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IEEE Standard Data Model for Nanoscale Communication Systems

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

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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

Approved 24 September 2020

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.
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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]+)?[ij])?
```

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

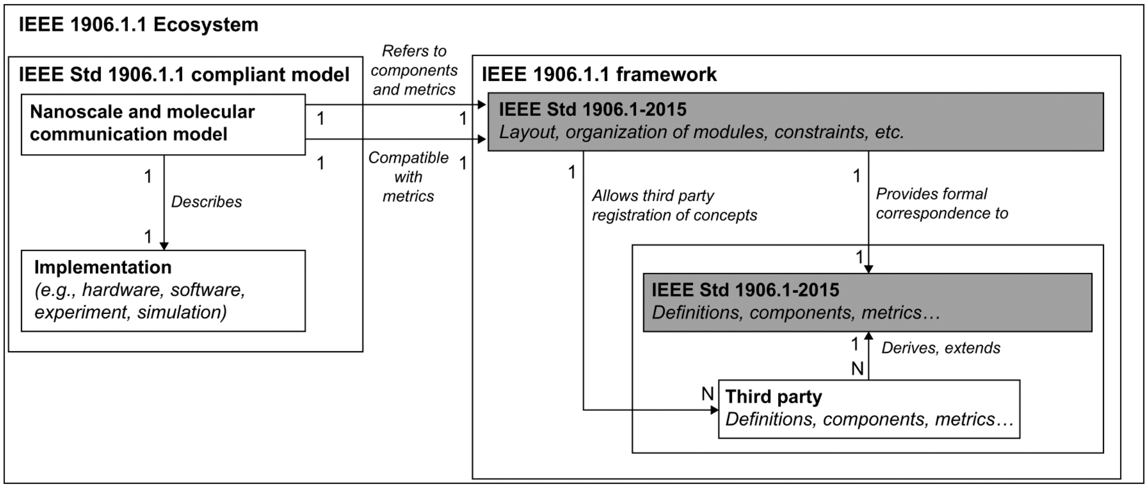

Figure 1—Functional relation between the framework and nanoscale and molecular communication models

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.

a) 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.

b) 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.

c) 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.

d) 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.

e) 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]

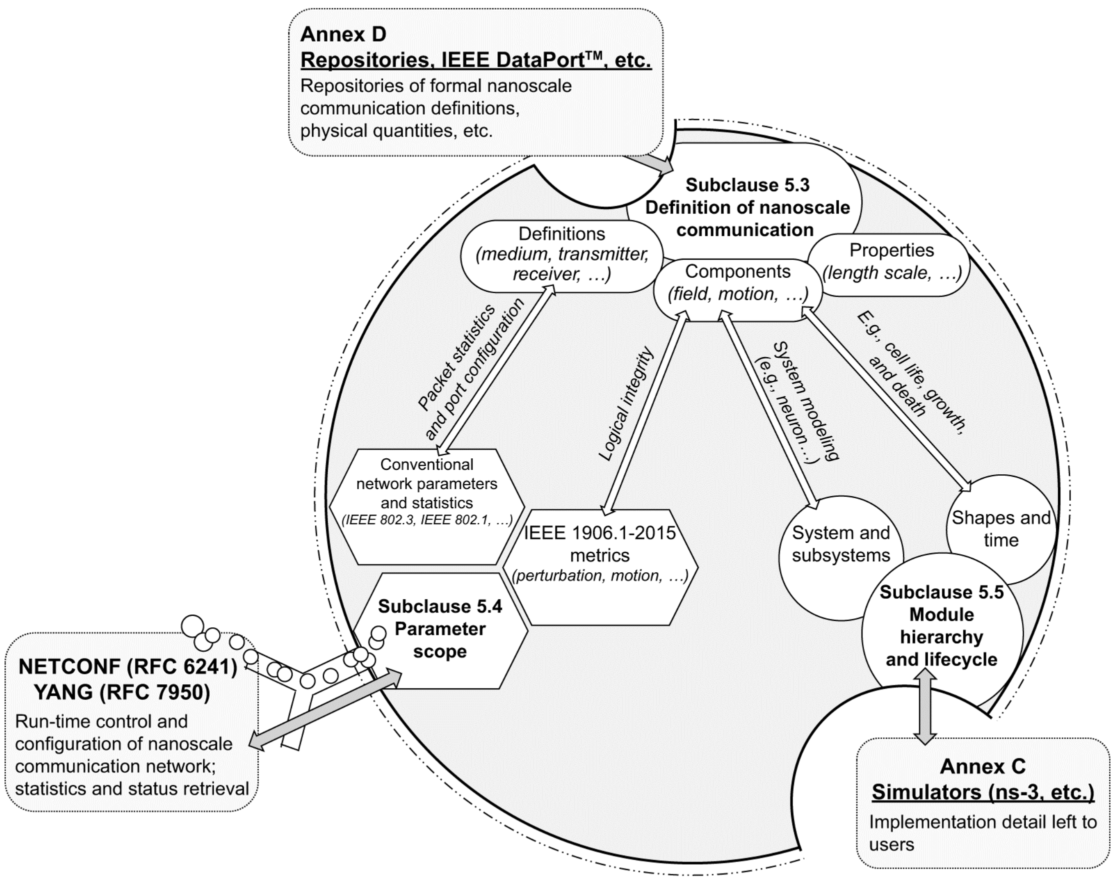

Figure 2—Framework goals and relationships

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 microtubles) 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.

