



IEEE Standard Data Model for Nanoscale Communication Systems

IEEE Communications Society

Developed by the
Edge, Fog, Cloud Communications with IOT and Big Data Standards Committee

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STANDARDS

IEEE Standard Data Model for Nanoscale Communication Systems

Developed by the

Edge, Fog, Cloud Communications with IOT and Big Data Standards Committee
of the
IEEE Communications Society

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IEEE SA Standards Board

Abstract: A set of YANG modules describing nanoscale communication systems and their associated physical quantities in conformance with IEEE Std 1906.1-2015—a common framework for all nanoscale communication technologies—are comprised by this data model. Physics unique to the nanoscale are represented by the model. The physics are referred to as *non-standard*, required by IEEE Std 1906.1-2015. Remote configuration and management for remote simulation, operation, and analysis of nanoscale communication systems are defined by the model. A self-describing data structure is defined by the model for datastores and repositories of nanoscale communication experimental data enabling a common understanding of the data from a wide variety of nanoscale communication media and technologies. Augmentation of the IEEE Std 1906.1-2015 common core components with details specific to the physics of the nanoscale communication system is allowed by the model. Techniques used by the model facilitate reuse and augmentation. In addition, extensions to IEEE Std 802.1Q and Internet Engineering Task Force (IETF) interfaces—allowing reusability within existing networks, which implies a macroscale to nanoscale interface, and defines nanoscale communication as a feature for bridge ports as defined in IEEE Std 802.1—are provided. The model is composed of simple, required core components while allowing optional, device-specific components and metrics to be added. There is conformity with best practices as defined by the IEEE 802 YANG editors' coordination committee and IETF RFC 6087, and consideration of coexistence and interoperability with existing domain models and tools, such as the Systems Biology Markup Language (SBML).

Keywords: communication networks, communication standards, communication systems, data model, IEEE 1906.1, molecular communication, multi-scale network, nanobioscience, nanobiotechnology, nanobots, nanodevice, nanoelectrochemical systems, nanoelectromechanical systems, nanofluidics, nanomedicine, nanophysics, nanopositioning, nanoscale, nanoscale communication framework, nanoscale devices, nanosensors, nanostructured materials, nanotechnology, nanotube devices, nanowires, network management, quantum mechanics, simulation, standards development, YANG

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Introduction

This introduction is not part of IEEE Std 1906.1.1-2020, IEEE Standard Data Model for Nanoscale Communication Systems.

IEEE Standard 1906.1™-2015 provides a clear, universal definition, metrics, and conceptual framework to solidify and guide development of practical nanoscale communication systems in any media. IEEE Std 1906.1.1 enhances the aforementioned standard by creating a common data model, specified in yet another next generation (YANG) language, that conforms to IEEE Std 1906.1-2015 for nanoscale communication systems.

The IEEE 1906.1.1 YANG data model defines a common network management and configuration data model for nanoscale communication systems designed to fulfill several goals:

- Helps guide conformance with IEEE Std 1906.1-2015
- Uses a self-describing data structure for management and control of nanoscale communication systems
- Represents fundamental physics impacting IEEE 1906.1 systems
- Defines configuration and management for simulation and analysis
- Defines a self-describing data structure used in repositories of nanoscale communication experimental data

A standard network and management and configuration data model enables efficient understanding and use of nanoscale systems and simulations. The data model addresses the problem caused by the continuing development of many tools for nanoscale communication simulation, emulation, and data analysis that have different interfaces and cannot easily be composed into more useful toolchains.

The data model also addresses the problem that nanoscale systems and tools make different assumptions about what data to collect and how to compare performance among a wide variety of different underlying nanoscale communication media and technologies. This common data model is needed to accurately and fairly compare nanoscale communication systems while serving as human and machine-readable documentation of nanoscale communication systems.

This data model also addresses the lack of YANG data models dealing with small-scale communication system interaction directly with nanoscale physics by providing a data model for relevant fundamental physics and the System of International Units.

Repositories, such as IEEE DataPort™ (<https://ieee-dataport.org/>), of experimental data from small-scale communication systems require clear and accurate documentation for the data to be meaningful from a wide variety of media and technologies to an equally wide variety of researchers and disciplines. This common data model provides a self-describing data model that addresses this purpose.

A reader new to the topic is invited to begin by first reading Annex A for concrete, simple examples.

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IEEE Standard Data Model for Nanoscale Communication Systems

1. Overview

1.1 Scope

This standard defines a common yet another next generation (YANG) (IETF RFC 7950) data model for IEEE 1906.1 nanoscale communication systems.

1.2 Purpose

The YANG data model defines a common network management and configuration data model for nanoscale communication systems. In so doing, it fulfills several purposes:

- It enforces requirements to conform to IEEE Std 1906.1™-2015.
- It describes nanoscale communication systems.
- It represents the fundamental physics impacting IEEE 1906.1 systems.
- It defines configuration and management for simulation and analysis.
- It defines a self-describing data structure used in repositories of nanoscale communication experimental data.

A standard network, management, and configuration data model enables efficient understanding and use of IEEE 1906.1 systems and simulations. A standard data model is needed to ensure that systems and simulations conform to IEEE Std 1906.1-2015. A standard data model is also needed to serve as human and machine-readable documentation of IEEE 1906.1 systems. Because small-scale communication systems interact directly with nanoscale physics, a data model is needed that represents fundamental physics. A common data model is needed to accurately and fairly compare IEEE 1906.1 systems. Repositories of experimental data from small-scale communication systems require clear and accurate documentation for the data to be meaningful. This common data model provides a self-describing data model that addresses this purpose.

1.3 Requirements

This standard defines the following high-level requirements for the data model:

- a) The model shall describe nanoscale communication systems and their associated physical quantities.
 - 1) Subclauses 6.2.2 and 6.2.3 help ensure that YANG module definitions represent only nanoscale communication and conform to IEEE Std 1906.1-2015.
 - 2) Subclause 6.2.4 helps ensure that models describing nanoscale communications using the IEEE 1906.1 framework conform with IEEE Std 1906.1-2015.
 - 3) Subclauses 6.2.5 through 6.2.9 help ensure that YANG module definitions representing nanoscale communication describe standard equations and physical quantities.
- b) The model shall conform to IEEE Std 1906.1-2015.
 - 1) Subclause 5.3 helps ensure that the data model conforms to IEEE Std 1906.1-2015 and provides one-to-one correspondence to metrics, components, and types defined in IEEE Std 1906.1-2015.
- c) The model shall represent physics unique to the nanoscale, referred to as *non-standard*¹, required by IEEE Std 1906.1-2015.
 - 1) Subclause 5.4 of IEEE Std 1906.1-2015 specifies that “Nanoscale communication networks shall describe their physical layer by denoting: transmitter, receiver, message, medium, components that have dimension from 1 nm to 100 nm, the communication physics suited to the nanoscale, message carrier, motion, field, perturbation, and specificity.” A mechanism for representing unique, or non-standard, physics is demonstrated in A.2.3. Specifically, it points to the inheritance capability of YANG identities to ground non-standard physics to the framework using the taxonomy as defined in 5.4. Annex C of 1906.1-2015 lists scaling laws relevant to nanoscale physics.
- d) The model shall define remote configuration and management for remote simulation, operation, and analysis of nanoscale communication systems.
 - 1) Subclause 6.5 defines YANG modules that are inherently designed to work with network management protocols, such as network configuration protocol (NETCONF), to provide configuration of network devices.
- e) The model shall define a self-describing data structure used in repositories of nanoscale communication experimental data enabling a common understanding of the data from a wide variety of nanoscale communication systems.
 - 1) Instance data in the YANG modules defined beginning in 6.5 are inherently stored in self-describing data structures such as Extensible Markup Language (XML) and JavaScript Object Notation (JSON).
 - 2) Subclause 5.3 provides one-to-one correspondence with properties, components, and metrics defined in IEEE Std 1906.1-2015.
- f) The model shall allow augmentation of IEEE 1906.1 core components with details specific to the physics of the nanoscale communication system.
 - 1) A mechanism for representing non-standard physics is demonstrated in A.2.3 using the inheritance capability of YANG identities.
 - 2) Subclause 5.3 provides a standard definition and examples for refining specific parts of the YANG framework to address physics not covered by the framework itself.

¹ Non-standard physics refers to unconventional mechanics used for communication.

- g) The model shall represent the definition, mapping, and metrics; Clause 4, Clause 5, and Clause 6, respectively, of IEEE Std 1906.1-2015.
 - 1) Mapping refers to 5.4 of IEEE Std 1906.1-2015, which specifies that “Nanoscale communication networks shall describe their physical layer by denoting: transmitter, receiver, message, medium, components that have dimension from 1 nm to 100 nm, the communication physics suited to the nanoscale, message carrier, motion, field, perturbation, and specificity.”
 - 2) Subclause 5.5.5 specifies per-component properties that help users link specific components to their associated length scale. Subclause 6.5 presents dimension as an enumeration.
- h) The model should specify common type definitions to help maximize reuse.
 - 1) Subclause 5.3 provides common type definitions as defined in IEEE Std 1906.1-2015 and schemes to inherit properties.
 - 2) Subclause 5.4 links common definitions with other aspects of the framework, for example linking a component type to an associated metric.
 - 3) Figure 12 and 6.2.4 defines how to link models to the framework to reuse type definitions within the framework, or to refine definitions linked to the framework.
- i) The model should use techniques that allow it to be easily augmented or extended, e.g., use of YANG identities rather than YANG groupings.
 - 1) Subclause 5.3.3 uses inheritance to derive properties from a parent concept (definition and component) to the derived property.
 - 2) Subclause 5.4 defines the exposure of metrics to definitions and components and specifies how inheritance gives access to the metrics associated to the parent definition or component and to the metrics associated with a derived property.
 - 3) In Clause 6, YANG identities, type-of-component, and type-of-definition YANG leaves implement the described concepts in 5.3.3 and 5.4.
- j) The model should provide extensions to IEEE Std 802.1Q [B3] and Internet Engineering Task Force (IETF) interfaces to allow reusability within existing networks, which implies a macroscale to nanoscale interface.
 - 1) Subclause 6.2.4 specifies a YANG module augmenting the IETF interface and International Assigned Numbers Authority (IANA) type of interface to link a nanoscale communication device to an IETF interface.
 - 2) Figure 2 and 5.4 presents a set of metrics to be used to interact with existing networks and management systems.
- k) The model should define nanoscale communication as a feature for bridge ports as defined in IEEE Std 802.1.
 - 1) This requirement implies that hello messages in a NETCONF handshake advertises to the client that the server is capable of supporting an `ieee19061nanocom` interface where `ieee19061nanocom` is the IANA interface number, explained in 6.3.3, and implies support for the YANG model defined in this standard.
- l) The model should be composed of simple, required core components while allowing optional, device-specific components and metrics to be added.
 - 1) Subclause 5.3 presents a one-to-one correspondence to IEEE 1906.1 definitions and components. The definitions and the components in the framework constitute required core components. Subclause 5.3 also defines inheritance enabling users to refine the core components with linked device-specific components. Subclause 5.4 defines the mechanics to link device-specific metrics and core metrics to device-specific components.

