A Secure Connectivity Model for Internet of Things Analytics Service Delivery

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Abstract—Wide scale interest and adoption of Internet of Things (IoT) technologies is fuelling innovation in the way individuals and even machines can interact to exchange knowledge. One area of particular interest is that of analytics. Ever-decreasing form factor hardware is enabling computation and data storage to be embedded into many different devices. The combination of network connectivity and emerging distributed models of service orchestration is allowing the creation of new ways of measuring, monitoring and analysing performance. Using an approach inspired by the NIST seven layer model of cloud computing, we propose a model of connectivity that enables analytics services to be consumed across individual system components that are distributed, such as those found in the IoT and Industrial IoT (IIoT) domains.

Keywords—Cloud computing, distributed systems, security, authentication, trust, multiparty, Internet of Things.

I. INTRODUCTION

The ubiquity of opportunity offered by the Internet of Things (IoT) is providing new ways to embed computation and storage into everyday devices. Reductions in the cost of hardware, coupled with technological advancements, are enabling a constant stream of innovative new products and services that rely upon IoT architectures. Such developments are particularly evident in the ‘wearable’ and healthcare industries, with parallel innovations occurring in the Industrial Internet of Things (IIoT) [1], [2]

Along with the ability to sense environments, conditions and processes, comes the requirement to measure, monitor, analyse and evaluate performance. As such, Business Intelligence (BI) is undergoing a resurgence as consumer demand moves beyond traditional dashboards through forecasting, towards prescriptive analytics. Of late, vendors have delivered BI often as a flexible, on-demand service, making use of the underlying elastic cloud platforms that enterprise software applications are typically deployed upon [4], [10], [5], [3].

Advancements in technology have increased the ability to connect such a variety of embedded devices to larger pools of resources such as clouds. Integrating embedded devices and cloud servers raises an important discussion regarding the nature of data generated or transmitted by IoT devices. These approaches must be secure and provide the necessary privacy controls for users. At present, the security and privacy concerns created by these devices play a central role in the successful integration of these two technologies [6].

The heterogeneous nature of IoT environments makes it much harder to detect the insider and outsider attacks in such universal platforms [7].

Experiences with clouds, especially those that have public or hybrid architectures, illustrates that cloud services and applications require multi-layered approaches to external and internal threats to security. This is most pertinent in the IIoT environment, where business systems contain valuable Intellectual Property (IP) that can only be protected by retaining tight security over working practices.

This article describes a model for delivering analytics services to and between components such as those encountered in IoT architectures. A number of adversarial attacks are simulated to demonstrate the effectiveness of a cloud-inspired multi-layer security model in the IoT domain.

II. CLOUD COMPUTING MODEL

The core principles of cloud computing: on-demand self-service, broad network access, resource pooling, rapid elasticity and service metering (NIST Special Publication 800-145) [15], make utility computing an attractive proposition for environments that contain distributed resources. The NIST definition [12] describes five options for the deployment of cloud computing as follows: public clouds, private clouds hosted onsite, private clouds hosted off-site, onsite community clouds and offsite community clouds.

Abstraction is one of the most compelling motivations for system architects; this enables myriad heterogeneous resources to be viewed as a homogeneous whole. Cloud architectures of any of the five types defined by NIST are modelled using a framework that consists of seven layers. The physical infrastructure foundation is layer one, upon which a resource abstraction (virtualisation) second layer resides. Layer three is the resource composition layer, and layer four refers to the Infrastructure as a Service model (IaaS). Platform as a Service (PaaS) exists on layer five, Software as a Service (SaaS) on layer seven and finally the cloud tenants’ applications sit within layer seven [14], [15].

