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A Reference Model for Autonomic Networking
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Abstract

This document describes a reference model for Autonomic Networking for managed networks. It defines the behaviour of an autonomic node, how the various elements in an autonomic context work together, and how autonomic services can use the infrastructure.

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Table of Contents

1. Introduction 3
2. The Network View 4
3. The Autonomic Network Element 5
3.1. Architecture 5
3.2. The Adjacency Table 6
3.3. State Machine 8
3.3.1. State 1: Factory Default 8
3.3.2. State 2: Enrolled 9
3.3.3. State 3: In ACP 9
4. The Autonomic Networking Infrastructure 10
4.1. Naming 10
4.2. Addressing 10
4.3. Discovery 12
4.4. Signaling Between Autonomic Nodes 12
4.5. Routing 13
4.6. The Autonomic Control Plane 13
4.7. Information Distribution (*) 13
5. Security and Trust Infrastructure 14
5.1. Public Key Infrastructure 14
5.2. Domain Certificate 14
5.3. The MASA 15
5.4. Sub-Domains (*) 15
5.5. Cross-Domain Functionality (*) 15
6. Autonomic Service Agents (ASA) 15
6.1. General Description of an ASA 15
6.2. ASA Life-Cycle Management 17
6.3. Specific ASAs for the Autonomic Network Infrastructure . 18
6.3.1. The enrollment ASAs 18
6.3.2. The ACP ASA 19
6.3.3. The Information Distribution ASA (*) 19
7. Management and Programmability 19
7.1. Managing a (Partially) Autonomic Network 19
7.2. Intent (*) 20
7.3. Aggregated Reporting (*) 21
7.4. Feedback Loops to NOC (*) 21
7.5. Control Loops (*) 22
7.6. APIs (*) 22
7.7. Data Model (*) 23
8. Coordination Between Autonomic Functions (*) 24

8.1. The Coordination Problem (*) 24
8.2. A Coordination Functional Block (*) 25
9. Security Considerations 25
9.1. Protection Against Outsider Attacks 26
9.2. Risk of Insider Attacks 27
10. IANA Considerations 27
11. Acknowledgements 28
12. Contributors 28
13. References 28
13.1. Normative References 28
13.2. Informative References 28
Authors' Addresses 30

1. Introduction

The document "Autonomic Networking - Definitions and Design Goals" [RFC7575] explains the fundamental concepts behind Autonomic Networking, and defines the relevant terms in this space, as well as a high level reference model. [RFC7576] provides a gap analysis between traditional and autonomic approaches.

This document defines this reference model with more detail, to allow for functional and protocol specifications to be developed in an architecturally consistent, non-overlapping manner.

As discussed in [RFC7575], the goal of this work is not to focus exclusively on fully autonomic nodes or networks. In reality, most networks will run with some autonomic functions, while the rest of the network is traditionally managed. This reference model allows for this hybrid approach.

For example, it is possible in an existing, non-autonomic network to enrol devices in a traditional way, to bring up a trust infrastructure with certificates. This trust infrastructure could then be used to automatically bring up an Autonomic Control Plane (ACP), and run traditional network operations over the secure and self-healing ACP. See [I-D.ietf-anima-stable-connectivity] for a description of this use case.

The scope of this model is therefore limited to networks that are to some extent managed by skilled human operators, loosely referred to as "professionally managed" networks. Unmanaged networks raise additional security and trust issues that this model does not cover.

This document describes a first, simple, implementable phase of an Autonomic Networking solution. It is expected that the experience from this phase will be used in defining updated and extended specifications over time. Some topics are considered architecturally in this document, but are not yet reflected in the implementation specifications. They are marked with an (*).

2. The Network View

This section describes the various elements in a network with autonomic functions, and how these entities work together, on a high level. Subsequent sections explain the detailed inside view for each of the autonomic network elements, as well as the network functions (or interfaces) between those elements.

Figure 1 shows the high level view of an Autonomic Network. It consists of a number of autonomic nodes, which interact directly with each other. Those autonomic nodes provide a common set of capabilities across the network, called the "Autonomic Networking Infrastructure" (ANI). The ANI provides functions like naming, addressing, negotiation, synchronization, discovery and messaging.

Autonomic functions typically span several, possibly all nodes in the network. The atomic entities of an autonomic function are called the "Autonomic Service Agents" (ASA), which are instantiated on nodes.

```
   +- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
   :            :       Autonomic Function 1        :                 :
   : ASA 1      :      ASA 1      :      ASA 1      :          ASA 1  :
   +- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
                :                 :                 :
                :   +- - - - - - - - - - - - - - +  :
                :   :   Autonomic Function 2     :  :
                :   :  ASA 2      :      ASA 2   :  :
                :   +- - - - - - - - - - - - - - +  :
                :                 :                 :
   +- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
   :                Autonomic Networking Infrastructure               :
   +- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
   +--------+   :    +--------+   :    +--------+   :        +--------+
   | Node 1 |--------| Node 2 |--------| Node 3 |----...-----| Node n |
   +--------+   :    +--------+   :    +--------+   :        +--------+
```

Figure 1: High level view of an Autonomic Network

In a horizontal view, autonomic functions span across the network, as well as the Autonomic Networking Infrastructure. In a vertical view, a node always implements the ANI, plus it may have one or several Autonomic Service Agents. ASAs may be standalone, or use other ASAs in a hierarchical way.

The Autonomic Networking Infrastructure (ANI) therefore is the foundation for autonomic functions.

