Innovation, Sciences et Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 2949020 C 2018/09/04

(11)(21) **2 949 020**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

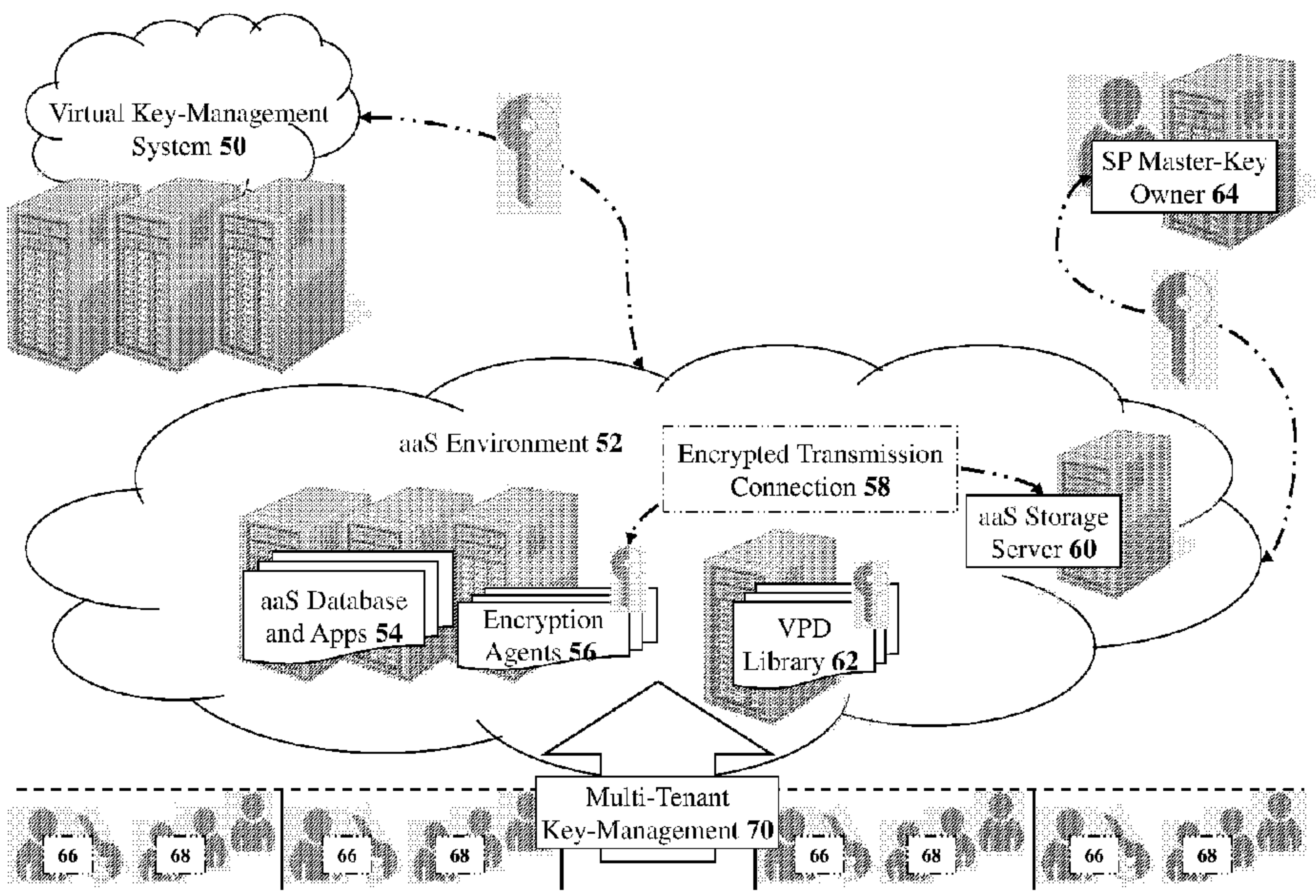
(86) Date de dépôt PCT/PCT Filing Date: 2015/06/23
(87) Date publication PCT/PCT Publication Date: 2015/12/30
(45) Date de délivrance/Issue Date: 2018/09/04
(85) Entrée phase nationale/National Entry: 2016/11/14
(86) N° demande PCT/PCT Application No.: IL 2015/050638
(87) N° publication PCT/PCT Publication No.: 2015/198314
(30) Priorités/Priorities: 2014/06/23 (US62/015,547); 2015/06/23 (US14/746,853)

(51) Cl.Int./Int.Cl. *G06F 21/62* (2013.01)
(72) Inventeur/Inventor:
PARANN-NISSANY, GILAD, IL

(73) Propriétaire/Owner:
PORTICOR LTD., IL

(74) Agent: OSLER, HOSKIN & HARCOURT LLP

(54) Titre : PROCEDES ET DISPOSITIFS DE GESTION DE CLE DANS UN CONTEXTE « EN TANT QUE SERVICE »
(54) Title: METHODS AND DEVICES FOR KEY MANAGEMENT IN AN AS-A-SERVICE CONTEXT



(57) Abrégé/Abstract:
The present invention discloses methods and devices for key management in an as-a- service (aaS) context. Methods include the steps of: upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in the provider computing-environment by repetitively computing respective specific-key contributions: in a set of N computing resources in the provider computing-environment; and in a set of M customer locations in a customer computing-environment; and applying the respective specific-key contributions to change a specific-key value in the computing resources, wherein the respective specific-key contributions are never revealed to any computing resources, and to any customer locations, other than respective contributors; wherein at least one location is a region of memory located in a computing resource operationally connected to the provider computing-environment, wherein the customer locations are regions of memory located in a computing resource operationally connected to the customer computing-environment.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 December 2015 (30.12.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/198314 A1

(51) International Patent Classification:
G06F 21/62 (2013.01)

(21) International Application Number:
PCT/IL2015/050638

(22) International Filing Date:
23 June 2015 (23.06.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/015,547 23 June 2014 (23.06.2014) US
14/746,853 23 June 2015 (23.06.2015) US

(71) Applicant: **PORTICOR LTD.** [IL/IL]; Haharash 4, 4527607 Hod Hasharon (IL).

(72) Inventor: **PARANN-NISSANY, Gilad**; 10 Yirmiyahu Street, 47298 Ramat Hasharon (IL).

(74) Agents: **MOUALLEM, Reuven** et al.; Flashpoint Ip Ltd., Rabban Gamliel 2, 4083201 Elad (IL).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) **Title**: METHODS AND DEVICES FOR KEY MANAGEMENT IN AN AS-A-SERVICE CONTEXT

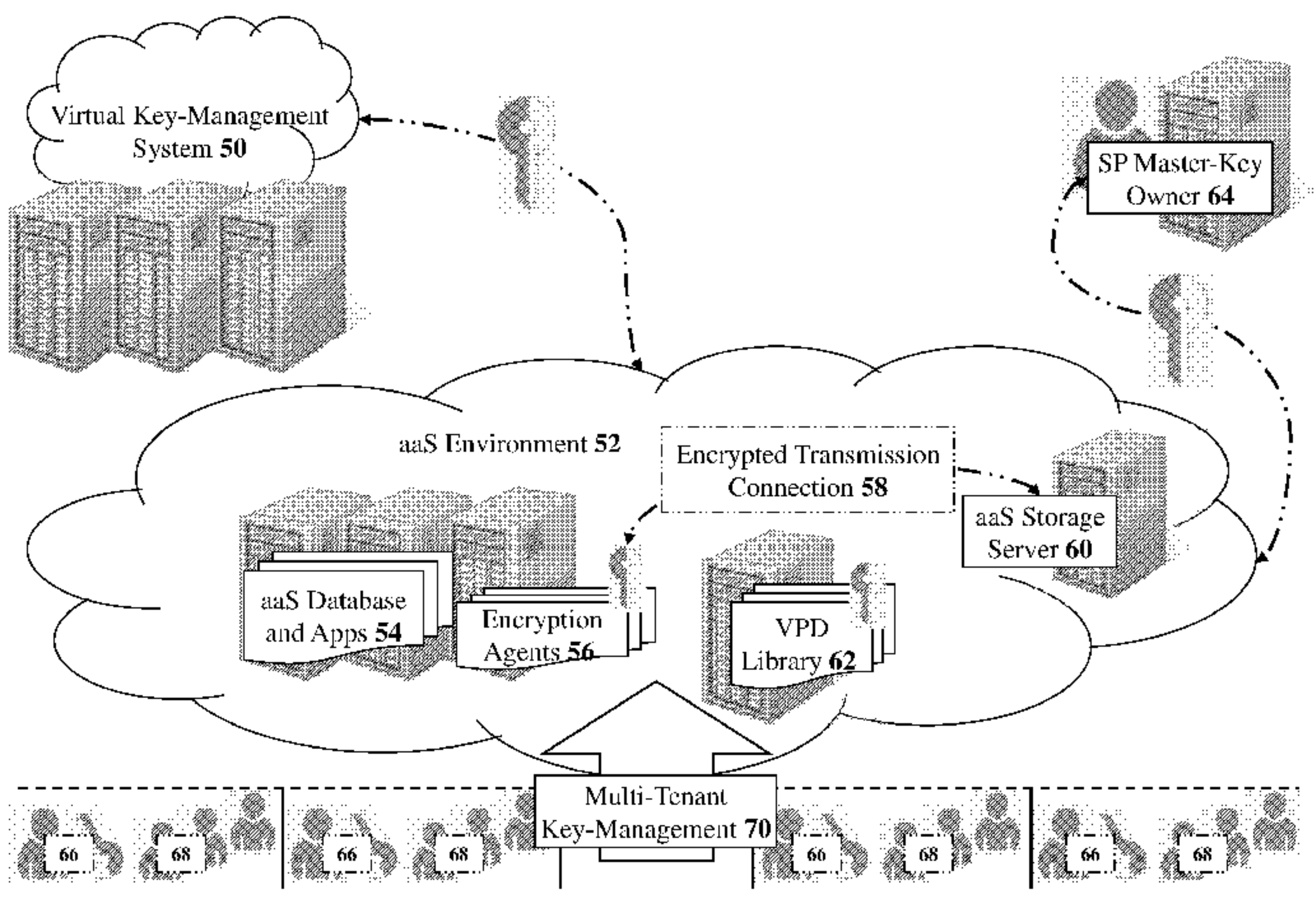


Figure 5

(57) **Abstract**: The present invention discloses methods and devices for key management in an as-a- service (aaS) context. Methods include the steps of: upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in the provider computing-environment by repetitively computing respective specific-key contributions: in a set of N computing resources in the provider computing-environment; and in a set of M customer locations in a customer computing-environment; and applying the respective specific-key contributions to change a specific-key value in the computing resources, wherein the respective specific-key contributions are never revealed to any computing resources, and to any customer locations, other than respective contributors; wherein at least one location is a region of memory located in a computing resource operationally connected to the provider computing-environment, wherein the customer locations are regions of memory located in a computing resource operationally connected to the customer computing-environment.