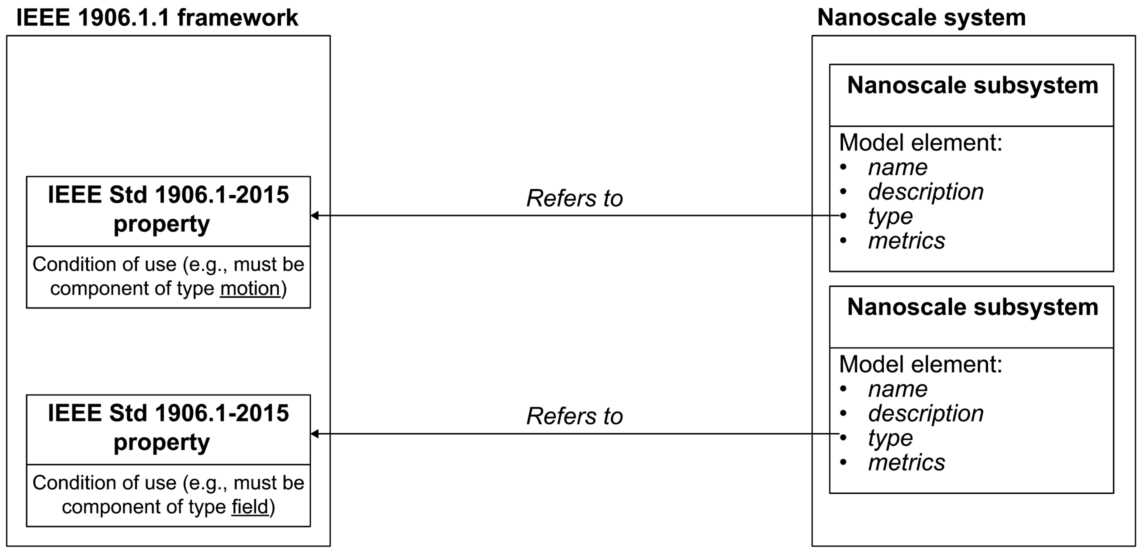

Figure 3—IEEE Std 1906.1-2015 components and definitions are composed of the same set of attributes; only the values differ

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.

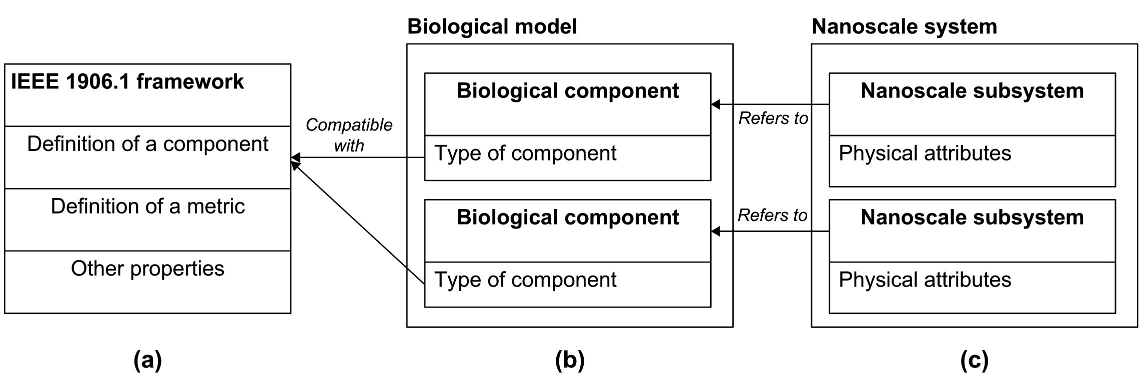

Figure 4—Nanoscale and molecular communication model: (a) framework, (b) biological model, (c) practical implementation

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.

