about the PDE architecture, and describes the processes involved in the provision of ubiquitous services. Section 3 contains an overview of trusted computing and the security functionality that is applied later in this chapter. Section 4 provides an overview of the security issues surrounding the use and provision of PDEs. Section 5 addresses the problem of securing service discovery, and section 6 considers anonymous watermarking for content distribution detection. Finally, in section 7 we provide some concluding remarks.

2 The Mobile Ubiquitous Environment

The Mobile VCE vision of future mobile ubiquitous computing has the following characteristics:

[2]See `www.trustedcomputinggroup.org` for further details, including the Trusted Computing Group specifications.

- users own multiple devices of varying capabilities,
- users (and their devices) are highly mobile, and
- users communicate using a variety of different wireless network access technologies.

This leads to an environment of the type shown in Figure 1. Such an environment has three fundamental components — users, network technology, and service providers.

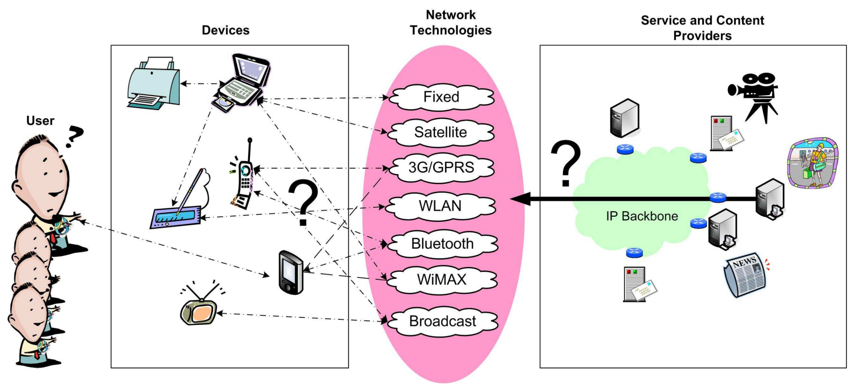


Figure 1: A mobile ubiquitous computing environment

The diversity of network technology will help to realise the Mobile VCE vision of ubiquitous computing, although addressing this heterogeneity is beyond the scope of this chapter. Instead, we focus on the two end-parties, users and service providers, and introduce the key concepts underpinning this environment. In the ongoing Mobile VCE Core 4 programme of research into Ubiquitous Services[3], it is envisaged that users will be able to seamlessly discover and access a rich offering of services and content, from a wide choice of service and content providers, via their mobile devices; any necessary switching between network technologies should be transparent to the user.

As discussed above, Mobile VCE has developed a model encompassing a user's diverse range of communication devices, called the 'Personal Distributed Environment' [2, 15]. In section 2.1, we introduce the key concepts of a PDE. A PDE will assist in the delivery of new ubiquitous services, central to these new dynamic environments. In section 2.2, we examine two key issues surrounding the provision of these 'anywhere-anytime' services — service discovery and content distribution protection.

2.1 Personal Distributed Environments

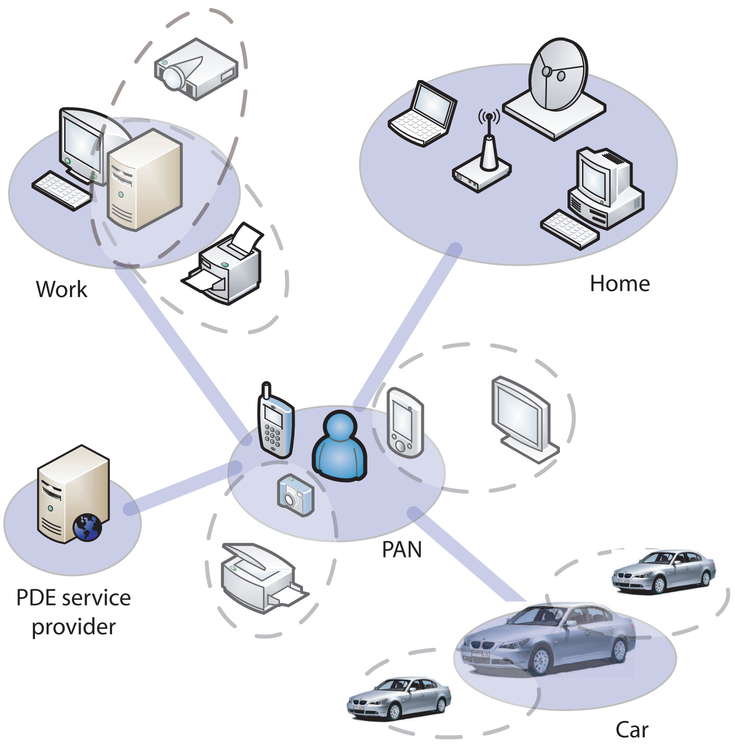
A PDE is an overlay networking concept that allows a user to form a 'virtual network' consisting of the networked devices that the user owns, or is autho-

[3]See `www.mobilevce.com`.

rised to use. The capabilities of these devices will typically vary in terms of computational power, energy source, mobility, communication and network interfaces, and may reside in different physical locations. Other related overlay architectures, similar to the PDE concept, include those described in [36, 39, 40].

2.1.1 PDE scenario

Figure 2 illustrates an example of a PDE consisting of devices that the user owns, 'home devices', and also third-party devices that the user may or may not have pre-established rights to access — these are called 'foreign devices' in PDE terminology.



The shaded ovals represent the user's subnetworks, and the ovals with dashed outlines show foreign devices that are connected to the user's PDE.

Figure 2: A Personal Distributed Environment

For example, a user may have a home network consisting of a desktop computer, a printer and an ADSL connection for Internet access. Also at home might be the user's digital set-top box and satellite receiver used to receive digital broadcasts. At work, the user might also have a desktop computer that is connected to the corporate network, allowing access to foreign devices such as corporate servers, applications, etc., that the user is authorised to access and use, possibly remotely.

In addition to the home and work environments, a user may also have a number of mobile environments. The user's car may have an intelligent networking capability enabling it to retrieve satellite navigation data and traffic news via satellite or ad hoc network communications. A user may also carry smaller devices, such as a mobile phone, PDA, and a laptop — these home devices can communicate to form a Personal Area Network (PAN). It is further envisaged that additional foreign devices may connect to the PAN on an ad hoc basis. These could, for example, include a display monitor on a train, allowing a user to view content on a larger screen, a printer in an airport lounge, or perhaps the devices of another user's PDE used to transfer data or play computer games.

This example illustrates how heterogenous networks and devices can be integrated to form a PDE. While this results in additional complexity, the diversity of technologies can be used to deliver ubiquitous services to the user, where the most capable devices and communications means available are selected.

2.1.2 PDE management

Given the potential complexity of a PDE, there must be a way for a user to manage a PDE in a simple and intuitive way. This is achieved through a semi-distributed construct called the Device Management Entity (DME). The primary task for the DME is to intelligently select the most appropriate device for service delivery, acting as a Session Initiation Protocol (SIP) [46] proxy to redirect session setup requests. In order to perform this task, the DME requires the following functional components:

- Equipment register,
- Location register, and
- Security register.

The equipment register records and stores the capabilities of devices as they are initialised and registered with the PDE. The location register maintains the location of each PDE device. The security registry stores information and data used to support PDE security functionality — this is discussed further in section 4.

As stated previously, a user's PDE may consist of a number of subnetworks in disparate locations. For reasons of efficiency and scale, DME functions are distributed to a 'local DME' within each subnetwork, each reporting to a root DME. This effectively creates a two layer management hierarchy.

It is proposed that the root DME will normally reside on the most capable device in a static subnetwork, such as the user's home desktop or, perhaps preferably, an online PDE service provider that the user has subscribed to [50]. Since the DME provides the features that enable a PDE, ensuring its availability is extremely important.

Within each PDE subnetwork, the most capable device is chosen as the local DME. In the case of mobile subnetworks the local DME selection process is dynamic, since one of the fundamental factors influencing capability is residual energy. Atkinson et al. [2] have proposed a broadcast-based protocol to discover the local, home, DME-capable device with the most residual energy — also included in their proposal is a handover protocol to move control of the local DME between devices.

In section 4 we discuss how the security issues arising in a PDE might be addressed using trusted computing functionality.

2.2 Ubiquitous Services

In a ubiquitous setting, as shown in Figure 1, a central user goal is to be able to seamlessly access ubiquitous services (or content) at any time, and anywhere, via a user device (in the user's PDE). For example, a subscriber to digital sports content may wish to watch live, streamed action of a football game, while on the move.

Recent advances in wireless networking technologies (such as WiFi, WiMax, Bluetooth, ZigBee, UWB), coupled with the ever increasing computation and communication capabilities of small form factor devices, have made such a vision a reality. These technological advances, however, have also introduced new security challenges and vulnerabilities. Existing security solutions are not well suited to a mobile ubiquitous environment, because of the dynamic and highly mobile nature of users and their devices. Of particular concern are the following.

1. As users roam and move about, they may need to interact with other entities from different administrative or security domains. To facilitate secure communications, or to establish some form of trust between two entities with no prior service interactions, online access to a trusted third party (TTP) may be required (e.g. in a PKI setting). This task is particularly difficult in a dynamic environment.

2. User devices are typically resource constrained because of their small form factor, and thus may not be capable of performing computationally intensive cryptographic operations (e.g. performing public key algorithms). Lightweight solutions may need to be devised.

3. One other problem which is exacerbated by this new communications medium is that of content distribution protection. The mobile ubiquitous environment not only allows content and service providers to reach a big pool of users and customers with greater ease, but similarly allows content pirates and illegal content distribution activities to flourish.

Whilst numerous security issues arise in a mobile ubiquitous environment, we focus here on two particularly important issues for service interactions between users and service providers, namely secure service discovery and content distribution protection.