WO 2015/198314 A1

METHODS AND DEVICES FOR KEY MANAGEMENT IN AN AS-A-SERVICE CONTEXT

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to methods and devices for key management in an as-a-service (aaS) context (e.g., SaaS (software as a service), PaaS (platform as a service), and IaaS (infrastructure as a service)).

Key-management processes involving splitting keys are well-established. All data-encryption keys are split using a master key. The master key is: (1) a real key, not a password; (2) known (i.e., revealed) only to the customer; and (3) very easy to manage. Keys are encrypted and integrity-protected using standard algorithms. Keys are associated with (encrypted and integrity-protected) metadata. Customer-side key hierarchies provide deployment flexibility.

Assume that a key may be legitimately used by several entities in an environment (each is called an “appliance”); some of the appliances may create the key, while other appliances may use the key. Each such creation operation or usage operation may in principal be performed by the same or a different entity.

Also, the appliances are in communication with a Protected Virtual Key Manager (PVKM) which may provide services to the abovementioned appliances and to the users of the system. Such services are related to managing the keys of the system, and also related to enhancing the security of the system.

In the discussion below, the PVKM may be viewed as a “location” (whether physical or virtual) in such an environment, while each appliance and other security element may be viewed as another “location” (whether physical or virtual). However, for the avoidance of doubt, while the PVKM itself may be implemented as a collection or a cluster, it is still referred to as a location for the sake of simplicity.

Referring to the drawings, the overall processes have been depicted according to separate, sequential time lines (going from top to bottom in the drawings) for two primary generalized components, an appliance **A** and a PVKM **B**, in order to representationally isolate the parallel processes that are occurring on each component independently.

Figure 1 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for splitting keys in a key-management system, according to the prior art. To split key-pairs (Sub-Process **I**), an appliance **A** and a PVKM **B** are shown in which PVKM **B** generates an appropriate key-pair (Block Step **2**), and transmits a half-key to appliance **A** (Arrow Step **4**). Appliance **A** then uses the half-key with a master key (Block Step **6**) to create a data encryption key (Block Step **8**).

It is noted that appliance **A** is intended to be a simplified example of a plurality of appliances in order to provide clarity throughout the description. It is understood that the present invention has broader applicability to a collection or cluster of such appliances. Furthermore, PVKM **B** is intended to be one conceptual entity (e.g., a server); however, in practical implementations, PVKM **B** may be a plurality of entities (e.g., a cluster of servers for fail-over protection). In generalizations of this approach, there may be more locations, and therefore more timelines.

The master key is critical to the security of the whole system. Initially, it is kept only in memory. A passive attacker that takes a “snapshot” of the storage device cannot see the master key. The master key is then encrypted so that even an active attack is mitigated. Such encryption is access-controlled, policed on the key-management service, and integrated with customer access-control.

In order to encrypt the key, and yet still use the key, Homomorphic Key Management (HKM) has been shown to be an effective protocol. Homomorphic functions have $F(a\Theta b) = F(a)\Theta F(b)$ in which Θ is a suitable operator. Partially-homomorphic functions are employed for key management only (e.g., ElGamal encryption).

ElGamal encryption is homomorphic and entails a secret key x and a public key $(g, h = g^x)$ in which g is a generator. Encryption is random and produces a pair: $Enc(m) = (c, d) = (g^r, h^r \cdot m)$ in which r is random, and $Dec(c, d) = d/c^x = m$. Such keys can be used to exploit the homomorphic property. As an example, under a multiplication operation: $Enc_{pk}(m; r)$ ¤ $Enc_{pk}(m'; r') = Enc_{pk}(m \cdot m'; r+r')$ for element-wise multiplication. Such HKM methods employing split-key encryption are amenable to exact proofs of strength.

Figure 2 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating an appliance using homomorphic key-management, according to the prior art. To create a new appliance using HKM (Sub-Process **II**), PVKM **B** picks an ElGamal key (Block Step **10**), stores a secret half-key, SK_i (Block Step **12**), and transmits a public half-key, PK_i, to appliance **A** (Arrow Step **14**), which stores PK_i (Block Step **16**). Appliance **A** uses PK_i to encrypt a user-supplied master-key K as $E_{PK_i}(K)$ (Block Step **18**). Appliance **A** then generates and stores a random mask, $mask_i$ (Block Step **20**). Appliance **A** performs a homomorphic operation by calculating $E_{PK_i}(K \Theta mask_i)$ (Block Step **22**), and transmits the result to PVKM **B** (Arrow Step **24**), which then decrypts and stores the masked master-key, $(K \Theta mask_i)$ (Block Step **26**). It is denoted that Θ is a suitable operator for encryption; the inverse of Θ is denoted as "/" (sometimes represented by the symbol "÷") for decryption.

Figure 3 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a new key using homomorphic key-management, according to the prior art. To create a new key using HKM (Sub-Process **III**), appliance **A** creates a request to generate a new key, k_i (Block Step **30**), and transmits the key request to PVKM **B** (Arrow Step **32**). PVKM **B** picks and stores a random number, a_i (Block Step **34**), and then calculates $b_{ij}=a_j/(K \ominus mask_i)$ (Block Step **36**), which is then transmitted to appliance **A** (Arrow Step **38**). Appliance **A** then uses the result to calculate a specific key, $S_j = b_{ij} \ominus mask_i = a_j/K$ (Block Step **40**). It is noted that S_j is independent of *i* (i.e., common to all appliances with the same master-key, K).

As mentioned, the master key is known (i.e., revealed) only to the customer. However, in "as-a-Service" use-cases, there are actually a chain of customers. For example, one customer of the key-management mechanisms may be a service provider, which may know the master key. However, "end" customers further down the chain may be customers of the service provider. A security-conscious end-customer desires to be able to use available shared or distributed resources in the aaS context configured for a multi-tenant environment, as provided by the service provider, and yet enjoy full security and control – by controlling their own keys in such a way that the service provider knows nothing about the keys.

It would be desirable to have methods and devices methods and devices for key management in an as-a-service (aaS) distributed environment. Such methods and devices would, *inter alia,* expand on the capabilities and applications of the methods mentioned above.

SUMMARY

It is the purpose of the present invention to provide methods and devices for key management in an as-a-service (aaS) context.

It is noted that the term "exemplary" is used herein to refer to examples of embodiments and/or implementations, and is not meant to necessarily convey a more-desirable use-case. Similarly, the terms "alternative" and "alternatively" are used herein to refer to an example out of an assortment of contemplated embodiments and/or implementations, and is not meant to necessarily convey a more-desirable use-case. Therefore, it is understood from the above that “exemplary” and “alternative” may be applied herein to multiple embodiments and/or implementations. Various combinations of such alternative and/or exemplary embodiments are also contemplated herein.

Embodiments of the present invention enable the security-conscious customer to use available shared or distributed resources in an aaS context configured for a multi-tenant environment, and yet enjoy full security and control – with emphasis placed on key management. While three-way key-splitting in an aaS computing environment using homomorphic key-management is described below as an exemplary embodiment, it is contemplated, and within the scope of the present invention, to extend such methods to splitting keys into more than three key-shares. For example, such further key splitting could accommodate secondary (and further-distant) customers of the primary customers of a service provider.

Therefore, according to the present invention, there is provided for the first time a method for key management in an as-a-service (aaS) context, the method including the steps of: (a) upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in the provider computing-environment by repetitively computing respective specific-key contributions: (i) in a set of N computing resources in the provider computing-environment, wherein N is a non-negative integer; and (ii) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, and wherein the customer computing-environment is outside of the provider computing-environment; and (b) applying the respective specific-key contributions to change a specific-key value in the computing resources, wherein the respective specific-key contributions are never revealed to any computing resources, and to any customer locations, other than respective contributors associated with the respective specific-key contributions; wherein at least one location is a region of memory located in a computing resource operationally connected to the provider computing-environment, wherein the customer locations are regions of memory located in a computing resource operationally connected to the customer computing-environment, wherein the provider computing-environment is a computing environment of an aaS service provider, wherein the customer computing-environment is a computing environment of a customer of the aaS service provider, and wherein the provider computing-environment and the customer computing-environment are configured to exchange data with each other.

Alternatively, the repetitively computing includes computing at_least three specific-key contributions.

Alternatively, the step of applying is performed using at least one technique selected from the group consisting of: key joining, blinding, and homomorphic encryption.

According to the present invention, there is provided for the first time a device for key management in an as-a-service (aaS) context, the device including: (a) a server including: (i) a CPU for performing computational operations; (ii) a memory module for storing data; and (iii) a network connection for communicating across a network; and (b) a protection module, residing on the server, configured for: (i) upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in the provider computing-environment by repetitively computing respective specific-key contributions: (A) in a set of N computing resources in the provider computing-environment, wherein N is a non-negative integer; and (B) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, and wherein the customer computing-environment is outside of the provider computing-environment; and (ii) applying the respective specific-key contributions to change a specific-key value in the computing resources, wherein the respective specific-key contributions are never revealed to any computing resources, and to any customer locations, other than respective contributors associated with the respective specific-key contributions; wherein at least one location is a region of memory located in a computing resource operationally connected to the provider computing-environment, wherein the customer locations are regions of memory located in a computing resource operationally connected to the customer computing-environment, wherein the provider computing-environment is a computing environment of an aaS service provider, wherein the customer computing-environment is a computing environment of a customer of the aaS service provider, and wherein the provider computing-environment and the customer computing-environment are configured to exchange data with each other.

Alternatively, the repetitively computing includes computing at least three specific-key contributions.

Alternatively, the applying is performed using at least one technique selected from the group consisting of: key joining, blinding, and homomorphic encryption.

According to the present invention, there is provided for the first time a non-transitory computer-readable medium, having computer-readable code embodied on the non-transitory computer-readable medium for key management in an as-a-service (aaS) context, the computer-readable code including: (a) program code for, upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in the provider computing-environment by repetitively computing respective specific-key contributions: (i) in a set of N computing resources in the provider computing-environment, wherein N is a non-negative integer; and (ii) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, and wherein the customer computing-environment is outside of the provider computing-environment; and (b) program code for, applying the respective specific-key contributions to change a specific-key value in the computing resources, wherein the respective specific-key contributions are never revealed to any computing resources, and to any customer locations, other than respective contributors associated with the respective specific-key contributions: wherein at least one location is a region of memory located in a computing resource operationally connected to the provider computing-environment, wherein the customer locations are regions of memory located in a computing resource operationally connected to the customer computing-environment, wherein the provider computing-environment is a computing environment of an aaS service provider, wherein the customer computing-environment is a computing environment of a customer of the aaS service provider, and wherein the provider computing-environment and the customer computing-environment are configured to exchange data with each other.