- m) The model should conform with best practices as defined by the IEEE 802 YANG editors' coordination committee and IETF RFC 6087 [B4].
 - 1) The style used within the content of the YANG modules conforms to best-practices and guidelines.
- n) The model should consider coexistence and interoperability with existing models, such as the Systems Biology Markup Language (SBML).
 - 1) Both SBML and YANG can represent information in XML. However, design goals differ: SBML's purpose is machine communication and storage of computational models of biological processes while YANG's purpose is to provide a data structure for configuration and control of network devices. While YANG could model everything that SBML models, including rules, constraints, compartments, reactions, etc., it makes more sense for YANG to configure SBML on a network device for a biological simulation if they work cooperatively, rather than to develop a YANG model to duplicate SBML.

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{2, 3}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Bureau International des Poids et Mesures, The International System of Units (SI).⁴

IEEE Std 260.1-2004™, IEEE Standard Letter Symbols for Units of Measurement (SI Customary Inch-Pound Units, and Certain Other Units).^{5, 6}

IEEE Std 1906.1-2015™, IEEE Recommended Practice for Nanoscale and Molecular Communication Framework.

² The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

³ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

⁴ The International System of Units is available from the International Committee of Weights and Measures (<http://www.bipm.org/utis/common/pdf>).

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IETF RFC 6536, Network Configuration Protocol (NETCONF) Access Control Model.⁷

IETF RFC 6963, A Uniform Resource Name (URN) Namespace for Examples.

IETF RFC 7224, IANA Interface Type YANG Module.

IETF RFC 7950, The YANG 1.1 Data Modeling Language.

IETF RFC 7951, JSON Encoding of Data Modeled with YANG.

IETF RFC 7952, Defining and Using Metadata with YANG.

IETF RFC 8141, Uniform Resource Names (URNs).

IETF RFC 8343, A YANG Data Model for Interface Management.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁸

active network: A network composed of packets flowing through a telecommunications pathway that dynamically modify network operation. *See also:* **program**. (Defined in IEEE Std 1906.1-2015)

affinity: The tendency of an atom or compound to combine with atoms or other compounds. *See also:* **receiver**. (Defined in IEEE Std 1906.1-2015)

communication: The act of conveying a message from a transmitting party to a receiving party. *See also:* **message**. (Defined in IEEE Std 1906.1-2015)

component: A required element of the framework that provides a service for communication in a network. See IEEE Std 1906.1-2015 for the specifics of a component. (Defined in IEEE Std 1906.1-2015)

compound module: A logical element of the model (component or definition) that contains subelements (other components and or definitions).

contained module: A logical element (component or definition) of the model that is contained by a parent element (either a component or a definition).

docking: An affinity interaction that results in a method that predicts the preferred orientation of one molecule to a second when bound to each other to form a stable complex. *See also:* **affinity**. (Defined in IEEE Std 1906.1-2015)

false positive: Incorrect classification of an anticipated signal. A signal did not occur but was erroneously detected as occurring. (Defined in IEEE Std 1906.1-2015)

⁷ IETF documents (i.e. RFCs) are available for download at <http://www.rfc-archive.org/>.

⁸ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

flattened model: A model in which data are represented as a list of items and where associations between the items are stored as attributes of these items, as opposed to a tree or hierarchical model.

framework: The framework described in Clause 5 of IEEE Std 1906.1-2015.

hybridization: The process of establishing a non-covalent, sequence-specific interaction between two or more complementary strands of nucleic acids into a single complex. (Defined in IEEE Std 1906.1-2015)

interplanetary scale: Length scale at which the speed of light significantly impacts communication performance and the effects of relativity are negligible. (Defined in IEEE Std 1906.1-2015)

length scale: A length or distance determined with the precision of an order of magnitude, denoted by L . (Defined in IEEE Std 1906.1-2015)

local realism: Is the combination of the principle of locality, an object is only directly influenced by its immediate surroundings, with the realistic assumption that all objects shall objectively have a pre-existing value for any possible measurement before the measurement is made. (Defined in IEEE Std 1906.1-2015)

macroscale: The transmitter, receiver, and message carrier exist on a length scale visible, unaided by the human eye, and the speed of light is negligible to communication performance. (Defined in IEEE Std 1906.1-2015)

medium: The environment connecting the transmitter and receiver, which includes gas, gel, or liquid. (Defined in IEEE Std 1906.1-2015)

message carrier: A physical entity that conveys a message across the medium. *See also:* **message;** **medium.** (Defined in IEEE Std 1906.1-2015)

message: The information to be conveyed that is known to the transmitting party interfacing with a receiver, and unknown, but recognizable, to the receiving party. (Defined in IEEE Std 1906.1-2015)

microscale: The transmitter, receiver, and message carrier exist on a length scale that requires magnification to be visible to the human eye and are longer than the nanoscale. (Defined in IEEE Std 1906.1-2015)

nanoscale: Nanoscale refers to dimensions of 1 nanometer (nm) to 100 nm as defined in ISO/TS 27687:2008 definition 2.1. (Defined in IEEE Std 1906.1-2015)

packet: A packet information encapsulated to be transported through a communication network. *See also:* **active network.** (Defined in IEEE Std 1906.1-2015)

Planck length scale: Length scale where concepts of size and distance break down. (Defined in IEEE Std 1906.1-2015)

program or **programmed:** A series of instructions to define and control outcome. (Defined in IEEE Std 1906.1-2015)

property: An IEEE 1906.1 component attribute refining physical meanings. For instance, length scale is a property of a component defining the application of physical laws.

quantum entanglement: The situation in which the quantum state of particles cannot be described independently; instead, a quantum state may only be given for the system as a whole. (Defined in IEEE Std 1906.1-2015)

quantum length scale: The length scale where properties are related to their de Broglie wavelength. (Defined in IEEE Std 1906.1-2015)

receiver: A device used to collect messages from a transmitter. (Defined in IEEE Std 1906.1-2015)

receptor: A component that receives signals. (Defined in IEEE Std 1906.1-2015)

reduced-length scale-area network: Communication whose performance is dominated by properties caused by a reduction in length scale. (Defined in IEEE Std 1906.1-2015)

regime change: Length scale at which a physical property relevant to communication changes the bandwidth-volume ratio by an order of magnitude. (Defined in IEEE Std 1906.1-2015)

relativistic scale: Length scale at which relativity impacts communication performance. (Defined in IEEE Std 1906.1-2015)

relay: A component that facilitates communication between a transmitter and the receiver. *See also:* **transmitter**; **receiver**. (Defined in IEEE Std 1906.1-2015)

sensitivity: A measure of the proportion of true positives, which are events that occurred and have been correctly detected. *See also:* **specificity**. (Defined in IEEE Std 1906.1-2015)

specificity: A measure of precision in matching between components. *See also:* **sensitivity**. (Defined in IEEE Std 1906.1-2015)

swarm: The collective behavior of many entities that results in an emergent behavior which does not involve central coordination and arises from simple rules that are followed by individuals. (Defined in IEEE Std 1906.1-2015)

thrust: Force described by Newton's Second Law that induces motion when applied perpendicular to a plane. *See also:* **motion**. (Defined in IEEE Std 1906.1-2015)

transmitter: A device used to convey a message to a receiver. (Defined in IEEE Std 1906.1-2015)

true positive: The correct classification of a signal. (Defined in IEEE Std 1906.1-2015)

3.2 Acronyms and abbreviations

IANA	International Assigned Numbers Authority
IETF	internet engineering task force
JSON	JavaScript Object Notation
NETCONF	network configuration protocol
ns-3	network simulator version 3
RFC	request for comment
RPC	remote procedure call
SI	Système International

URL	Uniform Resource Locator
URN	Uniform Resource Name
XML	Extensible Markup Language
YANG	yet another next generation

4. Conventions

4.1 General

This clause defines various conventions and notations used in the standard, i.e., naming convention, unit conventions, and data type definitions.

4.2 Unit specification and notation

This standard uses the units from the International System of Units to represent fundamental physics impacting IEEE Std 1906.1-2015. Should any discrepancy between this standard and the corresponding definition in the International System of Units occur, the definitions in the International System of Units shall take precedence.

Seven Système International (SI) base units are used to derive SI and non-SI units for expressing fundamental physics impacting IEEE Std 1906.1-2015:

- Unit of length
- Unit of mass
- Unit of time
- Unit of electric current
- Unit of thermodynamic temperature
- Unit of amount of substance
- Unit of luminous intensity

IEEE Std 260.1-2004 provides the recommended abbreviations, symbols, and units for IEEE publications, including this standard.

4.3 Naming notation

In Clause 6 defining YANG notation, labels and keywords used to name these concepts shall not contain spaces, shall be in lowercase, and include hyphens (e.g., “message-carrier”).

4.4 Numerical representation

Real and complex decimal numerals are used within this document. Decimal real numbers are represented in their usual 0, 1, 2, ... format and may have a plus (+) or a minus (−) sign prepended. Decimal numerals may or may not be represented with an exponent. Complex numbers are represented as the sum of two real numbers as decimal numerals in their real and imaginary bases under the following format: $a + bi$.

This standard assumes that complex numbers as decimal numerals are considered by default. Real numbers (i.e., 0, 1, 0.12, etc.) are complex numbers with an imaginary part of 0, thus $b = 0$ in $a + bi$ complex numeral representation.

This standard makes no assumption about the format of the corresponding number stored in a target implementation. It considers that implementations follow IEEE Std 754™, but is not restricted to it. This standard assumes that software libraries are available, converting a complex number as decimal numeral into the appropriate number stored in the target implementation.

4.5 Primitive data types specifications

All non-primitive data types are derived from the primitive types in Table 1.

Table 1—Primitive data types

Data type	Definition
Boolean	TRUE or FALSE
String	Array of characters terminated by NULL (\0)

4.6 Derived data type specifications

4.6.1 URN

A Uniform Resource Name (URN) is a Uniform Resource Identifier (URI) that is assigned under the “urn” URI scheme and a URN namespace, with the intent that the URN shall be a persistent, location-independent resource identifier.

IETF RFC 8141 defines the canonical syntax for URNs (in a way that is consistent with URI syntax), specifies methods for determining URN equivalence, and discusses URI conformance. IETF RFC 8141 specifies a method for defining a URN namespace and associating it with a namespace identifier, and it describes procedures for registering namespace identifiers with the Internet Assigned Numbers Authority (IANA).

A URN namespace is a collection of such URNs, each of which is (1) unique, (2) assigned in a consistent and managed way, and (3) assigned according to a common definition. The assignment of URNs is done by an organization (or, in some cases, according to an algorithm or other automated process) that has been formally delegated a URN namespace within the “urn” scheme (e.g., a URN in the “example” URN namespace [IETF RFC 6963] might be of the form “urn:example:foo”).