3. The Autonomic Network Element

This section explains the general architecture of an Autonomic Network Element (Section 3.1), how it tracks its surrounding environment in an Adjacency Table (Section 3.2), and the state machine which defines the behaviour of the network element (Section 3.3), based on that adjacency table.

3.1. Architecture

This section describes an autonomic network element and its internal architecture. The reference model explained in the document "Autonomic Networking - Definitions and Design Goals" [RFC7575] shows the sources of information that an autonomic service agent can leverage: Self-knowledge, network knowledge (through discovery), Intent (see Section 7.2), and feedback loops. There are two levels inside an autonomic node: the level of Autonomic Service Agents, and the level of the Autonomic Networking Infrastructure, with the former using the services of the latter. Figure 2 illustrates this concept.

```
   +------------------------------------------------------------+
   |                                                            |
   | +-----------+        +------------+        +------------+  |
   | | Autonomic |        | Autonomic  |        | Autonomic  |  |
   | | Service   |        | Service    |        | Service    |  |
   | | Agent 1   |        | Agent 2    |        | Agent 3    |  |
   | +-----------+        +------------+        +------------+  |
   |       ^                    ^                     ^         |
   | -  -  | -  - API level -  -| -  -  -  -  -  -  - |-  -  -  |
   |       V                    V                     V         |
   |------------------------------------------------------------|
   | Autonomic Networking Infrastructure                        |
   |    - Data structures (ex: certificates, peer information)  |
   |    - Generalized Autonomic Control Plane (GACP)            |
   |    - Autonomic Node Addressing and naming                  |
   |    - Discovery, negotiation and synchronisation functions  |
   |    - Distribution of Intent and other information          |
   |    - Aggregated reporting and feedback loops               |
   |    - Routing                                               |
   |------------------------------------------------------------|
   |             Basic Operating System Functions               |
   +------------------------------------------------------------+
```

Figure 2: Model of an autonomic node

The Autonomic Networking Infrastructure (lower part of Figure 2) contains node specific data structures, for example trust information about itself and its peers, as well as a generic set of functions, independent of a particular usage. This infrastructure should be generic, and support a variety of Autonomic Service Agents (upper part of Figure 2). It contains addressing and naming of autonomic nodes, discovery, negotiation and synchronisation functions, distribution of information, reporting and feedback loops, as well as routing inside the Autonomic Control Plane.

The Generalized Autonomic Control Plane (GACP) is the summary of all interactions of the Autonomic Networking Infrastructure with other nodes and services. A specific implementation of the GACP is referred to here as the Autonomic Control Plane (ACP), and described in [I-D.ietf-anima-autonomic-control-plane].

The use cases of "Autonomics" such as self-management, self-optimisation, etc, are implemented as Autonomic Service Agents. They use the services and data structures of the underlying Autonomic Networking Infrastructure, which should be self-managing.

The "Basic Operating System Functions" include the "normal OS", including the network stack, security functions, etc.

Full AN nodes have the full Autonomic Networking Infrastructure, with the full functionality described in this document. At a later stage ANIMA may define a scope for constrained nodes with a reduced ANI and well-defined minimal functionality. They are currently out of scope.

3.2. The Adjacency Table

Autonomic Networking is based on direct interactions between devices of a domain. The Autonomic Control Plane (ACP) is normally constructed on a hop-by-hop basis. Therefore, many interactions in the ANI are based on the ANI adjacency table. There are interactions that provide input into the adjacency table, and other interactions that leverage the information contained in it.

The ANI adjacency table contains information about adjacent autonomic nodes, at a minimum: node-ID, IP address in data plane, IP address in ACP, domain, certificate. An autonomic node maintains this adjacency table up to date. The adjacency table only contains information about other nodes that are capable of Autonomic Networking; non-autonomic nodes are normally not tracked here. However, the information is tracked independently of the status of the peer nodes; specifically, it contains information about non-enrolled nodes, nodes of the same and other domains. The adjacency table may contain information about the validity and trust level of the adjacent autonomic nodes.

The adjacency table is fed by the following inputs:

- Link local discovery: This interaction happens in the data plane, using IPv6 link local addressing only, because this addressing type is itself autonomic. This way the nodes learns about all autonomic nodes around itself. The related standards track documents ([I-D.ietf-anima-grasp], [I-D.ietf-anima-bootstrapping-keyinfra], [I-D.ietf-anima-autonomic-control-plane]) describe in detail how link local discovery is used.

- Vendor re-direct: A new device may receive information on where its home network is through a vendor based Manufacturer Authorized Signing Authority (MASA, see Section 5.3) re-direct; this is typically a routable address.

- Non-autonomic input: A node may be configured manually with an autonomic peer; it could learn about autonomic nodes through DHCP options, DNS, and other non-autonomic mechanisms. Generally such non-autonomic mechansims require some administrator intervention. The key purpose is to by-pass a non-autonomic device or network. As this pertains to new devices, it is covered in appendix A and B of [I-D.ietf-anima-bootstrapping-keyinfra].

The adjacency table is defining the behaviour of an autonomic node:

- If the node has not bootstrapped into a domain (i.e., doesn't have a domain certificate), it rotates through all nodes in the adjacency table that claim to have a domain, and will attempt bootstrapping through them, one by one. One possible response is a re-direct via a vendor MASA, which will be entered into the adjacency table (see second bullet above). See [I-D.ietf-anima-bootstrapping-keyinfra] for details.

- If the adjacent node has the same domain, it will authenticate that adjacent node and, if successful, establish the Autonomic Control Plane (ACP). See [I-D.ietf-anima-autonomic-control-plane].