2.2.1 Service Discovery

O'Sullivan et al. [41] define a *Service* as: 'An action performed by an entity on behalf of another and this action involves the transfer of value'. In the context of a mobile ubiquitous environment, examples of a service may include streaming of digital broadcast content, online network gaming, etc. to multiple users and their devices. Against this backdrop, *Service Discovery* can thus be defined as: 'The act or process of finding and locating such services in the network environment'. Since a value (which may not always be monetary, e.g. reputation) is attached to a service, it is important that measures are taken to protect and secure the service discovery process.

Service discovery typically takes place immediately prior to service provisioning. Many different service discovery mechanisms have been proposed (such as Java Jini [53], UPnP [56], SLP [25], DEAPspace [38] and Salutation [48]), but few address the issue of security and privacy. Regardless of the type of service discovery mechanism employed, a typical service discovery process normally involves the exchange of service messages (i.e. service advertisements and service requests) between a service user and a service provider. These messages, if divulged to an eavesdropper, may reveal information about a service user (e.g. the type of services that a user is accessing or searching). It is therefore important that the process of service discovery be conducted in such a way that user security and privacy is protected. Similarly, a service discovery scheme should also protect service providers from rogue users.

In section 5, we discuss in greater detail the security issues arising from service discovery. We describe one way in which trusted computing functionality can be used to protect and secure the process of service discovery whilst preserving user privacy.

2.2.2 Content Distribution Protection

Illegal distribution of copyrighted digital content (e.g. music and movies) through new communications media poses a major challenge to the digital content industries. The challenge for content providers is how to prevent or deter illegal distribution of copyrighted materials, whilst embracing new opportunities (e.g. a more efficient distribution channel to reach a bigger customer pool) presented by a mobile ubiquitous environment.

One way of deterring illegal content distribution is for the content provider to embed a unique 'watermark' into every piece of content. If unauthorised copies of the content are found, then this watermark should enable the content provider to trace this copy of the content back to the original buyer. Such an approach suffers from two problems. Firstly, an honest buyer may be wrongly accused (framed) of unauthorised distribution (e.g. if the content provider matches the wrong identity to the suspect copies of the content). Secondly, it is also possible for a malicious buyer to claim that an unauthorised copy was in fact leaked by the content provider.

To address these problems, two types of content distribution protection

(CDP) scheme have been proposed to protect the interests of both buyers and sellers, namely, *Buyer-Seller Watermarking* (BSW) schemes [34] and *Asymmetric Fingerprinting* (AF) schemes [43]. These schemes require content to include a buyer watermark in addition to a watermark generated by the seller. Several anonymous BSW and AF schemes [10, 13, 27, 30, 44] have also been proposed, with the goal of preserving a buyer's privacy.

In BSW schemes, a TTP generates buyer watermarks, while in the AF schemes a buyer generates his/her own watermark, which is proven to be well-formed to the content provider (using zero-knowledge proofs). Both these approaches prevent an honest buyer from being framed, as well as a malicious buyer from denying that he/she has illegally distributed copyrighted content. If buyer privacy is desired, then a TTP can be employed to provide buyers with certified pseudonyms.

The requirement for an (online) TTP in existing BSW and AF schemes, either to generate the buyer watermarks or to provide pseudonyms for buyers, represents a major constraint, especially in a mobile ubiquitous environment, where online TTPs may not always be readily available. It is clearly important to try to remove this constraint, so that the schemes are more scalable and suitable for use in distributed environments (see section 1).

Trusted computing functionality can be used to meet this objective. In section 6 we describe one way of building an anonymous watermarking scheme for content distribution protection that exploits this functionality. This scheme minimises reliance on a TTP for privacy protection, as the buyer can generate verifiable pseudonyms on its own. As a result, the communication overheads are reduced, and the overall efficiency, compared to existing BSW and AF schemes, improved. Also, through the use of TC functionality, the content provider is able to obtain assurance that a buyer-generated watermark is well formed.

3 Introduction to Trusted Computing

Trusted computing, as developed by the Trusted Computing Group[4] (TCG), is a technology designed to enhance the security of computing platforms. This objective is achieved through the incorporation of trusted hardware functionality, or so called 'roots of trust', into platforms. As a result, users can gain greater assurance that the platform with which they are interacting is in the expected configuration [3, 35, 55].

As briefly discussed above, the trusted hardware functionality is provided by a special hardware component called the TPM, embedded into a host platform. The TPM provides the platform with a foundation of trust, as well as the basis on which a suite of trusted computing security functionality is built. The TPM and its host are collectively referred to as a *Trusted Platform*, and provide a set of commands, or *Protected Capabilities*, with exclusive access to shielded locations. Shielded locations are areas (memory, registers, etc.) where

[4]http://www.trustedcomputinggroup.org

sensitive data, including cryptographic keys, can be processed with guarantees of confidentiality. Protected capabilities also enable the following functionality.

- Integrity measurement enables a Trusted Platform to record events that modify its state, in the form of *integrity metrics*.
- Integrity measurement provides a mechanism for a Trusted Platform to measure its own integrity at start-up, and, as a consequence, a means to authenticate that it has booted to a certain state.
- Sealed storage covers the ability to bind data objects, including cryptographic keys, to specific platform states, verified by the authenticated boot process.
- The use of integrity metrics is not restricted to internal use — a Trusted Platform can attest to its measured platform configuration to an external entity (or verifier).

The functions of Integrity Measurement, Storage and Reporting (IMSR) can be used to determine the software state of a trusted platform; this information can then be used to make an assessment of a platform's trustworthiness.

Other TPM protected capabilities include the following.

- A TPM provides cryptographic key management functions such as key generation, random number generation, an RSA engine and a SHA-1 engine.
- Attestation Identity Keys (AIKs) are 2048-bit RSA keys associated with TPM-generated platform aliases, that can be used to interact pseudonymously with external entities. Trust in AIKs is provided through the use of an AIK credential (public key certificate), provided by a trusted third party called a Privacy-CA.
- The reliance on Privacy-CAs may not be appropriate for applications where strong unlinkability guarantees are required. Hence, the Direct Anonymous Attestation (DAA) signature scheme is also provided, which provides additional anonymity protection for a trusted platform.

We describe the IMSR functions and DAA signature scheme in sections 3.2 and 3.3, respectively. We first give an introduction to the various types of key used by a TPM (section 3.1). The descriptions below are based upon v1.2 of the TCG TPM specifications [55].

3.1 TPM Keys and Identities

Each TPM has a unique 2048-bit RSA key pair called the *Endorsement Key* (EK). The EK is likely to be generated by the TPM manufacturer, and the EK private key, together with a certificate for the corresponding public key, can be used to prove that a genuine TPM is contained in a platform. However, since a TPM only has one such key pair, a TPM can be uniquely identified by its EK.

The EK is therefore only used in very special circumstances. A TPM can, however, generate an arbitrary number of 2048-bit RSA *Attestation Identity Key* (AIK) key pairs, which are used for interacting with other entities. AIKs function as pseudonyms for a trusted platform, and platform privacy can be achieved by using a different AIK to interact with different entities. In order to prove that a particular AIK originates from a genuine TPM, a platform has to prove that the AIK public key is associated with a genuine trusted platform; this involves use of the EK in an exchange with a trusted third party in such a way that the AIK cannot be linked with a particular EK, even by the trusted third party that sees the EK public key. The DAA protocol (discussed in section 3.3) is used to support this process.

3.2 Integrity Measurement, Storage and Reporting

Integrity Measurement, Storage and Reporting (IMSR) is one of the key features of trusted computing. IMSR builds upon the three 'roots of trust' in a trusted platform, namely, the *root of trust for measurement* (RTM), the *root of trust for storage* (RTS), and the *root of trust for reporting* (RTR). Together, they allow a verifier to learn the exact operational state of a platform, and hence obtain evidence of a platform's behaviour. This functionality is extremely important as a platform may potentially enter one of a wide range of operational states, including those that are insecure and undesirable.

3.2.1 Integrity Measurement

IMSR begins with the process of integrity measurement. The RTM, a computing engine in the TPM, measures the platform's operational state and characteristics. The measured values, known as integrity metrics, convey information about the platform's current state (and hence trustworthiness).

3.2.2 Integrity Storage

Details of exactly which measurements have been performed are stored in a file called the *Stored Measurement Log* (SML). Using the RTS, a digest (i.e. a cryptographic hash computed using Secure Hash Algorithm 1 (SHA-1) [37]) of the integrity metrics is saved in one of the TPM's internal registers, called *Platform Configuration Registers* (PCRs).

The SML contains the sequence of all measured events, and each sequence shares a common measurement digest. Since an SML may become fairly large, it does not reside in the TPM. Integrity protection for the SML is not necessary, since it functions as a means to interpret the integrity measurements in the PCRs, and any modifications to the SML will cause subsequent PCR verifications to fail.

There are only a limited number of PCRs in the TPM to hold the measurement digests. So, in order to ensure that previous and related measured values are not ignored/discarded, and the order of operations is preserved, new measurements are appended to a previous measurement digest, re-hashed, and then put back into the relevant PCR. This technique is known as *extending* the digest, and operates as follows:

$$PCR_i[n] \leftarrow \textit{SHA-1}(PCR_{i-1}[n] \,||\, \text{New integrity metric}),$$

where $PCR_i[n]$ denotes the content of the nth PCR after i extension operations, and || denotes the bit string concatenation operator.

The processes of integrity measuring and storage can be used by a trusted platform to authenticate its boot process — at each stage of the boot process a measurement is taken of the components required for the subsequent stage, before control is passed to those measured components [24] (see Figure 3).

