Multilayer Network Diagnostics

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Outline

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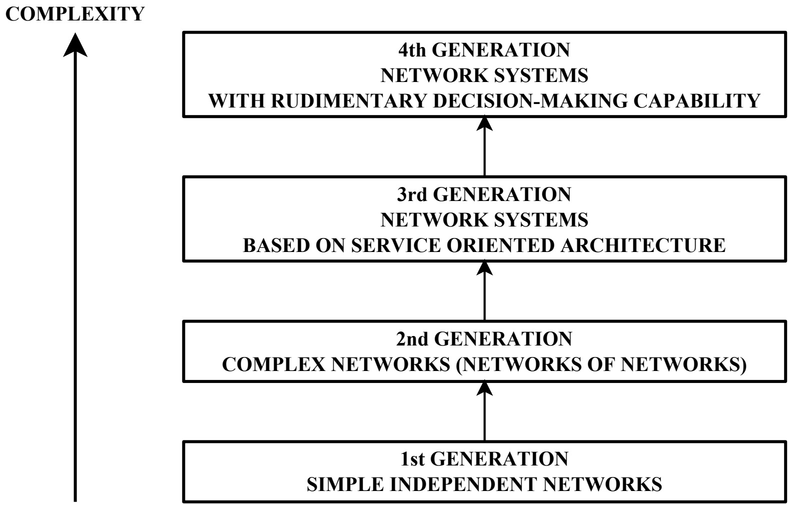
Generations of Networking [McC07]



Distributed System

a collection of independent computers that appears to its users as a single coherent system [TS13]

- a collection of components/products (hardware and software) - the viewpoint of the vendor community;
- a collection of the above plus external communication infrastructure - the viewpoint of the network engineer community;
- a collection of services/applications - the viewpoint of the software/system engineer community;
- all of the above plus end-users/customers - the viewpoint of the business community.

Outline

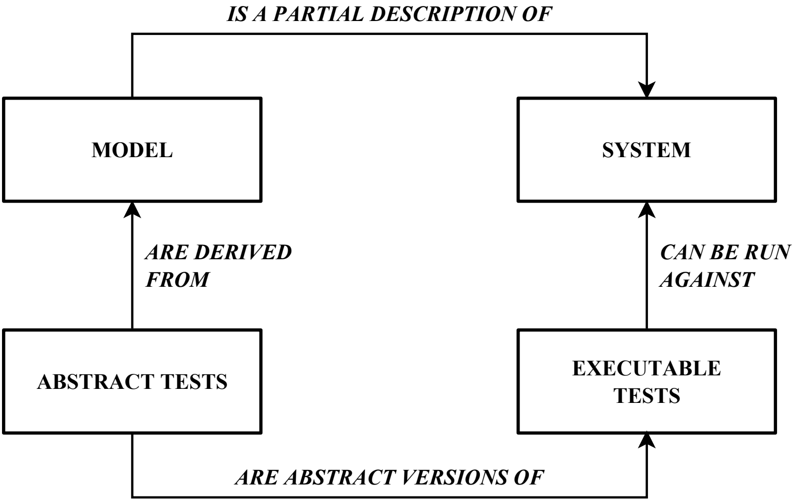
Model-based Testing (MBT)

The basic idea of MBT is that, instead of creating test cases manually, a selected algorithm generates them automatically from an abstract formal model.

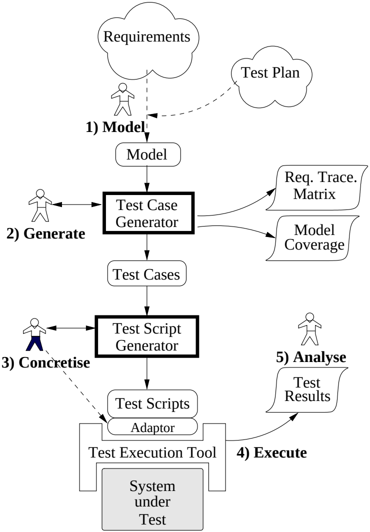
In general, MBT involves the following major activities [UPL12]:

- building the formal model from informal requirements or existing specification documents;
- defining test selection criteria and transforming them into operational test specifications or test cases;
- generating executable tests based on test cases;
- executing the tests (including conceiving and setting up adaptor components).

General Model-based Testing Setting [Wik]



Model-based Testing Workflow 1 [UL07]



Outline

Multilayer Model [KAB+14]

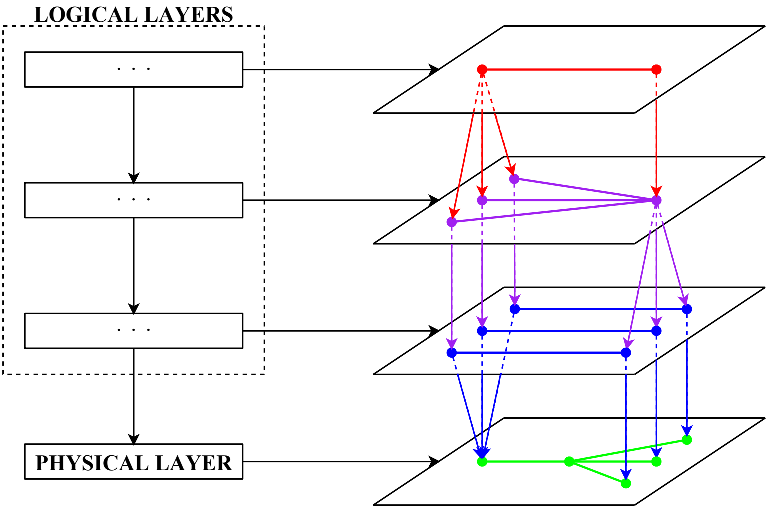
A **hierarchical multilayer network** [KAB+14] is a type of multilayer network of particular relevance for computer networks

- in which the bottom layer constitutes a *physical network* and
- the remaining layers are *virtual layers* that operate on top of the physical layer.

The concept is based on the facts:

- for each node on a given layer there is a corresponding node (or nodes) on the layer below;
- for each path between two nodes on a given layer there is a path (or paths) between the corresponding nodes on the layer below.

Hierarchical Multilayer Model [Shc15]



Multilayer Projection Network [Shc17]

Let the graph M denote the system under test (SUT) as a **multilayer projection network**:

$$M = (V, E)$$

where M is a multi-layered 3D graph, derived from the SUT specification;
$V(M)$ is a finite, non-empty set of components of SUT; and
$E(M)$ is a finite, non-empty set of component-to-component interconnections:

$$V = \bigcup_{\alpha=1}^{L} V^{\alpha} \quad \text{and} \quad E = \left(\bigcup_{\alpha=1}^{L} E^{\alpha}\right) \bigcup \left(\bigcup_{\alpha=2}^{L} E^{\alpha,(\alpha-1)}\right)$$

where V^{α} is a finite, non-empty set of components of SUT on layer α;
E^{α} is a finite, non-empty set of intralayer component-to-component interconnections on layer α;
$E^{\alpha,(\alpha-1)}$ is a finite, non-empty set of interlayer relations (so called projections) between components of the layer α and the layer below $(\alpha - 1)$; and
L is the number of SUT layers $(1 \leq \alpha \leq L)$.

Elements of Multilayer Network [Shc17]

- Two main elements of multilayer networks are
  - intra-layer graphs and
  - inter-layer graphs [KAB+14].
- The intralayer subgraph G^α of M can be represented as [BBC+14]:

$$G^\alpha = \left(V^\alpha, E^\alpha\right)$$

  where
  - V^α is a finite, non-empty set of components on layer α; and
  - $E^\alpha \subseteq V^\alpha \times V^\alpha$ is a finite, non-empty set of intralayer component-to-component interconnections on layer α.
- In practice, intralayer subgraphs G^α are usually not monolithic structures:
  - A set of protocols is predefined for each (physical or virtual) layer.
  - These protocols can support different topologies.

Layer of SUT [Shc17]

Let the subgraph G^α denote a layer of SUT as:

$$G^\alpha = \left(V^\alpha, E^\alpha, S_V^\alpha, S_E^\alpha\right)$$

where

- G^α is a labeled intralayer subgraph of M;
- V^α is a finite, non-empty set of components on layer α;
- $E^\alpha \subseteq V^\alpha \times V^\alpha$ is a finite, non-empty set of intralayer component-to-component interconnections on layer α;
- S_V^α is a vertex label set for layer α; and
- S_E^α is an edge label set for layer α.

Node and Edge Labels [Shc17]

- $$S_V^\alpha = \bigcup_{v_i^\alpha \in V^\alpha} S_i^\alpha$$

  where

  - $S_i^\alpha \subset \boldsymbol{S^\alpha}$ is a finite non-empty set of specifications of SUT components (a set of supported communication protocols) that defines the label of the vertex v_i^α of G^α; and
  - $\boldsymbol{S^\alpha}$ is the universal set of all possible communication protocols on layer α.