[a]M = Mandatory for nanoscale communication systems, O = optional for nanoscale communication systems

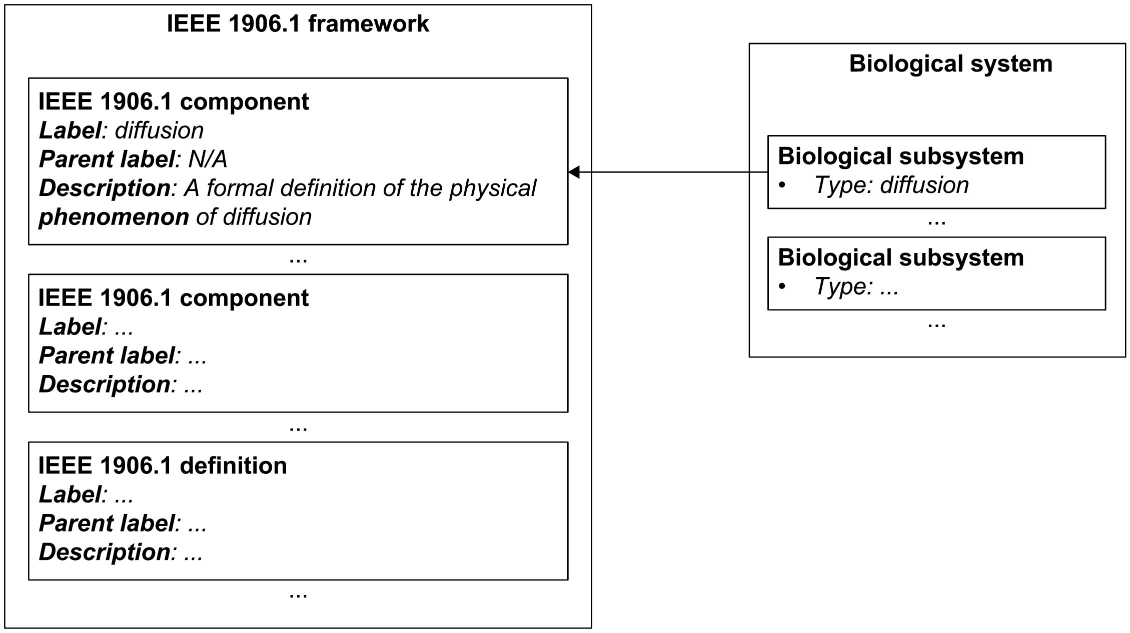

Figure 5—Example use of the framework for component identification

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.

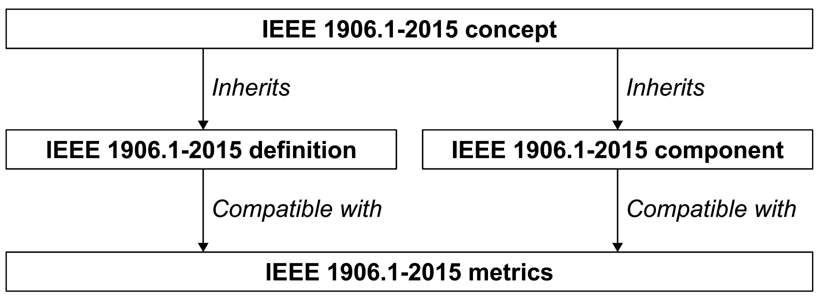

Figure 6—Inheritance within the IEEE 1906.1 framework

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—*message-carrier*, *motion*, *field*, *perturbation*, and *specificity* should name *component* as their parent component to allow future augmentation of the core components. Naming *component* as a parent component for physical implementations or making a nanoscale subsystem refer to these core components and *component* 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.

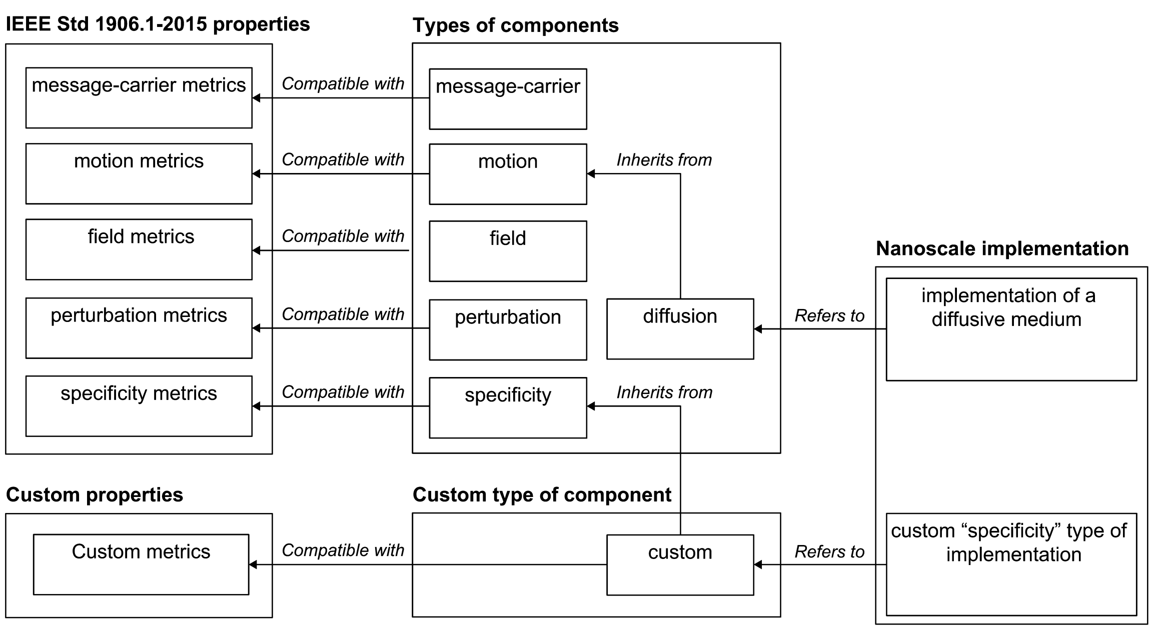

Figure 7—Principles for identifying components

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.