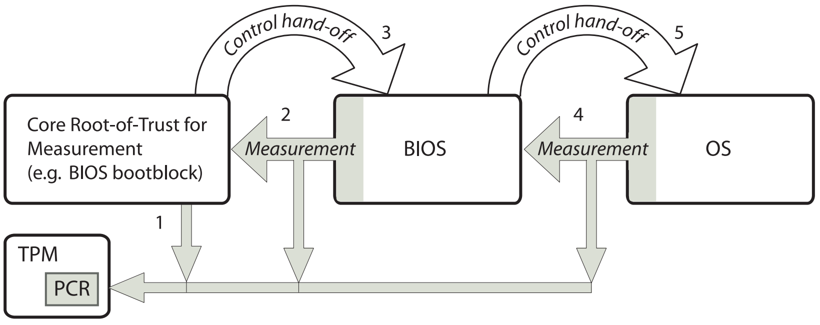


Figure 3: An example of an authenticated boot process

3.2.3 Integrity Reporting

The final phase of the IMSR process is Integrity Reporting. The RTR has two main responsibilities during Integrity Reporting:

1. to retrieve and provide a challenger with the requested integrity metrics (i.e. the relevant portion of the SML, and the corresponding PCR values); and

2. to *attest to* (prove) the authenticity of the integrity metrics to a challenger by signing the PCR values using one of the TPM's AIK private keys.

To verify the integrity measurements, the verifier computes the measurement digest (using the relevant portion of the SML), compares it with the corresponding PCR values, and checks the signature on the PCR values. The process of integrity reporting is also often referred to as *Attestation*.

3.3 Direct Anonymous Attestation

Direct Anonymous Attestation (DAA) [8, 9] is a special type of signature scheme that can be used to anonymously authenticate a TCG v1.2 compliant platform to a remote verifier. The key feature that DAA provides is the capability for a TPM (a prover) to convince a remote verifier that:

- it is indeed a genuine TPM (and hence it will behave in a trustworthy manner) without revealing any unique identifiers;
- an AIK public key is held by a TPM, without allowing multiple verifiers to collude and link transactions involving different AIKs from the same platform.

The above-mentioned features help to protect the privacy of a TPM user. Another important feature of DAA is that the powers of the supporting TTP (the DAA Issuer) are minimised, as it cannot link the actions of users (even when it colludes with a verifier), and hence compromise the user's privacy.

DAA works by allowing a prover to anonymously convince a remote verifier that it has obtained an anonymous attestation credential, or DAA Certificate (a Camenisch-Lysyanskaya (CL) signature [11]) from a specific DAA Issuer (Attester). The DAA Certificate also serves to provide the implicit 'link' between an EK and an AIK. The DAA scheme is made up of two sub-protocols: *DAA Join* and *DAA Sign.* We now provide a short description of these two sub-protocols [8].

3.3.1 DAA Join Protocol

The DAA Join protocol enables the TPM to obtain a DAA Certificate (also known as an anonymous attestation credential) from a DAA Issuer. The Join protocol is based on the CL signature scheme [11].

Let (n, S, Z, R) be the public key of the DAA Issuer, where n is an RSA modulus, and S, Z and R are integers modulo n. We assume that the platform (TPM) is already authenticated to the DAA Issuer via its Endorsement Key, EK.

The platform (TPM) first generates a DAA secret value, f, and makes a commitment to f by computing $U = R^f S^{v'} \bmod n$, where v' is a value chosen randomly to 'blind' f. The platform (TPM) also computes $N_I = \zeta_I^f \bmod \Gamma$, where ζ_I is derived from the DAA Issuer's name, and Γ is a large prime. The platform (TPM) then sends (U, N_I) to the DAA Issuer, and convinces the DAA Issuer that U and N_I are correctly formed (using a Zero Knowledge Proof [20, 21]). If the DAA Issuer accepts the proof, it will sign the hidden message, U, by computing $A = (\frac{Z}{US^{v''}})^{1/e} \bmod n$, where v'' is a random integer and e is a random prime. The DAA Issuer then sends the platform (i.e. the TPM) the triple (A, e, v''), and proves that A was computed correctly. The DAA Certificate is then $(A, e, v = v' + v'')$.

3.3.2 DAA Sign Protocol

The DAA Sign protocol allows a platform to prove to a verifier that it is in possession of a DAA Certificate, and, at the same time, to sign and authenticate a message.

The platform signs a message, m, using its DAA Secret, f, its DAA Certificate, and the public parameters of the system. The message, m, may be an Attestation Identity Key (AIK) generated by the TPM, or an arbitrary message. The platform also computes $N_V = \zeta^f \bmod \Gamma$ as part of the signature computation (the selection of ζ will be discussed in the next section). The output of the Sign protocol is known as the DAA Signature, σ.

The verifier verifies the DAA Signature, σ, and, on successful verification of σ, is convinced that:

1. the platform has a DAA Certificate (A, e, v) from a specific DAA Issuer, and hence it is a genuine TPM containing a legitimate EK; this is accomplished by a zero-knowledge proof of knowledge of a set of values f, A, e and v such that $A^e R^f S^v \equiv Z \pmod{n}$;

2. a message, m, was signed by the TPM using its DAA secret, f, where f is the same as the value in the DAA Certificate (used in step 1); if m includes an AIK public key, then the AIK originates from a genuine TPM.

In summary, once a platform (TPM) has obtained a DAA Certificate (which only needs to be done once), it is able to subsequently DAA-Sign as many AIKs as its wishes, without involving the DAA Issuer.

3.3.3 Variable Anonymity

Anonymity and unlinkability are provided to a user by using two parameters: ζ, also referred to as the *Base*, and the AIK. The choice of the base directly affects the degree of anonymity afforded to a TPM user. If perfect anonymity is desired, then a different, random base value should be used for every interaction with a verifier. Conversely, if the same base value is used for every interaction with a verifier, then the verifier can identify that this is the same TPM. In addition, if the same base value is used to interact with different verifiers, then they are able to correlate the activities of a particular TPM. (A more detailed discussion of the effects of choices of base values is given in [54]).

As discussed in section 3.1, a TPM is capable of generating multiple platform identities, simply by generating different AIK key pairs. Different AIKs may therefore be used to interact with different verifiers so that the actions of a TPM are unlinkable (provided the base is different).

4 PDE security

Pervasive availability of a user's devices is central to the PDE concept, as stated in section 2.1. This means that subnetworks of a PDE use whatever communications and access networks are available to maintain connectivity. This introduces complex management problems; for example, determining the most appropriate network to use when there are several choices [22, 23] is in itself a non-trivial problem. In this section we focus on the security issues that arise from such an architecture, and then discuss ways of addressing some of these issues using trusted computing functionality.

4.1 Security issues

The following procedures need to be defined as part of the overall PDE system definition:

- Secure initialisation of a PDE,
- Secure home device registration,
- Secure foreign device registration,
- Secure negotiation protocols within the Digital Marketplace, and
- Secure content download.

The first stage of secure initialisation includes creating and registering a user with a PDE service provider [50]. The user is then in a position to register home and foreign devices — this process includes populating the DME registers with a globally unique PDE identifer for each device, and storing a set of security credentials for each device. Credentials are stored for both PDE-to-device and device-to-device mutual authentication protocols, and for logging into the local domains that the device is authorised to operate in. Note that, in the case of home devices, these credentials can be used to support a single-sign-on capability. The same information is stored for any foreign devices registered.

The Digital Marketplace is a suite of negotiation protocols designed to manage the provision of third party services; these could be used, for example, in a market for network access, or a market for downloadable content. Goo et al. [22, 23] define security mechanisms for the negotiation protocol suite.

Gallery and Tomlinson [18] propose a pair of protocols, one based on public key cryptography and the other on the use of secret keys, that service providers can use to protect the download of proprietary conditional access software to their subscribers. It is proposed that the conditional access software is encrypted with a secret key, and that this software is then downloaded onto the user's device (if it is not already present). The user's device is assumed to be equipped with trusted computing software and hardware, including a TPM.

In the public key based protocol, a download application agent on the user's device requests its TPM to measure the current platform state, and create a public key pair that is 'sealed' to the resulting integrity measurements. The TPM creates a certificate for the associated public key and the integrity measurements, and this is sent to the service provider.

On verifying the certificate[5], the service provider has information on which to make an informed decision about whether the user's device contains software that could circumvent any conditional access protection applied to content delivered to that device. If the service provider is satisfied with the provided integrity metrics, then it can use the public key to encrypt data objects in the knowledge that the associated TPM will only decrypt them if the platform state matches that represented by the integrity measurements. In this case, the service provider encrypts two symmetric keys, one to decrypt the encrypted conditional access software, and a second to verify the software's data integrity.

The secret key version of the protocol works in a similar way, but in this case the two symmetric keys are derived from a secret key agreed between the application download agent and the service provider, using the Diffie-Hellman key agreement protocol. The two keys are stored in the device TPM and sealed to the platform state.

4.2 User perspective

We next investigate how other aspects of the PDE can be made robust from the user's perspective, using trusted computing functionality. In particular we investigate remote device integrity assurance and device revocation.

Trusted computing has often been viewed as a tool primarily designed to enable remote parties to control the handling of their data on user machines, e.g. for content owners to protect the use of proprietary content, as described in the overview above, or, for organisations to manage the dissemination of sensitive data. Indeed, this type of use has been the main source of some of the criticisms of the technology (see, for example, [1]). However, as we now describe, trusted computing can also be utilised by users as a means to protect their own devices connected in a PDE.

4.2.1 Remote device integrity assurance

Whilst a PDE offers many distributed computing benefits, it also introduces many vulnerabilities. Since the devices in a PDE will vary in terms of capability, it is likely that the level of protection for devices will also vary; some devices may be more prone to malicious physical or network attacks than others. It would be extremely useful to alert a user of potential attacks on their PDE, much like the warnings provided by current personal firewall software. Such a service would be particularly useful for remote devices where the user may not be able to physically intervene.