We have considered the application of analytics services in the context of an enterprise Business Intelligence application that is likely to be delivered across a heterogeneous network
of devices. In a cloud environment this is typified by off-site private or community clouds, whereby multiple disparate business organisations can host their own enterprise software services and data repositories in what is, to all intents and purposes, a set of hardware resources that is dedicated to each tenant [13], [15]. The tenants access their dedicated resources via a VPN, thus maintaining clear separation between corporate services and their respective analytics implementations. However, should any of the businesses wish to share services to promote operational efficiencies, this can be enabled via community-based agreements [13].

We have used the cloud model as inspiration to propose a multi-layer service-oriented framework that can deliver secure services (such as BI analytics) across distributed infrastructure. Security and privacy are key concerns for tenants of shared cloud infrastructure such as that found in off-site private and community clouds. The sharing of services such as malware detection and inoculation has significant benefits for organisations who may not otherwise have strategies or the resources to maintain their own defences. We shall now briefly review services dedicated to security and privacy within clouds in the following section.

III. Secure Service Delivery

In keeping with the service orientation models described so far, security as a service can be considered as a multi-layer framework in itself [9], protecting each layer of the cloud computing model [16]. Such a service lends itself to a utility offering in the same way that clouds are rapidly provisioned and expanded on demand, for a cost that is quantifiable and chargeable to the consumer.

As described above, resource abstraction through virtualisation is a key principle for a cloud-inspired architecture, and therefore any security and privacy services need to be made available to all relevant Virtual Machines (VM) for each client [19], [17].

Therefore, security and privacy control services must be orchestrated via appropriate service interfaces between each cloud and its respective tenants that are accessing the services [19]. This control will be managed by the relevant virtualisation security manager for each VM, and as a consequence the control must be located within the virtualisation layer.

Privacy is managed via policy resources that need to be retained securely in a protected space such as a digital vault for encryption keys or digital certificates and such like [20], [21], all contained within a tier above other layers such as authentication and client metadata layers [22], [23].

Any instances whereby session packets do not have the requisite authority to invoke a particular service interaction will result in the session being terminated, and is a key security feature that is embedded within the framework.

IV. Multi-Layered Security Model

Our proposed model is illustrated in Figure 1 and describes the cloud-inspired architecture containing multiple layers. Each layer incorporates security and privacy services that make use of firewalls as gateways for session traffic from each of the respective clients.

We have implemented the model within Opnet, the description of which is as follows. Each firewall is represented by a Cisco PIX 535, which operates across the various layers including network, transport and application. Access control lists within the firewalls enable the governance of traffic based on IP addresses, protocols and ports for common and bespoke applications.

The firewalls are configured at the application layer to filter traffic from different URLs, encrypted sessions (HTTPS) and various clients such as Java, and are able to utilise Internetwork Key Exchange (IKE) to encrypt all sessions via DES, 3DES or AES. As an example we have defined four separate LANs to represent different clients/cloud tenants, and they each access the cloud through separate firewalls.

To illustrate an adversarial scenario, we have incorporated a simulated distributed attack from three malicious parties, who each are attempting to access the network through independent firewalls. Such an attack is a key concern for early adopters of IoT technologies, as the pervasive use of wireless communications presents many opportunities for business vulnerabilities to be exposed.

All of the multiple layers of the cloud are illustrated in Figure 2. We have embraced the cloud concept of resource abstraction and exploited this in the multi-layer model by representing each of the layers as separate clouds. Within each cloud layer exists an array of computing hardware to maximise performance and therefore minimise response times to service requests. It is an imperative that the model must not introduce excessive overheads into the normal functionality of the system.

The cloud layers are arranged such that inbound traffic from clients are filtered by the firewalls and then passed through successive layers until the system is satisfied that the requests can be delivered to the analytics functionality residing on the cloud applications layer. We now describe each of the layers and the role that they play within the model in turn:
• **Tenant firewalls.** This cloud layer consists of a number of databases that hold authentication data for each of the tenants, in order for them to be permitted access to the VM that have been assigned to them as part of their subscription. This is the gateway for each session, S to be invoked.