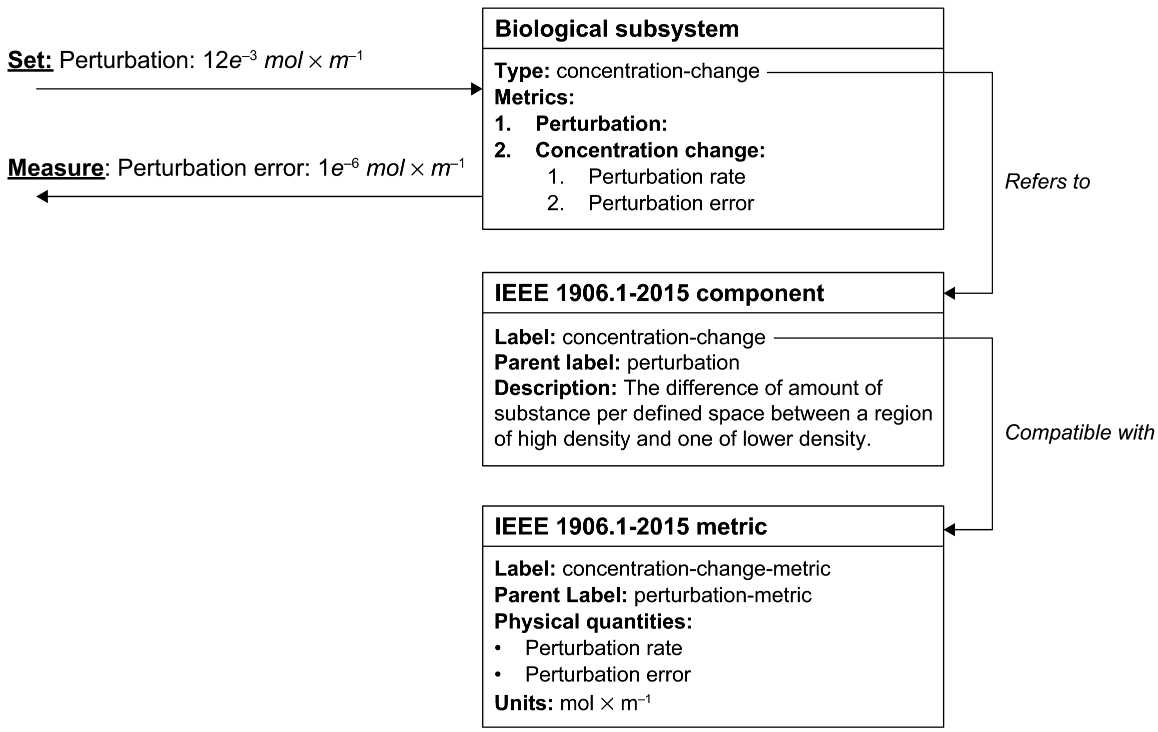

Figure 8—Metrics define the set of physical quantities and units to be exposed

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) A component data structure links to its associated metrics.

b) 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.

[a]M = 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.