Trusted computing can be used to detect whether or not a PDE device has undergone modification; this can be achieved using the integrity measuring capability and attestation mechanisms provided by trusted computing, as outlined in section 3. Additional mechanisms are needed to determine if modifications

[5]It is assumed that there is a public key infrastructure in place, so that the service provider can access a certified copy of the TPM's public key.

are authorised, unauthorised but harmless, or unauthorised and represent a threat to PDE security.

During the process of adding a home device to a PDE [50], the PDE initialisation agent can also request the device's TPM to measure the platform state. The resulting integrity measurements can be uploaded to the local DME, and, if possible, to the root DME. This process should ideally be preceded by a scan for viruses and malicious software on the device, alerting the user and possibly preventing the device from joining the PDE if such software is found. The platform image can be distributed to all local DMEs; this will mean that the DME had an initial platform image that it can compare with future attestation images from the same device. Modifications to a device that are not authorised by the user will change subsequent integrity measurements, allowing the DME to detect and react to any changes.

Attestation of platform state could be made periodically or on demand. On-demand attestation could be requested before any remote operation involving sensitive data, such as the transfer of personal data. If direct connectivity to a particular PDE device is not available, but communication can be routed via a number of devices to the end target, then transitive attestation can be performed — each device on the communications route attests to its platform state to the device upstream towards the local DME. This creates an attestation chain which is valid if, and only if, the attestation image of each device has not changed from the stored value.

If devices are to upload integrity measurements periodically, then this could be most efficiently achieved by devices attesting to the local DME, which can then update the root DME on a less frequent basis. This allows a local DME to readily detect and swiftly react to a device in its subnetwork that has been modified. If and when connectivity to the root DME is present, then the local DME can alert the root DME of the device that caused the alert. Using the transitive attestation method described above, the root DME requests that the reporting local DME attests to its platform state, in order to determine whether the local DME has itself been modified and can be trusted. If a remote device is believed to have been modified, then an alert is sent to the user and the remote device can be revoked from the PDE until a user intervenes, e.g. to re-initialise the device — this procedure is discussed further in the next section.

Foreign devices can also be monitored using the same attestation techniques, but, in this case, state verification might take place on a more frequent basis because of the higher risks that they pose. On initialisation, a foreign device attests to its platform state to the local DME of the subnetwork to which the device has connected. The local DME, perhaps through the root DME, could use a web service that verifies whether or not the image of the foreign device can be trusted. Periodic attestation can then be used to monitor the foreign device while it is connected to the user's PDE. In this case, responsibility for terminating a connection to a foreign device suspected of being modified is delegated to the local DME.

4.2.2 Device revocation

Just as in a conventional network, a PDE and its devices are vulnerable to attacks in which a compromised device is used to conduct attacks on the rest of the network. Therefore, a fundamental requirement is that the compromise of a single device should not affect the whole PDE. When a modified device is detected, as described above, this device could be temporarily revoked from the PDE until a user intervenes, e.g. to re-initialise the device. Furthermore, this should apply even if multiple devices, perhaps even a whole subnetwork, are compromised simultaneously.

PDE access can be controlled using key management, in particular, through the use of a secret PDE group key that is distributed to PDE devices, via the local DMEs, from the root DME. Additional secret keys for mechanisms such as confidentiality and data integrity can then be derived from this key. The controlled use and update of this key would enable the root DME to enforce PDE access control, where only those devices in possession of the current group key are able to participate in PDE communication. By changing the PDE group key whenever a potentially compromised device is detected, such a device could be prevented from accessing future communication. Conversely, the PDE group key can also be refreshed whenever a new device joins the PDE, so that the new device is prevented from accessing past PDE communication.

In the previous section, we suggested that, when devices are initialised, their platform integrity measurements could be stored by the root DME, and also each local DME. In addition, the initialisation agent of a device could request the TPM to create a non-migratable key pair that is bound to the platform state. The TPM could certify the public key and platform measurements and the result could then be sent to the root DME. This is analogous to the download application agent sending the same data objects to a service provider in the software download protocols proposed by Gallery and Tomlinson (see above).

As a result, the root DME would know the public key bound to the platform state of each device; the root DME could issue key updates encrypted with the public keys of the devices hosting a local DME. If a local DME device has been modified then it will not be able to decrypt the key update designated for it. In this case, another device in the subnetwork can take over as the local DME host; it could indicate this by presenting an update message that is both encrypted using the latest PDE group key and signed by the root DME.

Since a subnetwork may not always be online and accessible by the root DME, each local DME is responsible for maintaining a subnetwork key encrypting key. This is used to encrypt and deliver the PDE group key update to unmodified devices. The same key distribution method can be used for root DME to local DME key distribution, so that modified PDE devices will not be able to recover the subnetwork key in order to retrieve PDE group key update data. If scalability is required, i.e. to cope with the possibility that the number of PDE devices in a subnetwork becomes large, then multicast key update techniques can be used (see, for example, [57, 58, 59]).

5 Secure and Private Service Discovery

Before a user can access and consume a service, the service will first need to be discovered via a service discovery process. Service discovery is an essential precursor to the process of service provisioning. Securing the process of service discovery is equally important, in order to protect the interests and privacy of both users and service providers. Many service discovery schemes have been proposed for ubiquitous environments (see, for example, [12, 16, 60]), but none addresses the issues of user security and privacy.

We describe below one way in which trusted computing functionality, specifically IMSR and DAA, can be used to preserve user privacy whilst securing the process of service discovery in a mobile ubiquitous environment. We first discuss the security and privacy issues arising from service discovery. We then introduce Ninja, a privacy preserving authentication scheme for ubiquitous service discovery, proposed in [31]. Finally we provide a brief analysis and discussion of this latter scheme.

5.1 Service Discovery Security Issues

A variety of security and privacy threats apply to service discovery, from which corresponding security requirements are derived.

5.1.1 Security Threats

Threats applying to service discovery include the following.

1. **Spoofing:** A malicious entity could masquerade as a legitimate service provider or service user, either by sending false service advertisements or false service requests. This could, for example, be achieved using replay or man-in-the-middle attacks.

2. **Information Disclosure**

   (a) **User's Personally Identifiable Information (PII):** During the process of service discovery, a user's PII, such as his/her identity (e.g. in the form of a long lived key) or physical location, might be revealed (either willingly or unwillingly) to a service provider or passive eavesdropper.

   (b) **Service Information (SI):** By observing the service information exchanged by a user and service provider (e.g. the types of service request), a passive adversary could build up a profile of the user. This information could be used later to predict future patterns and habits of the user. The privacy of the user is potentially compromised as a result.

3. **Profile Linking:** Colluding service providers could buy, sell or exchange information about their users or customers. This could not only provide

service providers with monetary benefits, but also enhance their business intelligence and gain competitive advantage, e.g. if they are able to build more comprehensive user profiles (with or without user permission). Finally, the consequences for user privacy could be even more serious if a TTP colludes with service providers.

4. **Encouragement of Rogue Behaviour:** With the knowledge that privacy enhancing technologies are employed to protect their identities, users may be tempted to 'misbehave' or act maliciously, since it may be difficult or even impossible for service providers to determine who is misbehaving.

5.1.2 Security Requirements

From the above threat analysis, we derive the following corresponding security and privacy requirements:

- **Mutual Authentication:** This is one of the most important requirements because it can prevent spoofing (by either malicious users or malicious service providers). Any mutual authentication scheme should also be designed to prevent replay and man-in-the-middle attacks. To protect privacy, a user may want to remain anonymous to a service provider. So, instead of authenticating his/her identity to a service provider, the user may want to somehow prove or authenticate his/her 'trustworthiness' to the service provider.

- **User Anonymity:** Unique user identifying information (e.g. an identifier or a long lived key) should not be divulged to a service provider during service discovery. A user may interact with service providers using a pseudonym.

- **Service Information Confidentiality:** To further preserve the privacy of the user, service information originating from the user may be encrypted.

- **Unlinkability:** Colluding service providers should not be able to link the activities of a user. Similarly, when a TTP colludes with a service provider, they should not be able to correlate the actions of a particular user. In other words, it should be impossible for colluding service providers to tell if two sets of prior service transactions (made with different providers) involved the same or different user(s).

- **Transaction Linkability/History:** For billing or other purposes, it may be necessary for a service provider to maintain the transaction histories of its users. A service provider may thus need to be able to determine whether a particular user is a repeat user (and, if so, which one) or a first time user, whilst still being unable to determine the unique identity of the user. This is not always a requirement, and providing it may require user consent.

- **Rogue Blacklisting:** Service providers should be able to identify and blacklist malicious and untrustworthy hosts.

5.1.3 The Security Challenges

A mutual authentication scheme meeting all the above requirements is therefore required. This is particularly challenging for several reasons. Conventional mutual authentication schemes normally require the user identity to be authenticated to a verifier. But, in this environment, user privacy is a priority, and so user anonymity is required during authentication. How then can we convince a service provider that an anonymous user is trustworthy? Also, if user anonymity is provided, can we detect malicious or illegitimate users? We are, in fact, trying to achieve security and privacy concurrently, whilst protecting the interests of both users and service providers. This challenge has been addressed by the scheme we describe immediately below.

5.2 The Ninja Authentication Scheme

To address the above challenge, Ninja, a privacy preserving authentication scheme for service discovery has been proposed [31]. This scheme uses two trusted computing functionalities, namely IMSR and DAA, and offers the following security and privacy properties: user anonymity, service information confidentiality and unlinkability.