Alternatively, the repetitively computing includes computing at least three specific-key contributions.

Alternatively, the applying is performed using at least one technique selected from the group consisting of: key joining, blinding, and homomorphic encryption.

These and further embodiments will be apparent from the detailed description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for splitting keys in a key-management system, according to the prior art;

Figure 2 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating an appliance using homomorphic key-management, according to the prior art;

Figure 3 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a new key using homomorphic key-management, according to the prior art;

Figure 4 is a simplified high-level block diagram of the system architecture for three-way key-splitting in an aaS computing environment using homomorphic key-management, according to embodiments of the present invention;

Figure 5 is a simplified high-level block diagram of the system architecture for a multi-tenant configuration in an aaS computing environment using homomorphic key-management, according to embodiments of the present invention;

Figure 6 is a simplified high-level block diagram of the system architecture for system deployment of a multi-tenant configuration in an aaS data center using homomorphic key-management, according to embodiments of the present invention;

Figure 7 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a cloud instance with library using homomorphic key-management, according to embodiments of the present invention;

Figure 8 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a new key for a cloud instance using homomorphic key-management, according to embodiments of the present invention;

Figure 9 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for obtaining a specific key using homomorphic key-management, according to embodiments of the present invention;

Figure 10 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for obtaining a specific key with a blinding value using homomorphic key-management, according to alternative embodiments of the present invention.

DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

The present invention relates to methods and devices for key management in an as-a-service (aaS) context. The principles and operation for providing such methods and devices, according to the present invention, may be better understood with reference to the accompanying description and the drawings.

Consider a computing system (e.g., a software application) that includes multiple computing resources. Such resources may be defined broadly (e.g., data, secret phrases, keys, memory segments, storage areas, storage segments, networks, network segments, and computing resources). Some or all of such resources are protected by keys. It is required to use a master key (a "key-encryption key") to secure some of the keys in the system.

In computing environments involving an aaS context, several assumptions must be made related to aaS requirements.

1. Customers with sensitive data want the data to be encrypted when stored in the aaS environment;
2. Such customers want to own the encryption keys (i.e., not to have the keys stored in the aaS environment or known (i.e., revealed) to the service provider); and
3. There is no installation of any key-management software or hardware on the customer's premises: in the aaS model, the end-customer wishes to have all such complexity managed for her.

It is assumed that for such customers, it is acceptable that their data will be decrypted while being processed, but only in memory and in the customer's context (e.g., for a query or a report in a particular service application server, which is serving that customer at that moment). It is assumed that it is also acceptable that the decryption key will exist only in memory of the aaS environment for the time needed for decryption and in the customer's context (e.g. for a query or report in a particular service application server, which is serving that customer at that moment).

Considering a chain of customers, the provider of the service is a customer of the key-management system, and has a master key to ensure that no data leaks outside its control. The end-customers are the customers of the service provider, so they are customers of the customer. Such end-customers also need to have a master key, different for each of the end-customers, and unknown to anyone but themselves. The end-customers desire their own master key so that other tenants of the service, and also the service provider, are not be able to know a particular end-customer's data. Therefore, three-way splitting of keys is desired. One key-share is "owned" by the service provider, and unknown to anyone but the service provider. Another key-share is "owned" by the end-customer, and unknown to any other end-customer, or to the service provider. Yet another key-share is a "finer-granularity" key (i.e., specific to the resource intended to be protected).

It is clear that each end-customer has their own master key, and the service provider has a master key. All these master keys are protected through homomorphic encryption, thereby creating a Homomorphic Key-Management (HKM) approach which keeps all such master keys secret, even when the master keys are in use. Even when the complete computing system is running, and such master keys are in memory, an attacker looking into the memory will find all master keys encrypted at all times.

Referring again to the drawings, Figure 4 is a simplified high-level block diagram of the system architecture for three-way key-splitting in an aaS computing environment using homomorphic key-management, according to embodiments of the present invention. A virtual key-management (VKM) system **50** is shown operationally connected to an aaS environment **52** having an aaS database and apps **54** with encryption agents **56**. In such a configuration using encryption agents **56**, HKM encrypts keys all the way down to the "app context." This means that keys can remain homomorphically encrypted even after key-shares are joined, so key-shares (i.e., key contributions) and final specific keys remain hidden. The app context can be as specific as a specific thread or process during the brief time of use for the needs of an individual tenant (i.e., customer) in the aaS system.

Encryption agents **56** can exchange encrypted data, via an encrypted transmission connection **58**, with an aaS storage server **60**. aaS environment **52** also includes a server or cluster of servers with a VPD (Virtual Private Data) library **62**. VPD library **62** is the location where keys are split into (three) shares before storage, or joined from (three) shares before use. It is noted that such splitting and joining is performed by VPD library **62** under homomorphic encryption, so the actual key-shares and final keys are never revealed to VPD library **62**.

aaS environment **52** is able to receive service provider (SP) master-keys from an SP master-key owner **64**. SP master-key owner **64** may be either a human using an appropriate homomorphic-encryption tool provided by VKM system **50**, or a server configured for that purpose. Customers access and utilize aaS environment **52** only after providing customer-scoped master-keys **66** which are homomorphically encrypted before being provided, while the customer's users access and utilize aaS environment **52** using user access tokens **68**.

It is noted that master-key scope (e.g., a customer organization) is usually defined by the service provider in a way that is convenient for the running of aaS environment **52**. In other words, scope depends upon an appropriate system definition of the idea of a customer. Such a definition is common in all aaS systems as they must define their tenants.

Scoped master-keys never leave a customer's premises, except under homomorphic encryption, meaning customer's appointed owners always control and own the customer's data. Furthermore, specific encryption keys never exist anywhere other than in the memory of a requesting thread, not even in an appliance, due to homomorphic encryption. Moreover, user tokens **68** are an access-control mechanism with an API. Projects can include mapping to aaS access control (e.g., user level, role level, organizational level, or scope level). The flexible architecture allows encryption/decryption of data to be performed by aaS environment **52** or by a system agent. VPD library **62** requires no long-term state memory, and can be placed on virtual instances as defined by aaS environment **52**, meaning that the instances are completely stateless, and this approach is massively scalable.

Figure 5 is a simplified high-level block diagram of the system architecture for a multi-tenant configuration in an aaS computing environment using homomorphic key-management, according to embodiments of the present invention. Figure 5 mainly depicts the system architecture of Figure 4, emphasizing the multi-tenant adaptability of the architecture. In aaS scenarios in which numerous customers and their users are accessing aaS environment **52** via customer-scoped master-keys **66** and user tokens **68**, respectively, operation of a multi-tenant key-management **70** is enabled.

Figure 6 is a simplified high-level block diagram of the system architecture for system deployment of a multi-tenant configuration in an aaS data center using homomorphic key-management, according to embodiments of the present invention. aaS environment **52** is shown with VKM **50** (e.g., storing/generating millions of half-keys or key shares) and SP master-key owner **64** (which may be, as mentioned, a human owner with an appropriate homomorphic-encryption tool provided by VKM system **50**, or an appropriately configured server, such as a tamper-resistant security module (TRSM) or hardware security module (HSM)). SP master-key owner **64** has the system master-key owned by SP CISOs (Chief Information Security Officers), for example. VKM **50** and SP master-key owner **64** are shown interfacing with VPD Library **62** on aaS cloud instances for performing operations such as key joining, key splitting, retrieving keys that are unreadable in memory, and maintaining multi-tenant operability.

Customer premises **82** include customer-scoped master-keys **66** (which are provided in homomorphically-encrypted form to VPD library **62** as needed) and user tokens **68** (which provide access to applications on aaS database and apps **54**). Encryption agents **56** provide data encryption for the applications on aaS database and apps **54** and interface to VPD library **62** via a REST API **84**.

Figure 7 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a cloud instance with library using homomorphic key-management, according to embodiments of the present invention. To create a cloud instance with a library using HKM (Sub-Process **IV**), a service-provider cloud API is used to create a cloud instance within the aaS environment, and deploy upon the cloud instance a VPD library. Clusters of such cloud instances with the VPD library may be created using the service provider's cloud APIs. Then, PVKM **B** picks an ElGamal key (Block Step **90**) which is different for each of the customers of the aaS environment, stores a secret half-key, SK_j (Block Step **92**) (wherein the index j denotes the end customer), and transmits a public PKI (public-key infrastructure) key, PK_j, to a cloud instance $\boldsymbol{i}$ (Arrow Step **94**), which stores PK_j (Block Step **96**).

Instance $\boldsymbol{i}$ uses PK_j to encrypt a service-provider-supplied master key K (Block Step **97**), and also to encrypt a customer-supplied master-key k_j as $E_{PKj}(k_j)$. Using the homomorphic property, instance $\boldsymbol{i}$ then calculates $E_{PKj}(K) \ominus E_{PKj}(k_j) = E_{PKj}(K \ominus k_j)$ (Block Step **98**). Block Step **98** defines a new value, the combined master key, $K_j = K \ominus k_j$, which is encrypted homomorphically, and never revealed to anyone (neither customer, service provider, nor key management system ever know it). Instance $\boldsymbol{i}$ therefore holds a vector of combined, encrypted master-key values K_j indexed by j. Instance $\boldsymbol{i}$ also generates and stores a random mask, $mask_i$ (Block Step **100**). Instance $\boldsymbol{i}$ performs a homomorphic operation by calculating $E_{PKj}(K_j \ominus mask_i)$

(Block Step **102**), and transmits the result to PVKM **B** (Arrow Step **104**), which then decrypts and stores the masked master-key, ($K_j \ominus mask_i$) (Block Step **106**).

It is denoted that ϴ is a suitable operator for encryption; the inverse of ϴ is denoted as "/" (sometimes represented by the symbol "÷") for decryption. It is further noted that instance ***i*** (as with appliance **A** in Figures 1-3) is intended to be a simplified example of a plurality of cloud instances in order to provide clarity in the description.