The recommended pattern to validate a URN is the following:

```
[uU][rR][nN]:(?![uU][rR][nN]:)[a-zA-Z0-9][a-zA-Z0-9\~]{1,31}:?(:[a-zA-Z0-9)(+,\~.:=@;$ !*'%/?#]|%([2][1-9a-fA-F]|[3-9a-fA-F][0-9a-fA-F]))+
```

4.6.2 Number

This standard represents numbers (see 4.4) as strings and assumes that implementations are available to convert (e.g., parse) these numbers into corresponding formats. For instance, “1” is the real number for 1 that can be stored as an integer of any size, although it is not recommended to be stored as a double precision floating-point value of any size.

The recommended pattern to validate a number is the following:

```
[ -+ ] ? [ 0-9 ] * \. ? [ 0-9 ] + ( [ eE ] [ -+ ] ? [ 0-9 ] + ) ? ( \s * [ -+ ] \s * [ 0-9 ] * \. ? [ 0-9 ] + ( [ eE ] [ -+ ] ? [ 0-9 ] + ) ? [ i j ] ) ?
```

Representation of a number under the format defined by this subclause maintains type consistency under different scales as defined in IEEE Std 1906.1-2015. For example, an integer could become a decimal number by change of scale, for instance from picometers to millimeters.

The target computing architecture should support this representation of a number. Support of this representation of a number shall be a feature advertised by target applications as capabilities (e.g., in network configuration protocol [NETCONF] hello handshakes). If the target application cannot support this representation of a number for the following reasons:

- a) No support in the kernel space
- b) This representation of a number is too CPU intensive for the target hardware (e.g., IoT, embedded, nanoplatform, etc.)
- c) For any other reason

then constraints on the use of the scale shall be chosen appropriately to help avoid data type inconsistency or quantization errors exceeding thresholds due to truncation.

Suggested practice is to provide a fallback type for architectures that do not support this representation of a number, e.g., by using a union switching between this representation and a default data type such as the YANG decimal64 format.

4.6.3 Variable

A variable is either a complex number as defined in 4.4 and in 4.6.2 or a well-known name (i.e., pi, e, c, etc.).

```
Union variable{  
    Number number;  
    char *label;
```

5. Nanoscale and molecular communication modeling

5.1 Overview

Clause 5 describes a modular framework providing flexibility and generality to nanoscale and molecular communication models and hardware defined by users of the standard while:

- Providing one-to-one correspondance with the formal definition of nanoscale components, definitions, and metrics as defined by IEEE Std 1906.1-2015

- Offering a means of augmenting the existing components, definitions, and metrics to reflect specific needs of any biomedical experiment
- Defining a set of attributes to use to describe a model corresponding to a nanoscale and molecular communication system, including simulators and hardware
- Exposing a set of corresponding metrics to ease reproducibility and formal definition of experiments across different scientific fields and length scales

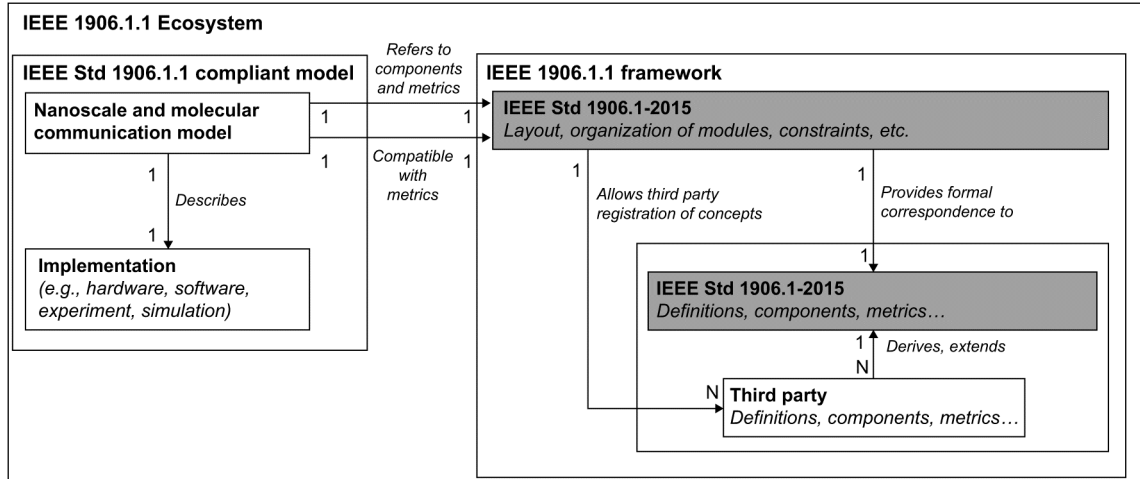


Figure 1—Functional relation between the framework and nanoscale and molecular communication models

The functional depiction of the roles of the framework is provided in Figure 1. Blocks in grey define entities defined directly by IEEE Std 1906.1-2015 and blocks in white represent third-party modules provided by users of the standard.

- Users may implement nanoscale and molecular communication hardware, software, experiment, or simulator at their convenience. Implementation of the model is out of scope of this standard.
- Users shall describe a model of a nanoscale and molecular communications system as defined in a), following the set of mandatory and optional attributes to define the layout of the model and potential constraints. See 5.5.4.
- Optionally, users may extend IEEE Std 1906.1-2015 with refined definitions, components, and metrics. Consequently, the framework may be enriched with new definitions. See 5.3.3.
- The model and its corresponding implementation described in b) following the layout and defining the required and optional attributes of the framework constitute a model that conforms with IEEE Std 1906.1-2015. A conformant model should be easily imported by other teams of scientists and laboratories.
- The complete set of IEEE 1906.1 conformant models and the framework constitute the IEEE 1906.1 ecosystem. The models and the framework should be used seamlessly among laboratories.

5.2 Objectives

This subclause defines the set of logical modules and associations required to implement the IEEE 1906.1 framework and the set of attributes and rules to define a nanoscale model using this framework. The logical entities comprise components, definitions, and metrics, and define extra properties for such concepts as

biological communication processes. The associations among IEEE 1906.1 components, definitions, and metrics include inheritance, composition, and identification to provide flexibility and to allow third-party users to refine the IEEE 1906.1 model. The objectives of the framework are to provide:

- Formal system description for universal storage in databases of nanoscale and molecular communication models, status, configurations, and results.
- Parameter exposure for statistics retrieval and perturbation injection, thus leveraging interaction with target systems including nanoscale and molecular experiments, hardware and software involving nanoscale and molecular communication models, and may involve human subjects.
- Support for advanced modeling in active networks, such as generation of life and death cycles, cell growth, hierarchical representation of nanoscale components within a system, and advanced system modeling.

NOTE—This standard uses the terms *component*, *definitions*, and *metrics* to refer to framework counterparts as specialized entities in IEEE Std 1906.1-2015.⁹

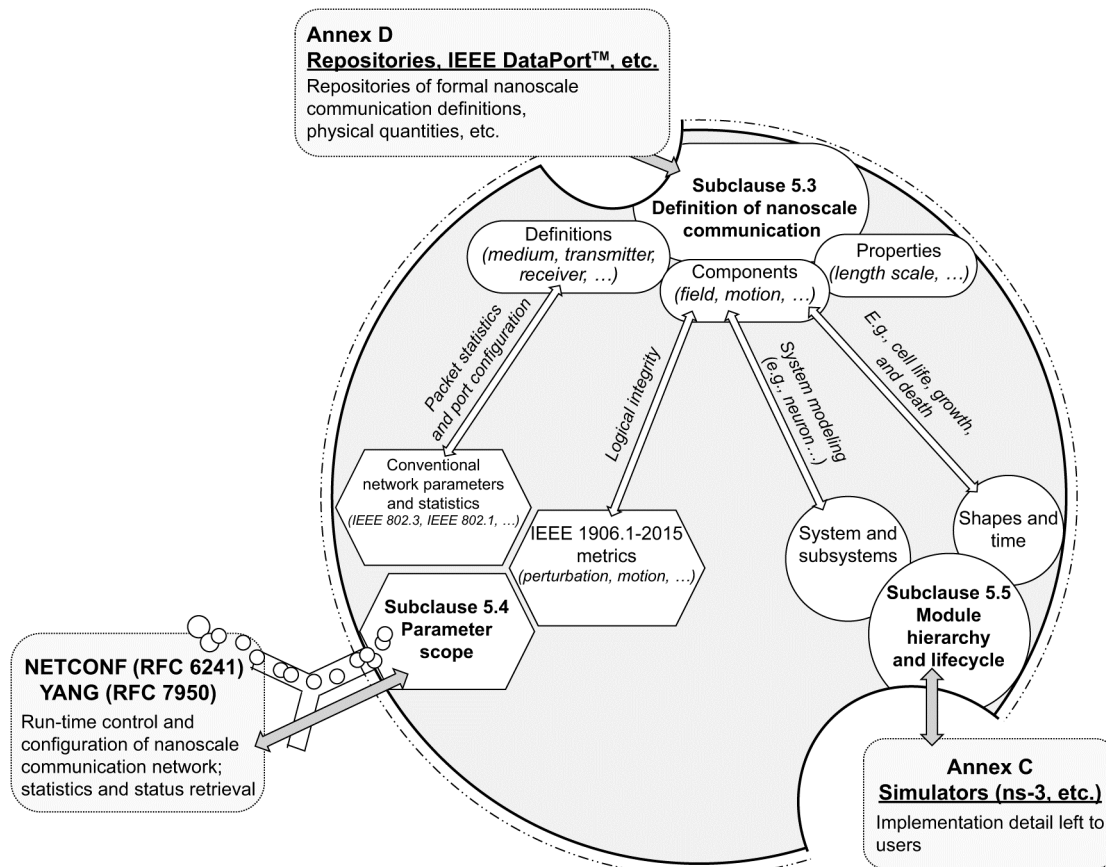


Figure 2—Framework goals and relationships

Figure 2 shows the corresponding model used by the framework to fulfill its three objectives:

- a) Definition of nanoscale systems as defined in 5.3 defines nanoscale systems, experiments, and simulations using the mandatory concepts defined in IEEE Std 1906.1-2015, such as components,

⁹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

definitions, and properties. Concepts of IEEE Std 1906.1-2015 are declared using keywords, and an optional description is provided or stored in external databases and linked to the model via URN identifiers. The framework also provides logical associations and derivations to enable third-party concepts within the framework.

- b) The framework provides exposure to relevant statistics and configuration parameters as defined in 5.4 by linking IEEE 1906.1 metrics to corresponding components and definitions defined in a) for increased interaction with the target model. For instance, the NETCONF protocol issues XML remote procedure call (RPC) causing a perturbation to be triggered in the target system within the set of parameters defined in a) and retrieve a set of metrics from a component of the target system.
- c) Optionally, the framework includes the ability to define a component hierarchy and interaction as defined in 5.5, allowing the dynamic creation and destruction of entities within a system and supporting complex queries based on time and space. If systems require partitioning into subsystems to create complex models (such as a neuron axon composed of multiple microtubules or sets of microtubules) or following the model of a molecular communication model as described in IEEE Std 1906.1-2015, the framework defines a set of rules to identify each component and link them to parent and sibling components.