- Once the node is part of the ACP of a domain, it will use GRASP [I-D.ietf-anima-grasp] to find Registrar(s) of its domain and potentially other services.

- If the node is part of an ACP and has discovered at least one Registrar in its domain via GRASP, it will start the "join assistant" ASA, and act as a join assistant for neighboring nodes that need to be bootstrapped. See Section 6.3.1.2 for details.

- Other behaviours are possible, for example establishing the ACP also with devices of a sub-domain, to other domains, etc. Those will likely be controlled by Intent. They are outside scope for the moment. Note that Intent is distributed through the ACP; therefore, a node can only adapt Intent driven behaviour once it has joined the ACP. At the moment, ANIMA does not consider providing Intent outside the ACP; this can be considered later.

Once a node has joined the ACP, it will also learn the ACP addresses of its adjacent nodes, and add them to the adjacency table, to allow for communication inside the ACP. Further autonomic domain interactions will now happen inside the ACP. At this moment, only negotiation / synchronization via GRASP [I-D.ietf-anima-grasp] is being defined. (Note that GRASP runs in the data plane, as an input in building the adjacency table, as well as inside the ACP.)

Autonomic Functions consist of Autonomic Service Agents (ASAs). They run logically above the AN Infrastructure, and may use the adjacency table, the ACP, negotiation and synchronization through GRASP in the ACP, Intent and other functions of the ANI. Since the ANI only provides autonomic interactions within a domain, autonomic functions can also use any other context on a node, specifically the global data plane.

3.3. State Machine

Autonomic Networking applies during the full life-cycle of a node. This section describes a state machine of an autonomic node, throughout its life.

A device is normally expected to store its domain specific identity, the LDevID (see Section 5.2), in persistent storage, to be available after a powercycle event. For device types that cannot store the LDevID in persistent storage, a powercycle event is effectively equivalent to a factory reset.

3.3.1. State 1: Factory Default

An autonomic node leaves the factory in this state. In this state, the node has no domain specific configuration, specifically no LDevID, and could be used in any particular target network. It does however have a vendor/manufacturer specific ID, the IDevID [IDevID]. Nodes without IDevID cannot be autonomically and securely enrolled into a domain; they require manual pre-staging, in which case the pre-staging takes them directly to state 2.

Transitions:

- o Bootstrap event: The device enrols into a domain; as part of this process it receives a domain identity (LDevID). If enrollment is successful, the next state is state 2. See [I-D.ietf-anima-bootstrapping-keyinfra] Section 3 for details on enrollment.

- o Powercycle event: The device loses all state tables. It remains in state: 1.

3.3.2. State 2: Enrolled

An autonomic node is in the state "enrolled" if it has a domain identity (LDevID), and has currently no ACP channel up. It may have further configuration or state, for example if it had been in state 3 before, but lost all its ACP channels. The LDevID can only be removed from a device through a factory reset, which also removes all other state from the device. This ensures that a device has no stale domain specific state when entering the "enrolled" state from state 1.

Transitions:

- o Joining ACP: The device establishes an ACP channel to an adjacent device. See [I-D.ietf-anima-autonomic-control-plane] for details. Next state: 3.

- o Factory reset: A factory reset removes all configuration and the domain identity (LDevID) from the device. Next state: 1.

- o Powercycle event: The device loses all state tables, but not its domain identity (LDevID). it remains in state: 2.

3.3.3. State 3: In ACP

In this state, the autonomic node has at least one ACP channel to another device. The node can now participate in further autonomic transactions, such as starting autonomic service agents (e.g., it must now enable the join assistant ASA, to help other devices to join the domain. Other conditions may apply to such interactions, for example to serve as a join assistant, the device must first discover a bootstrap Registrar.

Transitions:

- o Leaving ACP: The device drops the last (or only) ACP channel to an adjacent device. Next state: 2.

- Factory reset: A factory reset removes all configuration and the domain identity (LDevID) from the device. Next state: 1.

- Powercycle event: The device loses all state tables, but not its domain identity (LDevID). Next state: 2.

4. The Autonomic Networking Infrastructure

The Autonomic Networking Infrastructure provides a layer of common functionality across an Autonomic Network. It provides the elementary functions and services, as well as extensions. An Autonomic Function, comprising of Autonomic Service Agents on nodes, uses the functions described in this section.

4.1. Naming

Inside a domain, each autonomic device should be assigned a unique name. The naming scheme should be consistent within a domain. Names are typically assigned by a Registrar at bootstrap time and persistent over the lifetime of the device. All Registrars in a domain must follow the same naming scheme.

In the absence of a domain specific naming scheme, a default naming scheme should use the same logic as the addressing scheme discussed in [I-D.ietf-anima-autonomic-control-plane]. The device name is then composed of a Registrar ID (for example taking a MAC address of the Registrar) and a device number. An example name would then look like this:

```
0123-4567-89ab-0001
```

The first three fields are the MAC address, the fourth field is the sequential number for the device.

4.2. Addressing

Autonomic Service Agents (ASAs) need to communicate with each other, using the autonomic addressing of the Autonomic Networking Infrastructure of the node they reside on. This section describes the addressing approach of the Autonomic Networking Infrastructure, used by ASAs.

Addressing approaches for the data plane of the network are outside the scope of this document. These addressing approaches may be configured and managed in the traditional way, or negotiated as a service of an ASA. One use case for such an autonomic function is described in [I-D.ietf-anima-prefix-management].