Figure 8 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for creating a new key for a cloud instance using homomorphic key-management, according to embodiments of the present invention. Cloud instance ***i*** is the same as described above with regard to Figure 7. To create a new key for a cloud instance using HKM (Sub-Process **V**), instance ***i*** creates a request to generate a new key, S_j (Block Step **110**), and transmits the key request to PVKM **B** (Arrow Step **112**). PVKM **B** picks and stores a random number, a_i (Block Step **114**), and then calculates $b_{ij}=a_j/(K \ominus mask_i)$ with the appropriate K value (a combined master key) for that specific customer (Block Step **116**), which is then transmitted to instance ***i*** (Arrow Step **118**). Instance ***i*** then uses the result to calculate a cloud-instance key, $S_j = b_{ij} \ominus mask_i = a_j/K$ (Block Step **120**). It is noted that S_j is independent of *i* (i.e., common to all appliances with the same combined master-key, K).

Figure 9 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for obtaining a specific key using homomorphic key-management, according to embodiments of the present invention. Figure 9 describes in detail how a specific key can be delivered to an application server without any of the PVKM or VPD library knowing (i.e., revealing) the specific key. A specific key is a key for a specific resource, such as a specific string of data that belongs to the specific customer of the specific app. It is notable and important for security that no part of the key-management system, and no part of the service provider's aaS system, ever knows such a specific key, other than the specific thread serving that specific customer at that specific moment.

To obtain a specific key (Sub-Process **VI**), an aaS application client **C** picks a temporary ElGamal key (Block Step **130**), stores a secret PKI key, SK (Block Step **132**), and transmits a public PKI key, PK, to PVKM **B** (Arrow Step **134**), which stores PK (Block Step **136**). PVKM **B** then retrieves $S_j/mask_i$ (Block Step **138**), and calculates $E_{PK}(S_j/mask_i)$ (Block Step **140**). PVKM **B** transmits the result to instance ***i*** (Arrow Step **142**). Instance ***i*** performs a homomorphic operation by calculating $E_{PK}(S_j/mask_i)\Theta(E_{PK}(mask_i)) = E_{PK}(S_j)$ (Block Step **144**), and transmits the result to aaS application client **C** (Arrow Step **146**). aaS application client **C** then decrypts (since it knows SK), extracts, and uses the cloud-instance key, S_j (Block Step **148**).

Figure 10 is a simplified high-level block diagram of the scheme of major operational steps in an exemplary implementation for obtaining a specific key with a blinding value using homomorphic key-management, according to alternative embodiments of the present invention. To obtain a specific key with a blinding value using HKM (Sub-Process **VI**), an aaS application client **C** picks a temporary blinding value t and a temporary ElGamal key (Block Step **150**), stores a secret PKI key, SK (Block Step **152**), and transmits the public key, PK, and $E_{PK}(t)$ to PVKM **B** (Arrow Step **154**), which stores PK and the encrypted blinding, $E_{PK}(t)$ (Block Step **156**). PVKM **B** then retrieves $S_j/mask_i$ (Block Step **158**), and calculates $E_{PK}(S_j/t \; \Theta \; mask_i)$ (Block Step **160**). PVKM **B** transmits the result to instance ***i*** (Arrow Step **162**). Instance ***i*** performs a homomorphic operation by calculating $E_{PK}(S_j/t \; \Theta \; mask_i)\Theta(E_{PK}(mask_i)) = E_{PK}(S_j/t)$ (Block Step **164**), and transmits the result to aaS application client **C** (Arrow Step **166**). Finally, aaS application client **C** decrypts (since it knows SK), extracts (since it knows t), and uses the cloud-instance key, S_j (Block Step **168**).

While the present invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications, and other applications of the present invention may be made.

The embodiments of the present invention for which an exclusive property or privilege is claimed are defined as follows:

1. A method for key management in an as-a-service (aaS) context, the method comprising the steps of:

(a) upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in said provider computing-environment by repetitively computing respective specific-key contributions:

(i) in a set of N computing resources in said provider computing-environment, wherein N is a non-negative integer, and wherein said set of N computing resources includes all computing resources in said provider computing environment; and

(ii) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, wherein said set of M customer locations includes all customer locations in said customer computing environment, and wherein said customer computing-environment is outside of said provider computing-environment; and

(b) applying said respective specific-key contributions to change a specific-key value in said set of N computing resources, wherein said respective specific-key contributions are never revealed in unencrypted form to any computing resource of said set of N computing resources, and to any customer location of said set of M customer locations, other than respective creation-request contributors associated with said respective specific-key contributions during request initiation;

wherein said at least one location is a region of memory located in a given computing resource of said set of N computing resources, operationally connected to said provider computing-environment, wherein customer locations are regions of memory located in a given computing resource of said set of M customer locations, operationally connected to said customer computing-environment, wherein said provider computing-environment is a computing environment of an aaS service provider, wherein said customer computing-environment is a computing environment of a customer of said aaS service provider, and wherein said provider computing-environment and said customer computing-environment are configured to exchange data with each other.

2. The method of claim 1, wherein said repetitively computing includes computing at least three said specific-key contributions.

3. The method of claim 1, wherein said step of applying is performed using at least one technique selected from the group consisting of: key joining, blinding encryption, partially-homomorphic encryption, and fully-homomorphic encryption.

4. A device for key management in an as-a-service (aaS) context, the device comprising:

(a) a server including:

(i) a CPU for performing computational operations;

(ii) a memory module for storing data; and

(iii) a network connection for communicating across a network; and

(b) a protection module, residing on said server, configured for:

(i) upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in said provider computing-environment by repetitively computing respective specific-key contributions:

(A) in a set of N computing resources in said provider computing-environment, wherein N is a non-negative integer, and wherein said set of N computing resources includes all computing resources in said provider computing environment; and

(B) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, wherein said set of M customer locations includes all customer locations in said customer computing environment, and wherein said customer computing-environment is outside of said provider computing-environment; and

(ii) applying said respective specific-key contributions to change a specific-key value in said set of N computing resources, wherein said respective specific-key contributions are never revealed in unencrypted form to any computing resource of said set of N computing resources, and to any customer location said set of M customer locations, other than respective creation-request contributors associated with said respective specific-key contributions during request initiation;

wherein said at least one location is a region of memory located in a given computing resource of said set of N computing resources, operationally connected to said provider computing-environment, wherein customer locations are regions of memory located in a given computing resource of said set of M customer locations, operationally connected to said customer computing-environment, wherein said provider computing-environment is a computing environment of an aaS service provider, wherein said customer computing-environment is a computing environment of a customer of said aaS service provider, and wherein said provider computing-environment and said customer computing-environment are configured to exchange data with each other.

5. The device of claim 4, wherein said repetitively computing includes computing at least three said specific-key contributions.

6. The device of claim 4, wherein said applying is performed using at least one technique selected from the group consisting of: key joining, blinding encryption, partially-homomorphic encryption, and fully-homomorphic encryption.

7. A computer-readable memory, having computer-readable code embodied on the computer-readable memory for execution by a computer for key management in an as-a-service (aaS) context, the computer-readable code comprising:

(a) program code for, upon receiving a creation request in a provider computing-environment, creating a specific key in at least one location in said provider computing-environment by repetitively computing respective specific-key contributions:

(i) in a set of N computing resources in said provider computing-environment, wherein N is a non-negative integer, and wherein said set of N computing resources includes all computing resources in said provider computing environment; and

(ii) in a set of M customer locations in a customer computing-environment, wherein M is a non-negative integer, wherein said set of M customer locations includes all customer locations in said customer computing environment, and wherein said customer computing-environment is outside of said provider computing-environment; and

(b) program code for, applying said respective specific-key contributions to change a specific-key value in said set of N computing resources, wherein said respective specific-key contributions are never revealed in unencrypted form to any computing resource of said set of N computing resources, and to any customer location said set of M customer locations, other than respective creation-request contributors associated with said respective specific-key contributions during request initiation;

wherein said at least one location is a region of memory located in a given computing resource of said set of N computing resources, operationally connected to said provider computing-environment, wherein customer locations are regions of memory located in a given computing resource of said set of M customer locations, operationally connected to said customer computing-environment, wherein said provider computing-environment is a computing environment of an aaS service provider, wherein said customer computing-environment is a computing environment of a customer of said aaS service provider, and wherein said provider computing-environment and said customer computing-environment are configured to exchange data with each other.

8. The computer-readable memory of claim 7, wherein repetitively computing includes computing at least three said specific-key contributions.

9. The computer-readable memory of claim 7, wherein said applying is performed using at least one technique selected from the group consisting of: key joining, blinding encryption, partially-homomorphic encryption, and fully-homomorphic encryption.