5.3 Nanoscale system definition

5.3.1 Objectives

Subclause 5.3 provides recommendations to implement the IEEE 1906.1 framework by modeling reusable and generic modules that represent IEEE 1906.1 definitions, components, and metrics, and any third-party component, definition, or metric conformant with IEEE Std 1906.1-2015.

Generality allows the users of the framework to focus solely on their model by providing a unique set of attributes regardless of the type of component being modeled. For example, an IEEE 1906.1 *motion* or a *specificity component* shall be modeled using the same set of attributes and they shall differ only by the values of these attributes.

Figure 3 illustrates the goal of the framework of any nanoscale system definition. The box entitled *nanoscale system* is an example of a model describing an implementation of a nanoscale or molecular communication system and comprises two distinct subsystems (e.g., a *transmitter* and a *receiver*). Such a model could be defined by laboratories to represent their experiments in a common format.

The two subsystems refer to distinct IEEE 1906.1-compatible components or definitions as shown on the right side of Figure 3 and differ by pointing to two different types. For example, a transmitter and a receiver subsystem would share “type of definition” as the same attribute, but they would differ by their value. They would refer respectively to the IEEE 1906.1-defined transmitter and receiver. The framework shall control the set of metrics associated with each subsystem depending on the type of definition to which they refer.

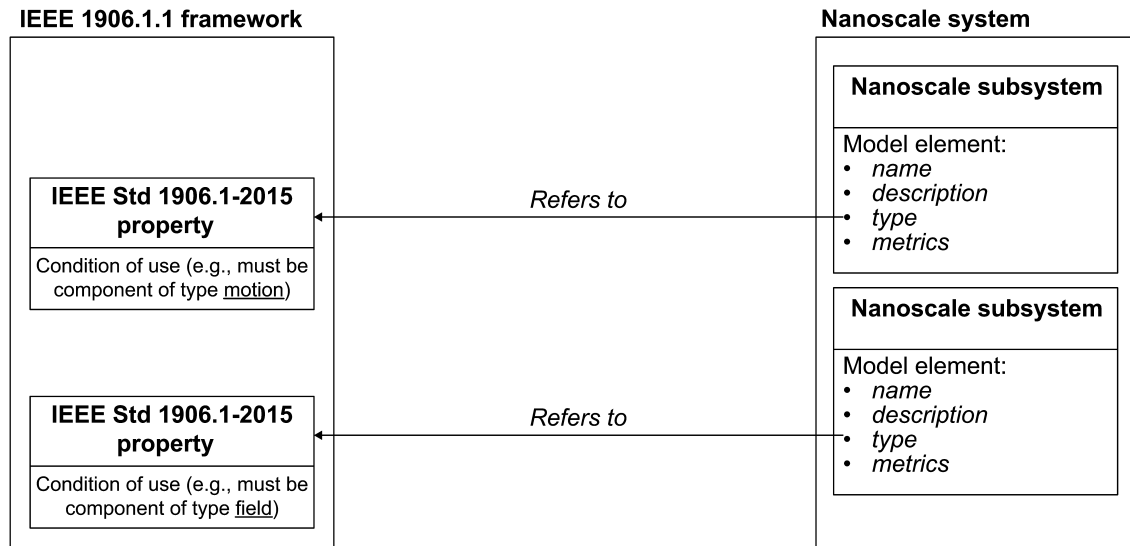


Figure 3—IEEE Std 1906.1-2015 components and definitions are composed of the same set of attributes; only the values differ

5.3.2 Using the framework

The framework is built to expose components, metrics, and definitions defined in IEEE Std 1906.1-2015 to third-party nanoscale and molecular communication (e.g., biological) models. In return, the model describes a practical implementation (e.g., nanoscale system) including experiments, simulations, hardware, and software.

A refined description of Figure 1 and Figure 3 is illustrated in Figure 4. Here, the nanoscale system is the physical implementation described by the biological model. The biological model describes a nanoscale system comprising two subsystems and exposing as inputs and outputs a set of metrics defined by IEEE Std 1906.1-2015.

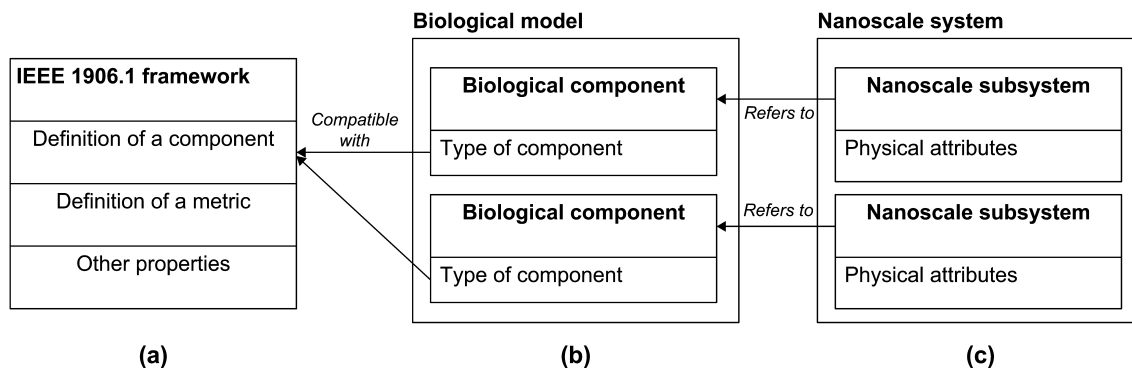


Figure 4—Nanoscale and molecular communication model: (a) framework, (b) biological model, (c) practical implementation

If the IEEE 1906.1 framework contains all the definitions and components required to describe the nanoscale system, users of the framework refer to them by linking their respective subsystems to them. If some definitions or components are missing in the IEEE 1906.1 framework or need to be refined, then users of the framework may extend the existing framework with their definitions and subsequently link their biological model to the new definitions.

Figure 4 describes the set of recommendation to use the IEEE 1906.1 framework in the following order:

- a) Definition of custom components, definitions, properties, and metrics that comply with the IEEE 1906.1 framework or the reuse of existing components and related metrics from the IEEE 1906.1 model defined by this standard (see Figure 4 [a]) as defined in 5.3.3
- b) Definition of the biological model, its components, their types, the set of procedures to describe how they interact, optionally their hierarchy within the nanoscale system or simulation (see Figure 4 [b])
- c) Implementation of the nanoscale system which refers to the biological model, by exposing the set of configuration and status parameters to manage its operation and to apply transformations; for example, creation or destruction of biological subsystems, transformation of shape, size, movement, etc. (see Figure 4 [c])

5.3.3 Component and definition identification

5.3.3.1 Introduction

To enable a nanoscale subsystem to access a component or definition as defined in the IEEE 1906.1 framework, and to access the corresponding metrics, this subsystem shall provide its *type of component* or *type of definition*. The type of component shall exist and be valid within the framework or within any third-party description extending the framework.

Subclause 5.3.3.2 describes the principles of naming components and definitions. Subclause 5.3.3.3 provides recommendations for framework model refinement. Subclause 5.3.3.4 shows the relationship among the framework components and definitions and a nanoscale and molecular communication system using the framework.

5.3.3.2 Component and definition typing

5.3.3.2.1 Introduction

The framework defines a set of components and definitions that refer to their counterpart in IEEE Std 1906.1-2015. Components and definitions within the framework, as well as extensions of the framework, shall define a set of attributes as shown in Table 2.

A subsystem defined in third-party biological models shall refer to the label as its type of component or definition. Figure 5 illustrates a biological subsystem pointing to an IEEE 1906.1 component called *diffusion* using the set of rules described in this subclause.

Table 2—Component and definition attributes

Name	Conformance ^a	Description
label	M	The name of this component to be referred to by nanoscale subsystems.
parent-label	M	The label of the parent component or definition from which this component or definition inherits. The parent component or definition shall be defined and valid within the framework. See 5.3.3.3 regarding inheritance.
description	O	An optional description providing further detail about the implementation or instructions that are out of the scope of this standard.

^aM = Mandatory for nanoscale communication systems, O = optional for nanoscale communication systems

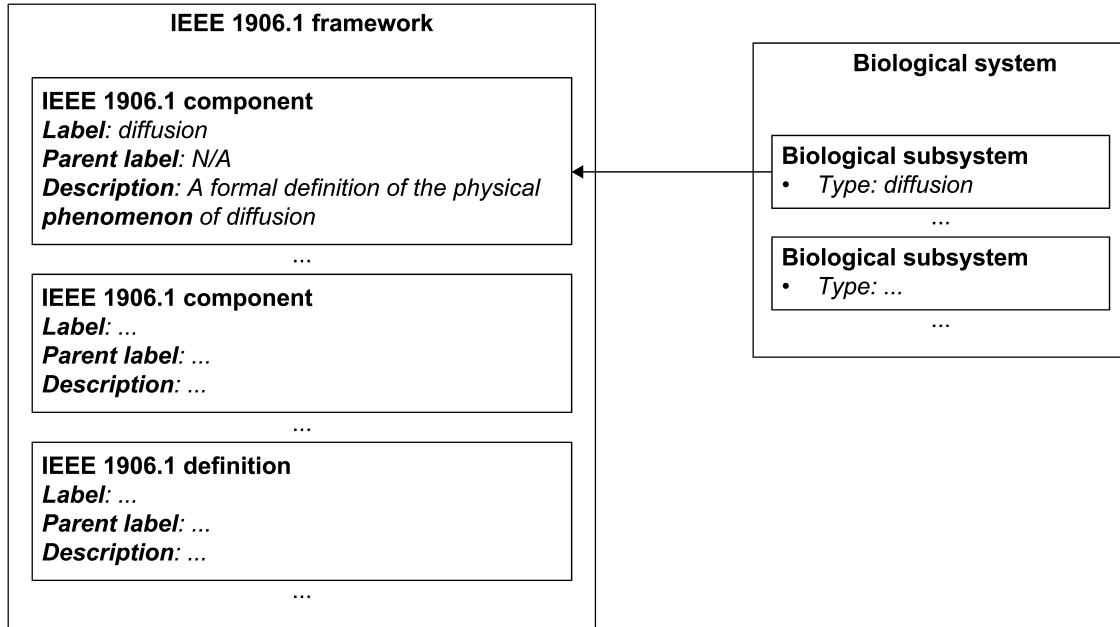


Figure 5—Example use of the framework for component identification

5.3.3.2.2 label

A label identifies a unique name for this component or definition within the framework. camelCase shall not be used. Spaces shall be replaced with hyphens. Label shall be unique within the framework to avoid ambiguity.

5.3.3.2.3 parent-label

The label of a parent component or definition that helps position this component or definition within the framework and deduce the rules of inheritance, or the logical connection with the parent in the case of a biological taxonomy. The parent label shall refer to an existing label (see 5.3.3.2.2) within the framework and the iteration of parent labels shall trace back to a component or definition within the framework.