Autonomic addressing is a function of the Autonomic Networking Infrastructure (lower part of Figure 2), specifically the Autonomic Control Plane. ASAs do not have their own addresses. They may use either API calls, or the autonomic addressing scheme of the Autonomic Networking Infrastructure.

An autonomic addressing scheme has the following requirements:

- Zero-touch for simple networks: Simple networks should have complete self-management of addressing, and not require any central address management, tools, or address planning.

- Low-touch for complex networks: If complex networks require operator input for autonomic address management, it should be limited to high level guidance only, expressed in Intent.

- Flexibility: The addressing scheme must be flexible enough for nodes to be able to move around, for the network to grow, split and merge.

- Robustness: It should be as hard as possible for an administrator to negatively affect addressing (and thus connectivity) in the autonomic context.

- Stability: The addressing scheme should be as stable as possible. However, implementations need to be able to recover from unexpected address changes.

- Support for virtualization: Autonomic functions can exist either at the level of the physical network and physical devices, or at the level of virtual machines, containers and networks. In particular, Autonomic Nodes may support Autonomic Service Agents in virtual entities. The infrastructure, including the addressing scheme, should be able to support this architecture.

- Simplicity: To make engineering simpler, and to give the human administrator an easy way to trouble-shoot autonomic functions.

- Scale: The proposed scheme should work in any network of any size.

- Upgradability: The scheme must be able to support different addressing concepts in the future.

The proposed addressing scheme is described in the document "An Autonomic Control Plane" ([I-D.ietf-anima-autonomic-control-plane]).

4.3. Discovery

Traditionally, most of the information a node requires is provided through configuration or northbound interfaces. An autonomic function should rely on such northbound interfaces minimally or not at all, and therefore it needs to discover peers and other resources in the network. This section describes various discovery functions in an autonomic network.

Discovering nodes and their properties and capabilities: A core function to establish an autonomic domain is the mutual discovery of autonomic nodes, primarily adjacent nodes and secondarily off-link peers. This may in principle either leverage existing discovery mechanisms, or use new mechanisms tailored to the autonomic context. An important point is that discovery must work in a network with no predefined topology, ideally no manual configuration of any kind, and with nodes starting up from factory condition or after any form of failure or sudden topology change.

Discovering services: Network services such as AAA should also be discovered and not configured. Service discovery is required for such tasks. An autonomic network can either leverage existing service discovery functions, or use a new approach, or a mixture.

Thus the discovery mechanism could either be fully integrated with autonomic signaling (next section) or could use an independent discovery mechanism such as DNS Service Discovery or Service Location Protocol. This choice could be made independently for each Autonomic Service Agent, although the infrastructure might require some minimal lowest common denominator (e.g., for discovering the security bootstrap mechanism, or the source of information distribution, Section 4.7).

Phase 1 of Autonomic Networking uses GRASP for discovery, described in [I-D.ietf-anima-grasp].

4.4. Signaling Between Autonomic Nodes

Autonomic nodes must communicate with each other, for example to negotiate and/or synchronize technical objectives (i.e., network parameters) of any kind and complexity. This requires some form of signaling between autonomic nodes. Autonomic nodes implementing a specific use case might choose their own signaling protocol, as long as it fits the overall security model. However, in the general case, any pair of autonomic nodes might need to communicate, so there needs to be a generic protocol for this. A prerequisite for this is that autonomic nodes can discover each other without any preconfiguration, as mentioned above. To be generic, discovery and signaling must be able to handle any sort of technical objective, including ones that require complex data structures. The document "A Generic Autonomic Signaling Protocol (GRASP)" [I-D.ietf-anima-grasp] describes more detailed requirements for discovery, negotiation and synchronization in an autonomic network. It also defines a protocol, GRASP, for this purpose, including an integrated but optional discovery protocol.

GRASP is normally expected to run inside the Autonomic Control Plane (ACP; see Section 4.6) and to depend on the ACP for security. It may run insecurely for a short time during bootstrapping.

An autonomic node will normally run a single instance of GRASP, used by multiple ASAs. However, scenarios where multiple instances of GRASP run in a single node, perhaps with different security properties, are not excluded.

4.5. Routing

All autonomic nodes in a domain must be able to communicate with each other, and later phases also with autonomic nodes outside their own domain. Therefore, an Autonomic Control Plane relies on a routing function. For Autonomic Networks to be interoperable, they must all support one common routing protocol.

The routing protocol is defined in the ACP document [I-D.ietf-anima-autonomic-control-plane].

4.6. The Autonomic Control Plane

The "Autonomic Control Plane" carries the control protocols in an autonomic network. In the architecture described here, it is implemented as an overlay network. The document "An Autonomic Control Plane" ([I-D.ietf-anima-autonomic-control-plane]) describes the implementation details suggested here. This document uses the term "overlay" to mean a set of point-to-point adjacencies congruent with the underlying interconnection topology. The terminology may not be aligned with a common usage of the "overlay" term in routing context. See [I-D.ietf-anima-stable-connectivity] for uses cases for the ACP.

4.7. Information Distribution (*)

Certain forms of information require distribution across an autonomic domain. The distribution of information runs inside the Autonomic Control Plane. For example, Intent is distributed across an autonomic domain, as explained in [RFC7575].

Intent is the policy language of an Autonomic Network, see also Section 7.2. It is a high level policy, and should change only infrequently (order of days). Therefore, information such as Intent should be simply flooded to all nodes in an autonomic domain, and there is currently no perceived need to have more targeted distribution methods. Intent is also expected to be monolithic, and flooded as a whole. One possible method for distributing Intent, as well as other forms of data, is discussed in [I-D.liu-anima-grasp-distribution]. Intent and information distribution are not part of phase 1 of ANIMA.