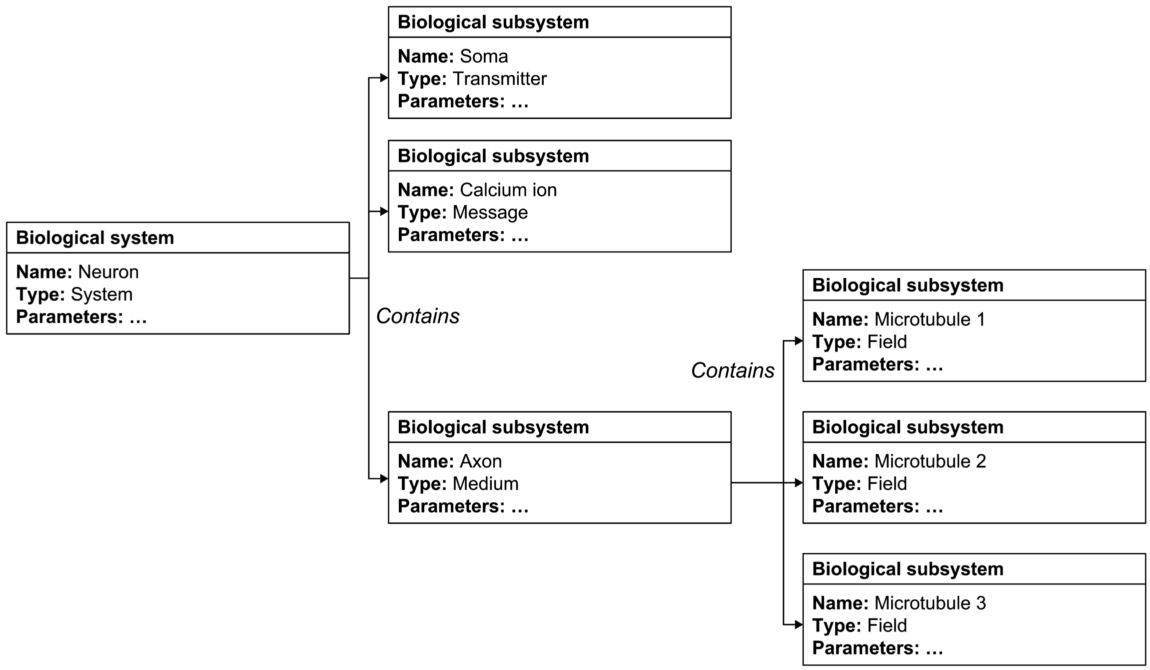

Figure 9—A neuron as a hierarchical system with subsystems referencing IEEE 1906.1 components and definitions

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.

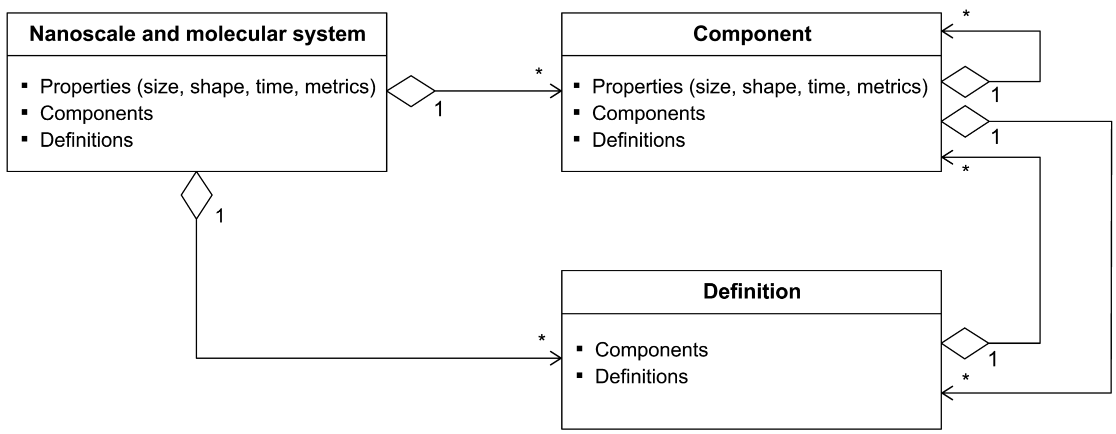

Figure 10 —Framework relationships

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.