- Let $S_{i,j}^\alpha \subset \boldsymbol{S^\alpha}$ be a finite non-empty set of specifications of component-to-component interconnections (the set of used communication protocols) that defines the label of the edge $\left\langle v_i^\alpha, v_j^\alpha \right\rangle$ of G^α.

Protocol Sublayers [Shc17]

- Let G^{α}_{β} be a sub-subgraph which is defined by a given communication protocol $s^{\alpha}_{\beta} \in S^{\alpha}_{E} \subset \boldsymbol{S^{\alpha}}$; and
- $E^{\alpha}_{\beta} \subseteq E^{\alpha}$ be a finite, non-empty set of intralayer component-to-component interconnections on sub-layer β of layer α.
- G^{α} is represented as a multiplex network:

$$G^{\alpha} = \bigcup_{\beta=1}^{|S^{\alpha}_{E}|} G^{\alpha}_{\beta}$$

and:

$$G^{\alpha}_{\beta} = \left(V^{\alpha}, E^{\alpha}_{\beta}\right)$$

Layer Protocols [Shc17]

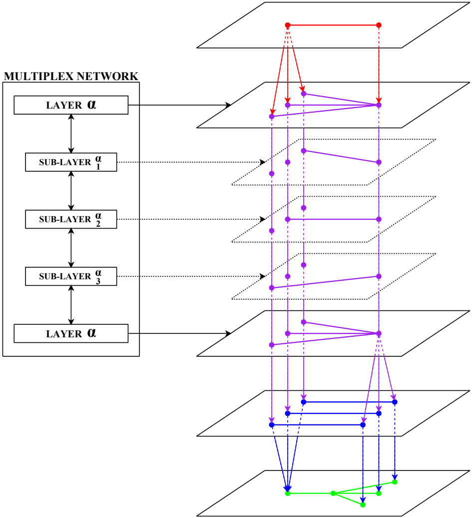
- $$S_E^\alpha = \bigcup_{\langle v_i^\alpha, v_j^\alpha \rangle \in E^\alpha} S_{i,j}^\alpha$$

  and:

  $$S_{i,j}^\alpha = \bigcup_{\substack{\langle v_i^\alpha, v_j^\alpha \rangle \in E^\alpha \\ s_\beta^\alpha \in S_i^\alpha \\ s_\beta^\alpha \in S_j^\alpha}} \{ s_\beta^\alpha \}$$

- If an edge $\langle v_i^\alpha, v_j^\alpha \rangle \in E^\alpha$ belongs to G_β^α then both components v_i^α and v_j^α support this protocol, i.e. $s_\beta^\alpha \in S_i^\alpha$ and $s_\beta^\alpha \in S_j^\alpha$
  - each pair of components v_i^α and v_j^α can be connected by at most $|S_E^\alpha|$ possible edges.

Intralayer Subgraph Representation as a Multiplex Network [Shc15]



Usage of Label Symbols [Shc17]

- The vertex label S_1^3 represents the set of communication protocols that is supported by the component $v_1^3 \in V^3$ on the layer 3.
    - The label S_V^3 represents the set of communication protocols that is supported by all components $v_i^3 \in V^3$ on the layer 3, i.e. $S_1^3 \subset S_V^3$.
    - The set $\boldsymbol{S^3}$ represents all possible communication protocols (standard and proprietary) that can be used on the layer 3, i.e. $S_1^3 \subset S_V^3 \subset \boldsymbol{S^3}$.
- The edge label $S_{1,5}^3$ represents the set of communication protocols that is used for communication between adjacent components v_1^3 and v_5^3 (the edge $\langle v_1^3, v_5^3 \rangle \in E^3$) on the layer 3.
    - The label S_E^3 represents the set of communication protocols that is used for communication between all adjacent components $\langle v_i^3, v_j^3 \rangle \in E^3$ on the layer 3, i.e. $S_{1,5}^3 \subset S_E^3 \subset \boldsymbol{S^3}$.

Cross-layer of SUT [Shc17]

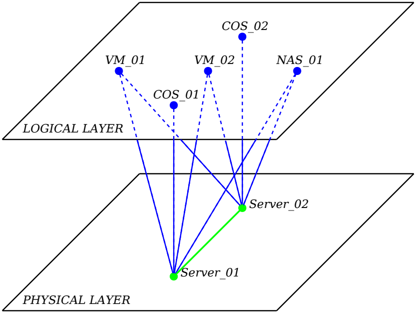
- Let the subgraph $G^{\alpha,(\alpha-1)}$ denote a cross-layer of SUT as

$$G^{\alpha,(\alpha-1)} = \left(V^{\alpha}, V^{(\alpha-1)}, E^{\alpha,(\alpha-1)}\right)$$

where
  - $G^{\alpha,(\alpha-1)}$ is an interlayer bipartite subgraph of M;
  - V^{α} is a finite, non-empty set of components on layer α,
  - $V^{(\alpha-1)}$ is a finite, non-empty set of components on layer $(\alpha-1)$; and
  - $E^{\alpha,(\alpha-1)} \subseteq V^{\alpha} \times V^{(\alpha-1)}$ is a finite, non-empty set of interlayer relations (all sets of projections) between components of the layer α $(2 \leq \alpha \leq L)$ and the layer below $(\alpha-1)$.
- The degree of vertices of $G^{\alpha,(\alpha-1)}$ represents the technological solutions which were used to build the system [Shc14].

Clustering Technology Representation [Shc17]

- $G^{\alpha,(\alpha-1)} = \left(V^{\alpha}, V^{(\alpha-1)}, E^{\alpha,(\alpha-1)}\right)$
- $d\left(v_i^{\alpha}\right) > 1; v_i^{\alpha} \in V^{\alpha}$
- Hardware cluster example

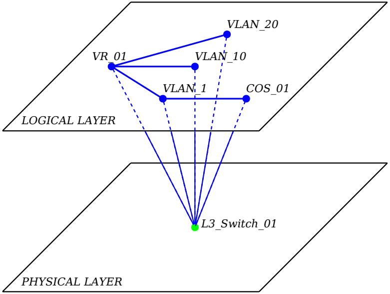


Server_XX	- Host (Cluster Member)
COS_XX	- Console Operating System (Host Operating System)
VM_XX	- Virtual Machine (Guest Operating System or Container)
NAS_XX	- Network-Attached Storage (Network File System)

Virtualization and Replication technologies Representation [Shc17]

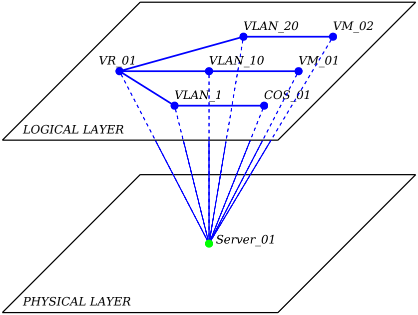
- $G^{\alpha,(\alpha-1)} = \left(V^{\alpha}, V^{(\alpha-1)}, E^{\alpha,(\alpha-1)}\right)$
- $d\left(v_j^{(\alpha-1)}\right) > 1; v_j^{(\alpha-1)} \in V^{(\alpha-1)}$

Network virtualization example



L3_Switch_XX - Multilayer Ethernet Switch
COS_XX - Console Operating System (Firmware)
VLAN_XX - Virtual Local Area Network
VR_XX - Virtual Router

Host virtualization example (VR . . . virtual router)



Server_XX - Virtualization Host
COS_XX - Console Operating System (Hypervisor or Host Operating System)
VM_XX - Virtual Machine (Guest Operating System)
VLAN_XX - Virtual Local Area Network
VR_XX - Virtual Router

Dedicated Components [Shc17]

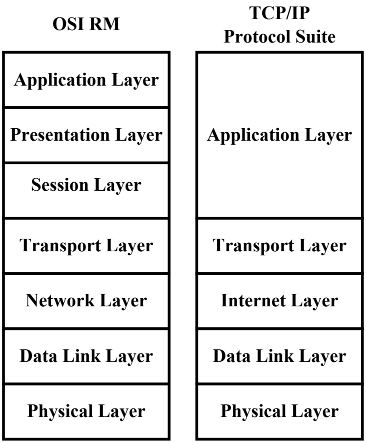
- $G^{\alpha,(\alpha-1)} = \left(V^{\alpha}, V^{(\alpha-1)}, E^{\alpha,(\alpha-1)}\right)$
- $d\left(v_i^{\alpha}\right) = d\left(v_j^{(\alpha-1)}\right) = 1; \left\langle v_i^{\alpha}, v_j^{(\alpha-1)} \right\rangle \in E^{\alpha,(\alpha-1)}$
- A special case of dedicated components.