The scheme has three phases (as shown in Figure 4). We briefly describe the workings of each phase. Full details of the protocol can be found in [31].

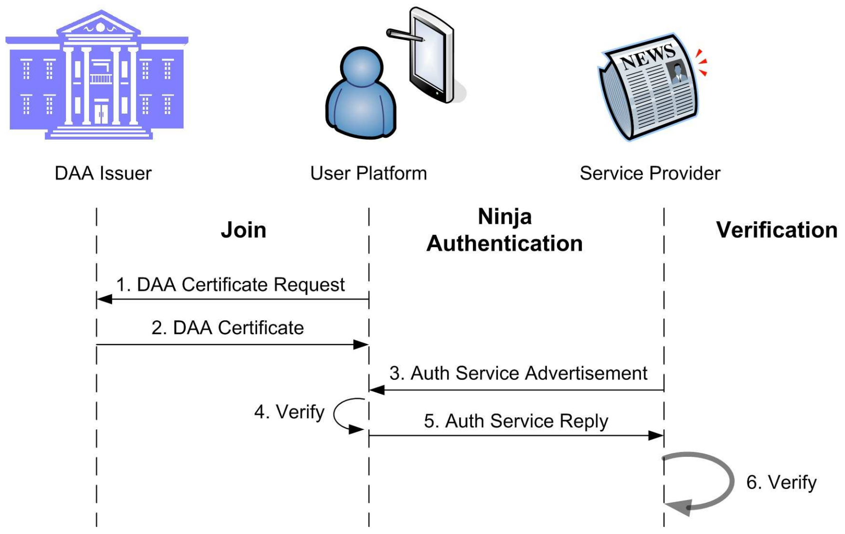


Figure 4: The Ninja Authentication Scheme

Join Phase The *Join Phase* enables a platform to obtain a *DAA Certificate* from a *DAA Issuer*. At a later time the platform can use this DAA Certificate, in the mutual authentication phase, to anonymously authenticate itself to a service provider. As shown in Figure 4, the entities involved are the *Platform* and the *DAA Issuer*. Since the Join Phase is identical to the DAA Join Protocol specified in [8], we do not discuss it further here. Note that the Join Phase may have taken place before a device is shipped to the user.

Mutual Authentication Phase Service discovery typically involves the exchange of service advertisement and service reply messages between a user and service provider. To avoid increasing the communication overheads, the (privacy preserving) authentication mechanisms are incorporated into these service messages. In other words, service discovery and mutual authentication take place concurrently.

We now examine how the goal of mutual authentication is achieved through these service messages. As shown in Figure 4, the mutual authentication process is initiated by the service provider through an authenticated service advertisement message. In other words, the service provider sends a signed copy of its service advertisement to prospective users. Also sent in this message are the public key certificate of the service provider and the public Diffie-Hellman parameters which are used to established a shared secret with the user.

Suppose that a prospective user receives the above service advertisement (via his/her platform), and is interested in the advertised service. The user's platform then authenticates the service provider by verifying the signature on the advertisement. If the verification outcome is satisfactory, then, at this point, the service provider is authenticated to the user. Using the platform, and via a service reply message (as shown in step 5 of Figure 4), the user now anonymously authenticates itself (i.e. its trustworthiness) to the service provider using the following procedure.

1. It generates an AIK key pair.
2. It retrieves its integrity metrics and signs them using the private part of the AIK (generated in step 1).
3. It computes a DAA Signature on the public part of the AIK.
4. It generates its own Diffie-Hellman exponent and computes a shared key K.
5. It then constructs the service reply message, which includes the integrity metrics and corresponding signature, the public part of the AIK, and the DAA signature.
6. It encrypts the service reply message and computes a MAC on the encrypted service reply.
7. It then sends the service provider the encrypted service reply, the MAC, and the platform's public Diffie-Hellman value.

Verification Phase On receiving a service reply message from a platform, the service provider *SP* performs the following steps to verify the platform's trustworthiness.

1. It computes the shared key K, and checks the integrity of the received message (i.e. it checks the MAC on the encrypted service reply).
2. Using K, it decrypts the encrypted service reply message.
3. From this, it obtains the DAA Signature. The service provider verifies this signature, and is thereby convinced that the platform possesses a legitimate DAA Certificate.
4. It also verifies the trustworthiness of the device (i.e. by verifying the signature on the integrity metrics and checking that these metrics correspond to a trusted software state).
5. If the service provider is satisfied with the integrity measurements, then the platform is authenticated to *SP*.

When being authenticated by another service provider, the user platform should generate a new AIK key pair, but only needs to repeat the mutual authentication phase, i.e. it does not need to perform the join phase again.

5.3 Analysis and Discussion

The Ninja authentication scheme meets all the security requirements identified above. A more detailed security analysis can be found in [31]. We conclude this section by briefly discussing why this scheme is appropriate for a mobile ubiquitous environment.

Firstly, as shown in Figure 4, mutual authentication between a service provider and user is achieved using a two-message exchange. This is particulary efficient in terms of communications overhead. The other advantage of Ninja is that, once a user has obtained a DAA Certificate from a DAA Issuer (which only needs to be done once), it is able to generate verifiable pseudonyms (i.e. the AIK key pairs) on its own, and interact with multiple service providers whilst protecting user privacy and preventing linking of transactions.

This scheme provides one example of how trusted computing can help provide security and privacy for the service discovery process. It remains of interest to consider what other approaches might be devised to achieve similar objectives — indeed, trusted computing has a very rich set of functionality, and it seems inevitable that any problem can be solved in a variety of ways.

6 Content Distribution Protection — Using Trusted Computing

We next consider how trusted computing can help provide content protection in a mobile distributed environment. In particular we consider an example of a trusted computing based anonymous watermarking scheme for content distribution, proposed in [32]. As discussed in section 2.2, one of the key motivations for the design of this scheme was to reduce reliance on an online Trusted Third Party (TTP). This is fundamentally important because an online TTP may not always be available in a mobile ubiquitous environment.

We begin with a review of the content distribution protection security issues affecting content consumers and content providers. We then go on to describe the operation of the scheme in greater detail, followed by a brief analysis.

6.1 Content Distribution Protection Security Issues

We start by examining the security issues arising from content distribution protection.

6.1.1 A CDP Threat Model

Potential security threats to content consumers (referred to below as 'buyers') and content providers include the following.

1. **Illegal Content Distribution:** A malicious user might distribute content without authorisation from the content owner (the content may have earlier been legally purchased from a content provider). This could result in the content being used by others without the appropriate payment being made to the content provider. This translates to a potential loss of revenue for the content provider.

2. **Framing:** To deter unauthorised content distribution, the content provider can use a digital watermarking scheme, where a unique seller-generated watermark is embedded into every piece of content purchased by the buyer. Such a scheme, however, does not prevent an honest buyer from being falsely accused (framed) of unauthorised content distribution. This is a problem if there is no way for the buyer to challenge the decision and prove his/her innocence.

3. **Information Disclosure**

   - **Buyer's Personally Identifiable Information (PII):** During the process of content purchase, a buyer's PII, such as his/her identity or physical location, might be revealed (either willingly or unwillingly) to a content provider or passive eavesdropper.
   - **Content Information:** By observing the type of content that a buyer purchases, a passive adversary might gradually build up a profile of the buyer. This information may later be used to infer or predict future patterns and habits of the buyer. The privacy of the buyer is potentially compromised as a result.

4. **Profile Linking:** Colluding content providers might buy, sell or exchange information about their clients. Such collusion could not only provide content providers with monetary benefits, but also enhance their business intelligence as they are able to build a more comprehensive profile of their customers. With the aid of a TTP, buyers can employ privacy enhancing mechanisms to protect their identity when they interact with content providers. The consequences for buyer privacy could be even more serious if such a TTP decides to collude with content providers.

6.1.2 CDP Security Requirements

We can derive a corresponding set of security requirements from the above list of threats.

1. **Framing Resistance:** It should not be possible for the content provider to falsely accuse an honest buyer of unauthorised content distribution.
2. **User Anonymity:** Unique identifying information for a buyer (such as a long lived key) should not be divulged to a content provider during the content purchasing process. A buyer may interact with content providers using pseudonyms.
3. **Content Information Confidentiality:** Eavesdroppers on the communications between a buyer and content provider should not be able to determine the type of content that is being purchased by the buyer.
4. **Unlinkability:** Colluding content providers should not be able to link the activities of the same buyer. Similarly, when a TTP colludes with a content provider, they should not be able to correlate the actions of a particular buyer. In other words, it should be impossible for colluding content providers to tell if two sets of prior content purchase transactions (made with different providers) have originated from the same or different buyers.
5. **Transaction History:** For billing or other purposes (e.g. loyalty rewards), it may be necessary for a content provider to maintain the transaction histories of its buyers. That is, a content provider may need to be able to identify whether a particular buyer is a repeat buyer (and, if so, which one) or a first time buyer, whilst still being unable to determine the unique identity of the buyer.
6. **Blacklisting of Rogue Buyers:** In the event that illegal copies of copyrighted content are found (e.g. on the Internet), content providers should be able to blacklist the buyers that purchased these copies of the content.

6.2 The Watermarking Scheme

We now present the anonymous content distribution protection watermarking scheme given in [32]. This scheme is designed to enable a buyer to anonymously purchase digital content, whilst allowing a seller to blacklist any buyer platforms that are distributing content illegally. Using the IMSR and DAA TC functionality, the scheme also allows a buyer to generate verifiable pseudonyms, and to convince a content provider that the buyer generated watermark is well formed, without the involvement of a TTP. The scheme is also designed to meet all the security requirements set out in section 6.1.

First, we introduce the entities participating in the protocol. Next, we state the assumptions upon which the scheme is based. Finally, we describe the operation of the scheme.