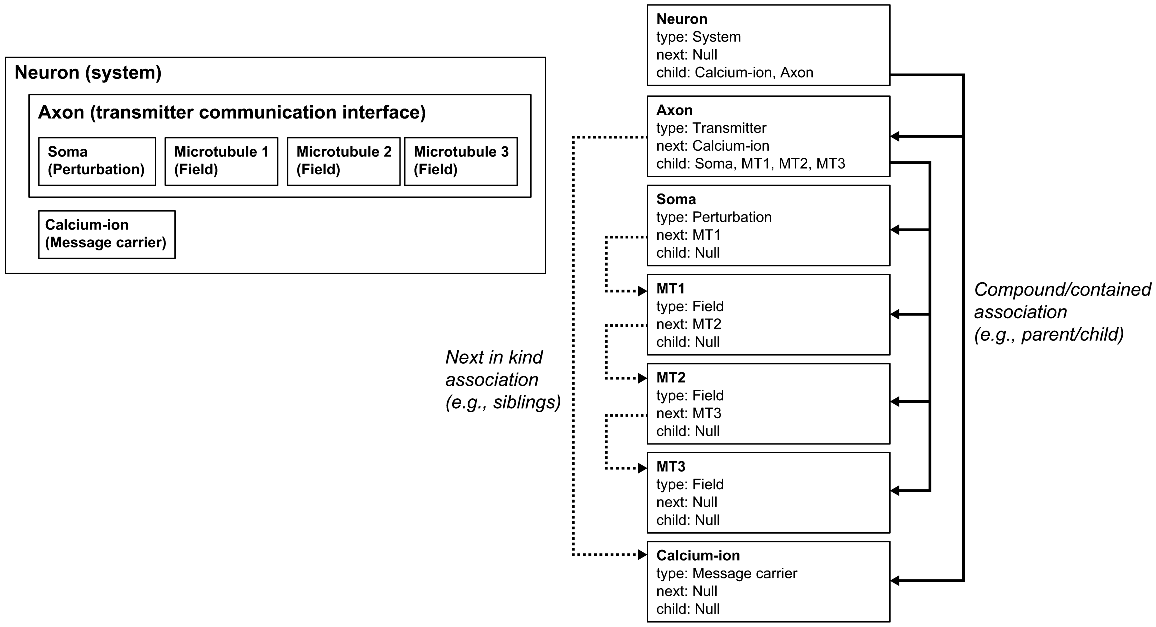

Figure 11—The IEEE 1906.1 framework (unflattened, left) and a list of components (flattened, right)

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

[a]M = 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

[a]M = 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.

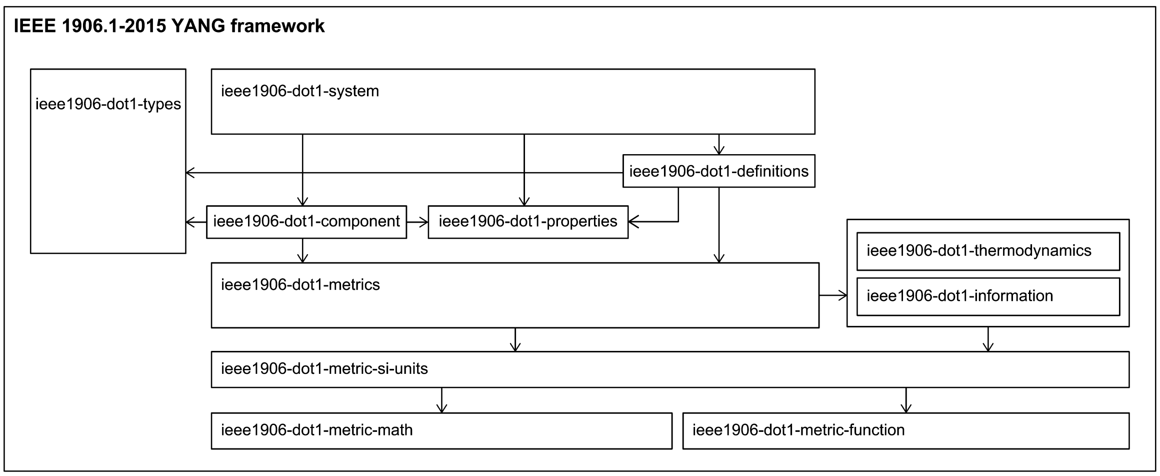

Figure 12—YANG module relationship

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.

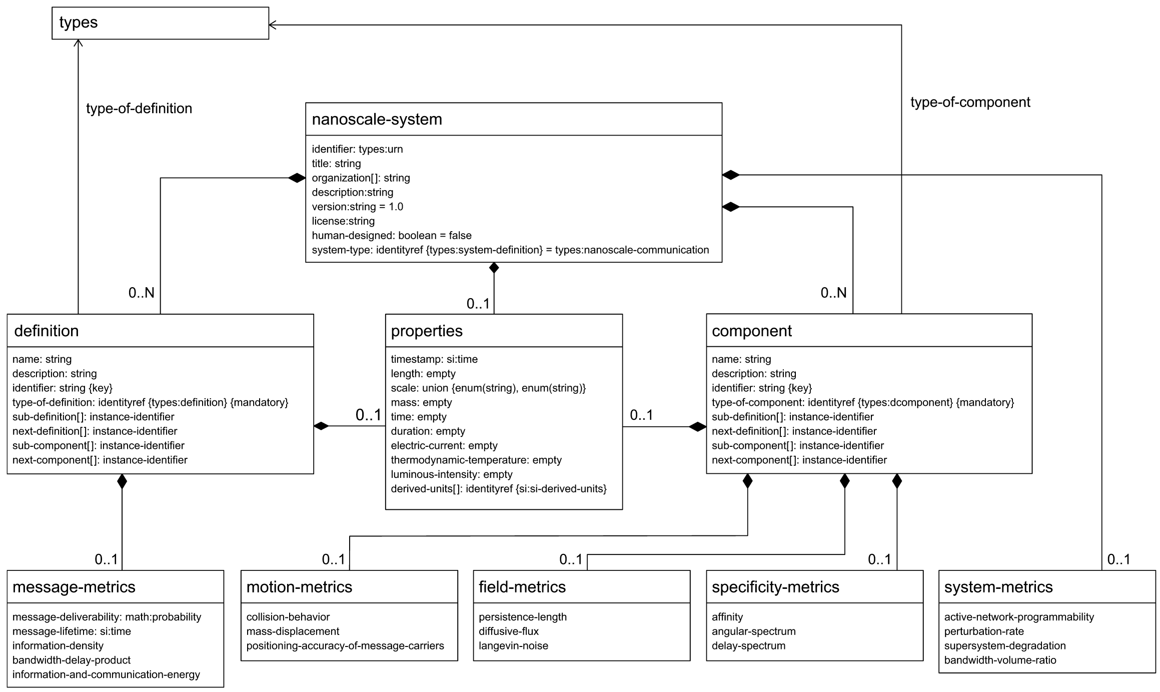

Figure 13—Simplified YANG framework in UML relation notation

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.