5.3.3.2.4 description

An optional description provides further details and defines the physical phenomenon behind the use of the label.

5.3.3.3 Component and definition inheritance

5.3.3.3.1 Relation among components, definitions, and metrics

The framework supports the option to refine the model by including new components and definitions. A taxonomy is constructed by linking a new component and definition to a parent component or definition in the sense that the parent encompasses the meaning of the new component. Thus, a hierarchical structure is provided by the framework. Components and definitions inherit properties from their parents with the following consequences:

- A biological subsystem linking to a component may use the metrics associated with that component.
- A biological subsystem linking to a component may use the metrics associated with any ancestors of that component.
- A biological subsystem linking to a component shall not use the metrics associated with siblings or children of that component.

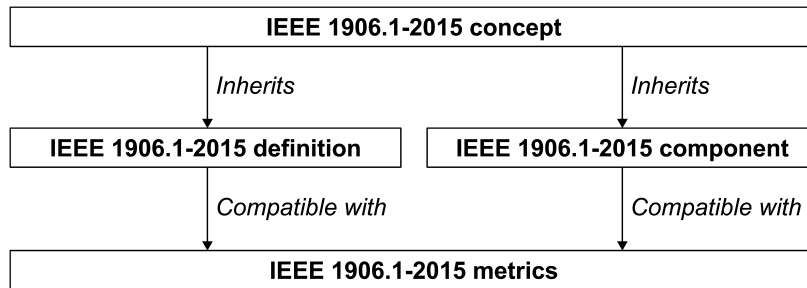


Figure 6—Inheritance within the IEEE 1906.1 framework

An IEEE 1906.1 concept in the above figure encompasses definitions, components, and metrics as defined in the standard. For example, a biological subsystem that is of type *motion* or of a type of component that derives from *motion* shall expose metrics associated with *motion-metrics* as defined in IEEE Std 1906.1-2015. A biological subsystem that is of type *transmitter* or of a definition deriving from transmitter shall expose parameters associated with that definition.

Figure 6 illustrates inheritance within the model explaining the relationship among definition, component, and metrics. Inheritance is based on keywords and parent label attributes as defined in 5.3.3.2. It follows that components scope the corresponding metrics based on inheritance. For instance, component A inheriting from component B scopes metrics that are relevant to both A and B.

5.3.3.3.2 Core component specification

Table 3 provides the list of components and definitions from IEEE Std 1906.1-2015 and the corresponding parent component. The description of these components is outside the scope of this standard.

Table 3—IEEE 1906.1 core component specification

Label (name)	Parent component
bacterium	message-carrier
calcium-ion	
charge	
electromagnetic-wave-variation	
ligand	
motor	
diffusion	motion
motion-type	
potential-difference	
walking	
wave-guided	
compartmentalized	field
concentration-gradient	
directional-antenna	
microtubule	
nanostructure-orientation	
concentration-change	perturbation
electrical-current-variation	
molecular-structure	
transmission-rate	
antenna-aperture	specificity
receptor-sensitivity	
electrical-charge	
NOTE— <i>message-carrier</i> , <i>motion</i> , <i>field</i> , <i>perturbation</i> , and <i>specificity</i> should name <i>component</i> as their parent component to allow future augmentation of the core components. Naming <i>component</i> as a parent component for physical implementations or making a nanoscale subsystem refer to these core components and <i>component</i> should be avoided.	

5.3.3.3.3 Component validation

The label used to name a component, or a definition and its parent component or parent definition, are used to create a logical association to the IEEE 1906.1 core components and determine if this component is allowed to use a specific set of metrics.

For instance, a component that names *message-carrier* as a parent component, or names a component that is inheriting from *message-carrier* may use the metrics associated to a message-carrier component but shall not use any metrics associated to other core components (i.e., *specificity*, *perturbation*, *field*, *motion*, and *system* metrics).

Any component or definition that fails to provide an ancestor within the IEEE 1906.1 framework is deemed invalid.

WARNING

Using “component” or “definition” as a parent label is valid, but highly discouraged.

5.3.3.3.4 Examples of component definitions

A nanoscale model provided by third-party experimentalists may rely on viruses as a means of transmitting information. The closest component defined in IEEE Std 1906.1-2015 is *bacterium*, but assigning the corresponding virus representation to a *bacterium* type of component is misleading. The specific implementation defines *virus* as a component and specifies *message-carrier* as the parent component for *virus*. The rules of inheritance make *virus* a type of *message-carrier* and thus is suitable to reuse metrics specific to *message-carrier*. The third-party experiment may then define a set of metrics corresponding to viruses in general but that cannot apply to message carriers.

In another nanoscale model, one may want to explicitly use *Yersinia pestis* as a type of *bacterium* because it exhibits unique behaviors in experiments and simulations. To explicitly refer to it, in opposition to any type of *bacterium*, or any other type of bacterium, the model defines *yersinia-pestis* as a component and then specifies *bacterium* as a parent component of *yersinia-pestis*. The rules of inheritance make *yersinia-pestis* a type of *message-carrier* and thus reuses metrics specific to *message-carrier*, and if defined, to *bacterium*.

NOTE—While specification of a nanoscale communication taxonomy is outside the scope of this standard, a taxonomy shall inherently be generated among users of this standard.

5.3.3.4 Relation between the model and the chain of inherited components and definitions

A new component or definition is defined by a label that explicitly refers to the corresponding component in IEEE Std 1906.1 (see 5.3.3.2). If the component is specific to a physical implementation, it should provide an explicit and specific label, and shall follow the naming convention of this standard (see 4.3). A component or a definition label cannot reuse existing labels. A component or a definition may provide a description of its meaning.

Figure 7 illustrates a use case of an implementation referring to IEEE Std 1906.1-2015 in a manner that allows addition of custom detail. The framework uses a list of components that enables access to a correlated set of properties (e.g., metrics) defined in IEEE Std 1906.1-2015. An implementation shall identify the type of component for each of its nanoscale subsystems.

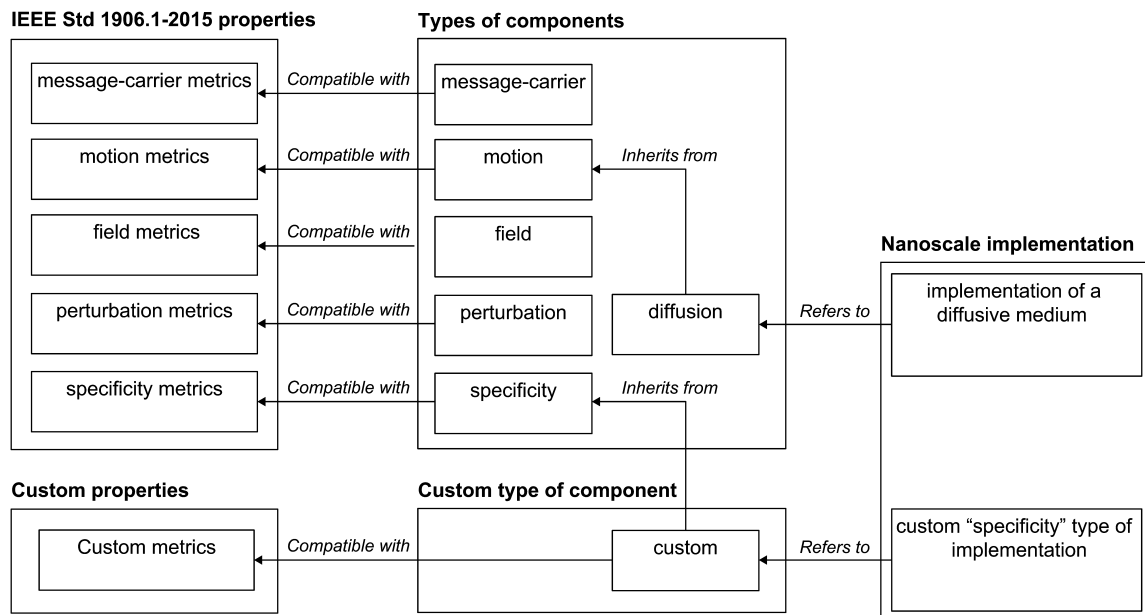


Figure 7—Principles for identifying components

In this example, one of the subsystems describes an implementation of an IEEE 1906.1 component called *diffusion*. Diffusion derives from the *motion* component. In return, the framework gives access to *diffusion* and *motion* metrics. A second subsystem refers to a custom component which refines the *specificity* component. In return, the framework gives access to *specificity* metrics as part of the inheritance scheme of the model, plus any custom metrics specified by the experiment that are relevant to this custom component.

The framework allows the addition of types of components enabling implementation-specific properties to be used that are not initially within the framework.

CAUTION

Creation of custom sub-components and metrics should be considered carefully. Every effort should be made to use standard components and metrics. Custom metrics result in the inability to maintain common performance metrics among nanoscale communication systems.

5.4 Parameter scope

5.4.1 Overview

The link between a subsystem of the nanoscale and molecular communication model and the corresponding component and definition of the IEEE 1906.1 counterpart provides the associated metrics. Consequently, the implementation of such a subsystem is expected to expose these metrics either as results and statistics of the associated experiment, or to provide input to perturb the said system.

The model of exposing parameters is illustrated in Figure 8. The framework defines the set of metrics, the corresponding physical quantities, and the associated physical units. Alternatively, the framework can be extended with new sets of metrics corresponding to new sets of components, as described in 5.3.

The biological subsystem refers to a component as defined in 5.3. In return, the framework controls the set of metrics allowed by the biological subsystem. In Figure 8, concentration change metrics along with perturbation metrics may be displayed by the subsystem.

Consequently, as this is a perturbation subsystem, the experiment may require that a user triggers such a perturbation and allows the associated perturbation rate as input to the system. Other metrics shall be read, such as perturbation error, which the subsystem returns as output to express the measured offset between the perturbation rate and the effective measured perturbation rate within the subsystem. These actions are illustrated in Figure 8.