6.2.1 The Entities

The entities participating in the scheme are:

- the **buyer** of digital content (e.g. music, video, podcasts, etc.);
- the **platform**, consisting of the TPM and its host — the platform is also the device which a content buyer will use to interact with other entities;
- the **seller** (also referred to as the content provider) of digital content;
- the **DAA Issuer**, i.e. the authority that issues DAA Certificates to legitimate platforms.

6.2.2 Assumptions

The correct working of scheme relies upon a number of assumptions.

- Using an out of band mechanism, such as the one given in [19]), the content buyer is already authenticated to the platform that is used for the CDP watermarking scheme. The buyer and the platform will collectively be referred to as the Buyer Platform.
- The device/platform running the CDP scheme is equipped with TCG functionality conforming to v1.2 of the TCG specifications [55] (see Section 3).
- The parties involved have agreed on the use of a homomorphic encryption algorithm $Enc_K(\cdot)$ (e.g. the Paillier probabilistic encryption scheme [42] that is homomorphic with respect to addition).
- The embedding operation $\otimes$ (as used to embed a watermark in a piece of content) is public knowledge, and the security of the embedding relies on the key used to embed the watermark W. (In this case the key is a random permutation ρ). In addition, the watermark W embedded with $\otimes$ is *collusion resistant*, which means that it is computationally infeasible for the attackers to remove W by comparing different copies of the content.

Table 1: Notation

Notation	Description
BP	The Buyer Platform
S	The Seller or Content Provider
DI	The DAA Issuer
f	A DAA secret value generated by the TPM
ID_A	The identity of a principal, A
(EK_{pk}, EK_{sk})	The pair of Public and Private Endorsement Keys
(AIK_{pk}, AIK_{sk})	A pair of Public and Private Attestation Identity Keys
X'	Watermarked Content
$X \otimes W$	Embed W into X with the embedding operation, $\otimes$
ρ	A random permutation function
H	A cryptographic hash-function
$Enc_K(M)$	The encryption of a message, M, using the key K
$Dec_K(M)$	The decryption of a message, M, using the key K
$Sig_K(M)$	A signature on a message, M, created using the key K

6.2.3 The Scheme

Before describing the scheme, it is first necessary to introduce some notation (see Table 1).

The CDP watermarking scheme involves three distinct phases (as shown in Figure 5), namely, the *Join Phase*, the *Watermarking Phase*, and the *Content Acquisition Phase*. We now describe each phase in greater detail.

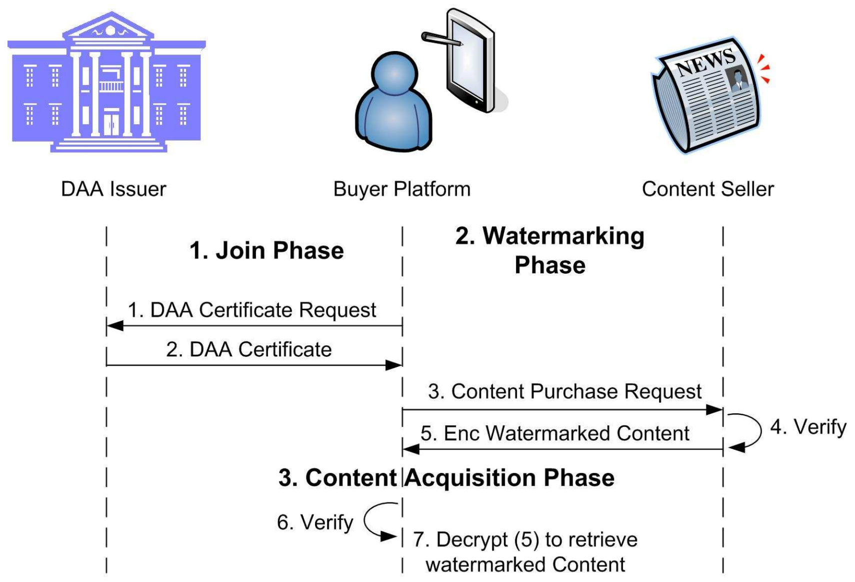

NEWS
DAA Issuer
Buyer Platform
Content Seller
1. Join Phase
2. Watermarking Phase
1. DAA Certificate Request
2. DAA Certificate
3. Content Purchase Request
4. Verify
5. Enc Watermarked Content
3. Content Acquisition Phase
6. Verify
7. Decrypt (5) to retrieve watermarked Content

Figure 5: An Anonymous Watermarking Scheme using Trusted Computing

Join Phase The objective of the *Join Phase* is for a buyer platform to obtain a *DAA Certificate* from a *DAA Issuer*. Since the Join Phase of the scheme is identical to the DAA Join Protocol of section 3.2, we do not describe the sequence of Join Phase steps. Note that the Join Phase may have taken place before a device is shipped to the content buyer.

Watermarking Phase The aim of this phase is for a buyer to contribute a watermark, and for the seller to embed the buyer's watermark into a piece of proprietary content. The entities involved in this phase are the *Buyer Platform*, *BP* and the *Seller*, *S*. The sequence of events is as follows:

1. *BP* generates a watermark, W, using the watermark generation function of a reliable watermarking algorithm (e.g. the spread spectrum watermarking algorithm given in [14]).

2. *BP* generates an encryption key pair (BEK_{pk}, BEK_{sk}), and encrypts the watermark, W, using BEK_{pk}, to create:

   $$Enc_{BEK_{PK}}(W).$$

3. *BP* (i.e. the TPM) generates a non-migratable signing key pair (BSK_{pk}, BSK_{sk}). *BP* then signs the encrypted watermark, $Enc_{BEK_{pk}}(W)$ (from step 2), and BEK_{pk}, to obtain:

   $$Sig_{BSK_{sk}}(Enc_{BEK_{pk}}(W), BEK_{pk}).$$

4. *BP* generates an AIK key pair, (AIK_{pk}, AIK_{sk}).

5. *BP* retrieves the Stored Measurement Log (SML), and the corresponding Platform Configuration Register (PCR) values. *BP* then signs the PCR values using AIK_{sk} (from step 4):

   $$Sig_{AIK_{sk}}(PCR).$$

   The SML and PCR values provide evidence that a particular watermarking algorithm was used (by the buyer) to generate the watermark.

6. *BP* computes $\zeta = \mathrm{H}(ID_S)$. It then creates a pseudonym, $N_v = \zeta^f$ (where f is the DAA Secret generated during the join phase) for use when interacting with the seller.

7. To prove (to the seller) that the AIK (from step 4) originates from a genuine TPM, the platform DAA-Signs AIK_{pk} using f, the DAA Certificate, and the other public parameters of the system. The output of DAA Sign is the DAA Signature, σ (which also includes ζ and N_v).

8. To prove that BSK originates from the TPM, *BP* signs (certifies) BSK_{pk} using AIK_{sk}:

   $$Sig_{AIK_{sk}}(BSK_{pk}).$$

9. BP sends the following to the Seller:

$$\begin{aligned} BP \rightarrow S :& Enc_{BEK_{pk}}(W), AIK_{pk}, BSK_{pk}, BEK_{pk}, \\ & \sigma, Sig_{BSK_{sk}}(Enc_{BEK_{pk}}(W), BEK_{pk}), \\ & Sig_{AIK_{sk}}(BSK_{pk}), SML, Sig_{AIK_{sk}}(PCR). \end{aligned}$$

On receiving the last message from the buyer, and, to subsequently incorporate the buyer's watermark into a piece of content, the seller S performs the following steps:

1. Verifies the DAA Signature, σ, and is thus convinced that:
    - BP is in possession of a legitimate DAA Certificate from a specific DAA Issuer, which implies that a genuine TPM is contained in BP.
    - AIK_{pk} was signed using BP's DAA Secret, f. Even though the value of f is never revealed to the seller, the seller knows that the value is related to the one in the DAA Certificate.
2. Examines the integrity measurements of the buyer platform. This is achieved by recursively hashing the values in the SML, and then comparing the result with the corresponding PCR values. If the outcome is satisfactory, the seller is convinced that a reliable watermarking algorithm was used by the buyer platform to generate its watermark, W.
3. Verifies $Sig_{AIK_{sk}}(BSK_{pk})$.
4. Verifies $Sig_{BSK_{sk}}(Enc_{BEK_{pk}}(W), BEK_{pk})$.
5. Generates a seller watermark, V, and then embeds it into the Content, X, to create:

    $$X' = X \otimes V.$$

6. Encrypts X' (from step 3) using BEK_{pk} to obtain:

    $$E(X') = Enc_{BEK_{pk}}(X').$$

7. Permutes $Enc_{BEK_{pk}}(W)$ (received from buyer) to obtain $E(\rho W)$.
8. The permuted watermark is then embedded into X' as follows:

    $$E(X' \otimes \rho W) = E(X') \otimes E(\rho W),$$

    which follows because of the homomorphic property of the encryption algorithm.
9. The encrypted, watermarked content is then sent back to the buyer.

    $$S \rightarrow BP : E(X' \otimes \rho W).$$

Content Acquisition Phase When the buyer receives the encrypted, watermarked content, $E(X' \otimes \rho W)$, from the seller, the buyer decrypts it using BEK_{sk}, to retrieve the watermarked content:

$$(X' \otimes \rho W).$$

The watermarked content is now ready for consumption (e.g. viewing or listening) by the buyer.

6.3 Analysis and Discussion

The watermarking scheme presented here meets all the security requirements identified earlier in section 6.1. The interested reader is referred to [32] for a more detailed security analysis. This watermarking scheme is suitable for use in a mobile ubiquitous environment for the following reasons.