SUT Representation [Shc17]

- $$M = \left(\bigcup_{\alpha=1}^{L} G^{\alpha}\right) \bigcup \left(\bigcup_{\alpha=2}^{L} G^{\alpha,(\alpha-1)}\right)$$
  $$= \left(\bigcup_{\alpha=1}^{L} \left(\bigcup_{\beta=1}^{|S_E^{\alpha}|} G_{\beta}^{\alpha}\right)\right) \bigcup \left(\bigcup_{\alpha=2}^{L} G^{\alpha,(\alpha-1)}\right)$$
- From the perspective of MBT, intralayer subgraphs G^{α} are the main source of initial data for the test case generation process; and
- interlayer subgraphs $G^{\alpha,(\alpha-1)}$ make this process consistent on all layers of the formal model.

Outline

ISO/OSI Reference Model and TCP/IP Protocol Suite [Shc17]



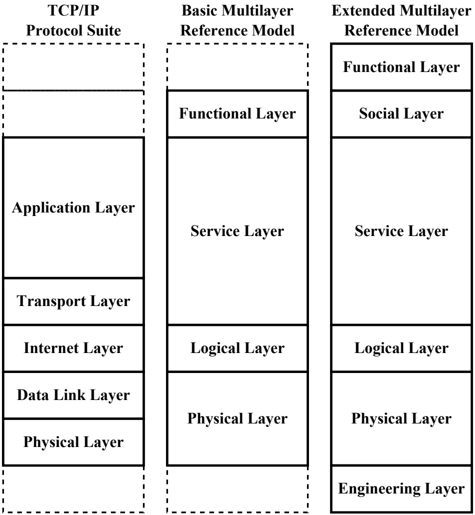
- ISO/OSI Reference Model [ISO94] and
- TCP/IP Protocol Suite (Five-layer Reference Model) [TW11] [KR12] [Com15]

Practical Network Architecture [Shc17]

- ISO/OSI Reference Model (OSI RM) [ISO94] conceptual model has never been implemented in practice.
- The business community (end-users) faces the following challenges [Shc14]:
  - Physical Layer and Data Link Layer cannot be separated in the case of commercial off-the-shelf (COTS) network equipment.
  - Transport Layer and Application Layer cannot be separated in the case of COTS software.
- A common joke is that OSI RM should have three additional layers [LHC07]:

8. User Layer;
9. Financial Layer;
10. Political Layer.

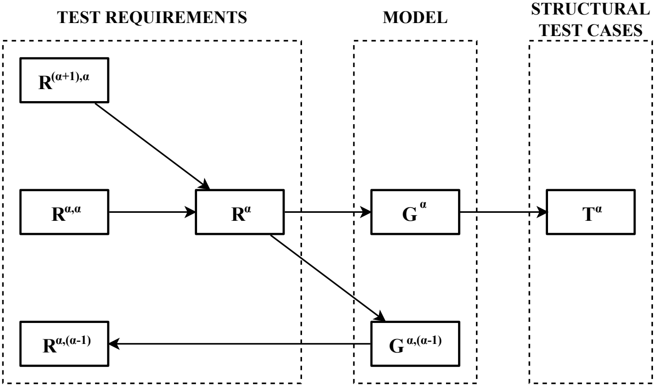
Practical Multilayer Reference Models [Shc15].



Outline

Framework of Test Case Generation Strategy [Shc17].

- The framework of structural test case generation strategy for a given layer of the formal model has the following key elements:
  - the formal model;
  - test requirements;
  - test cases.



Framework of Test Case Generation Strategy [Shc17].

- The framework of the structural test case generation strategy for a given layer α of the formal model where
  - G^{α} is an intralayer subgraph;
  - $G^{\alpha,(\alpha-1)}$ is an interlayer subgraph;
  - $R^{(\alpha+1),\alpha}$ is a set of interlayer projections of test requirements from upper layers to layer α;
  - $R^{\alpha,\alpha}$ is a set of intralayer test requirements (or the set of test requirement defined for layer α);
  - R^{α} is a resulting set of test requirements for layer α);
  - $R^{\alpha,(\alpha-1)}$ is a set of interlayer projections of test requirements from layer α to the layer below; and
  - T^{α} is a set of test cases (abstract test specifications) which relate to the structure of the formal model on layer α.

Internal Consistency Criterion [Shc17]

Criterion 1

The formal model based on the concept of multilayer networks is internally consistent on a given layer α iff:

- each vertex v_i^α of intralayer subgraphs G^α is incident with at least one edge of G^α, i.e. $d\left(v_i^\alpha \in G^\alpha\right) \geq 1$;
- each pair of adjacent vertices v_i^α and v_j^α of G^α which are incident with the edge $\left\langle v_i^\alpha, v_j^\alpha \right\rangle$ of G^α supports at least one common communication protocol, i.e. $S_{i,j}^\alpha \subseteq S_i^\alpha$; $S_{i,j}^\alpha \subseteq S_j^\alpha$ and $S_{i,j}^\alpha \neq \emptyset$;
- each vertex v_i^α of interlayer subgraphs $G^{\alpha,(\alpha-1)}$ $(2 \leq \alpha \leq L)$ is incident with at least one edge of $G^{\alpha,(\alpha-1)}$, i.e. $d\left(v_i^\alpha \in G^{\alpha,(\alpha-1)}\right) \geq 1$.

Test Requirements [Shc17]

- Some disadvantages of the path coverage criterion by using the requirements-based criteria.
- In this case, the test suite should cover only the paths which are defined by:
  1. end-user requirements; and
  2. requirements derived from technical specifications, i.e. defined by technological solutions used to build the SUT.
- The standard ISO/IEC/IEEE Std 29148:2011 [ISO11] defines:
  - the term *requirement* as a statement which translates or expresses a need and its associated constraints and conditions;
  - the term *condition* as a measurable qualitative or quantitative attribute that is stipulated for a requirement.
- Formal test requirements must determine:
  1. objects as associated elements of the SUT structure; and
  2. associated conditions of these objects (or requirement attributes).

Test Requirements for a Given Layer [Shc17]

- The definition of the test requirements introduces two sources of test requirements for a given layer of the formal model:

$$R^{\alpha} = \left(R^{\alpha,\alpha} \cup R^{(\alpha+1),\alpha}\right)$$

  where
  - R^{α} is a set of test requirements for the given layer α;
  - $R^{\alpha,\alpha}$ is a set of intralayer test requirements (or the set of test requirement defined for the layer α); and
  - $R^{(\alpha+1),\alpha}$ is a set of interlayer projections of test requirements from upper layers to the layer α.
- $R^{(\alpha+1),\alpha}$, $R^{\alpha,\alpha}$ (and $R^{\alpha,(\alpha-1)}$) - have the same formal operational specifications (the same presentation format).

Test Cases [Shc17]

Criterion 2

A test requirement induces a test case on a given layer α iff:

- the object defined by the test requirement for the layer α binds an element (at least one) of the formal model on the layer α;
- the specifications of the bound element match the requirement attributes on the layer α.

Criterion 3

The formal model based on the concept of multilayer networks is externally consistent on a given layer α with respect to the test requirements iff each test requirement defined for the layer α initiates at least one test case on the layer α.

Network Consistency Criterion [Shc17]

Criterion 4

The formal model based on the concept of multilayer networks is consistent with respect to the test requirements iff:

- there is at least one test requirement defined for the top architectural layer of the formal model;
- the formal model is internally consistent on all coexisting architectural layers;
- the formal model is externally consistent with respect to the test requirements on all coexisting architectural layers.

Outline

Communication Channels [Shc17]

- A **communication channel** (or channel) is a configuration of stubs, binders, protocol objects and interceptors providing a binding between a set of interfaces to basic engineering objects, through which interaction can occur [ISO10].
- Let $P_{i,j}^{\alpha}$ denote the set of communication channels (data flows) between a pair of SUT dedicated components v_i^{α} and v_j^{α} of G^{α} which can communicate as follows:

$$P_{i,j}^{\alpha} = \bigcup_{k=1}^{K_{i,j}^{\alpha}} \left\{ p_{i,j,k}^{\alpha} \right\}$$

where $p_{i,j,k}^{\alpha}$ is a k^{th} $\left(v_i^{\alpha}, v_j^{\alpha}\right)$-path[1] in G^{α}; and $K_{i,j}^{\alpha}$ is the finite number of duplicated (parallel/redundant) paths $p_{i,j,k}^{\alpha}$.

[1] A $\left(v_i^{\alpha}, v_j^{\alpha}\right)$-path in a graph G^{α} is an alternating sequence $[v_i, e_{\ell_1}, v_{\ell_1}, e_{\ell_2}, \ldots, v_{\ell_{(j-1)}}, e_{\ell_j}, v_j]$ of vertices and edges from G^{α} with $e_{\ell} = \left\langle v_{\ell(l-1)}, v_{\ell} \right\rangle$ in which all vertices and edges are distinct [Ste10].