5. Security and Trust Infrastructure

An Autonomic Network is self-protecting. All protocols are secure by default, without the requirement for the administrator to explicitly configure security, with the exception of setting up a PKI infrastructure.

Autonomic nodes have direct interactions between themselves, which must be secured. Since an autonomic network does not rely on configuration, it is not an option to configure, for example, pre-shared keys. A trust infrastructure such as a PKI infrastructure must be in place. This section describes the principles of this trust infrastructure. In this first phase of autonomic networking, a device is either within the trust domain and fully trusted, or outside the trust domain and fully untrusted.

The default method to automatically bring up a trust infrastructure is defined in the document "Bootstrapping Key Infrastructures" [I-D.ietf-anima-bootstrapping-keyinfra]. The ASAs required for this enrollment process are described in Section 6.3. An autonomic node must implement the enrollment and join assistant ASAs. The registrar ASA may be implemented only on a sub-set of nodes.

5.1. Public Key Infrastructure

An autonomic domain uses a PKI model. The root of trust is a certification authority (CA). A registrar acts as a registration authority (RA).

A minimum implementation of an autonomic domain contains one CA, one Registrar, and network elements.

5.2. Domain Certificate

Each device in an autonomic domain uses a domain certificate (LDevID) to prove its identity. A new device uses its manufacturer provided certificate (IDevID) during bootstrap, to obtain a domain certificate. [I-D.ietf-anima-bootstrapping-keyinfra] describes how a new device receives a domain certificate, and the certificate format.

5.3. The MASA

The Manufacturer Authorized Signing Authority (MASA) is a trusted service for bootstrapping devices. The purpose of the MASA is to provide ownership tracking of devices in a domain. The MASA provides audit, authorization, and ownership tokens to the registrar during the bootstrap process to assist in the authentication of devices attempting to join an Autonomic Domain, and to allow a joining device to validate whether it is joining the correct domain. The details for MASA service, security, and usage are defined in [I-D.ietf-anima-bootstrapping-keyinfra].

5.4. Sub-Domains (*)

By default, sub-domains are treated as different domains. This implies no trust between a domain and its sub-domains, and no trust between sub-domains of the same domain. Specifically, no ACP is built, and Intent is valid only for the domain it is defined for explicitly.

In phase 2 of ANIMA, alternative trust models should be defined, for example to allow full or limited trust between domain and sub-domain.

5.5. Cross-Domain Functionality (*)

By default, different domains do not interoperate, no ACP is built and no trust is implied between them.

In the future, models can be established where other domains can be trusted in full or for limited operations between the domains.

6. Autonomic Service Agents (ASA)

This section describes how autonomic services run on top of the Autonomic Networking Infrastructure.

6.1. General Description of an ASA

An Autonomic Service Agent (ASA) is defined in [RFC7575] as "An agent implemented on an autonomic node that implements an autonomic function, either in part (in the case of a distributed function) or whole." Thus it is a process that makes use of the features provided by the ANI to achieve its own goals, usually including interaction with other ASAs via the GRASP protocol [I-D.ietf-anima-grasp] or otherwise. Of course it also interacts with the specific targets of its function, using any suitable mechanism. Unless its function is very simple, the ASA will need to handle overlapping asynchronous operations. It may therefore be a quite complex piece of software in its own right, forming part of the application layer above the ANI. ASA design guidelines are available in [I-D.carpenter-anima-asa-guidelines].

Thus we can distinguish at least three classes of ASAs:

- Simple ASAs with a small footprint that could run anywhere.

- Complex, possibly multi-threaded ASAs that have a significant resource requirement and will only run on selected nodes.

- A few 'infrastructure ASAs' that use basic ANI features in support of the ANI itself, which must run in all autonomic nodes. These are outlined in the following sections.

Autonomic nodes, and therefore their ASAs, know their own capabilities and restrictions, derived from hardware, firmware or pre-installed software: They are "self-aware".

The role of an autonomic node depends on Intent and on the surrounding network behaviors, which may include forwarding behaviors, aggregation properties, topology location, bandwidth, tunnel or translation properties, etc. For example, a node may decide to act as a backup node for a neighbor, if its capabilities allow it to do so.

Following an initial discovery phase, the node properties and those of its neighbors are the foundation of the behavior of a specific node. A node and its ASAs have no pre-configuration for the particular network in which they are installed.

Since all ASAs will interact with the ANI, they will depend on appropriate application programming interfaces (APIs). It is desirable that ASAs are portable between operating systems, so these APIs need to be universal. An API for GRASP is described in [I-D.ietf-anima-grasp-api].

ASAs will in general be designed and coded by experts in a particular technology and use case, not by experts in the ANI and its components. Also, they may be coded in a variety of programming languages, in particular including languages that support object constructs as well as traditional variables and structures. The APIs should be designed with these factors in mind.

It must be possible to run ASAs as non-privileged (user space) processes except for those (such as the infrastructure ASAs) that necessarily require kernel privilege. Also, it is highly desirable that ASAs can be dynamically loaded on a running node.

Since autonomic systems must be self-repairing, it is of great importance that ASAs are coded using robust programming techniques. All run-time error conditions must be caught, leading to suitable minimally disruptive recovery actions, also considering a complete restart of the ASA. Conditions such as discovery failures or negotiation failures must be treated as routine, with the ASA retrying the failed operation, preferably with an exponential back-off in the case of persistent errors. When multiple threads are started within an ASA, these threads must be monitored for failures and hangups, and appropriate action taken. Attention must be given to garbage collection, so that ASAs never run out of resources. There is assumed to be no human operator - again, in the worst case, every ASA must be capable of restarting itself.