• **Tenant metadata.** Beyond the authentication criteria that is marshalled by the tenant firewalls layer, there exists further metadata for each client tenant. This metadata describes the credentials to authorise access to specific instances of repositories, applications and services. The detail is embedded within the session packets and is used to verify whether the session can continue or not.

• **Digital vaults.** The vaults are a secure place to retain digital signatures/certificates and decryption keys so that only the requisite authorities can access their own content and services. Public key encryption ensures that legitimate session requests are honoured and bogus requests are terminated.

• **Intrusion Prevention System.** The occurrence of adversarial attacks is not limited to the correct authentication at the start of a session. Intrusion detection prevents attacks on sessions that are in progress, such as SQL injection in web forms. This might be considered a route into the DBMETA or DBVAULT repositories from the perspective of an adversary. This cloud layer prevents such activity from continuing.

• **Malware protection.** Similar to the IPS cloud layer, an anti-malware layer continuously monitors for trojan activity, where malicious exploits are embedded and concealed within session packets, only to be executed at the application layer. Records of the monitoring and detection history are retained within DBANTIMAL.

• **Tenant applications.** This layer hosts the tenant’s applications themselves, in this case the analytics functionality of enterprise BI. The preceding layers ensure that only a marshalled session, S can access this layer, which in the case of BI potentially provides access to confidential business operations and performance data. For some functionality, there will be a requirement for further authentication from a user, such as an account and password, etc.

A. **Tenant repositories**

The final cloud layer hosts the back-end repositories that serve myriad tenant applications. For an analytics application, this would be the databases/data warehouses/data lakes that retain the underlying business data, together with any processed data objects for reporting and analysis. These objects are typically accessed by tenant users through reporting dashboards and data visualisation suites, abstracting users away from the complexities of database organisation.

B. **Simulation design**

We have elected to model and simulate the proposed system (Figure 2) so that we can examine the operational characteristics in terms of performance, and its ability to provide a collection of services that are resilient towards malicious attacks.

Figure 3 illustrates how the cloud layers have been mapped to individual profiles. Each profile consists of a collection of VMs, that host the contents of the model as described in the previous section, namely: security and privacy services, tenant applications and repositories.

V. **Modelling Adversarial attacks**

If we now consider an adversarial attack upon the model, we can see how the system protects against such a scenario. Figure 4 shows the situation where a malicious agent attempts to infiltrate the system to obtain access to an authorised tenant’s VM. Whilst the cloud service requires verification to be able to subscribe and access the remote
resources, what appears to be a legitimate tenant could actually be an adversary that is masquerading as a valid client, who has the objective of entering the cloud and then attacking other tenant VMs from within the same cloud.

Tools such as Metasploit can be employed to automate the delivery of exploits in a rapid fashion. This could enable a bogus tenant to create surreptitious means of exposing sensitive data, unbeknown to any other party.

Posing as a legitimate tenant, the adversarial agent would in this case be attacking from a VM that is authorised and hosted within the cloud. As such, the conventional cloud security processes would not be able to detect such activity. In effect, the activity is obscured by the sheer volume of VMs that exist within a cloud environment. This is a significant challenge for cloud service providers, particularly as service orientation through Microservice Architectures becomes more prevalent [18]. If we extend this to the IoT domain, there is a stronger desire to package functionality into services, to be hosted on distributed, connected hardware. Therefore, the ability to successfully address this issue is a key feature of this work. We propose a solution whereby the collection of VMs are organised into a hierarchy, as Figure 5 shows. If an adversarial agent enters the cloud via a subscription, and is assigned VM2, it has the potential to employ cross-channel attacks against VM1 and VM3, thereby exploiting the presence of virtual links between differing VMs. Typically, cloud security controls are deployed to prevent external attacks rather than insider attacking. This architecture limits the opportunity to commit further exploits since the attacker is prevented from moving to the next control using virtual links. The only option is to proceed using a real network link by requesting a session in Control A, to communicate with VMs 4, 5 and 6. Since there now exists Control A, the attacker has to successfully satisfy Tenant Metadata Inspection in order to proceed with the penetration. Of course, an orchestrated and sustained attempt to commit an attack will mean that we should anticipate an adversarial agent will also have obtained valid credentials, either by posing as a legitimate tenant or otherwise. In this case, Control B will have required that the malicious agent would need to navigate the entire stack of cloud layers before access could be gained to the analytics interface.