Layer Communication Channels [Shc17]

- Each pair of SUT components v_i^α and v_j^α can be connected by
- at most $K_{i,j}^\alpha$ possible $\left(v_i^\alpha, v_j^\alpha\right)$-paths
  - (the value of the variable $K_{i,j}^\alpha$ is dependent on the layer topology)[2].
- In turn:

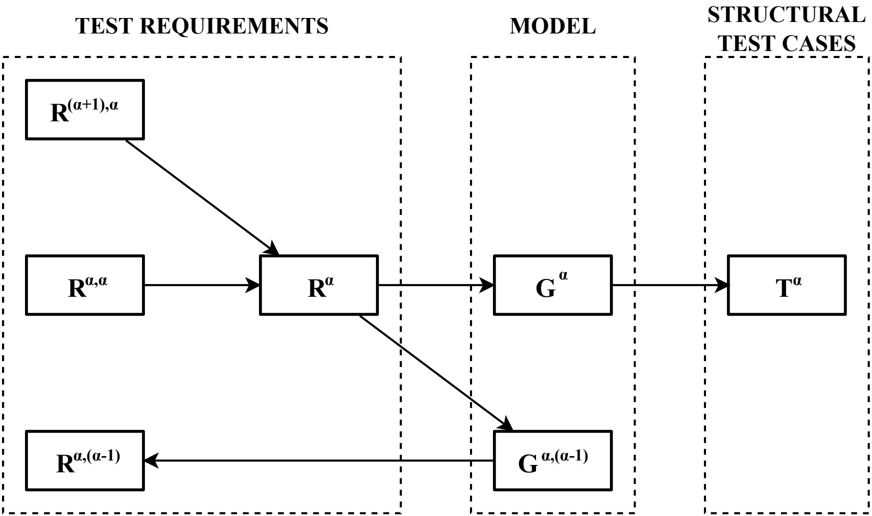
$$P^\alpha = \bigcup P_{i,j}^\alpha$$

  where
  - P^α is the complete set of communication channels on a given layer α.

[2] In the real engineering world under financial constraints commercial systems are usually based on redundant architectures [Pra96], i.e. in most cases $K_{i,j}^\alpha = 2$.

Outline

Framework of Test Case Generation Strategy [Shc17].



Structure of Test Requirements I [Shc17]

- $$R^{\alpha} = \left(R^{\alpha,\alpha} \cup R^{(\alpha+1),\alpha} \right)$$

  where
  - R^{α} is a set of test requirements for the given layer α;
  - $R^{\alpha,\alpha}$ is a set of intralayer test requirements (or the set of test requirements defined for the layer α); and
  - $R^{(\alpha+1),\alpha}$ is a set of interlayer test requirements (or the set of interlayer projections of test requirements from upper layers to the layer α).
- It is important to note that R^{α} represents the union of test requirements.

Structure of Test Requirements II [Shc17]

- Test requirements should cover: (1) SUT components; and (2) SUT communication channels.

$$R^{\alpha,\alpha} = \left(R^{\alpha,\alpha}_{comp} \cup R^{\alpha,\alpha}_{link}\right)$$

and:

$$R^{(\alpha+1),\alpha} = \left(R^{(\alpha+1),\alpha}_{comp} \cup R^{(\alpha+1),\alpha}_{link}\right)$$

where

- $R^{\alpha,\alpha}_{comp}$ is a set of intralayer test requirements of SUT components;
- $R^{\alpha,\alpha}_{link}$ is a set of intralayer test requirements of SUT communication channels;
- $R^{(\alpha+1),\alpha}_{comp}$ is a set of interlayer test requirements of SUT components; and
- $R^{(\alpha+1),\alpha}_{link}$ is a set of intralayer test requirements of SUT communication channels.

Intralayer Test Requirements for SUT Components [Shc17]

Let $R^{\alpha,\alpha}_{comp} = \left\{ r^{\alpha,\alpha}_{n,comp} \right\}$ denote the set of intralayer test requirements for SUT components as a set of triplets (3-tuples):

$$R^{\alpha,\alpha}_{comp} = \left\{ \left(v^{\alpha}_{i}, A^{\alpha}_{i}, A^{\alpha,(\alpha-1)}_{i} \right) \right\}$$

where

- v^{α}_{i} is a component of SUT on layer α;
- $A^{\alpha}_{i} \subset \boldsymbol{S^{\alpha}}$ is a set of required attributes for v^{α}_{i}; and
- $A^{\alpha,(\alpha-1)}_{i} \subset \boldsymbol{S^{(\alpha-1)}}$ is a set of required attributes for any interlayer projection of v^{α}_{i} on layer $(\alpha - 1)$.

Intralayer Test Requirements for SUT Communication Channels [Shc17]

Let $R^{\alpha,\alpha}_{link} = \left\{ r^{\alpha,\alpha}_{n,link} \right\}$ denote the set of intralayer test requirements for SUT communication channels as a set of quadruples (4-tuples):

$$R^{\alpha,\alpha}_{link} = \left\{ \left(v^{\alpha}_{i}, v^{\alpha}_{j}, A^{\alpha}_{i,j}, A^{\alpha,(\alpha-1)}_{i,j} \right) \right\}$$

where

- v^{α}_{i} and v^{α}_{j} is a pair of SUT dedicated components on layer α which must communicate;
- $A^{\alpha}_{i,j} \subset \boldsymbol{S^{\alpha}}$ is a set of required attributes for $\left(v^{\alpha}_{i}, v^{\alpha}_{j} \right)$-path; and
- $A^{\alpha,(\alpha-1)}_{i,j} \subset \boldsymbol{S^{(\alpha-1)}}$ is a set of required attributes for any interlayer projection of $\left(v^{\alpha}_{i}, v^{\alpha}_{j} \right)$-path on layer $(\alpha - 1)$.

Interlayer Projections of Test Tequirements for Components [Shc17]

Let $R_{comp}^{(\alpha+1),\alpha} = \left\{ r_{n,comp}^{(\alpha+1),\alpha} \right\}$ denote the set of interlayer projections of test requirements $R_{comp}^{(\alpha+1),(\alpha+1)} = \left\{ \left(v_k^{(\alpha+1)}, A_k^{(\alpha+1)}, A_k^{(\alpha+1),\alpha} \right) \right\}$ for SUT components from layer $(\alpha+1)$ to layer α as a set of triplets:

$$R_{comp}^{(\alpha+1),\alpha} = \left\{ \left(v_i^{\alpha}, A_i^{\alpha}, A_i^{\alpha,(\alpha-1)} \right) \right\}$$

where

- $v_k^{(\alpha+1)}$ is a component of SUT on layer $(\alpha+1)$;
- v_i^{α} is a corresponding component of $v_k^{(\alpha+1)}$ on layer α;
- $A_i^{\alpha} \subset \boldsymbol{S^{\alpha}}$ is a set of required attributes for v_i^{α}; and
- $A_i^{\alpha,(\alpha-1)} \subset \boldsymbol{S^{(\alpha-1)}}$ is a set of required attributes for any interlayer projection of v_i^{α} on layer $(\alpha-1)$.

Interlayer Projections of Test Requirements for SUT Communication Channels [Shc17]

Let $R_{link}^{(\alpha+1),\alpha} = \left\{ r_{n,link}^{(\alpha+1),\alpha} \right\}$ denote the set of interlayer projections of test requirements $R_{link}^{(\alpha+1),(\alpha+1)} = \left\{ \left(v_k^{(\alpha+1)}, v_l^{(\alpha+1)}, A_{k,l}^{(\alpha+1)}, A_{k,l}^{(\alpha+1),\alpha} \right) \right\}$ for SUT communication channels from layer $(\alpha+1)$ to layer α as a set of quadruples:

$$R_{link}^{(\alpha+1),\alpha} = \left\{ \left(v_i^{\alpha}, v_j^{\alpha}, A_{i,j}^{\alpha}, A_{i,j}^{\alpha,(\alpha-1)} \right) \right\}$$

where

- $v_k^{(\alpha+1)}$ and $v_l^{(\alpha+1)}$ is a pair of SUT dedicated components on layer $(\alpha+1)$ which must communicate;
- v_i^{α} and v_j^{α} is a pair of corresponding components of $v_k^{(\alpha+1)}$ and $v_l^{(\alpha+1)}$ on layer α;
- $A_{i,j}^{\alpha} \subset \boldsymbol{S^{\alpha}}$ is a set of required attributes for $\left(v_i^{\alpha}, v_j^{\alpha} \right)$-path; and
- $A_{i,j}^{\alpha,(\alpha-1)} \subset \boldsymbol{S^{(\alpha-1)}}$ is a set of required attributes for any interlayer projection of $\left(v_i^{\alpha}, v_j^{\alpha} \right)$-path on layer $(\alpha-1)$.

Requirement Attributes [Shc17]

- The presentation format of the requirement attributes should be fully compatible with the presentation format of the specifications of the formal model, i.e.
  - $A_i^{\alpha}, A_{i,j}^{\alpha} \subset \boldsymbol{S^{\alpha}}$ and
  - $A_i^{\alpha,(\alpha-1)}, A_{i,j}^{\alpha,(\alpha-1)} \subset \boldsymbol{S^{(\alpha-1)}}$.
- In general, a set of requirement attributes can be an empty set. In this case, the test requirement expresses the need for object (component or communication channel) existence only.