Firstly, as mentioned in section 2.2, having access to an online TTP may not be feasible in such an environment. To protect privacy, and using DAA, a buyer only has to interact with the DAA Issuer (the online TTP here) once, and he/she can subsequently generate verifiable pseudonyms on his/her own and interact with buyers.

Secondly, the scheme is extremely efficient in terms of communications overhead, because only two messages need to be exchanged between the content buyer and a seller. In a mobile environment, where users are predominantly using resource constrained devices, communications efficiency is an important feature.

6.4 The Future

We have presented just one example of a scheme exploiting the features offered by trusted computing for the purpose of protecting content distributed to mobile devices. If trusted computing functionality becomes as widespread as is commonly expected, then a variety of other such schemes are likely to be proposed. This appears to be an area of considerable promise for future research and exploitation.

7 Concluding Remarks

We have considered three ways in which trusted computing can help to address some of the most pressing security and privacy issues arising in future mobile ubiquitous networks. However, there are doubtless many other ways in which trusted computing can be exploited to help provide security for future mobile networks. If trusted computing technology becomes as ubiquitous as is envisaged by the technology's developers, then this is clearly an area of huge importance for the future. TPMs are already present in very large numbers of PCs on sale today, and it seems only a matter of time before similar functionality spreads to a wide range of mobile computing devices.

Other work on exploiting trusted computing functionality to provide security in mobile ubiquitous computing environments is already emerging. The work of Balfe, Lakhani and Paterson [4, 5] on using trusted computing to provide stable addresses in a peer-to-peer environment, and hence avoid Sybil attacks, has already been mentioned in section 1. The use of trusted computing's attestation mechanisms to detect node compromise in wireless sensor networks [29] has been proposed by Krauß, Stumpf and Eckrt. Other relevant work includes the efforts of the Mobile Phone Working Group of the TCG, as outlined in [17], the work of Kinateder and Pearson on using trusted computing to support a distributed reputation system [28], the use of trusted computing for securing the access, distribution and storage of confidential documents in a networked enterprise environments for mobile workers [51], as proposed by Sevinç, Strasser and Basin, and the possible use of trusted computing functionality to provide greater security for end nodes in peer-to-peer networks, as discussed by Schechter, Greenstadt and Smith [49].

Like any other technological innovation, trusted computing is no silver bullet. The technology is still evolving, and open issues remain. One such issue, highlighted by McCune *et al.* [33], is the *turtle problem*, i.e. the problem of establishing the first point of trust for the purpose of user based attestation in a network environment. Another area of considerable recent interest involves possible means of generalising the attestation mechanism, which is seen by many as too coarse and difficult to manage. Such work includes Shi et al.'s fine-grained code attestation [52], and property-based attestation [26, 47].

One technology likely to be fundamental to the deployment of trusted computing in general purpose computing platforms is *virtualisation*. This technology provides the ability to run multiple 'virtual machines' (VMs) on one physical platform, managed by a 'hypervisor' or Virtual Machine Monitor (VMM). Each virtual machine hosts a self-contained operating system or task-specific software. The VMs are isolated from each other, and one VM cannot access memory space allocated to another VM — the VMM ensures this with assistance from hardware enhancements. For example, Intel's LaGrande technology [24] provides hardware support enabling the creation of secure (and measurable) compartments for virtual machines. Virtualisation can be used to enhance the security properties of a trusted platform — for example, Haldar et al. [26] have proposed methods for extending platform integrity measuring to virtual machines.

Indeed, trusted computing could become a ubiquitous security infrastructure, used routinely in the provision of almost every security service — indeed, this would appear to be part of the vision of the TCG (see, for example, [45]). It therefore would seem prudent to further explore ways in which such technology can be exploited to solve some of the most difficult problems facing users and designers of ubiquitous computing systems, not least such issues as user privacy and trust establishment.

Acknowledgements

The work reported in this chapter has formed part of the Ubiquitous Services Core Research Programme of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, www.mobilevce.com. This research has been funded by the DTI-led Technology Programme and by the Industrial Companies who are Members of Mobile VCE. Fully detailed technical reports on this research are available to Industrial Members of Mobile VCE.

References

[1] R. Anderson. Cryptography and competition policy: Issues with 'trusted computing'. In *Proceedings of the 22nd annual symposium on Principles of Distributed Computing (PODC '03), Boston, Massachusetts, US, July 13–16, 2003*, pages 3–10. ACM Press, 2003.

[2] R. C. Atkinson, J. Irvine, J. Dunlop, and S. Vadagama. The personal distributed environment. *IEEE Wireless Communications*, 14(2):62–69, April 2007.

[3] B. Balacheff, L. Chen, S. Pearson, D. Plaquin, and G. Proudler. *Trusted Computing Platforms: TCPA Technology in Context.* Prentice Hall PTR, Upper Saddle River, New Jersey, 2003.

[4] S. Balfe, A. D. Lakhani, and K. G. Paterson. Securing peer-to-peer networks using trusted computing. In C. J. Mitchell, editor, *Trusted Computing*, chapter 10, pages 271–298. IEE Press, London, 2005.

[5] S. Balfe, A. D. Lakhani, and K. G. Paterson. Trusted computing: Providing security for peer-to-peer networks. In *Proceedings of the Fifth International Conference on Peer-to-Peer Computing (P2P '05), Konstanz, Germany, August 31–September 2, 2005*, pages 117–124. IEEE Computer Society, Aug-Sep 2005.

[6] F. Bao and R. H. Deng. Privacy protection for transactions of digital goods. In S. Qing, T. Okamoto, and J. Zhou, editors, *Third International Conference on Information and Communications Security (ICICS 2001), Xian, China, November 13–16, 2001. Proceedings*, volume 2229 of *Lecture Notes in Computer Science*, pages 202–213. Springer-Verlag, Berlin, 2001.

[7] B. Berendt, O. Günther, and S. Spiekermann. Privacy in e-commerce: Stated preferences vs. actual behavior. *Communications of the ACM*, 48(4):101–106, 2005.

[8] E. Brickell, J. Camenisch, and L. Chen. Direct anonymous attestation. In *Proceedings of the 11th ACM Conference on Computer and Communications Security, Washington DC, USA, October 25–29, 2004*, pages 132–145. ACM Press, 2004.

[9] E. Brickell, J. Camenisch, and L. Chen. The DAA scheme in context. In C. J. Mitchell, editor, *Trusted Computing*, chapter 5, pages 143–174. IEE Press, London, 2005.

[10] J. Camenisch. Efficient anonymous fingerprinting with group signatures. In T. Okamoto, editor, *Advances in Cryptology — ASIACRYPT 2000, 6th International Conference on the Theory and Application of Cryptology and Information Security, Kyoto, Japan, December 3–7, 2000, Proceedings*, volume 1976 of *Lecture Notes in Computer Science*, pages 415–428. Springer-Verlag, 2000.

[11] J. Camenisch and A. Lysyanskaya. A signature scheme with efficient protocols. In S. Cimato, C. Galdi, and G. Persiano, editors, *Third Conference on Security in Communication Networks (SCN 2002), Amalfi, Italy, September 12–13, 2002. Proceedings*, volume 2576 of *Lecture Notes in Computer Science*, pages 268–289. Springer-Verlag, Berlin, 2003.

[12] D. Chakraborty, A. Joshi, Y. Yesha, and T. Finin. Toward distributed service discovery in pervasive computing environments. *IEEE Transactions on Mobile Computing*, 5(2):97–112, 2006.

[13] J.-G. Choi, K. Sakurai, and J.-H. Park. Does it need trusted third party? Design of buyer-seller watermarking protocolwithout trusted third party. In J. Zhou, M. Yung, and Y. Han, editors, *First International Conference on Applied Cryptography and Network Security (ACNS 2003), Kunming, China, October 16–19, 2003. Proceedings*, volume 2846 of *Lecture Notes in Computer Science*, pages 265–279. Springer-Verlag, Berlin, 2003.

[14] I. J. Cox, J. Killian, T. Leighton, and T. Shamoon. Secure spread spectrum watermarking for multimedia. *IEEE Transactions on Image Processing*, 6(12):1673–1687, 1997.

[15] J. Dunlop, R. C. Atkinson, J. Irvine, and D. Pearce. A personal distributed environment for future mobile systems. In *Proceedings of 12th IST Mobile and Wireless Communications Summit, Aveiro, Portugal, June 15–18, 2003*, pages 705–709. Instituto de Telecomunicações, Jun 2003.

[16] A. Friday, N. Davies, N. Wallbank, E. Catterall, and S. Pink. Supporting service discovery, querying and interaction in ubiquitous computing environments. *Wireless Networks*, 10(6):631–641, 2004.

[17] E. M. Gallery and C. J. Mitchell. Trusted mobile platforms. In A. Aldini and R. Gorrieri, editors, *Foundations of Security Analysis and Design IV: FOSAD 2006/2007 Tutorial Lectures*, volume 4677 of *Lecture Notes in Computer Science*, pages 282–323. Springer-Verlag, Berlin, 2007.

[18] E. M. Gallery and A. Tomlinson. Secure delivery of conditional access applications to mobile receivers. In C. J. Mitchell, editor, *Trusted Computing*, chapter 7, pages 195–237. IEE Press, London, 2005.

[19] C. Gehrmann, C. J. Mitchell, and K. Nyberg. Manual authentication for wireless devices. *Cryptobytes*, 7(1):29–37, 2004.

[20] O. Goldreich, S. Micali, and A. Wigderson. Proofs that yield nothing but their validity or all languages in NP have zero-knowledge proof systems. *Journal of the ACM*, 38(3):690–728, 1991.

[21] S. Goldwasser, S. Micali, and C. Rackoff. The knowledge complexity of interactive proof systems. *SIAM Journal on Computing*, 18(1):186–208, 1989.