ASAs will automatically benefit from the security provided by the ANI, and specifically by the ACP and by GRASP. However, beyond that, they are responsible for their own security, especially when communicating with the specific targets of their function. Therefore, the design of an ASA must include a security analysis beyond 'use ANI security.'

6.2. ASA Life-Cycle Management

ASAs operating on a given ANI may come from different providers and pursue different objectives. Management of ASAs and its interactions with the ANI should follow the same operating principles, hence comply to a generic life-cycle management model.

The ASA life-cycle provides standard processes to:

- install ASA: copy the ASA code onto the node and start it,

- deploy ASA: associate the ASA instance with a (some) managed network device(s) (or network function),

- control ASA execution: when and how an ASA executes its control loop.

The life-cyle will cover the sequential states below: Installation, Deployment, Operation and the transitional states in-between. This Life-Cycle will also define which interactions ASAs have with the ANI in between the different states. The noticeable interactions are:

- Self-description of ASA instances at the end of deployment: its format needs to define the information required for the management of ASAs by ANI entities

- Control of ASA control-loop during the operation: a signaling has to carry formatted messages to control ASA execution (at least starting and stopping the control loop)

6.3. Specific ASAs for the Autonomic Network Infrastructure

The following functions provide essential, required functionality in an autonomic network, and are therefore mandatory to implement on unconstrained autonomic nodes. They are described here as ASAs that include the underlying infrastructure components, but implementation details might vary.

The first three together support the trust enrollment process described in Section 5. For details see [I-D.ietf-anima-bootstrapping-keyinfra].

6.3.1. The enrollment ASAs

6.3.1.1. The Pledge ASA

This ASA includes the function of an autonomic node that bootstraps into the domain with the help of an join assitant ASA (see below). Such a node is known as a Pledge during the enrollment process. This ASA must be installed by default on all nodes that require an autonomic zero-touch bootstrap.

6.3.1.2. The Join Assistant ASA

This ASA includes the function of an autonomic node that helps a non-enrolled, adjacent devices to enroll into the domain. This ASA must be installed on all nodes, although only one join assistant needs to be active on a given LAN. See also [I-D.ietf-anima-bootstrapping-keyinfra].

6.3.1.3. The Join Registrar ASA

This ASA includes the join registrar function in an autonomic network. This ASA does not need to be installed on all nodes, but only on nodes that implement the Join Registrar function.

6.3.2. The ACP ASA

This ASA includes the ACP function in an autonomic network. In particular it acts to discover other potential ACP nodes, and to support the establishment and teardown of ACP channels. This ASA must be installed on all nodes. For details see Section 4.6 and [I-D.ietf-anima-autonomic-control-plane].

6.3.3. The Information Distribution ASA (*)

This ASA is currently out of scope in ANIMA, and provided here only as background information.

This ASA includes the information distribution function in an autonomic network. In particular it acts to announce the availability of Intent and other information to all other autonomic nodes. This ASA does not need to be installed on all nodes, but only on nodes that implement the information distribution function. For details see Section 4.7.

Note that information distribution can be implemented as a function in any ASA. See [I-D.liu-anima-grasp-distribution] for more details on how information is suggested to be distributed.

7. Management and Programmability

This section describes how an Autonomic Network is managed, and programmed.

7.1. Managing a (Partially) Autonomic Network

Autonomic management usually co-exists with traditional management methods in most networks. Thus, autonomic behavior will be defined for individual functions in most environments. Examples for overlap are:

- Autonomic functions can use traditional methods and protocols (e.g., SNMP and NETCONF) to perform management tasks, inside and outside the ACP;

- Autonomic functions can conflict with behavior enforced by the same traditional methods and protocols;

- Traditional functions can use the ACP, for example if reachability on the data plane is not (yet) established.

The autonomic Intent is defined at a high level of abstraction. However, since it is necessary to address individual managed elements, autonomic management needs to communicate in lower-level interactions (e.g., commands and requests). For example, it is expected that the configuration of such elements be performed using NETCONF and YANG modules as well as the monitoring be executed through SNMP and MIBs.

Conflict can occur between autonomic default behavior, autonomic Intent, traditional management methods. Conflict resolution is achieved in autonomic management through prioritization [RFC7575]. The rationale is that manual and node-based management have a higher priority over autonomic management. Thus, the autonomic default behavior has the lowest priority, then comes the autonomic Intent (medium priority), and, finally, the highest priority is taken by node-specific network management methods, such as the use of command line interfaces.

7.2. Intent (*)

Intent is not covered in the current implementation specifications. This section discusses a topic for further research.

This section gives an overview of Intent, and how it is managed. Intent and Policy-Based Network Management (PBNM) is already described inside the IETF (e.g., PCIM) and in other SDOs (e.g., DMTF and TMF ZOOM).

Intent can be described as an abstract, declarative, high-level policy used to operate an autonomic domain, such as an enterprise network [RFC7575]. Intent should be limited to high level guidance only, thus it does not directly define a policy for every network element separately.

Intent can be refined to lower level policies using different approaches. This is expected in order to adapt the Intent to the capabilities of managed devices. Intent may contain role or function information, which can be translated to specific nodes [RFC7575]. One of the possible refinements of the Intent is using Event-Condition-Action (ECA) rules.