Interlayer Relations (Projections) for Components [Shc17]

The function $\mu_{comp}^{(\alpha+1),\alpha} : R_{comp}^{(\alpha+1),(\alpha+1)} \times G^{(\alpha+1),\alpha} \to R_{comp}^{(\alpha+1),\alpha}$:

$$\mu_{comp}^{(\alpha+1),\alpha}\left(\left(v_k^{(\alpha+1)}, A_k^{(\alpha+1)}, A_k^{(\alpha+1),\alpha}\right)\right) = \bigcup_{\left\langle v_k^{(\alpha+1)}, v_i^{\alpha}\right\rangle \in G^{(\alpha+1),\alpha}} \left\{\left(v_i^{\alpha}, A_i^{\alpha}, A_i^{\alpha,(\alpha-1)}\right)\right.$$

$$A_i^{\alpha} = A_k^{(\alpha+1),\alpha}, A_i^{\alpha,(\alpha-1)} = \emptyset$$

- In other words, for each test requirement $\left(v_k^{(\alpha+1)}, A_k^{(\alpha+1)}, A_k^{(\alpha+1),\alpha}\right) \in R_{comp}^{(\alpha+1),(\alpha+1)}$ on layer $(\alpha+1)$ the function $\mu_{comp}^{(\alpha+1),\alpha}$ determines the finite set of all possible corresponding triplets $\left(v_i^{\alpha}, A_i^{\alpha}, A_i^{\alpha,(\alpha-1)}\right) \in R_{comp}^{(\alpha+1),\alpha}$ on layer α where $A_i^{\alpha} = A_k^{(\alpha+1),\alpha}$ and $A_i^{\alpha,(\alpha-1)} = \emptyset$.
- If this set is an empty set then the formal model M is inconsistent according to Criterion 1.

Interlayer Relations (Projections) for Channels [Shc17]

The function $\mu_{link}^{(\alpha+1),\alpha} : R_{link}^{(\alpha+1),(\alpha+1)} \times G^{(\alpha+1),\alpha} \rightarrow R_{link}^{(\alpha+1),\alpha}$ is defined as follows:

$$\mu_{link}^{(\alpha+1),\alpha}\left(\left(v_k^{(\alpha+1)}, v_l^{(\alpha+1)}, A_{k,l}^{(\alpha+1)}, A_{k,l}^{(\alpha+1),\alpha}\right)\right) = \bigcup_{\substack{\left\langle v_k^{(\alpha+1)}, v_i^{\alpha}\right\rangle \in G^{(\alpha+1),\alpha} \\ \left\langle v_l^{(\alpha+1)}, v_j^{\alpha}\right\rangle \in G^{(\alpha+1),\alpha}}} \left\{\left(v_i^{\alpha}, v_j^{\alpha}, A_{i,j}^{\alpha}, A_{i,j}^{\alpha,(\alpha-1)}\right)\right.$$

$$A_{i,j}^{\alpha} = A_{k,l}^{(\alpha+1),\alpha}, A_{i,j}^{\alpha,(\alpha-1)} = \emptyset$$

- In other words, for each test requirement $\left(v_k^{(\alpha+1)}, v_l^{(\alpha+1)}, A_{k,l}^{(\alpha+1)}, A_{k,l}^{(\alpha+1),\alpha}\right) \in R_{link}^{(\alpha+1),(\alpha+1)}$ on layer $(\alpha+1)$ the function $\mu_{link}^{(\alpha+1),\alpha}$ determines the finite set of all possible corresponding quadruples $\left(v_i^{\alpha}, v_j^{\alpha}, A_{i,j}^{\alpha}, A_{i,j}^{\alpha,(\alpha-1)}\right) \in R_{link}^{(\alpha+1),\alpha}$ on layer α where $A_{i,j}^{\alpha} = A_{k,l}^{(\alpha+1),\alpha}$ and $A_{i,j}^{\alpha,(\alpha-1)} = \emptyset$.
- If this set is an empty set then the formal model M is inconsistent according to Criterion 1.

Test Requirement Summary [Shc17]

The sets of test requirements R^{α}_{comp} and R^{α}_{link} can be defined as:

$$R^{\alpha}_{comp} = \left(R^{\alpha,\alpha}_{comp} \cup R^{(\alpha+1),\alpha}_{comp} \right)$$

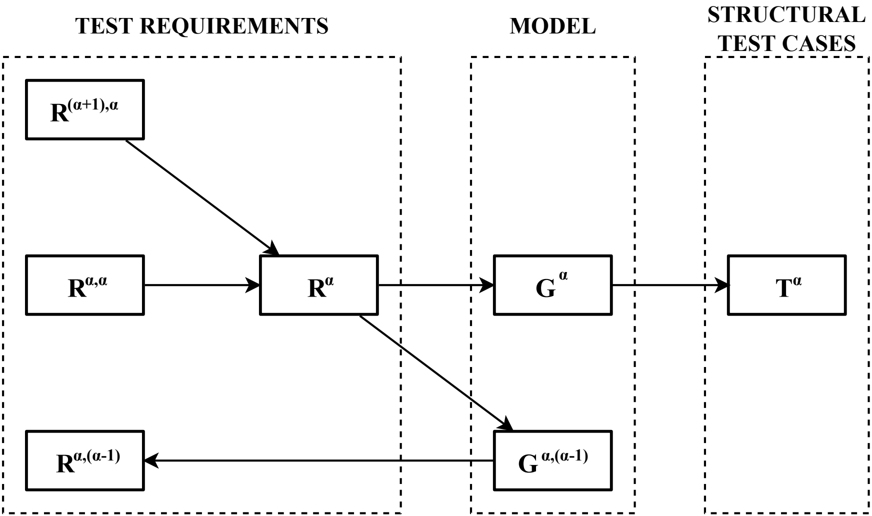
$$R^{\alpha}_{link} = \left(R^{\alpha,\alpha}_{link} \cup R^{(\alpha+1),\alpha}_{link} \right)$$

where

- R^{α}_{comp} is the set of test requirements of SUT components for the given layer α; and
- R^{α}_{link} is the set of test requirements of SUT communication channels for the given layer α.

Outline

Framework of Test Case Generation Strategy [Shc17]



Types of Test Cases [Shc17]

- Test cases should cover
  1. SUT components; and
  2. SUT communication channels
- The complete set of test cases T^{α} for a given layer α can be defined as:

$$T^{\alpha} = T^{\alpha}_{comp} \cup T^{\alpha}_{link}$$

Test Cases for Components [Shc17]

Let $T^{\alpha}_{comp} = \left\{ t^{\alpha}_{n,comp} \right\}$ denote the set of test cases of SUT components on layer α as a set of pairs:

$$T^{\alpha}_{comp} = \left\{ \left[\left(v^{\alpha}_{i}, S^{\alpha}_{i} \right), A^{\alpha}_{i} \right] \right\}$$

where

- v^{α}_{i} is a component of SUT on layer α; $S^{\alpha}_{i} \subset \boldsymbol{S^{\alpha}}$ is the set of specifications of v^{α}_{i}; and
- $A^{\alpha}_{i} \subset \boldsymbol{S^{\alpha}}$ is the set of required attributes for v^{α}_{i}.

In other words, each test case of that kind represents a SUT component whose characteristics or configuration should be verified according to corresponding required attributes.

Test Cases for Channels [Shc17]

- If there is a set of required attributes for a path then each set of specifications (labels) of edges which constitute this path should match the set of required attributes.
- Let $T^{\alpha}_{link} = \left\{ t^{\alpha}_{n,link} \right\}$ denote the set of test cases of SUT communication channels on layer α as a union of pairs:

$$T^{\alpha}_{link} = \left\{ \left[\left(\bigcup_{\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle \in p^{\alpha}_{i,j,k}} \left(\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle, S^{\alpha}_{(l-1),l} \right) \right), A^{\alpha}_{i,j} \right] \right\}$$

where

- $p^{\alpha}_{i,j,k}$ is a k^{th} $\left(v^{\alpha}_{i}, v^{\alpha}_{j}\right)$-path between the pair of SUT dedicated components v^{α}_{i} and v^{α}_{j} on layer α;
- $v^{\alpha}_{(l-1)}$ and v^{α}_{l} is a pair of adjacent components on layer α which constitute the path $p^{\alpha}_{i,j,k}$;
- $S^{\alpha}_{i,j,k} \subset \boldsymbol{S^{\alpha}}$ is the set of specifications of the edge $\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle \in p^{\alpha}_{i,j,k}$; and
- $A^{\alpha}_{i,j} \subset \boldsymbol{S^{\alpha}}$ is the set of required attributes for $\left(v^{\alpha}_{i}, v^{\alpha}_{j}\right)$-paths.