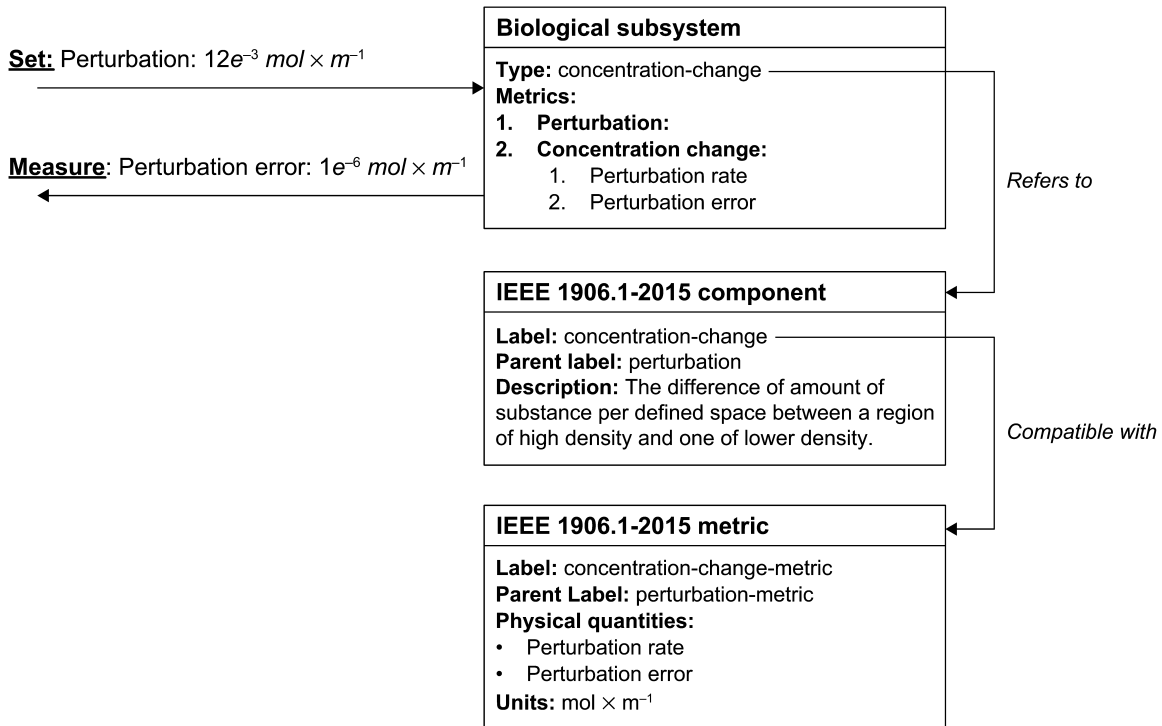


Figure 8—Metrics define the set of physical quantities and units to be exposed

5.4.2 Defining a new metric and controlling its scope

New metrics should follow recommendations specified in 5.3. Given that a taxonomy exists, physical quantities defined in new metrics shall refine existing physical quantities used in metrics derived from IEEE Std 1906.1-2015. For example, a concentration change metric is a kind of perturbation and, as such, it shall refine the physical quantity pertaining to perturbation rate. As it is a concentration change, the physical unit of the perturbation rate shall express an amount of substance per unit time.

Access control to specific metrics may operate via one of the following:

- A component data structure links to its associated metrics.
- The metric data structure applies rules that validate its associated components.

Such solutions are implementation specific and often depend on the data model of the technology being used to model the system. Even if access control is strongly recommended, its implementation is out of scope of this standard. However, Clause 6 utilizes YANG as the data model to define the framework and YANG offers native support for option b). See Clause 6 for the corresponding description of controlling access to metrics with YANG.

5.4.3 Metric typing

5.4.3.1 Overview

The framework defines a set of components and definitions that refer to their counterpart in IEEE Std 1906.1-2015. Components and definitions within the framework, or extensions of the framework, shall define a set of attributes as shown in Table 2.

Table 4—Component and definition attributes

Name	Conformance ^a	Description
label	M	The name of this metric to be used by nanoscale subsystems.
parent-label	M	The label of the parent metric for this component to ease recursive access. The parent metric shall be defined and valid within the framework. See 5.3.3.3 regarding inheritance.
description	O	An optional description providing further detail about the instructions regarding this metric that are out of the scope of this standard.
physical-quantities	O	An optional list of physical quantities and their physical units that may be empty if the metric is a placeholder.

^aM = Mandatory for nanoscale communication systems, O = optional for nanoscale communication systems

5.4.3.2 label

A unique name identifies this metric within the framework. camelCase shall not be used. Spaces shall be replaced with hyphens. The label shall be unique within the framework to avoid ambiguity.

5.4.3.3 parent-label

The label of a parent component or definition that helps position this component or definition within the framework and deduce the rules of inheritance, or the logical connection with the parent in the case of a taxonomy. The parent label shall refer to an existing label (see 5.3.3.2.1) within the framework or the iteration of parent labels shall trace back to a component or definition within the framework.

5.4.3.4 description

An optional description defines the physical phenomenon justifying use of the label.

5.4.3.5 physical-quantities

A list of parameters defined by fundamental physical units and including derived units following the SI unit model. These quantities are the metrics defined in IEEE Std 1906.1-2015. These quantities may be read by any external application or user and may be written to generate perturbation to the system (e.g., in order to produce any experiment).

5.5 Module hierarchy

5.5.1 Overview

The framework requires a flexible module hierarchy to allow modeling of nanoscale and molecular systems with diverse complexities. The model described by this standard also makes the distinction between a component and a definition as per IEEE Std 1906.1-2015 (see 5.3). The model also defines properties providing context to given components to associate physical laws (see 5.4).

The framework provides sufficient high-level detail of a nanoscale and molecular communication system such that a biological system is self-described, and no subsystem is required (see A.2). However, more complex systems may require a deeper level of description, fine tuning, or per subsystem statistics retrieval and parameter injection (see A.5).

The component hierarchy provides interfacing among components as defined in 4.3 of IEEE Std 1906.1-2015. An interface is implicitly created by letting a component or a definition identify a next component or definition in the hierarchy. For instance, the message definition may identify message-carrier as its next component.

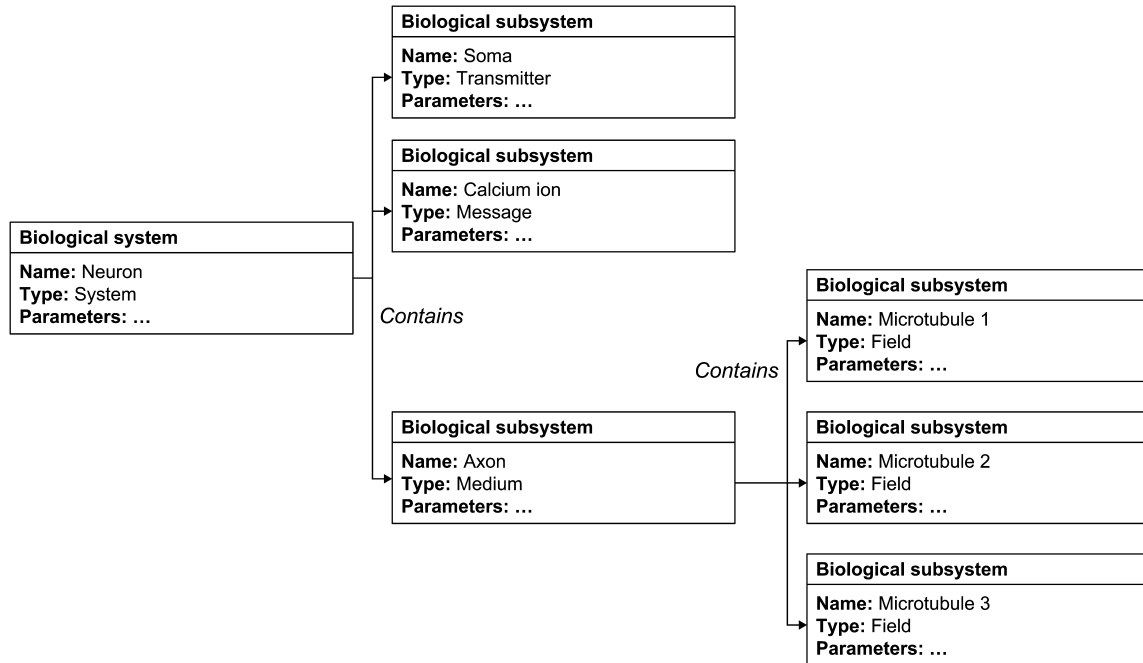


Figure 9—A neuron as a hierarchical system with subsystems referencing IEEE 1906.1 components and definitions

Figure 9 illustrates a model of a neuron involving a deeper level of description, using the reference model defined in Annex A of IEEE Std 1906.1-2015. Each of the subsystems and the system itself are described by the concepts defined in 5.3 and 5.4. However, hierarchical representation may be required if:

- The user wants specific statistics on a per-subsystem level, for example, observing the distribution of a concentration of calcium ions along three microtubule sets and impacts on cargo transport.
- The user wants these statistics in real-time.
- The user wants to simulate the behavior of a neuron in which the axon is growing or damaged.
- The user wants to simulate a network of neurons in which neurons are created and destroyed and create dendrites.

Consequently, the framework offers an optional set of recommendations and attributes to use when describing the model. These recommendations and rules do not apply to the framework itself. However, optional concepts, such as studying life and death cycles of subsystems, may also be required. The framework provides modules to describe *properties* used to describe a nanoscale and molecular communication system.

5.5.2 Description of the hierarchical model

The framework produces optional attributes to its components that may be reused by the biological model. The strategy is to produce a flattened model listing the components independently but providing associations, while flexible enough to allow any kind of hierarchy and structure between components and definitions from the framework and from third-party definitions extending the framework.

Figure 10 is a functional representation of a biological system and its subsystems in “one-to-many” relationships between a compound system and a contained subsystem in which a subsystem contains many different subsystems. However, a subsystem cannot be shared between two containing subsystems.

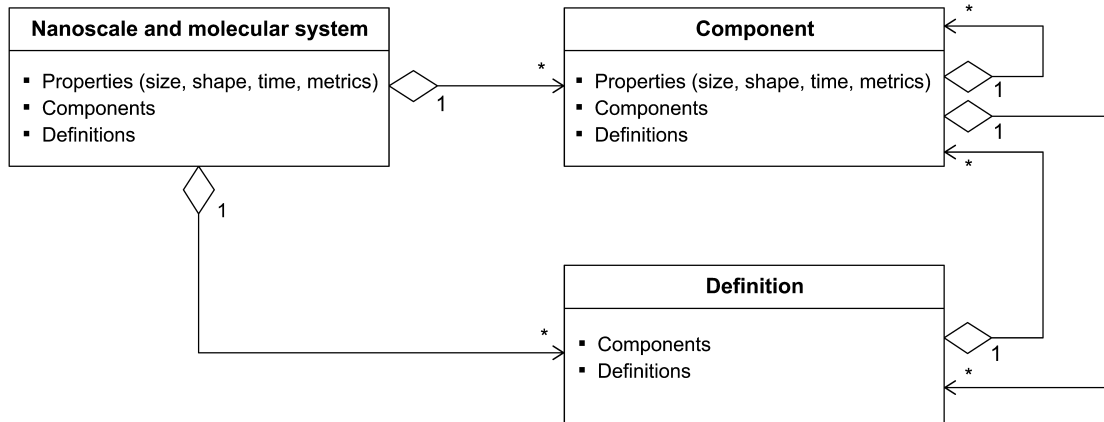


Figure 10—Framework relationships

NOTE—Figure 10 is a conceptual representation showing the relationship between the modules. Implementation of this illustration is out of scope of this standard. It is suggested to make use of the composite pattern as illustrated in Figure 10.