Different parameters may be configured for Intent. These parameters are usually provided by the human operator. Some of these parameters can influence the behavior of specific autonomic functions as well as the way the Intent is used to manage the autonomic domain.

Intent is discussed in more detail in [I-D.du-anima-an-intent]. Intent as well as other types of information are distributed via GRASP, see [I-D.liu-anima-grasp-distribution].

7.3. Aggregated Reporting (*)

Aggregated reporting is not covered in the current implementation specifications. This section discusses a topic for further research.

An Autonomic Network should minimize the need for human intervention. In terms of how the network should behave, this is done through an autonomic Intent provided by the human administrator. In an analogous manner, the reports which describe the operational status of the network should aggregate the information produced in different network elements in order to present the effectiveness of autonomic Intent enforcement. Therefore, reporting in an autonomic network should happen on a network-wide basis [RFC7575].

Multiple simultaneous events can occur in an autonomic network in the same way they can happen in a traditional network. However, when reporting to a human administrator, such events should be aggregated to avoid notifications about individual managed elements. In this context, algorithms may be used to determine what should be reported (e.g., filtering) and in which way and how different events are related to each other. Besides that, an event in an individual element can be compensated by changes in other elements to maintain a network-wide target which is described in the autonomic Intent.

Reporting in an autonomic network may be at the same abstraction level as Intent. In this context, the aggregated view of current operational status of an autonomic network can be used to switch to different management modes. Despite the fact that autonomic management should minimize the need for user intervention, possibly there are some events that need to be addressed by human administrator actions.

7.4. Feedback Loops to NOC (*)

Feedback loops are required in an autonomic network to allow the intervention of a human administrator or central control systems, while maintaining a default behaviour. Through a feedback loop an administrator must be prompted with a default action, and has the possibility to acknowledge or override the proposed default action.

Uni-directional notifications to the NOC, that do not propose any default action, and do not allow an override as part of the transaction are considered like traditional notification services, such as syslog. They are expected to co-exist with autonomic methods, but are not covered in this draft.

7.5. Control Loops (*)

Control loops are not covered in the current implementation specifications. This section discusses a topic for further research.

Control loops are used in autonomic networking to provide a generic mechanism to enable the Autonomic System to adapt (on its own) to various factors that can change the goals that the autonomic network is trying to achieve, or how those goals are achieved. For example, as user needs, business goals, and the ANI itself changes, self-adaptation enables the ANI to change the services and resources it makes available to adapt to these changes.

Control loops operate to continuously observe and collect data that enables the autonomic management system to understand changes to the behavior of the system being managed, and then provide actions to move the state of the system being managed toward a common goal. Self-adaptive systems move decision-making from static, pre-defined commands to dynamic processes computed at runtime.

Most autonomic systems use a closed control loop with feedback. Such control loops should be able to be dynamically changed at runtime to adapt to changing user needs, business goals, and changes in the ANI.

7.6. APIs (*)

APIs are not covered in the current implementation specifications. This section discusses a topic for further research.

Most APIs are static, meaning that they are pre-defined and represent an invariant mechanism for operating with data. An Autonomic Network should be able to use dynamic APIs in addition to static APIs.

A dynamic API is one that retrieves data using a generic mechanism, and then enables the client to navigate the retrieved data and operate on it. Such APIs typically use introspection and/or reflection. Introspection enables software to examine the type and properties of an object at runtime, while reflection enables a program to manipulate the attributes, methods, and/or metadata of an object.

APIs must be able to express and preserve the semantics of data models. For example, software contracts [Meyer97] are based on the principle that a software-intensive system, such as an Autonomic Network, is a set of communicating components whose interaction is based on precisely-defined specifications of the mutual obligations that interacting components must respect. This typically includes specifying:

- pre-conditions that must be satisfied before the method can start execution

- post-conditions that must be satisfied when the method has finished execution

- invariant attributes that must not change during the execution of the method

7.7. Data Model (*)

Data models are not covered in the current implementation specifications. This section discusses a topic for further research.

The following definitions are adapted from [I-D.ietf-supa-generic-policy-data-model]:

An information model is a representation of concepts of interest to an environment in a form that is independent of data repository, data definition language, query language, implementation language, and protocol. In contrast, a data model is a representation of concepts of interest to an environment in a form that is dependent on data repository, data definition language, query language, implementation language, and protocol (typically, but not necessarily, all three).

The utility of an information model is to define objects and their relationships in a technology-neutral manner. This forms a consensual vocabulary that the ANI and ASAs can use. A data model is then a technology-specific mapping of all or part of the information model to be used by all or part of the system.

A system may have multiple data models. Operational Support Systems, for example, typically have multiple types of repositories, such as SQL and NoSQL, to take advantage of the different properties of each. If multiple data models are required by an Autonomic System, then an information model should be used to ensure that the concepts of each data model can be related to each other without technological bias.

A data model is essential for certain types of functions, such as a Model-Reference Adaptive Control Loop (MRACL). More generally, a data model can be used to define the objects, attributes, methods, and relationships of a software system (e.g., the ANI, an autonomic node, or an ASA). A data model can be used to help design an API, as well as any language used to interface to the Autonomic Network.

8. Coordination Between Autonomic Functions (*)

Coordination between autonomic functions is not covered in the current implementation specifications. This section discusses a topic for further research.

8.1. The Coordination Problem (*)

Different autonomic functions may conflict in setting certain parameters. For example, an energy efficiency function may want to shut down a redundant link, while a load balancing function would not want that to happen. The administrator must be able to understand and resolve such interactions, to steer autonomic network performance to a given (intended) operational point.