Testing of Paths [Shc17]

- In some cases, diagnostic tools do not allow the testing of paths on the physical architectural layer [Ran14].
- As a consequence, each test case of SUT communication channels on this layer should be divided into subset of test cases of component-to-component interconnections which constitute the channels, i.e.:

$$t^{\alpha}_{n,link} = \left[\left(\bigcup_{\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle \in p^{\alpha}_{i,j,k}} \left(\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle, S^{\alpha}_{(l-1),l} \right) \right), A^{\alpha}_{i,j} \right] = \bigcup_{\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle \in p^{\alpha}_{i,j,k}} \left[\left(\left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \right\rangle, S^{\alpha}_{(l-1),l} \right), A^{\alpha}_{i,j} \right]$$

where

- layer α represents the physical architectural layer according to multilayer reference models.

Test Cases for Components [Shc17]

- The function $\varphi^{\alpha}_{comp} : R^{\alpha}_{comp} \times G^{\alpha} \to T^{\alpha}_{comp}$ is defined as follows:

$$\varphi^{\alpha}_{comp}\left(\left(v^{\alpha}_{i}, A^{\alpha}_{i}, A^{\alpha,(\alpha-1)}_{i}\right)\right) = \begin{cases} \left[\left(v^{\alpha}_{i}, S^{\alpha}_{i}\right), A^{\alpha}_{i}\right] & \text{if } A^{\alpha}_{i} \subseteq S^{\alpha}_{i} \\ \emptyset & \text{otherwise} \end{cases}$$

- In other words, for each test requirement $\left(v^{\alpha}_{i}, A^{\alpha}_{i}, A^{\alpha,(\alpha-1)}_{i}\right) \in R^{\alpha}_{comp}$ on a given layer α the function φ^{α}_{comp} determines the pair $\left(v^{\alpha}_{i}, S^{\alpha}_{i}\right) \in G^{\alpha}$ whose characteristics match the required attributes, i.e. $A^{\alpha}_{i} \subseteq S^{\alpha}_{i}$.
- If this pair does not exist then the formal model M is inconsistent according to Criterion 3.

Test Cases for Channels I [Shc17]

- The function $\varphi^{\alpha}_{link} : R^{\alpha}_{link} \times G^{\alpha} \to T^{\alpha}_{link}$ is defined as follows:

$$\varphi^{\alpha}_{link}\left(\left(v^{\alpha}_{i}, v^{\alpha}_{j}, A^{\alpha}_{i,j}, A^{\alpha,(\alpha-1)}_{i,j}\right)\right) = \bigcup_{p^{\alpha}_{i,j,k} \in P^{\alpha}_{i,j}} \left\{\widehat{t^{\alpha}_{n,link}}\right\}$$

where:

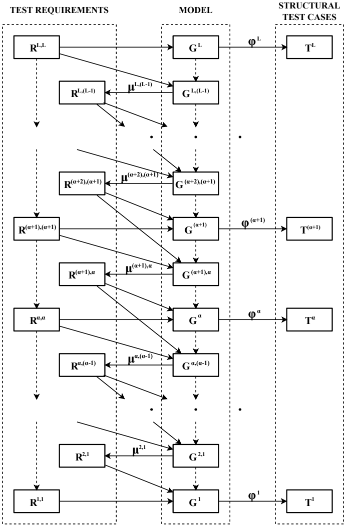
$$\widehat{t^{\alpha}_{n,link}} = \begin{cases} t^{\alpha}_{n,link} & \text{if } \forall \left\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l}\right\rangle \in p^{\alpha}_{i,j,k} : A^{\alpha}_{i,j} \subseteq S^{\alpha}_{(l-1),l} \\ \emptyset & \text{otherwise} \end{cases}$$

Test Cases for Channels I [Shc17]

- In other words:
  - For each test requirement $\left(v_i^\alpha, v_j^\alpha, A_{i,j}^\alpha, A_{i,j}^{\alpha,(\alpha-1)}\right) \in R_{link}^\alpha$ on a given layer α the function φ_{link}^α determines the finite set $P_{i,j}^\alpha$ of all possible (v_i^α, v_j^α)-paths $p_{i,j,k}^\alpha \in P_{i,j}^\alpha$ between the pair of SUT dedicated components v_i^α and v_j^α which should communicate.
    - If this set is an empty set then the formal model M is inconsistent according to Criterion 3
  - In turn, for each path $p_{i,j,k}^\alpha$ of $P_{i,j}^\alpha$ the function φ_{link}^α determines the finite set of all possible pairs $\left(\left\langle v_{(l-1)}^\alpha, v_l^\alpha \right\rangle, S_{(l-1),l}^\alpha\right) \in G^\alpha$ whose elements $\left\langle v_{(l-1)}^\alpha, v_l^\alpha \right\rangle$ constitute the path $p_{i,j,k}^\alpha$ and whose characteristics match the required attributes, i.e. $A_{i,j}^\alpha \subseteq S_{(l-1),l}^\alpha$.
    - If this set does not cover the path $p_{i,j,k}^\alpha$ completely then the formal model M is inconsistent according to Criterion 3.

Outline

Test Case Generation Strategy [Shc17].



Steps of Test Case Generation Strategy [Shc17].

- The set of interlayer test requirements $R^{(\alpha+1),\alpha}$ is the result of recursive applying of:
  1. the intralayer test requirements $R^{(\alpha+1),(\alpha+1)}$; and
  2. the interlayer test requirements $R^{(\alpha+2),(\alpha+1)}$ to the interlayer subgraph $G^{(\alpha+1),\alpha}$:

$$R^{(\alpha+1),\alpha} = \mu^{(\alpha+1),\alpha}\left(R^{(\alpha+1)}\right) = \mu^{(\alpha+1),\alpha}\left(R^{(\alpha+1),(\alpha+1)} \cup R^{(\alpha+2),(\alpha+1)}\right)$$

- The set of system infrastructure test cases T^{α} on the layer α is the result of applying of:
  1. the intralayer test requirements $R^{\alpha,\alpha}$; and
  2. the interlayer test requirements $R^{(\alpha+1),\alpha}$ to the intralayer subgraph G^{α} :

$$T^{\alpha} = \varphi^{\alpha}\left(R^{\alpha}\right) = \varphi^{\alpha}\left(R^{\alpha,\alpha} \cup R^{(\alpha+1),\alpha}\right)$$

Outline

End-user Requirements [Shc17].

ID	End-User Requirements
R101	*Business agility and flexibility should be increased*
R102	*Cost of doing business should be decreased*
R103	*Interaction delay (INTD) must be less than human response time (HRT)*
R104	*Availability of services is defined as 99.9 percent during core business hours*
R105	*Consolidate the existing 16 physical application servers down to 3 servers*
R106	*Centralized management tool must be used for the new infrastructure*
R107	*Separate management VLANs must be used for management traffic*
R108	*Server hardware maintenance should not affect application uptime*
R109	*Provide N+1 redundancy to support hardware failure during normal operation*

End-user Constraints [Shc17].

ID	End-User Constraints
C101	*VMware vSphere Essentials Plus Kit has been preselected as the virtualization platform*
C102	*Dell servers have been preselected as the compute platform*
C103	*Two 10G ports should be used per server*
C104	*VMware Virtual SAN tool has been preselected as the storage solution*
C105	*D-Link managed switches have been preselected as the network platform*

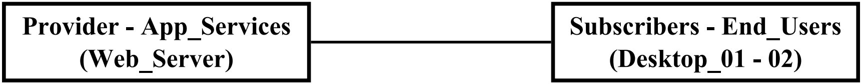
End-user Assumptions [Shc17].

ID	Assumptions
A101	*Sufficient power, cooling, and floor/rack space is available in the existing datacenter to support the new infrastructure during normal and maintenance operations*
A102	*Sufficient 10G ports are available in the existing core switches to support the new infrastructure*
A103	*System services (DNS, NTP and DHCP) are available in the existing infrastructure to support the new services and applications*

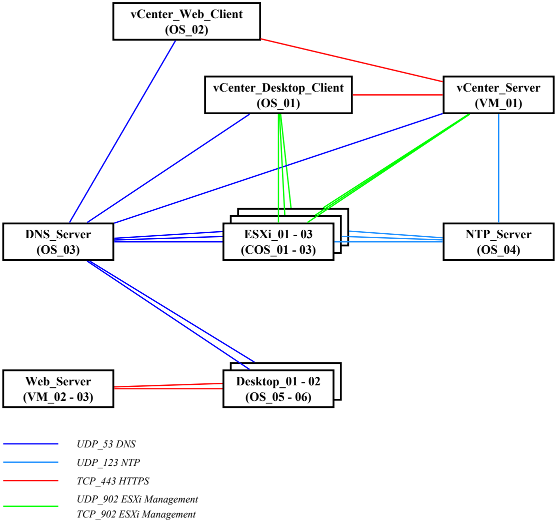
Derived Technical Requirements [Shc17].