If the attacker has satisfied the cloud validation and metadata inspection layers, the only way forward now is to plant exploits in the hope that these will lie undetected. However, the Intrusion Protection layer, and the Anti-Malware layer both offer protection for subversive, covert attacks from the inside. The result is that our proposed model prevents data breaches, even when adversarial attacks are launched from what appears to be genuine service subscribers. We can see in Figure 6 a sequence in which various security controls might be instantiated. The security policies of the host system (or systems) will inform the order in which controls are implemented, to suit the goals desired by the infrastructure provider. It is also evident how a tenant’s session is routed through the various VMs in order to access the relevant analytics services.

VI. SESSION PACKET INSPECTION

In this section we shall describe a detailed walkthrough of the security model and explain the use of session packet inspection.
Referring back to Figure 5, VM1 will host a client that ultimately will access the enterprise analytics application hosted in VM7. A malicious agent that has access to either VM2 or VM3 (or both) can only attack the client of the analytics application, rather than the application itself. VM2 will be used to test the validity of the VM1 client using a VM identification number, and assuming that all is well, will launch a form via VM3 to request details from the tenant. The details requested from the tenant will vary each time that VM3 is executed, but they will always refer to some personal details that can be used to help identify the correct tenant. Once the form on VM3 has been completed, VM2 will use the responses to verify the details against those held in the MetaDB repository. Once the metadata has been verified, the session can continue. If the malicious tenant has the intention of acquiring metadata about other tenants, it would need to deliver an exploit into MetaDB. Whilst it might be expected that the system is fully patched, it is still conceivable that a vulnerability exists, enabling an adversary to progress to the next cloud layer. Since a session cannot be interrupted, any evidence left by malicious exploits will still remain as the agent will not be able to remove the incriminating evidence of the exploit. As such, the attacker can only proceed to the next layer by exposing that an exploit has been used to obtain entry. If the malicious agent has obtained private keys, they still cannot progress without exposing details of the exploit within the session. Layers 5 and 6 both have the capability to detect malware, which of course is reliant upon adequate, proactive security maintenance to ensure that all exploit databases are current.

It is feasible that an attacker could compromise VMs 3 and 4 with a fresh exploit that has yet to be discovered and documented, in which case the anti-malware cloud layer will be unaware of this exploit as well. Whilst this situation may foil malware detection, there still exists Intrusion Prevention within the cloud layer, which by its nature monitors and reports upon anomalies.

Our model enables system architects the ability to add or subtract security controls as required for a given set of policies, merely by specifying additional cloud layers for the hierarchy. When a session is authenticated as satisfying the requirements of each layer, it can progress to subsequent layers until the destination application layer is reached. One advantage of the use of multiple VMs is that much of the computation can be performed in parallel, and therefore the majority of packet inspection incurs a minimal overhead in VMs 2,3 and 4. However, session packet inspection across cloud layers, especially anything that involves Intrusion Prevention or anti-malware detection will result in an additional overhead.

A. Mapping controls to the seven layer model

With reference back to the NIST seven layer model [12], the controls of our proposed model can be mapped to the PaaS layer as per Figure 7 with the exception of the firewalls which naturally reside in the IaaS layer [15], [16]. Tenant VMs are hosted in layers 1-3 of the NIST model; users interact directly with clients that do not store data. Sessions commence within tenant VMs, before moving to the application in layer 7 via several layers of verification and authentication in layers 4 and 5. If the tenant has a SaaS platform, this will be made available through layer 6, otherwise all bespoke applications are resident in layer 7.