Several interaction types may exist among autonomic functions, for example:

- Cooperation: An autonomic function can improve the behavior or performance of another autonomic function, such as a traffic forecasting function used by a traffic allocation function.

- Dependency: An autonomic function cannot work without another one being present or accessible in the autonomic network.

- Conflict: A metric value conflict is a conflict where one metric is influenced by parameters of different autonomic functions. A parameter value conflict is a conflict where one parameter is modified by different autonomic functions.

Solving the coordination problem beyond one-by-one cases can rapidly become intractable for large networks. Specifying a common functional block on coordination is a first step to address the problem in a systemic way. The coordination life-cycle consists in three states:

- At build-time, a "static interaction map" can be constructed on the relationship of functions and attributes. This map can be used to (pre-)define policies and priorities on identified conflicts.

- At deploy-time, autonomic functions are not yet active/acting on the network. A "dynamic interaction map" is created for each instance of each autonomic functions and on a per resource basis, including the actions performed and their relationships. This map provides the basis to identify conflicts that will happen at run-time, categorize them and plan for the appropriate coordination strategies/mechanisms.

- At run-time, when conflicts happen, arbitration is driven by the coordination strategies. Also new dependencies can be observed and inferred, resulting in an update of the dynamic interaction map and adaptation of the coordination strategies and mechanisms.

Multiple coordination strategies and mechanisms exist and can be devised. The set ranges from basic approaches such as random process or token-based process, to approaches based on time separation and hierarchical optimization, to more complex approaches such as multi-objective optimization, and other control theory approaches and algorithms family.

8.2. A Coordination Functional Block (*)

A common coordination functional block is a desirable component of the ANIMA reference model. It provides a means to ensure network properties and predictable performance or behavior such as stability, and convergence, in the presence of several interacting autonomic functions.

A common coordination function requires:

- A common description of autonomic functions, their attributes and life-cycle.

- A common representation of information and knowledge (e.g., interaction maps).

- A common "control/command" interface between the coordination "agent" and the autonomic functions.

Guidelines, recommendations or BCPs can also be provided for aspects pertaining to the coordination strategies and mechanisms.

9. Security Considerations

In this section we distinguish outsider and insider attacks. In an outsider attack all network elements and protocols are securely managed and operating, and an outside attacker can sniff packets in transit, inject and replay packets. In an insider attack, the attacker has access to an autonomic node or other means (e.g. remote code execution in the node by exploiting ACP-independent vulnerabilities in the node platform) to produce arbitrary payloads on the protected ACP channels.

If a system has vulnerabilities in the implementation or operation (configuration), an outside attacker can exploit such vulnerabilies to become an insider attacker.

9.1. Protection Against Outsider Attacks

Here, we assume that all systems involved in an autonomic network are secured and operated according to best current practices. These protection methods comprise traditional security implementation and operation methods (such as code security, strong randomization algorithms, strong passwords, etc.) as well as mechanisms specific to an autonomic network (such as a secured MASA service).

Traditional security methods for both implementation and operation are outside scope for this document.

AN specific protocols and methods must also follow traditional security methods, in that all packets that can be sniffed or injected by an outside attacker are:

- protected against modification.

- authenticated.

- protected against replay attacks.

- confidentiality protected (encrypted).

- and that the AN protocols are robust against packet drops and man-in-the-middle attacks.

How these requirements are met is covered in the AN standards track documents that define the methods used, specifically [I-D.ietf-anima-bootstrapping-keyinfra], [I-D.ietf-anima-grasp], and [I-D.ietf-anima-autonomic-control-plane].

Most AN messages run inside the cryptographically protected ACP. The unprotected AN messages outside the ACP are limited to a simple discovery method, defined in Section 2.5.2 of [I-D.ietf-anima-grasp]: The "Discovery Unsolicited Link-Local (DULL)" message, with detailed rules on its usage.

If AN messages can be observed by a third party, they might reveal valuable information about network configuration, security precautions in use, individual users, and their traffic patterns. If encrypted, AN messages might still reveal some information via traffic analysis.

9.2. Risk of Insider Attacks

An autonomic network consists of autonomic devices that form a distributed self-managing system. Devices within a domain have credentials issued from a common trust anchor and can use them to create mutual trust. This means that any device inside a trust domain can by default use all distributed functions in the entire autonomic domain in a malicious way.

If an autonomic node or protocol has vulnerabilities or is not securely operated, an outside attacker has the following generic ways to take control of an autonomic network:

- Introducing a fake device into the trust domain, by subverting the authentication methods. This depends on the correct specification, implementation and operation of the AN protocols.

- Subverting a device which is already part of a trust domain, and modifying its behavior. This threat is not specific to the solution discussed in this document, and applies to all network solutions.

- Exploiting potentially yet unknown protocol vulnerabilities in the AN or other protocols. Also this is a generic threat that applies to all network solutions.

The above threats are in principle comparable to other solutions: In the presence of design, implementation or operational errors, security is no longer guaranteed. However, the distributed nature of AN, specifically the Autonomic Control Plane, increases the threat surface significantly. For example, a compromised device may have full IP reachability to all other devices inside the ACP, and can use all AN methods and protocols.

For the next phase of the ANIMA work it is therefore recommended to introduce a sub-domain security model, to reduce the attack surface and not expose a full domain to a potential intruder. Furthermore, additional security mechanisms on the ASA level should be considered for high-risk autonomic functions.

10. IANA Considerations

This document requests no action by IANA.

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