ID	Source	Derived Technical Requirements
T101	C101 A103	*All components of the virtualization platform must communicate with DNS service*
T102	C101 A103	*Selected components of the virtualization platform - hyperviser (ESXi) and managenet (vCenter) servises - must communicate with NTP service*
T103	C101 R106 R108 R109	*Hyperviser services of the virtualization platform (ESXi) must communicate with the managemnt service of the virtualization platform (vCenter)*
T104	C101 R106	*Hyperviser services of the virtualization platform (ESXi) must communicate with vSphere Desktop Client with Update Manager*
T105	C101 R106	*vSphere Desktop Client and vSphere Web Client must communicate with the managemnt service of the virtualization platform (vCenter)*
T106	C101 R107	*Separate management VLAN must be used for the virtualization platform (vSphere) management traffic*
T107	C101 R107 R108 R109	*Separate management VLAN must be used for the live migration (vMotion) management traffic*
T108	C101 C104 R107 R108 R109	*Separate management VLAN must be used for the storage area network (vSAN) management traffic*

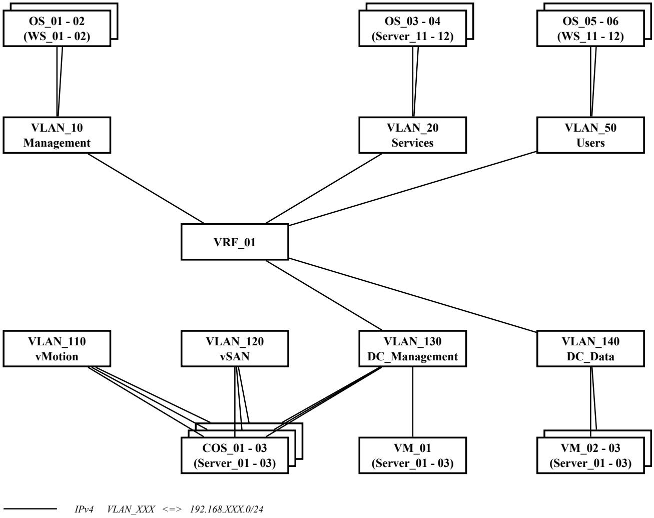
Functional Architectural Layer [Shc17].



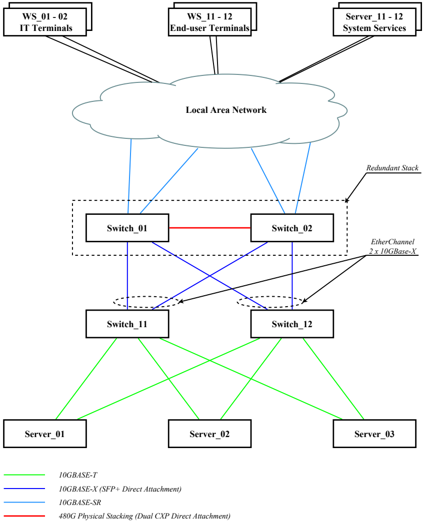
Service Architectural Layer [Shc17].



Logical Architectural Layer [Shc17].



Physical Architectural Layer [Shc17].



Outline

Layer Component Specifications [Shc17].

Record Number	Layer Identifier	Component Assignment	Component Identifier		Vendor Identifier	Component Attributes (3-tuples)			Notes
			Type	Index					
i	α	-	v_i^α		-	s_i^α			-
T1.La.01	**T1.La.02**	**T1.La.03**	**T1.La.04**		**T1.La.05**	**T1.La.06**			**T1.La.07**
1	4	Provider of Application Services	Provider	01	-	HTML/XML	INTD=100ms	Tasks=64	-
…	…	…	…	…	…	…	…	…	…
1	3	Apache HTTP Server	WEB	01	Apache Software Foundation	TCP 443	-	-	-
2	3	VMware vCenter Server	vCenter	01	VMware	UDP 53	-	-	-
						UDP 123	-	-	
						TCP 443	-	-	
						UDP/TCP 902	-	-	
3	3	VMware ESXi hypervisor 6.0	ESXi	01	VMware	UDP 53	-	-	-
						UDP 123	-	-	
						UDP/TCP 902	-	-	
…	…	…	…	…	…	…	…	…	…
1	2	VMware ESXi hypervisor 6.0	COS	01	VMware	IPv4	192.168.110.11	255.255.255.0	-
						IPv4	192.168.120.11	255.255.255.0	
						IPv4	192.168.130.11	255.255.255.0	
2	2	SUSE Linux Enterprise Server 12	VM	03	Novell	IPv4	192.168.140.12	255.255.255.0	-
3	2	VLAN vMotion	VLAN	110	-	IPv4	192.168.110.0	255.255.255.0	-
4	2	Virtual Router	VRF	01	-	IPv4	192.168.0.0	255.255.0.0	-
…	…	…	…	…	…	…	…	…	…
1	1	Dell PowerEdge R730xd Rack Server	Server	01	Dell	10GBASE-T	Full Duplex	-	-
2	1	DXS-3600-32S 10 Gigabit Managed Switch	Switch	01	D-Link	10GBASE-X	Full Duplex	-	-
						10GBASE-SR	Full Duplex	-	
						120G CXP	-	-	

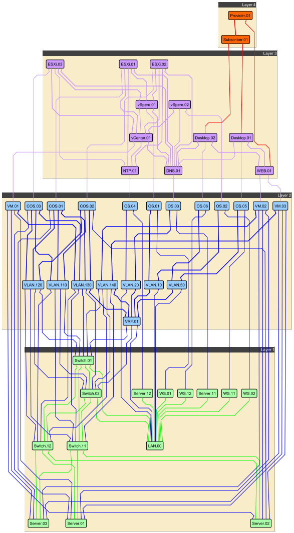
Intralayer Component Specifications [Shc17].

Record Number	Layer Identifier	Link Identifier								Link Attributes (3-tuples)			Notes
		Source Identifier				Target Identifier							
		Component Identifier		Port Identifier		Component Identifier		Port Identifier					
		Type	Index	Type	Index	Type	Index	Type	Index				
n	α	v_i^α		-		v_j^α		-		$S_{i,j}^\alpha$			-
T2.La .01	T2.La .02	T2.La .04		T2.La .05		T2.La .06		T2.La .07		T2.La .08			T2.La .09
1	4	Provider	01	-	-	Subscriber	01	-	-	HTML/XML	INTD=100ms	Tasks=64	-
…	…	…	…	…	…	…	…	…	…	…	…	…	…
1	3	ESXi	01	UDP	53	DNS	01	UDP	53	UDP 53	-	-	-
2	3	ESXi	01	UDP	123	NTP	01	UDP	123	UDP 123	-	-	-
3	3	ESXi	01	TCP/UDP	902	vCenter	01	TCP/UDP	902	UDP/TCP 902	-	-	-
…	…	…	…	…	…	…	…	…	…	…	…	…	…
1	2	OS	01	IPv4	192.168.10.101/24	VLAN	10	IPv4	192.168.10.0/24	IPv4	192.168.10.0	255.255.255.0	-
2	2	COS	01	IPv4	192.168.110.11/24	VLAN	110	IPv4	192.168.110.0/24	IPv4	192.168.110.0	255.255.255.0	-
3	2	VM	01	IPv4	192.168.130.1/24	VLAN	130	IPv4	192.168.130.0/24	IPv4	192.168.130.0	255.255.255.0	-
4	2	VLAN	140	IPv4	192.168.140.0/24	VRF	01	IPv4	192.168.0.0/16	IPv4	192.168.0.0	255.255.0.0	-
…	…	…	…	…	…	…	…	…	…	…	…	…	…
1	1	Switch	01	120G CXP	01, 02	Switch	02	120G CXP	01, 02	120G CXP	-	-	Stacking Ring
2	1	Switch	01	10GBASE-X	16	Switch	11	10GBASE-X	09	10GBASE-X	Full Duplex	-	EtherChannel 1
3	1	Switch	11	10GBASE-T	01	Server	01	10GBASE-T	01	10GBASE-T	Full Duplex	-	-
4	1	WS	01	1000BASE-T	01	LAN	00	1000BASE-T	00	1000BASE-T	-	-	-

Interlayer Component Specifications [Shc17].

Record Number	Layer Identifier	Projection Assignment	Projection Identifier				Distribution Index	Projection Attributes	Notes
			Source Component Identifier		Target Component Identifier				
			Type	Index	Type	Index			
n	α	-	v_i^α		$v_j^{(\alpha-1)}$		-	-	-
T3.La .01	T3.La .02	T3.La .03	T3.La .04		T3.La .05		T3.La .06	T3.La .07	T3.La .08
1	4	-	Provider	01	WEB	01	1:1	-	-
2	4	-	Subscriber	01	Desktop	01	1:2	-	-
					Desktop	02	1:2	-	-
…	…	…	…	…	…	…	…	…	…
1	3	-	WEB	01	VM	02	1:2	Active/Standby	AppServer Cluster 1
					VM	03	1:2	Standby/Active	AppServer Cluster 1
2	3	-	ESXi	01	COS	01	1:1	-	-
3	3	-	vCenter	01	VM	01	1:1	-	-
…	…	…	…	…	…	…	…	…	…
1	2	-	OS	01	WS	01	1:1	-	-
2	2	-	COS	01	Server	01	1:1	-	-
3	2	-	VM	01	Server	01	1:3	-	-
					Server	02	1:3	-	
					Server	03	1:3	-	
4	2	-	VLAN	110	Switch	01	1:4	-	-
					Switch	02	1:4	-	
					Switch	11	1:4	-	
					Switch	12	1:4	-	

Multilayer Model [Shc17].