Exemplary Embodiment – Prior Art

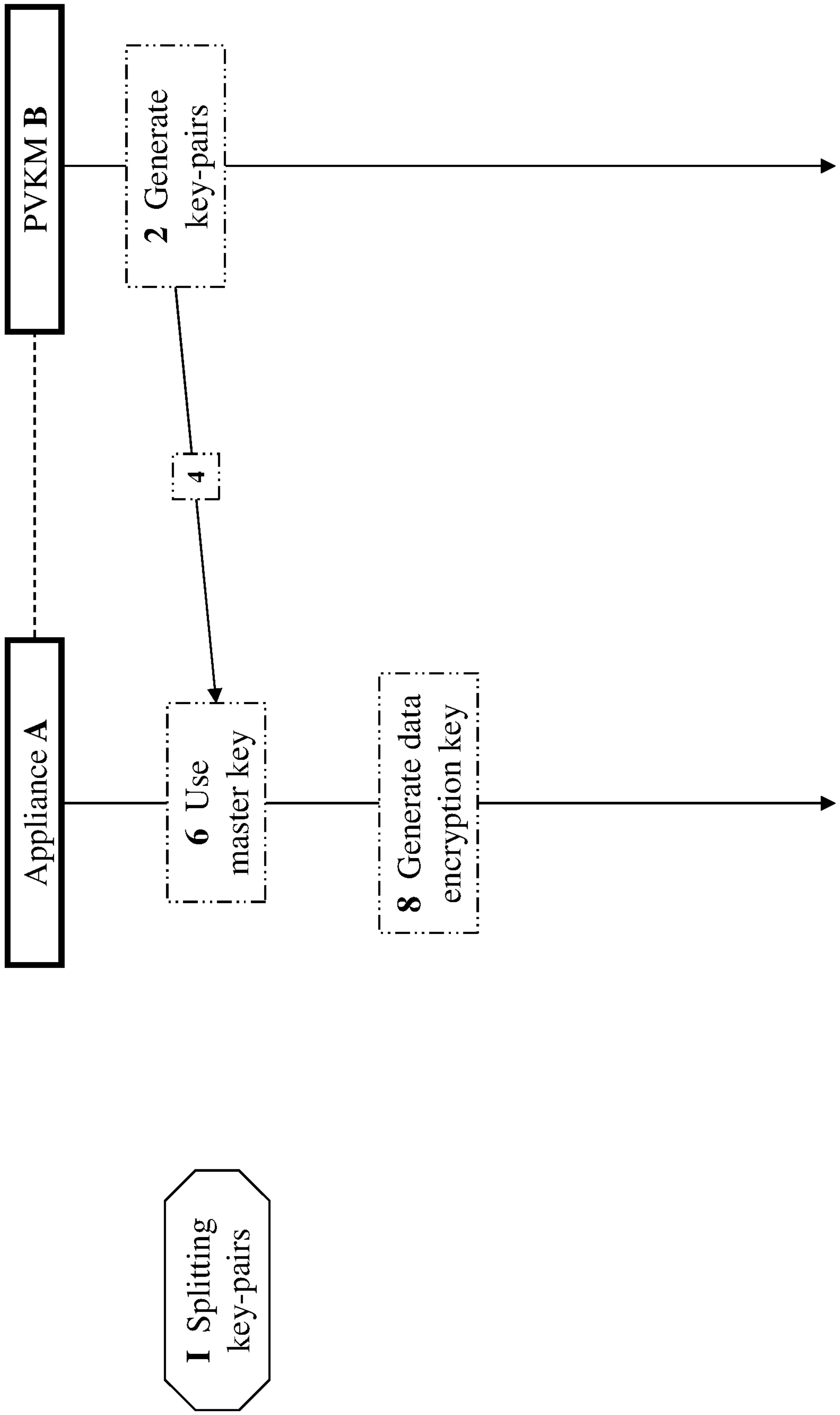


Figure 1

Exemplary Embodiment – Prior Art

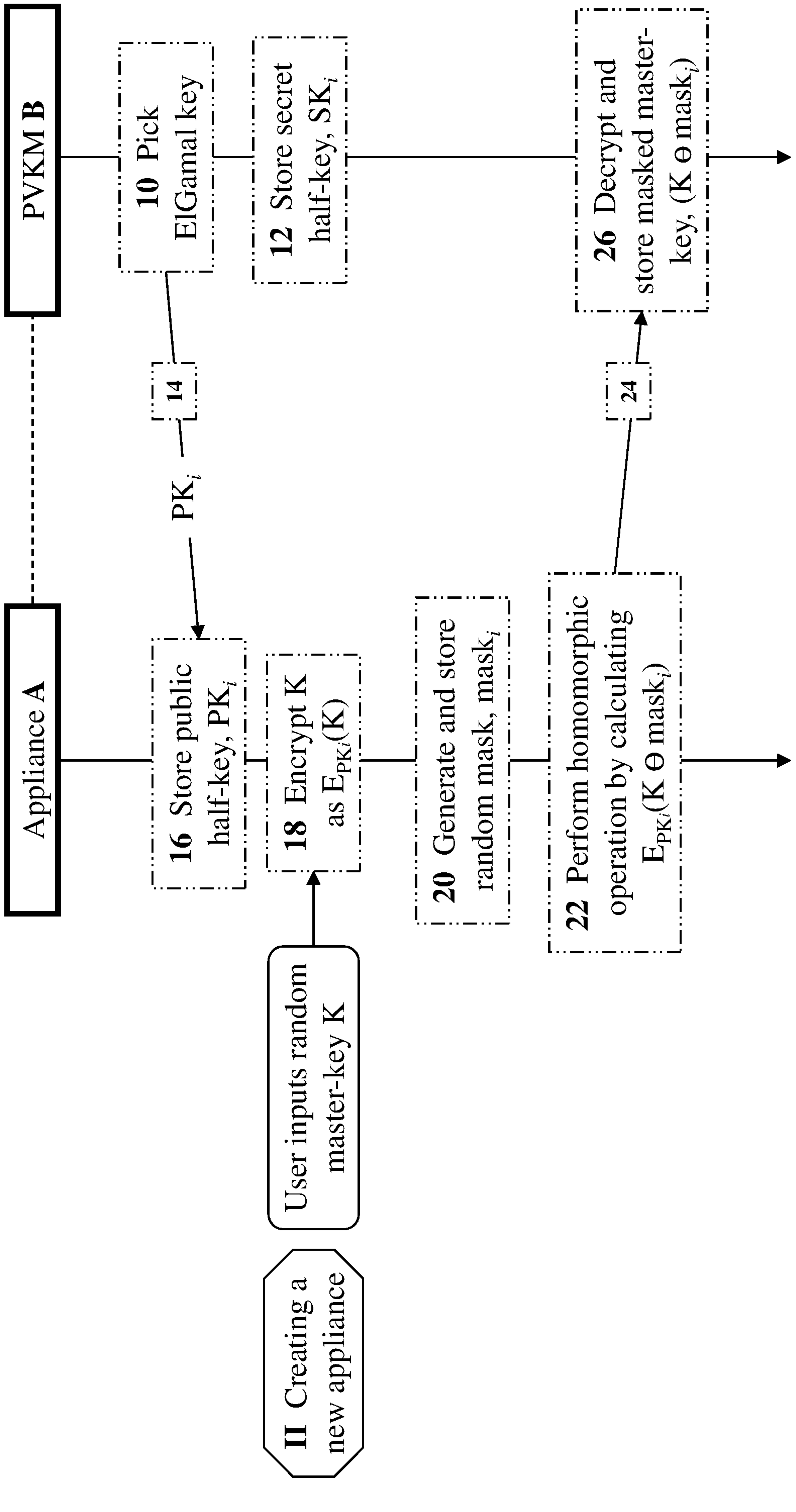


Figure 2

Exemplary Embodiment – Prior Art

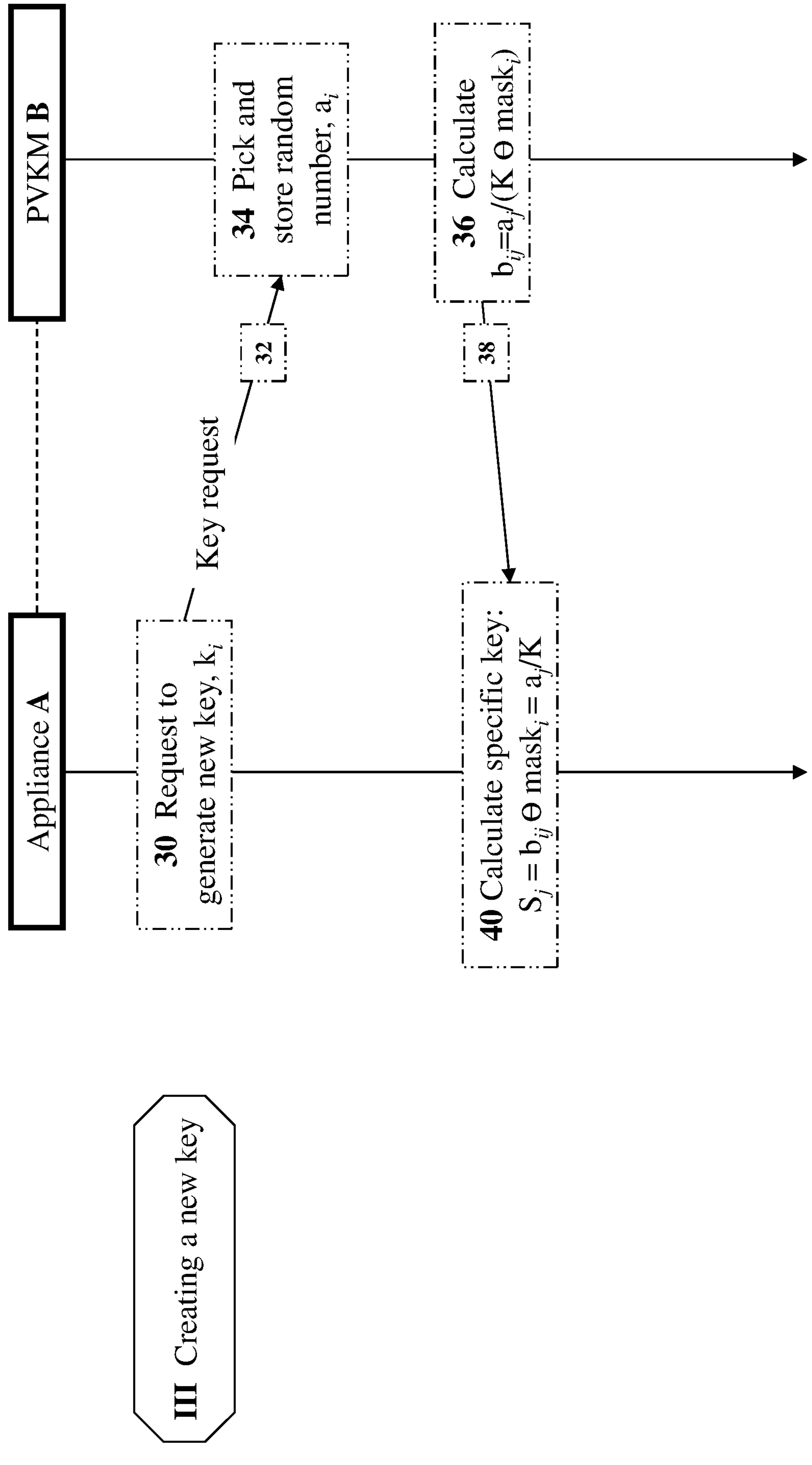


Figure 3

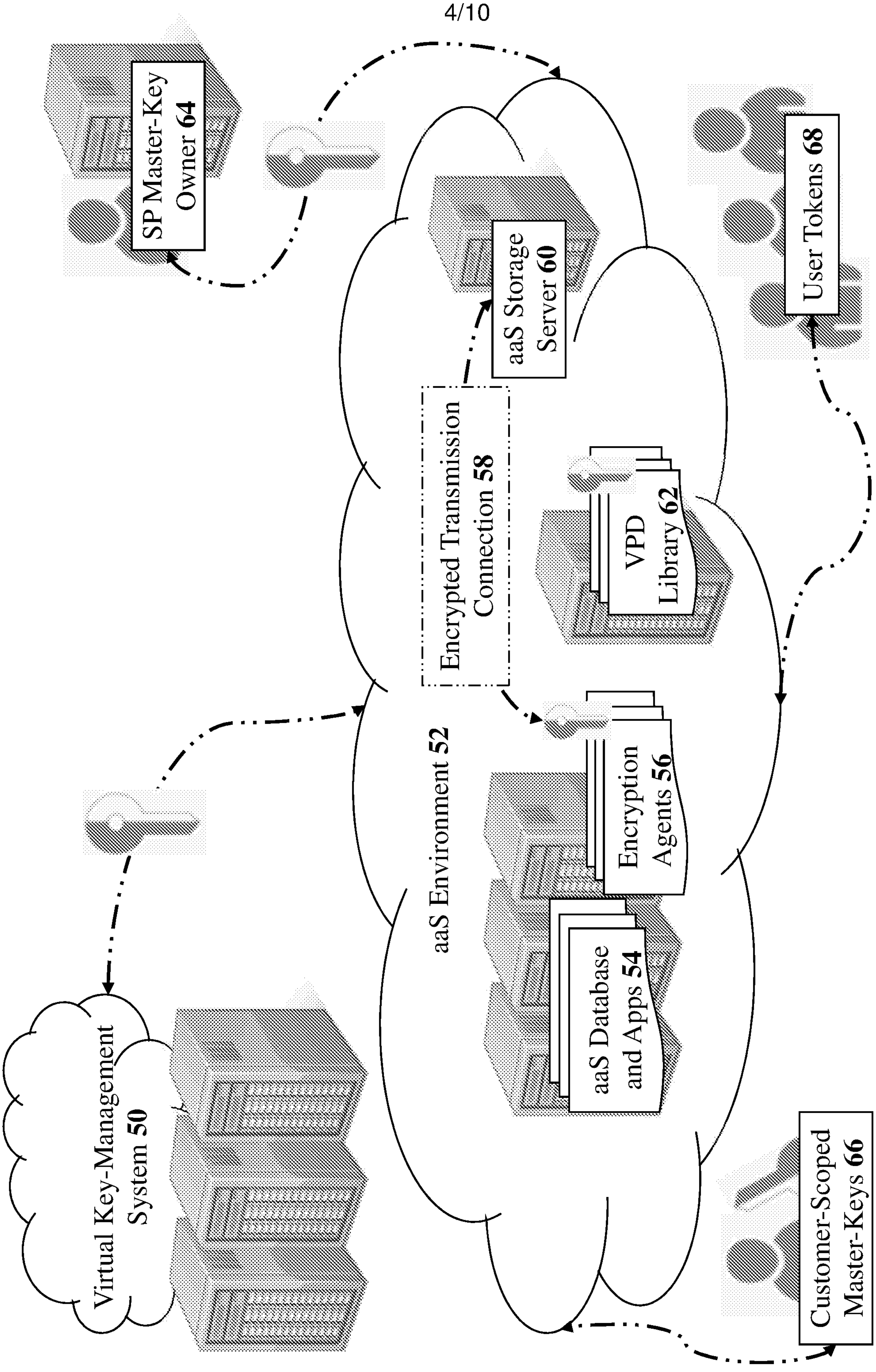

SP Master-Key Owner 64
aaS Storage Server 60
User Tokens 68
Encrypted Transmission Connection 58
VPD Library 62
aaS Environment 52
Encryption Agents 56
aaS Database and Apps 54
Virtual Key-Management System 50
Customer-Scoped Master-Keys 66