A nanoscale model that is conformant with the framework and that optionally uses the hierarchical model shall conform with the following rules:

- A module that contains another component or definition is called a *compound module*. A component or a definition that is part of a compound module is called a *contained module*.
- A nanoscale molecular system comprises any number of definitions and any number of components. The molecular system is a component and possesses various global properties, such as system metrics as defined in 6.4 of IEEE Std 1906.1-2015.
- Definitions include medium, transmitter, receiver, and message and comprise any number of definitions and any number of components.
- Components include message-carrier, motion, field, specificity, perturbation, and system and comprise any number of definitions and any number of components.
- A nanoscale model or system shall comprise at least one system component acting as a root (compound) module.

5.5.3 Component hierarchy

A nanoscale system shall provide a list of all its components and definitions. To allow flexibility with languages and models that do not allow recursion, the list of components shall be linear. A set of optional variables is provided to let an implementation flatten and unflatten the model of a nanoscale system:

- Flattening consists of converting any module hierarchy into a linear list of components.
- Unflattening is the opposite operation restoring the initial module hierarchy from a linear list of components.

NOTE—While YANG Language allows for lists within lists and an ordered-by statement, the flattened hierarchy enables greater clarity and allows for more complex relationships to be clearly represented.

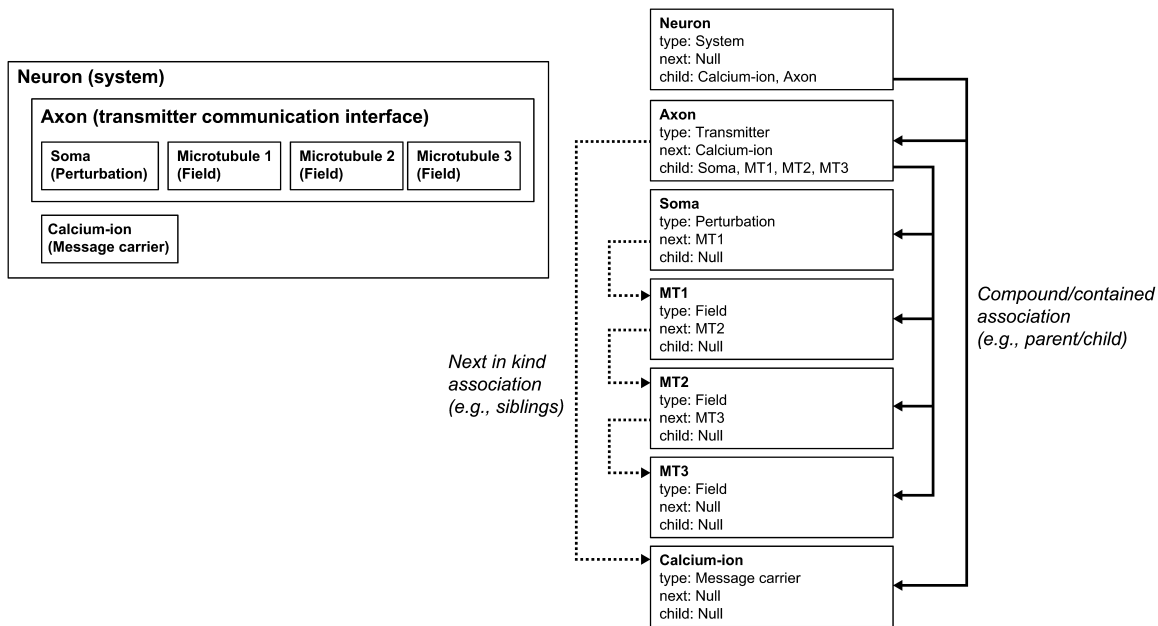


Figure 11 —The IEEE 1906.1 framework (unflattened, left) and a list of components (flattened, right)

5.5.4 Component variables

5.5.4.1 Overview

Subclause 5.5.4 defines the list of variables to help ensure proper use of the IEEE 1906.1 framework (see Figure 1 [b]).

Table 5—Component variable definitions

Name	Data type	Conformance ^a	Reference (subclause)
identifier	URN	M	5.5.4.2
name	String	O	5.5.4.3
description	String	O	5.5.4.4
type-of-component	String	M	5.5.4.5
sub-component	List of URN	O	5.5.4.6
next-component	List of URN	O	5.5.4.7

^aM = Mandatory for nanoscale communication systems, O = optional for nanoscale communication systems

5.5.4.2 identifier (URN)

A URN as defined in 4.6.1 that uniquely identifies the component within the model, and that can be used as a reference by the corresponding nanoscale subsystem.

5.5.4.3 name

The optional name of this biological component used by the implementation. The name can bear a user-friendly meaning or can simply be used as an instance name for an implementation or a biological simulator.

5.5.4.4 description

The optional description details the structure and the behavior of the component from the biological model.

5.5.4.5 type-of-component

The mandatory keyword associating this biological model component to IEEE Std 1906.1-2015 or its custom-derived components as discussed in 5.3. This variable is used by the framework to control access to related properties (i.e., metrics) for this component.

5.5.4.6 sub-component

The optional list of identifiers (see 5.5.4.2) of biological components that are considered child nodes in a hierarchical model, as defined in 5.4.

5.5.4.7 next-component

next-component is an optional list identifying (see 5.5.4.2) biological components that are considered sibling nodes in a hierarchical model when ordering is needed. Direction of propagation of message-carriers may be a motivation for ordering and for the use of next-component lists.

5.5.5 Component properties

5.5.5.1 Overview

Subclause 5.5.5 describes the set of component properties defined by the IEEE 1906.1 framework. This is an optional set of properties providing hints about the experiment. Properties refer to physical quantities providing more qualitative details about the nanoscale and molecular communication system being described. Properties are used to refine the units expressed by the experiment (e.g., metrics value). By default, units shall be in SI fundamental units (e.g., meters, kilograms, seconds etc.). However, nanoscale models may redefine units to scale to the system under description (e.g., nanometers, milligrams, milliseconds etc.). These properties and the units they define shall match the SI unit model regarding base and derived units.

Table 6—List of optional properties and link to the SI unit system

Name	Conformance	Reference
timestamp	O	5.5.5.2
length	O	5.5.5.3
length-scale	O	5.5.5.4
mass	O	5.5.5.5
time	O	5.5.5.6
duration	O	5.5.5.7
electric-current	O	5.5.5.8
thermodynamic-temperature	O	5.5.5.9
amount-of-substance	O	5.5.5.10
luminous-intensity	O	5.5.5.11
derived-units	O	5.5.5.12
component-shape	O	5.5.5.13

^aM = Mandatory for nanoscale communication systems, O = optional for nanoscale communication systems

NOTE—Component properties can be added, and custom implementations can augment the existing framework. See 5.3.

Component properties shall be omitted if using SI base units. If the contained component does not define a property, but the compound component does, then the compound component properties apply to the contained component.

5.5.5.2 timestamp

The timestamp provides a correlation between metrics associated with this component or this definition and a point in time. Reference zero may be epoch, the start of simulation, or a specific event used as a basis for comparison.

5.5.5.3 length

Length defines the corresponding unit to describe any metrics using length, surfaces, and volumes. By default, length is in meters, however nanoscale systems may want to use nanometers instead to make metrics more tractable, e.g., 10 nm instead of 10^{-8} m.

5.5.5.4 length-scale

The length-scale is defined in IEEE Std 1906.1-2015 on which physical laws are coupled to the nanoscale system. Annex C of IEEE Std 1906.1-2015 lists the impact of length scale on physical properties. The length-scale is of type variable as defined in 4.6.2. Users may provide a number and specify a unit, or choose among the following list of ranges:

- Planck
- Quantum
- Nanoscale
- Microscale
- Macroscale

- Interplanetary
- Relativistic

Alternatively, the following list may be used to define nanoscale properties:

- Less than 1 micrometer
- Less than 100 nanometers
- Less than 10 nanometers

5.5.5.5 mass

mass defines a corresponding unit to describe metrics in terms of mass and densities. By default, mass is in kilograms, however nanoscale systems may want to use milligrams and micrograms instead to make metrics more tractable, e.g., 1 mg instead of 10^{-6} kg.

5.5.5.6 time

time defines a unit to describe metrics using time, velocity, and acceleration. By default, time is in seconds, however nanoscale systems may utilize milliseconds instead to make metrics more tractable, e.g., 1 ms instead of 10^{-3} s.

5.5.5.7 duration

duration is another definition of time. duration expresses a time delta between two events. If time (see 5.5.5.6) is already defined, then defining duration with a conflicting unit is an error and shall be avoided.

5.5.5.8 electric-current

electric-current defines a unit to describe flow of electric charge. By default, electric-current is in amperes, however, nanoscale systems may utilize microamperes, e.g., 1 uA instead of 10^{-6} A.

5.5.5.9 thermodynamic-temperature

thermodynamic-temperature defines a unit to describe absolute measure of temperature. By default, temperature is in kelvin, however nanoscale systems may utilize Celsius or Fahrenheit.

5.5.5.10 amount-of-substance

amount-of-substance defines a unit to describe any related metric. By default, it is in moles, however nanoscale systems may utilize millimoles and micromoles, e.g., 1 umol instead of 10^{-6} mol.

5.5.5.11 luminous-intensity

luminous-intensity defines a unit to describe any related metric. By default, it is expressed in candela, however nanoscale systems may utilize fractions of this unit.

5.5.5.12 derived-unit

The model may list any SI-derived units (e.g., frequency, surface, velocity, resistance, etc.) and redefine the corresponding unit. If a derived-unit used by any metric of the model is not defined by the model following this subclause then either:

- Its corresponding unit is derived from one of the redefined the SI base units as described in 5.5.5.3 through 5.5.5.11 (except 5.5.5.4), if the model redefined it. For example, if the model redefined time in milliseconds, and frequencies is not redefined, then it is assumed that frequency units are in kilohertz and any value represented by the model regarding frequency metrics are in kilohertz.
- Its corresponding unit is derived from an SI base unit. For example, if the model is not redefining frequency, and is not redefining time, then it is assumed that any value represented by the model regarding frequency metrics is in Hertz because time is in seconds.

Derived units may conflict with corresponding base units. For example, the model may define time in milliseconds, but frequencies may be in terahertz. In this case, the scope of derived unit is the derived unit itself, and the scope of base unit is all the units (base units and all its derived units) except the redefined derived units. For instance, if model only redefines time in milliseconds and only frequencies in terahertz, then frequencies shall be expressed in terahertz, time shall be expressed in milliseconds, and velocities in meter per milliseconds.

5.5.5.13 Component shape

5.5.5.13.1 Overview

Table 7 lists the shapes supported by this document to model the shape of a component.

Table 7—List of component shapes supported

Name	Reference (subclause)
point	5.5.5.13.2
line	5.5.5.13.3
circle	5.5.5.13.4
sphere	5.5.5.13.5
polygon	5.5.5.13.6
box	5.5.5.13.7
cylinder	5.5.5.13.8
cone	5.5.5.13.9

5.5.5.13.2 point

A point is defined by at least one space dimension, and at most three space-coordinates, and a time-coordinate.

5.5.5.13.3 line

A line is a sequence of points. The points within the sequence shall have the same number of dimensions.