Table 9—Types YANG module definition

Name	Definition (subclause)	Reference (subclause)
IEEE 1906.1 message carrier component		
bacterium	5.3.3.3.2	6.5.4.3
calcium-ion		
charge		
electromagnetic-wave		
ligand		
motor		
IEEE 1906.1 motion component		
diffusion	5.3.3.3.2	6.5.4.4
motion		
potential-difference		
walking		
wave-guided		
IEEE 1906.1-2015 field component		
compartmentalized	5.3.3.3.2	6.5.4.5
concentration-gradient		
directional-antenna		
microtubule		
nanostructure-orientation		
IEEE 1906.1 perturbation component		
concentration-change	5.3.3.3.2	6.5.4.6
electrical-current-variation		
electromagnetic-wave-variation		
molecular-structure		
transmission-rate		
IEEE 1906.1 specificity component		
antenna-aperture	5.3.3.3.2	6.5.4.7
receptor-sensitivity		
electrical-charge		
IEEE 1906.1 definitions		
transmitter	Clause 4 of IEEE Std 1906.1-2015	6.5.4.9
receiver		
medium		
message		
non-standard-physics		
component-less-than-100nm		
IEEE 1906.1 system definition		
nanoscale-communication	5.5	6.5.10
IANA interface type		
nanoscale-communication-interface	IANA interface type YANG module (IETF RFC 7224)	6.5.11

6.2.3 Metrics module

Table 10 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 metrics.

Table 10 —Metrics YANG module definition

Name	Definition (subclause)	Reference (subclause)
IEEE 1906.1 message-metrics		
message-deliverability	Subclause 6.1 of IEEE Std 1906.1-2015	6.5.5.3
message-lifetime	Subclause 6.2 of IEEE Std 1906.1-2015	
information-density	Subclause 6.3 of IEEE Std 1906.1-2015	
bandwidth-delay	Subclause 6.4 of IEEE Std 1906.1-2015	
information-and-communication-energy	Subclause 6.5 of IEEE Std 1906.1-2015	
IEEE 1906.1 motion metrics		
collision-behavior	Subclause 6.6 of IEEE Std 1906.1-2015	6.5.5.4
mass-displacement	Subclause 6.7 of IEEE Std 1906.1-2015	
position-accuracy-of-message-carriers	Subclause 6.8 of IEEE Std 1906.1-2015	
IEEE 1906.1 field metrics		
persistence-length	Subclause 6.9 of IEEE Std 1906.1-2015	6.5.5.5
diffusive-flux	Subclause 6.10 of IEEE Std 1906.1-2015	
langevin-noise	Subclause 6.11 of IEEE Std 1906.1-2015	
IEEE 1906.1 specificity metrics		
specificity	Subclause 6.12 of IEEE Std 1906.1-2015	6.5.5.6
affinity	Subclause 6.13 of IEEE Std 1906.1-2015	
sensitivity	Subclause 6.14 of IEEE Std 1906.1-2015	
angular-spectrum	Subclause 6.15 of IEEE Std 1906.1-2015	
delay-spectrum	Subclause 6.16 of IEEE Std 1906.1-2015	
IEEE 1906.1 system metrics		
active-network-programmability	Subclause 6.17 of IEEE Std 1906.1-2015	6.5.5.7
perturbation-rate	Subclause 6.18 of IEEE Std 1906.1-2015	
supersystem-degradation	Subclause 6.19 of IEEE Std 1906.1-2015	
bandwidth-volume-ratio	Subclause 6.20 of IEEE Std 1906.1-2015	

6.2.4 Components module

Table 11 shows the structure of the YANG model and the relationship of the YANG objects required to build a biological model conformant with IEEE Std 1906.1-2015. The module is also connected to types (see 6.2.2) and metrics (6.2.3). The module also defines an IETF interface (https://tools.ietf.org/html/rfc8343) to use the framework “out of the box.”