Figure 4

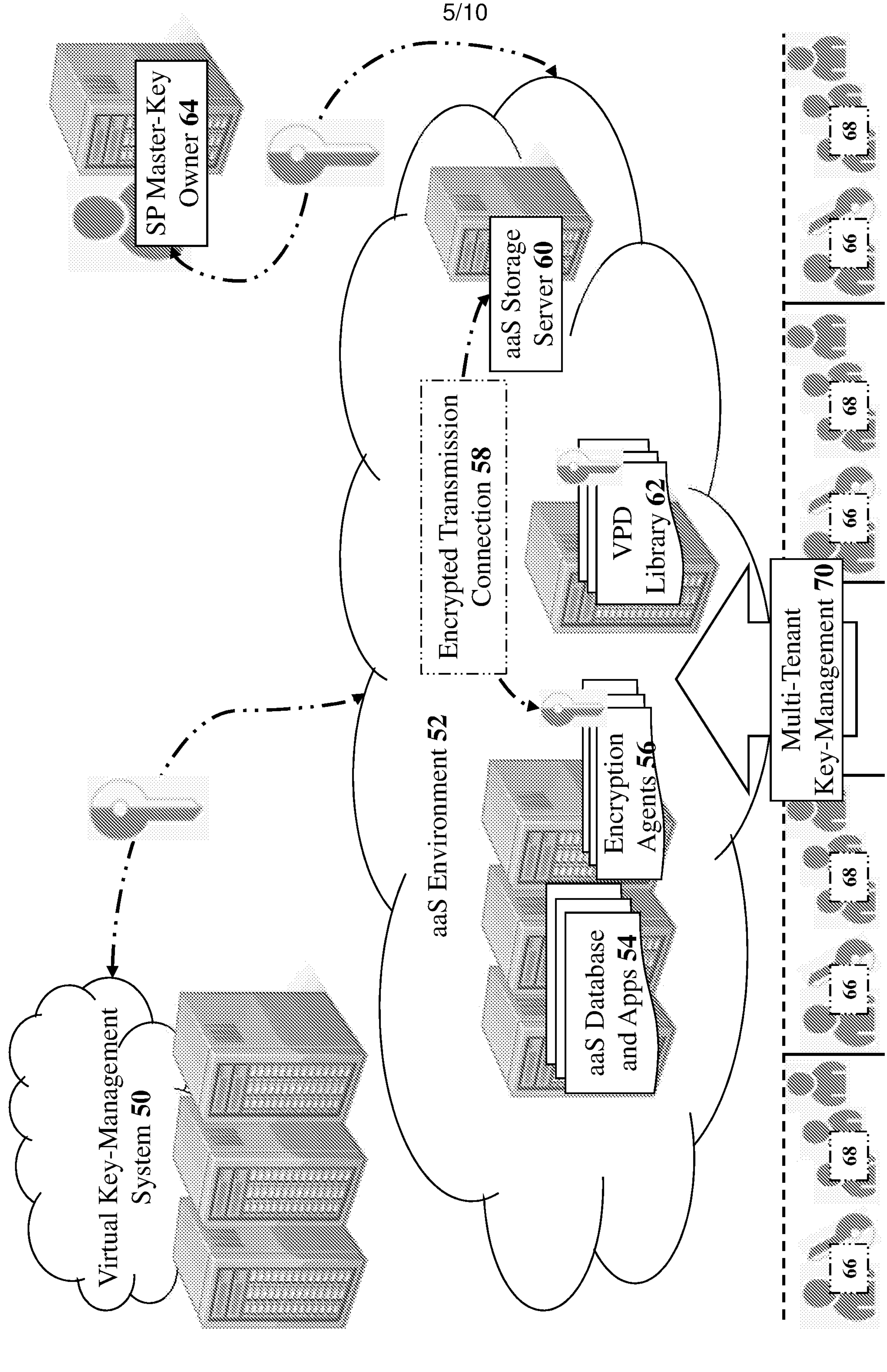

SP Master-Key Owner 64
aaS Storage Server 60
Encrypted Transmission Connection 58
VPD Library 62
aaS Environment 52
Encryption Agents 56
aaS Database and Apps 54
Multi-Tenant Key-Management 70
Virtual Key-Management System 50
66
68
66
68
66
68
66
68

Figure 5

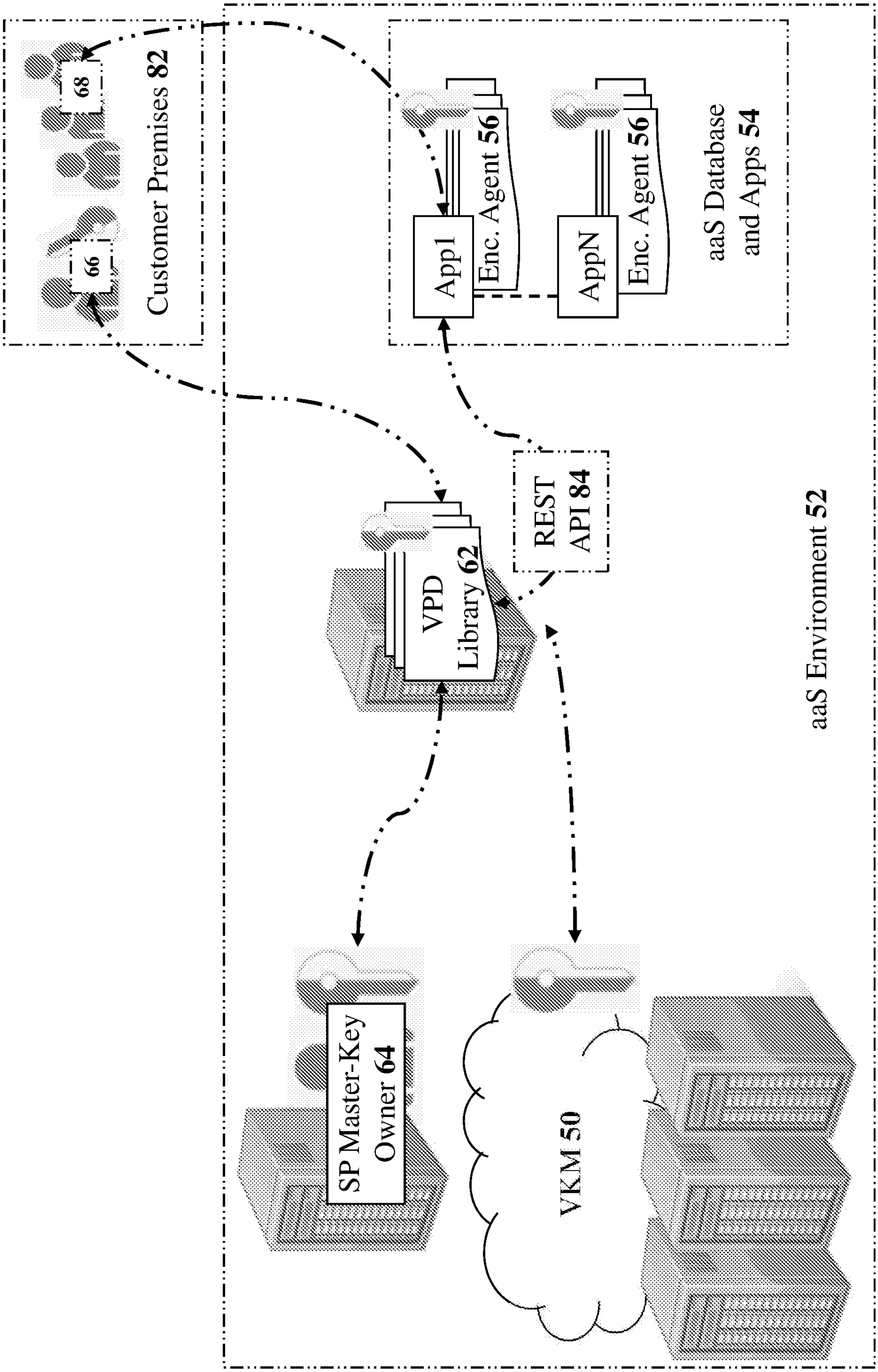

Customer Premises 82
66
68
App1
Enc. Agent 56
AppN
Enc. Agent 56
aaS Database and Apps 54
REST API 84
VPD Library 62
aaS Environment 52
SP Master-Key Owner 64
VKM 50