[22] S. K. Goo, J. Irvine, and R. Atkinson. Personal distributed environment securing the dynamic service platformsbeyond 3G. In *Proceedings of 4th International Conference on 3G Mobile Communication Technologies, London, UK, June 25–27, 2003*, pages 18–22. IEE Conference Publication 494, 2003.

[23] S. K. Goo, J. Irvine, J. Dunlop, A. Tomlinson, and S. Schwiderski-Grosche. Security requirements for mobile service provision via a digital marketplace. In *Proceedings of 11th European Wireless Conference (EW 2005), Nicosia, Cyprus, April 10–13, 2005*, volume 2, pages 573–581, 2005.

[24] D. Grawrock. *The Intel safer computing initiative: building blocks for trusted computing.* Intel Press, 2006.

[25] E. Guttman, C. Perkins, J. Veizades, and M. Day. Service Location Protocol, Version 2. RFC 2608, The Internet Engineering Task Force (IETF), June 1999.

[26] V. Haldar, D. Chandra, and M. Franz. Semantic remote attestation — A virtual machine directed approach to Trusted Computing. In *Proceedings of the 3rd USENIX Virtual Machine Research & Technology Symposium (VM '04), San Jose, CA, USA, May 6–7, 2004*, pages 29–41. USENIX, May 2004.

[27] H. S. Ju, H. J. Kim, D. H. Lee, and J. I. Lim. An anonymous buyer-seller watermarking protocol with anonymity control. In P. J. Lee and C. H. Lim, editors, *5th International Conference on Information Security and Cryptology (ICISC 2002), Seoul, Korea, November 28–29, 2002. Proceedings*, volume 2587 of *Lecture Notes in Computer Science*, pages 421–432. Springer-Verlag, Berlin, 2002.

[28] M. Kinateder and S. Pearson. A privacy-enhanced peer-to-peer reputation system. In K. Bauknecht, A. Min Tjoa, and G. Quirchmayr, editors, *E-Commerce and Web Technologies, 4th International Conference, EC-Web, Prague, Czech Republic, September 2–5, 2003, Proceedings*, volume 2738 of *Lecture Notes in Computer Science*, pages 206–216. Springer-Verlag, Berlin, 2003.

[29] C. Krauß, F. Stumpf, and C. Eckert. Detecting node compromise in hybrid wireless sensor networks using attestation techniques. In F. Stajano, C. Meadows, S. Capkun, and T. Moore, editors, *4th European Workshop on Security and Privacy in Ad-hoc and Sensor Networks (ESAS 2007), Cambridge, UK, July 2–3, 2007. Proceedings*, volume 4572 of *Lecture Notes in Computer Science*, pages 203–217. Springer-Verlag, Berlin, 2007.

[30] C.-L. Lei, P.-L. Yu, P.-L. Tsai, and M.-H. Chan. An efficient and anonymous buyer-seller watermarking protocol. *IEEE Transactions on Image Processing*, 13(12):1618–1626, 2004.

[31] A. Leung and C. J. Mitchell. Ninja: Non identity based, privacy preserving authentication for ubiquitousenvironments. In J. Krumm, G. D. Abowd, A. Seneviratne, and T. Strang, editors, *9th International Conference on Ubiquitous Computing (Ubicomp 2007), Innsbruck, Austria, September 16–19, 2007. Proceedings*, volume 4717 of *Lecture Notes in Computer Science*, pages 73–90. Springer-Verlag, Berlin, 2007.

[32] A. Leung and G. S. Poh. An anonymous watermarking scheme for content distribution protection using trusted computing. In *Proceedings of the International Conference on Security and Cryptography (SECRYPT 2007), Barcelona, Spain, August 28–31, 2007*, pages 319–326. INSTICC Press, 2007.

[33] J. M. McCune, A. Perrig, A. Seshadri, and L. van Doorn. Turtles all the way down: Research challenges in user-based attestation. In *Proceedings of the 2nd USENIX Workshop on Hot Topics in Security (HotSec '07), Boston, MA, USA, August 7, 2007*, 2007.

[34] N. Memon and P. W. Wong. A buyer-seller watermarking protocol. *IEEE Transactions on Image Processing*, 10(4):643–649, 2001.

[35] C. J. Mitchell, editor. *Trusted Computing*. IEE Press, London, 2005.

[36] W. Mohr. The wireless world research forum — WWRF. *Computer Communications*, 26(1):2–10, Jan 2003.

[37] National Institute of Standards and Technology (NIST). Secure Hash Standard. Federal information processing standards publication (FIPS) 180-2, 2002.

[38] M. Nidd. Service discovery in DEAPspace. *IEEE Personal Communications*, 8(4):39–45, 2001.

[39] N. Niebert, A. Schieder, H. Abramowicz, G. Malmgren, J. S. C. Prehofer, and H. Karl. Ambient networks: An architecture for communication beyond 3G. *IEEE Wireless Communications*, 11(2):14–22, April 2004.

[40] I. G. Niemegeers and S. M. H. de Groot. Research issues in ad-hoc distributed personal networking. *Wireless Personal Communications*, 26(2–3):149–167, 2003.

[41] J. O'Sullivan, D. Edmond, and A. Hofstede. What's in a service? Towards accurate description of non-functional service properties. *Distributed and Parallel Databases Journal*, 12(2/3):117–133, 2002.

[42] P. Paillier. Public-key cryptosystems based on composite degree residuosity classes. In J. Stern, editor, *EUROCRYPT '99, Prague, Czech Republic, May 2–6, 1999. Proceedings*, volume 1592 of *Lecture Notes in Computer Science*, pages 223–238. Springer-Verlag, Berlin, 1999.

[43] B. Pfitzmann and M. Schunter. Asymmetric fingerprinting. In U. M. Maurer, editor, *EUROCRYPT '96, Zaragoza, Spain, May 12-16, 1996. Proceedings*, volume 1070 of *Lecture Notes in Computer Science*, pages 84–95. Springer-Verlag, Berlin, 1996.

[44] B. Pfitzmann and M. Waidner. Anonymous fingerprinting. In W. Fumy, editor, *EUROCRYPT '97, Konstanz, Germany, May 11–15, 1997. Proceedings*, volume 1233 of *Lecture Notes in Computer Science*, pages 88–102. Springer-Verlag, Berlin, 1997.

[45] G. J. Proudler. Concepts of trusted computing. In C. J. Mitchell, editor, *Trusted Computing*, chapter 2, pages 11–27. IEE Press, London, 2005.

[46] J. Rosenburg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley, and E. Schooler. SIP: Session initiation protocol. RFC 3261, Internet Engineering Task Force, Jun 2002.

[47] A.-R. Sadeghi and C. Stüble. Property-based attestation for computing platforms: Caring about properties, not mechanisms. In *Proceedings of the 2004 Workshop on New Security Paradigms (NSPW '04), Nova Scotia, Canada, September 20–23, 2004*, pages 67–77. ACM Press, 2004.

[48] Salutation Consortium. Salutation Architecture Specification, June 1999. http://www.salutation.org/.

[49] S. E. Schechter, R. A. Greenstadt, and M. D. Smith. Trusted computing, peer-to-peer distribution, and the economics of pirated entertainment. In *Proceedings of The Second Annual Workshop on Economics and Information Security*, 2003. College Park, Maryland, May 29–30, 2003.

[50] S. Schwiderski-Grosche, A. Tomlinson, and D. B. Pearce. Towards the secure initialisation of a personal distributed environment. Technical Report RHUL–MA–2005–9, Mathematics Department, Royal Holloway, University of London, July 2005.

[51] P. E. Sevinç, M. Strasser, and D. A. Basin. Securing the distribution and storage of secrets with trusted platform modules. In D. Sauveron, K. Markantonakis, A. Bilas, and J.-J. Quisquater, editors, *First International Workshop in Information Security Theory and Practices: Smart Cards, Mobile and Ubiquitous Computing Systems (WISTP 2007), Heraklion, Crete, Greece, May 9–11, 2007. Proceedings*, volume 4462 of *Lecture Notes in Computer Science*, pages 53–66. Springer-Verlag, Berlin, 2007.

[52] E. Shi, A. Perrig, and L. V. Doorn. BIND: A fine-grained attestation service for secure distributed systems. In *Proceedings of the 2005 IEEE Symposium on Security and Privacy, Oakland, CA, USA, May 8–11, 2005*, pages 154–168. IEEE Press, 2005.

[53] Sun Microsystems. Jini Architecture Specification. Version 1.2, Sun Microsystems, Palo Alto, CA, USA, December 2001. http://www.sun.com/software/jini/specs/.

[54] Trusted Computing Group (TCG). TPM v1.2 Specification Changes. A summary of changes, Trusted Computing Group, Portland, Oregon, USA, October 2003.

[55] Trusted Computing Group (TCG). TCG Specification Architecture Overview. Version 1.2, The Trusted Computing Group, Portland, Oregon, USA, April 2004.

[56] Universal Plug and Play (UPnP) Forum. UPnP Device Architecture. version 1.0, December 2003. http://www.upnp.org/.

[57] M. Waldvogel, G. Caronni, D. Sun, N. Weiler, and B. Plattner. The versakey framework: versatile group key management. *IEEE Journal on Selected Areas in Communications*, 17(9):1–16, Aug 1999.

[58] D. Wallner, E. Harder, and R. Agee. Key management for multicast: Issues and architectures. RFC 2627, Internet Engineering Task Force, Jun 1999.

[59] C. K. Wong, M. Gouda, and S. S. Lam. Secure group communications using key graphs. *IEEE/ACM Transactions on Networking*, 8(1):16–30, Feb 2000.

[60] F. Zhu, M. Mutka, and L. Li. Service discovery in pervasive computing environments. *IEEE Pervasive Computing*, 4(4):81–90, 2005.