5.5.5.13.4 circle

A circle is a point defining its center and a radius. The point shall have at least two space coordinates and may have a time coordinate.

5.5.5.13.5 sphere

A sphere is a point defining its center and a radius. The point shall have three space-coordinate and may have a time-coordinate.

5.5.5.13.6 polygon

A polygon shall have more than three points, and each point shall have at least two space-coordinates and may have a time-coordinate.

5.5.5.13.7 box

A box shall have one point defining its center and shall have three space coordinates and may have a time-coordinate. The box shall have a size which shall have three space coordinates and may have a time-coordinate.

5.5.5.13.8 cylinder

A cylinder shall have one point defining its center and shall have three space coordinates and may have a time-coordinate. The cylinder shall have a height and a radius which shall have three dimensions and may have a time-coordinate.

5.5.5.13.9 cone

A cone shall have one point defining its apex and shall have three space coordinates and may have a time-coordinate. The cone shall have a height and a radius which shall be of three dimensions and may have a time-coordinate.

6. Nanoscale and molecular communication YANG model definition

6.1 Overview

Clause 6 defines the nanoscale and molecular communication YANG model for use with NETCONF in TCP/IP. It defines the operation and management of nanoscale communication systems based on the specifications of 5.3, 5.4, and 5.5.

Within Clause 6, the words *element* and *group* are defined in 46.2 of IEEE Std 802.1Qcc™ [B3]. The word *element* refers to a single item of information used for configuration. The word *group* refers to a collection of related elements. Groups are organized hierarchically, such that a group can be contained within another group. A single low-level group can be contained within multiple higher-level groups.

The YANG specifications provide YANG text for each group of elements. Each configuration element is specified using a YANG *leaf*. In addition to the *leaf*'s data type, the YANG text provides substatements, such as *range* of valid values, *description*, and so on. The YANG specifications in this subclause are intended for use within a protocol's complete YANG module. The YANG specifications use a YANG *grouping* where applicable, to facilitate reuse in a YANG module.

NOTE—The YANG text in subclauses below are provided as snippets, and not a complete YANG module. A nanoscale communication system may use the snippets as is, or as part of a complete YANG module. A nanoscale communication system may reuse YANG groupings in external YANG modules. Such YANG modules shall contain additional features that are not specified in these subclauses.

In the following YANG modules, should any discrepancy between the YANG description statement and the corresponding definition in the clauses of this standard occur, the definitions in the clauses shall take precedence over YANG description statements.

6.2 Structure of nanoscale and molecular communication YANG models

6.2.1 Overview

The nanoscale and molecular communication YANG models comprise the following set of modules, as defined in Clause 5:

- The `ieee1906-dot1-types` YANG module provides definitions from IEEE Std 1906.1-2015 and defines the set of types of components (see 5.3), and the condition to extend IANA and IEEE 802.1 definitions of network interface to enable nanoscale communications.
- The `ieee1906-dot1-metrics` YANG module provides definitions from IEEE Std 1906.1-2015 and defines the set of metrics (see 5.4) used to correspond to types of components defined in 6.2.2.
- The `ieee1906-dot1-components` YANG module provides definitions of mandatory and optional attributes used to validate a biological model and declare whether it conforms with IEEE 1906.1 framework (see 5.5.4).
- The `ieee1906-dot1-definitions` YANG module provides definitions to conform with IEEE 1906.1 framework Clause 4: transmitter, message, medium, receiver, non-standard physics, and nanoscale component definition.
- The `ieee1906-dot1-system` YANG module provides definition of a nanoscale system as component-containing mandatory components and definitions from IEEE Std 1906.1-2015; The `ieee1906-dot1-si-units` YANG module provides definitions of physical quantities and their respective fundamental and derived units and dimensions, as per the International Bureau of Weights and Measures.
- The `ieee1906-dot1-properties` YANG module helps nanoscale models adapt SI units to the scale of such systems (see 5.5.5).
- The `ieee1906-dot1-thermodynamics` YANG module bridges SI units with metrics and provides a set of formal metrics and equations regarding thermodynamics.
- The `ieee1906-dot1-information` YANG module bridges SI units with metrics and provides a set of formal metrics and equations pertaining to the theory of information (e.g., bandwidth, density, etc.).
- The `ieee1906-dot1-math` YANG module provides formal mathematical definitions used within the metrics of the IEEE 1906.1 framework.
- The `ieee1906-dot1-function` YANG module provides the formal definition of a number and a variable for the IEEE 1906.1 framework as defined in 4.4, 4.6.2, and 4.6.3.

Each YANG module corresponds to a logical goal as shown in Figure 12 to allow selective YANG support for the operating mode, or nanoscale function achieved by the molecular communication system. Arrows indicate a relationship from an importing module toward the imported module. Biological models reuse and implement or augment the ieee1906-dot1-components YANG module.

NOTE 1—Other engineering and scientific fields may add their own modules to extend this family of metrics.

NOTE 2—These modules may use YANG units and data types instead of SI units.

NOTE 3—Note that functions and math are in separate abstractions, and SI units are physical aspects of these concepts.

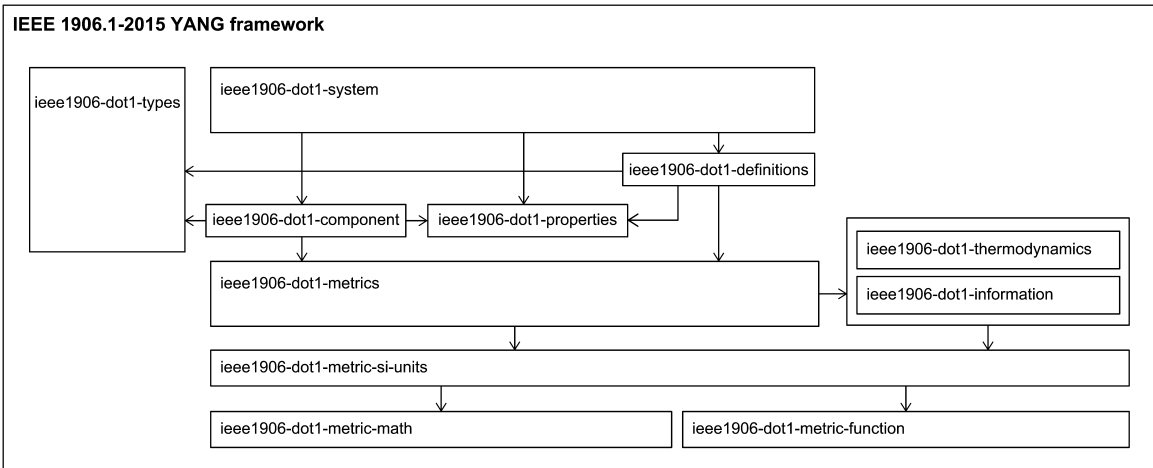


Figure 12—YANG module relationship

Table 8 summarizes the object groups required for each operating mode or function. The basic YANG module shall comply with the YANG conformance section for the operating mode or function supported.

Table 8—YANG module

Name	Conformance	Reference (subclause)
ieee1906-dot1-types	M	6.2.2
ieee1906-dot1-metrics	M	6.2.3
ieee1906-dot1-components	M	6.2.4
ieee1906-dot1-system	M	6.2.5
ieee1906-dot1-definitions	M	6.2.6
ieee1906-dot1-si-units	M	6.2.7
ieee1906-dot1-properties	O	6.2.8
ieee1906-dot1-thermodynamics	M	6.2.9
ieee1906-dot1-information	M	6.2.10
ieee1906-dot1-math	O	6.2.11
ieee1906-dot1-function	M	6.2.12

Figure 13 shows corresponding UML classes for YANG modules and containers, and their relationships. First layer at the bottom represents the metrics, then second layer represents IEEE 1906.1 definition and components, and adds properties used to represent SI units developed by the metrics. System and types complete the diagram. This figure is simplified, metrics do not expand to their subclasses for example, and all the equations, SI units, functions, and math objects are not represented. Rather, they are expressed in this figure as types for class attributes.

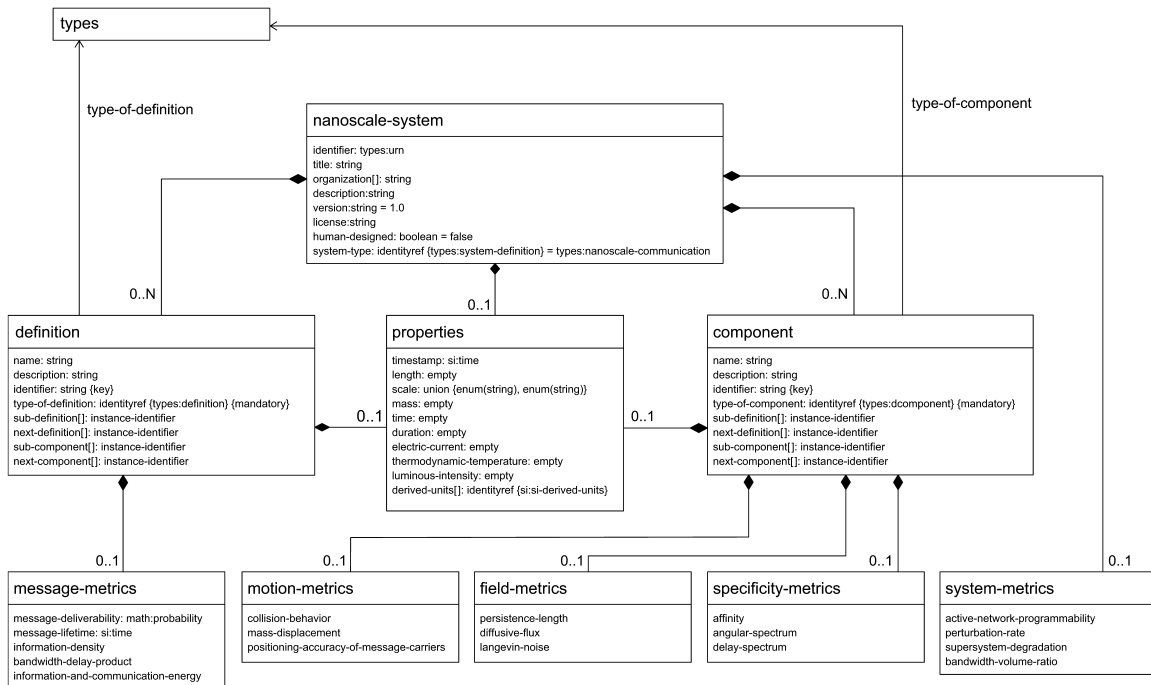


Figure 13—Simplified YANG framework in UML relation notation

6.2.2 Types module

Table 9 shows the structure of the YANG model and the relationship of the YANG objects that constitute the IEEE 1906.1 framework. Specifically, the corresponding YANG module defines IEEE 1906.1 components and definitions. It also defines an IANA interface type to use the framework “out of the box” and define a YANG module that augments an IANA-defined telecommunication interface.