Figure 6

Exemplary Embodiment

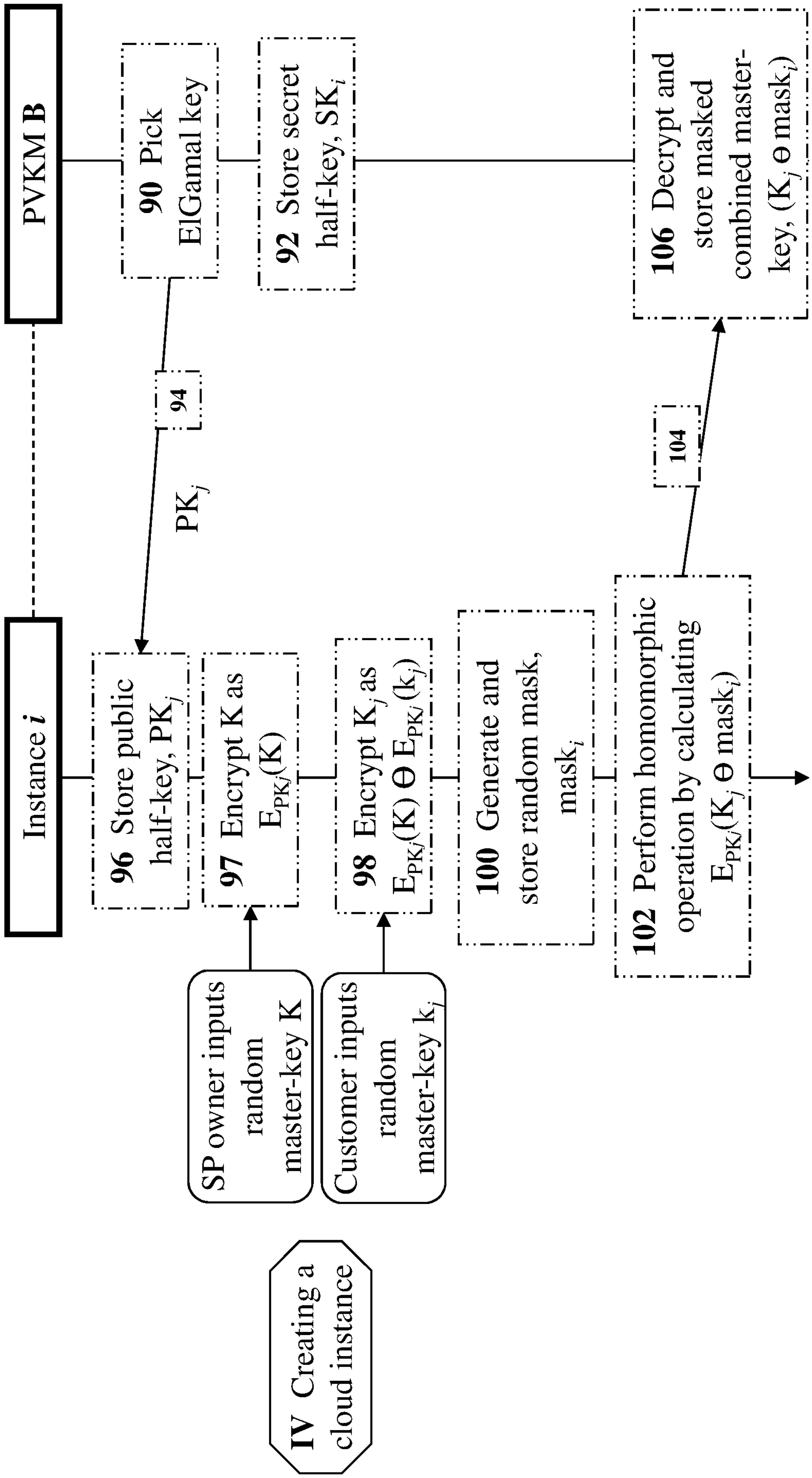


Figure 7

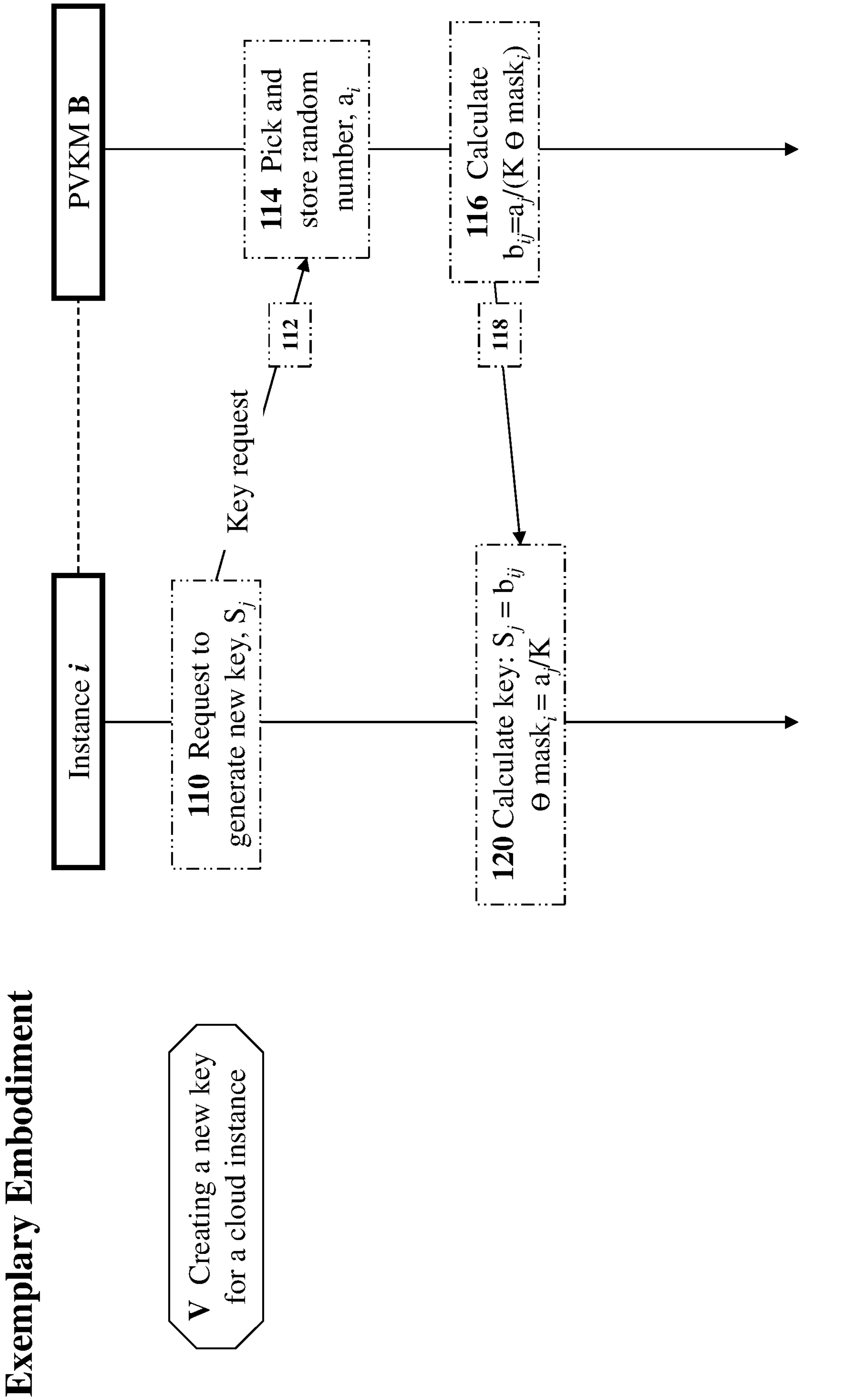

Exemplary Embodiment
V Creating a new key for a cloud instance
Instance i
PVKM B
110 Request to generate new key, S_j
Key request
112
114 Pick and store random number, a_i
116 Calculate $b_{ij}=a_i/(K \ominus mask_i)$
118
120 Calculate key: $S_j = b_{ij} \ominus mask_i = a_i/K$