Test Requirements for SUT Components [Shc17].

Record Number	Layer Identifier	Requirement Assignment	Component Identifier		Requirement Attributes (3-tuples)						Notes
			Type	Index							
i	α	-	v_i^α		A_i^α			$A_i^{\alpha,(\alpha-1)}$			-
T1.*La*.01	T1.*La*.02	T1.*La*.03	T1.*La*.04		T1.*La*.06						T1.*La*.07
1	4	R105	Provider	01	HTML/XML	-	-	-	-	-	End User Requirement
2	4	R105	Subscriber	01	-	-	-	-	-	-	End User Requirement
…	…	…	…	…	…	…	…	…	…	…	…
1	3	R105	WEB	01	TCP 443	-	-	-	-	-	End User Requirement
2	3	C101, R106, R108, R109	vCenter	01	-	-	-	-	-	-	End User Requirement
3	3	C101	ESXi	01	-	-	-	-	-	-	End User Requirement
…	…	…	…	…	…	…	…	…	…	…	…
1	2	C101	OS	01	-	-	-	-	-	-	End User Requirement
2	2	C101	COS	01	-	-	-	-	-	-	End User Requirement
3	2	C101, R108, R109	VM	01	-	-	-	-	-	-	End User Requirement
4	2	C101, R107, R108, R109	VLAN	110	-	-	-	-	-	-	End User Requirement
…	…	…	…	…	…	…	…	…	…	…	…
1	1	C102, C103	Server	01	10GBASE-T	-	-	-	-	-	End User Requirement
2	1	C102	WS	01	-	-	-	-	-	-	End User Requirement
3	1	C105	Switch	01	-	-	-	-	-	-	End User Requirement

Test Requirements for SUT Channels [Shc17].

Record Number	Layer Identifier	Requirement Assignment	Link Identifier				Requirement Attributes (3-tuples)						Notes
			Source Identifier		Target Identifier								
			Type	Index	Type	Index							
n	α	-	v_i^α		v_j^α		$A_{i,j}^\alpha$			$A_{i,j}^{\alpha,(\alpha-1)}$			-
T2.La.01	T2.La.02	T2.La.03	T2.La.04		T2.La.06		T2.La.08						T2.La.09
1	4	R103, R104, R105	Subscriber	01	Provider	01	HTML/XML	INTD ≤ 200ms	Tasks ≥ 16	TCP 443	-	-	End User Requirement
…	…	…	…	…	…	…	…	…	…	…	…	…	…
1	3	T101	DNS	01	ESXi	01	UDP 53	-	-	IPv4	-	-	Technical Requirement
2	3	T102	NTP	01	ESXi	01	UDP 123	-	-	IPv4	-	-	Technical Requirement
3	3	T103	vCenter	01	ESXi	01	UDP/TCP 902	-	-	IPv4	-	-	Technical Requirement
4	3	T105	vCenter	01	vSpere	01	TCP 443	-	-	IPv4	-	-	Technical Requirement
…	…	…	…	…	…	…	…	…	…	…	…	…	…
1	2	T107	VLAN	110	COS	01	IPv4	192.168.110.0	255.255.255.0	10GBASE-T	-	-	Technical Requirement
2	2	T108	VLAN	120	COS	01	IPv4	192.168.120.0	255.255.255.0	10GBASE-T	-	-	Technical Requirement

Outline

Test Cases for SUT Components [Shc17].

Test cases of SUT components on layer α

$$T^{\alpha}_{comp} = \{[(v^{\alpha}_i, S^{\alpha}_i), A^{\alpha}_i]_n\}$$

Record Number	Layer Identifier	Component Identifier	Component Attributes (3-tuples)			Requirement Attributes (3-tuples)		
n	α	v^{α}_i	S^{α}_i			A^{α}_i		
1	1	Server, 01	10GBASE-T	Full Duplex	-	10GBASE-T	-	-
2	1	Switch, 01	10GBASE-X	Full Duplex	-	-	-	-
			10GBASE-SR	Full Duplex	-			
			120G CXP	-	-			
3	1	WS, 01	10BASE-T	-	-	-	-	-
			100BASE-T	-	-			
			1000BASE-T	-	-			
…	…	…	…	…	…	…	…	…
1	2	OS, 01	IPv4	192.168.10.101	255.255.255.0	-	-	-
2	2	COS, 01	IPv4	192.168.110.11	255.255.255.0	-	-	-
			IPv4	192.168.120.11	255.255.255.0			
			IPv4	192.168.130.11	255.255.255.0			
3	2	VLAN, 110	IPv4	192.168.110.0	255.255.255.0	-	-	-
…	…	…	…	…	…	…	…	…
1	3	WEB, 01	TCP 443	-	-	TCP 443	-	-
2	3	vCenter, 01	UDP 53	-	-	-	-	-
			UDP 123	-	-			
			TCP 443	-	-			
			UDP/TCP 902	-	-			
3	3	ESXi, 01	UDP 53	-	-	-	-	-
			UDP 123	-	-			
			UDP/TCP 902	-	-			

Test Cases for SUT Channels [Shc17].

Test cases of SUT communication channels on layer α

$$T^{\alpha}_{link} = \left\{ \left[\left(\bigcup_{\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \rangle \in p^{\alpha}_{i,j,k}} \left(\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \rangle, S^{\alpha}_{(l-1),l} \right) \right), A^{\alpha}_{i,j} \right]_{n} \right\}$$

Record Number	Layer Identifier	Path Identifier	Attributes of component-to-component interconnections (3-tuples)			Requirement Attributes (3-tuples)		
n	α	$p^{\alpha}_{i,j,k} = \{\langle v^{\alpha}_{(l-1)}, v^{\alpha}_{l} \rangle\}$	$S^{\alpha}_{(l-1),l}$			$A^{\alpha}_{i,j}$		
1	1	(Switch, 01; Switch, 11)	-	-	-	-	-	-
		<Switch, 01; Switch, 11>	10GBASE-X	Full Duplex	-			
2	1	(Switch, 11; Server, 01)	-	-	-	-	-	-
		<Switch, 11; Server, 01>	10GBASE-T	Full Duplex	-			
3	1	(WS, 01; LAN, 00)	-	-	-	-	-	-
		<WS, 01; LAN, 00>	1000BASE-T	-	-			
…	…	…	…	…	…	…	…	…
1	2	(VLAN, 110; COS, 01)	-	-	-	IPv4	192.168.110.0	255.255.255.0
		<VLAN, 110; COS, 01>	IPv4	192.168.110.0	255.255.255.0			
2	2	(VM, 01; COS, 01)	-	-	-	IPv4	-	-
		<VM, 01; VLAN, 130>	IPv4	192.168.130.0	255.255.255.0			
		<VLAN, 130; COS, 01>	IPv4	192.168.130.0	255.255.255.0			
3	2	(OS, 01; COS, 01)	-	-	-	IPv4	-	-
		<OS, 01; VLAN, 10>	IPv4	192.168.10.0	255.255.255.0			
		<VLAN, 10; VRF, 01>	IPv4	192.168.10.0	255.255.255.0			
		<VRF, 01; VLAN, 130>	IPv4	192.168.130.0	255.255.255.0			
		<VLAN, 130; COS, 01>	IPv4	192.168.130.0	255.255.255.0			
…	…	…	…	…	…	…	…	…
1	3	(DNS, 01; ESXi, 01)	-	-	-	-	-	-
		<DNS, 01; ESXi, 01>	UDP 53	-	-			
2	3	(vCenter, 01; ESXi, 01)	-	-	-	-	-	-
		<vCenter, 01; ESXi, 01>	UDP/TCP 902	-	-			
2	3	(vSphere, 01; vCenter, 01)	-	-	-	-	-	-
		<vSphere, 01; vCenter, 01>	TCP 443	-	-			
3	3	(Desktop, 01; WEB, 01)	-	-	-	TCP 443	-	-
		<Desktop, 01; WEB, 01>	TCP 443	-	-			

Summary

- Model-based testing of distributed systems
- Multilayer model
- Test case generation strategy
  - Multilayer project network
  - Test requirements
  - Test cases
- A case study

Competencies

- Describe model based testing
- Describe SUT multilayer model
- Describe conditions of clustering, virtualization, and replication technologies.
- Specify practical multilayer reference models
- Describe the framework of structural test case generation strategy for a given layer.
- Describe formal test requirement
- Describe formal test case

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