B. Session flow

The proposed architecture is located on layers 4 (IaaS) and 5 (PaaS) of the NIST seven-layer model. All firewalls are categorised as IaaS due to the functionality of verifying VM instance IDs, and also relating these checks to the authorisation data provided by a tenant to secure access to the cloud. Whilst VM IDs are assigned in layers 2 and 3, access controls are assigned at layer 4. Subsequent controls are assigned outside of the VM layer, and are primarily concerned with session packet inspection, for a given session $S$. Information is requested directly from the tenant to satisfy the DBMETA and DBVAULT checkpoint controls, and is supplemented by DBIPS and DBANTIMAL controls that perform the session packet inspection function. DBIPS and DBMETA are therefore categorised as PaaS controls. It is likely that controls will also exist at the application layer. For instance, a SaaS instance will require user authentication, as well a custom enterprise application[8]. User role profiles are useful in such scenarios to manage different levels of system access within an enterprise application, to reflect the role, responsibilities and authority of a particular stakeholder.

VII. ALGORITHM DESIGN

Algorithm 1 describes the sequence of inspections that are performed within the proposed multi-layer security model. This algorithm represents the core functionality and can be augmented as additional cloud layers are defined in response to the security needs of an organisation. In the case of a single enterprise the model may tend towards fewer augmentations. However, enterprises that collaborate, or who choose to adopt shared services across distributed platforms, will no doubt adopt additional layers in order to securely manage service access.

A. Security model logic

Our proposed model seeks to address security concerns in distributed service applications across heterogeneous hardware resources by enabling session packet inspection to take place at a number of checkpoints. Each session packet is scrutinised and compared with a number of repositories such as DBMETA, DBVAULT, etc. Each inspection stage shall now be described in turn.

1) DBFW: For each instance, a client initiates a session, which is inspected as a second stage. This session will possess a VM ID together with authentication and authorisation verification data. In addition, the DBFW must have an entry that relates to the VM ID, otherwise the session is terminated.

2) DBMETA: A further inspection is then performed to confirm tenant metadata as requested by the cloud host.
Algorithm 1: Multi-layer hierarchical packet inspection

1. Input: $S, P_{CT}, (DB_{FW}, DB_{META}, DB_{VAULT}, DB_{IPS}, DB_{ANTIMAL}), 1=permit, 0=deny$
2. Tenant session: $S$
3. Contents of session packets: $P_{CT}$
4. Contents of FW: $DB_{FW}$
5. Contents of $TENANT_{META}: DB_{META}$
6. Contents of $TENANT_{VAULT}: DB_{VAULT}$
7. Contents of $IPS: DB_{IPS}$
8. Contents of $ANTIMALWARE: DB_{ANTIMAL}$
9. Flags: 1=permit, 0=deny
10. Initialise $S$;
11. Set $S = 1$, Match($P_{CT}$);
12. foreach ($DB_{FW}, DB_{META}, DB_{VAULT}, DB_{IPS}, DB_{ANTIMAL}$) do
   13. if $P_{CT} \in \{DB_{FW}, DB_{META}, DB_{VAULT}\}$ AND $P_{CT} \notin \{DB_{IPS}, DB_{ANTIMAL}\}$ then
      14. set $S = 1$; AuthoriseTenantAccess();
      //tenant access authorised;
   15. else
      16. set $S = 0$; DenyTenantAccess();
      //tenant access denied;
   17. end
18. end
19. Output: $S$

The algorithm ensures that after a session is initiated, it is inspected at each layer, where each layer is represented by a separate cloud. A key principle is that session packet data must match the firewall data, tenant metadata and vault data before a session can be authorised. Furthermore, the session cannot be granted access to application layers until it has been successfully screened against IPS and anti-malware repositories.
B. Implementing the model