Figure 8

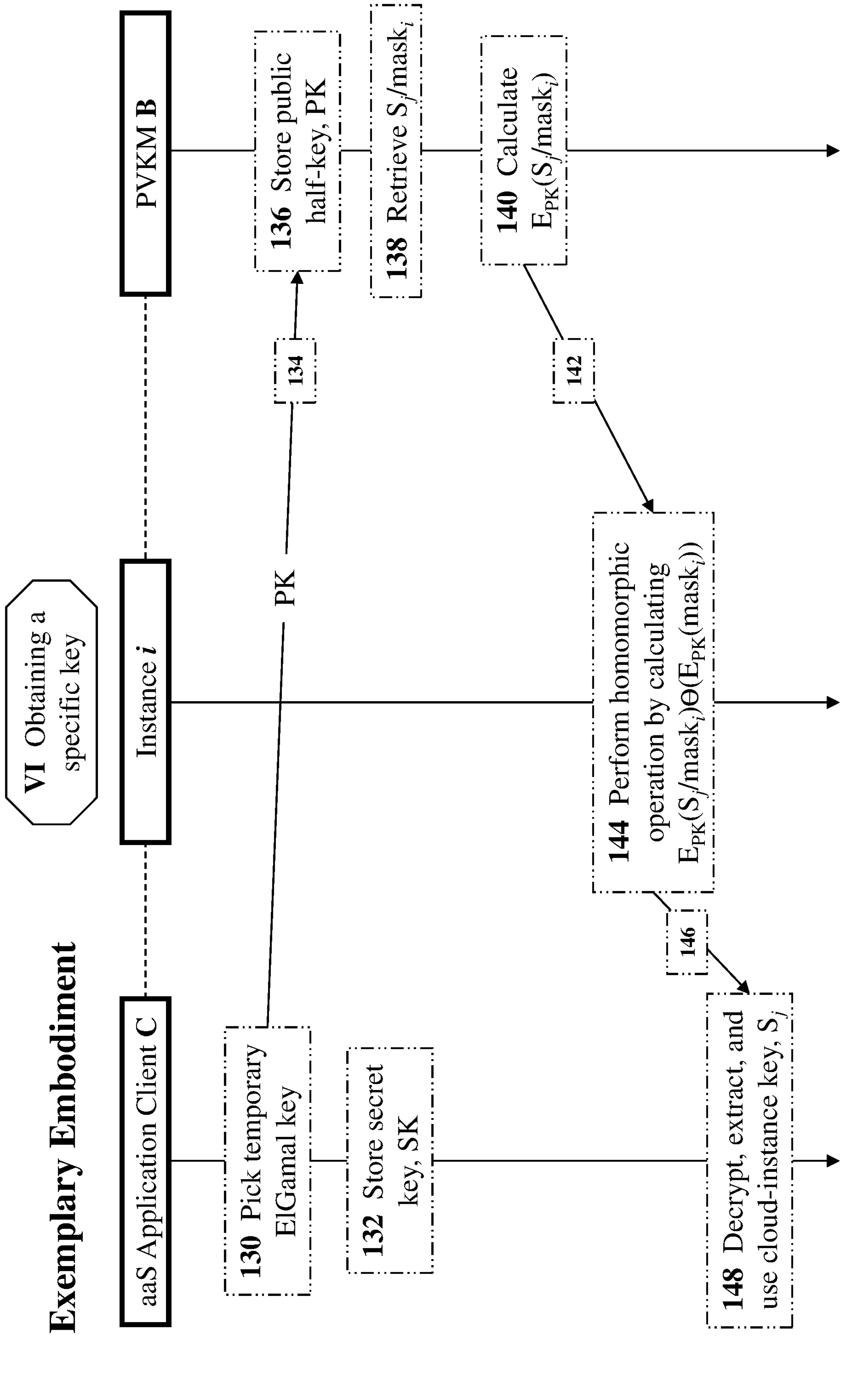

Exemplary Embodiment
aaS Application Client C
Instance *i*
PVKM B
VI Obtaining a specific key
130 Pick temporary ElGamal key
132 Store secret key, SK
PK
134
136 Store public half-key, PK
138 Retrieve S_j/mask$_i$
140 Calculate $E_{PK}(S_j/mask_i)$
142
144 Perform homomorphic operation by calculating $E_{PK}(S_j/mask_i)\Theta(E_{PK}(mask_i))$
146
148 Decrypt, extract, and use cloud-instance key, S_j

Figure 9

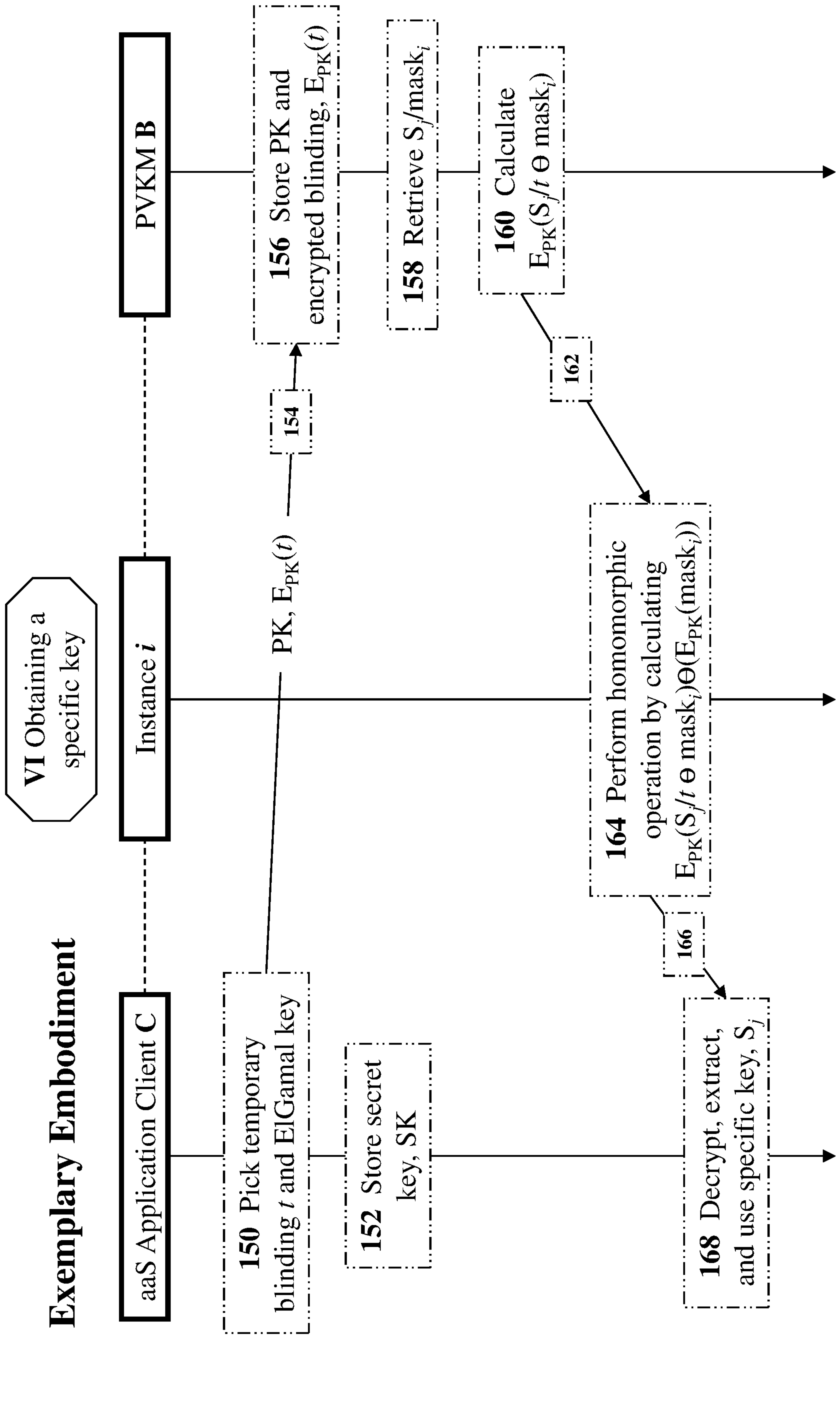
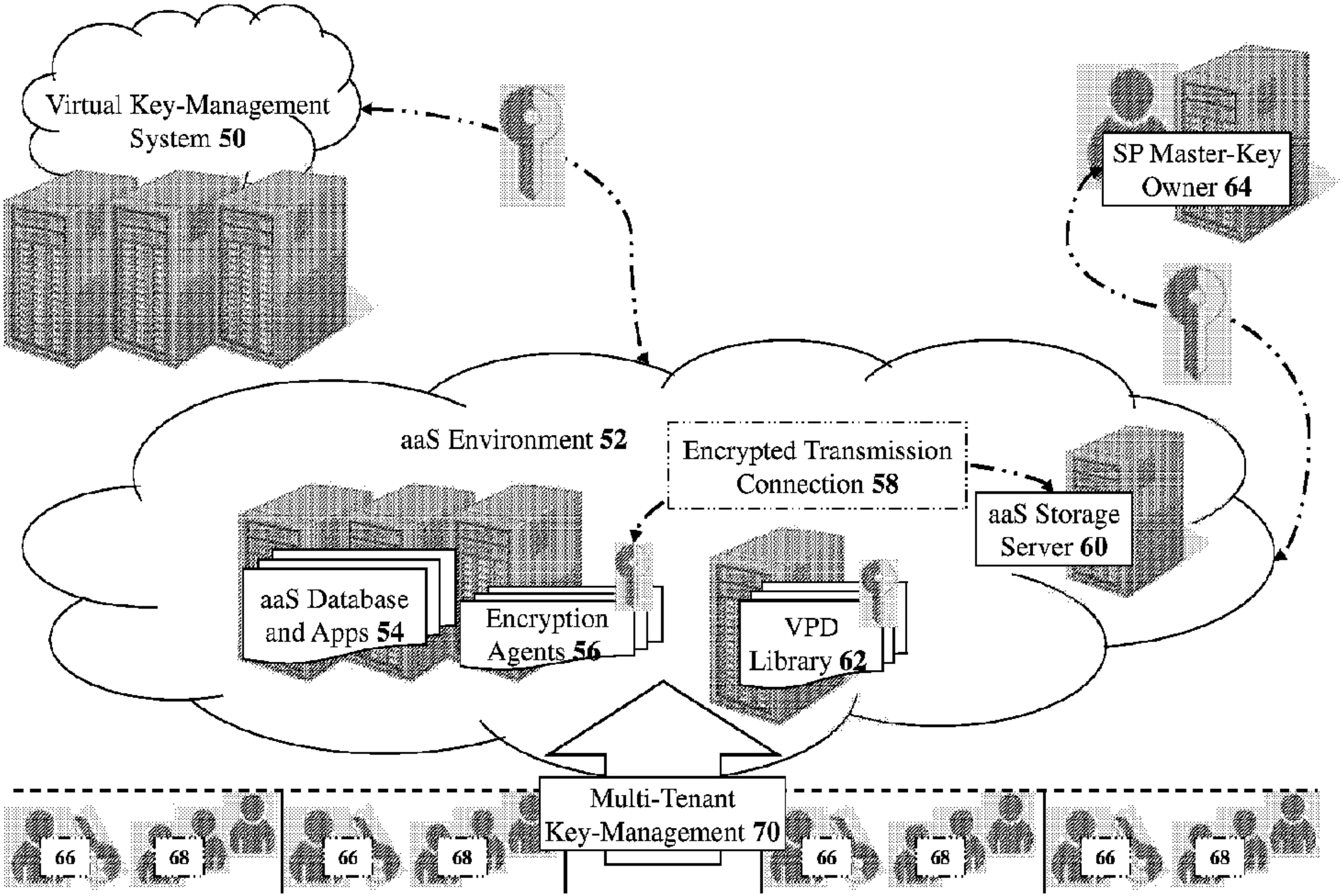

Exemplary Embodiment
VI Obtaining a specific key
aaS Application Client C
Instance i
PVKM B
150 Pick temporary blinding t and ElGamal key
152 Store secret key, SK
PK, E_PK(t)
154
156 Store PK and encrypted blinding, E_PK(t)
158 Retrieve S_j/mask_i
160 Calculate E_PK(S_j/t ϴ mask_i)
162
164 Perform homomorphic operation by calculating E_PK(S_j/t ϴ mask_i)ϴ(E_PK(mask_i))
166
168 Decrypt, extract, and use specific key, S_j

Figure 10


Virtual Key-Management System 50
SP Master-Key Owner 64
aaS Environment 52
Encrypted Transmission Connection 58
aaS Storage Server 60
aaS Database and Apps 54
Encryption Agents 56
VPD Library 62
Multi-Tenant Key-Management 70
66
68
66
68
66
68
66
68