For our example scenario, the LAN contains 500 clients. Each of the clients is assigned three VMs, with an assigned destination being the tenant client’s metadata repositories rather than the eventual analytics application. This was a conscious decision to prohibit any tenant sessions from attempting to subvert the security and privacy controls of the cloud. For a physical network, this control would most likely be enacted by a firewall in an application layer, or as part of a setting in a virtual network controller. For consistency we have replicated this by ensuring that the destinations of the metadata servers are directed towards the tenant vaults; this is a faithful representation of the intentions of the algorithm, in that it is governing the marshalling of each session packet by enforcing checkpoints in a particular sequence. In the case of a session packet not containing a tenant key that matches a corresponding entry in DB\textsubscript{VAULT}, the encryption key is not assigned and the packets are dropped \cite{21}. We have represented the adversarial agents as clients who have the authorisation of a valid tenant, in order to simulate an attack from within.

VIII. RESULTS

Figure 8 shows the sessions that have been hosted by the tenant LAN in the simulation. We observed that sessions only existed within the tenant LAN for tenants that had matching metadata in DB\textsubscript{META}. It follows that the sessions that were invoked within the tenant LAN, had consistency between tenant metadata (DB\textsubscript{META}), tenant vault (DB\textsubscript{VAULT}), and the associated VM ID from the initial authentication. The simulation demonstrated that these validations were maintained throughout the experiment for all network hops, illustrating that VMs were complying with their specified destination configurations, and there was no evidence of VMs by-passing authentication layers. As such, all security and privacy control rules are enforced by the model.

VMs initiated by malicious agents have separate profiles from those of legitimate tenants, even though a malicious agent may appear legitimate at the outset. This means that adversaries had distinct metadata and decryption keys in their vault repositories. We can see in Figure 9 the instances where a malicious agent’s packets have been dropped as a result of packet inspection through either the IPS or anti-malware layers, preventing deeper penetration into the system. As discussed earlier, an internal attack (an agent with legitimate DB\textsubscript{META} data) would need to compromise DB\textsubscript{VAULT}, DB\textsubscript{IPS} and DB\textsubscript{ANTI-MAL} in sequence if it is to successfully reach the analytics application layer. Conversely, an authorised tenant may elect to execute DB sessions on their own LAN, since the application profiles can include references to their VMs, as per Figure 10. In such cases, the sessions are authorised in the sense that they fulfil the relevant rule in Algorithm 1. Since we have chosen to model each of the layers as clouds, each of the multiple layers can in fact be serviced by different cloud providers. This architecture thus demonstrates significant flexibility and is attractive to system architects who are proactively designing systems that will rely upon heterogeneous hardware and distributed resources, such as the IoT and IIoT environments. An enterprise may adopt this security model so that it can take the opportunity to employ software applications and services that are themselves hosted on offsite private or community clouds. However, the use of these services may increase operational costs, although this is off-set by a reduction in capital expenditure. Operational costs may also increase indirectly through the maintenance charges associated with managing the database updates of five security control layers.

IX. CONCLUSIONS

This article proposes a multi-layer hierarchical inter-cloud security model, that is inspired by the NIST seven-layer model of cloud computing. By using sequential session packet inspection techniques, we have demonstrated an architecture that exhibits considerable resilience towards both external attack as well as more surreptitious internal adversarial behaviour. Whilst VM vulnerabilities are well documented in multi-tenant shared environments, our five layers for packet inspection enables the architecture to identify and compartmentalise malicious activity. Thus, penetration of a firewall is in itself insufficient as a means of attempting to access the application layer, as it is then necessary to create an evidence trail of exploits that cannot be hidden from the IPS and anti-malware packet inspection layers. The proposed model is particularly suited to architectures that have a requirement to remain flexible for future scaling (which is often a driver for the adoption of cloud infrastructure), such as those built upon microservices. Our solution is mapped...
to the NIST model in order to assist cloud and IoT system architects to incorporate this work into their own designs.

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