Table 11—Component YANG module definition

Name	Definition (subclause)	Reference (subclause)
Definition of a component		
name	5.5.4.3	6.5.6
description	5.5.4.4	
identifier	5.5.4.2	
human-designed	Subclause 4.2 in IEEE Std 1906.1-2015	
properties	Subclause 4.2 in IEEE Std 1906.1-2015	
type-of-component	5.5.4.5	
sub-definition	5.5.4.6	
next-definition	5.5.4.7	
sub-component	5.5.4.6	
next-component	5.5.4.7	
motion-metrics	5.3.3.3.2	
field-metrics	5.3.3.3.2	
specificity-metrics	5.3.3.3.2	
Definition of an IETF interface		
nanoscale-interface		6.5.11

6.2.5 System module

Table 12 shows the structure of the YANG model and the relationship of the YANG objects required to build a biological model conformant with IEEE Std 1906.1-2015. The module is also connected to types (see 6.2.2) and metrics (6.2.3). The module also defines “nanoscale-system” used “out of the box” by any model describing such nanoscale system but that does not need to use it as an IETF interface (see 6.2.4).

Table 12 —Component YANG module definition

Name of property	Definition (subclause)	Reference (subclause)
Definition of a system		
title	5.5.4.3	6.5.9
organization	Optional (user-defined)	
contact	Optional (user-defined)	
description	5.5.4.4	
identifier	5.5.4.2	
version	Optional (user-defined)	
license	Optional (user-defined)	
human-designed	Subclause 4.2 of IEEE Std 1906.1-2015	
system-type	Subclause 4.2 of IEEE Std 1906.1-2015	
definitions	5.5.4	
components	5.5.4	
properties	5.5.5	
system-metrics	5.3.3.3.2	
Definition of a nanoscale system		
nanoscale-system	5.5	6.5.10

6.2.6 Definitions

Table 13 shows the structure of the YANG model and the relationship of the YANG objects required to build a biological model conformant with IEEE Std 1906.1-2015. The module is also connected to types (see 6.2.2) and metrics (6.2.3).

Table 13 —Component YANG module definition

Name	Definition (subclause)	Reference (subclause)
Definition of a nanoscale communication definition		
name	5.5.4.3	6.5.8
description	5.5.4.4	
identifier	5.5.4.2	
human-designed	Subclause 4.2 in IEEE Std 1906.1-2015	
properties	5.5.5	
type-of-definition	5.5.4.5	
sub-definition	5.5.4.6	
next-definition	5.5.4.7	
sub-component	5.5.4.6	
next-component	5.5.4.7	

6.2.7 SI units module

The structure of the YANG model and the relationship of the YANG objects required to define IEEE 1906.1 metrics are defined within IEEE Std 1906.1.1-2020 (this standard) and the International Bureau of Weights and Measures.

6.2.8 Properties

Table 14 shows the structure of the YANG model and builds relationship between the YANG objects required to build a biological model conformant with IEEE Std 1906.1-2015 and the SI units defined in 6.2.7.

Table 14—Component YANG module definition

Name of property	Definition (subclause)	Reference (subclause)
timestamp	5.5.5.2	6.5.7
length	5.5.5.3	
scale	5.5.5.4	
mass	5.5.5.5	
time	5.5.5.6	
duration	5.5.5.7	
electric-current	5.5.5.8	
thermodynamic-temperature	5.5.5.9	
amount-of-substance	5.5.5.10	
luminous-intensity	5.5.5.11	
derived-units	5.5.5.12	

6.2.9 Thermodynamics

Table 15 shows the structure of the YANG model and the relationship of the YANG objects required to build metrics regarding the field of thermodynamics.

Table 15—Thermodynamics YANG module definition

Name	Symbol	Units	Equation	Reference (subclause)
flow-velocity	v	$m \times s^{-1}$		6.5.5.1.2
mass-flow-rate	$\dot{m}$	$kg \times s^{-1}$	$\dot{m} = \rho \times Q = \rho \times v \times A = j_m \times A$	6.5.5.1.5
mass-flux	j_m	$kg \times s^{-1} \times m^{-2}$	$j_m = \rho \times v$	6.5.5.1.3
volumetric-flow-rate	Q	$m^3 \times s^{-1}$	$Q = v \times A$	6.5.5.1.4

6.2.10 Information

Table 16 shows the structure of the YANG model and the relationship of the YANG objects required to build metrics regarding the field of information theory.

Table 16—Information YANG module definition

Name	Units	Reference (subclause)
amount-of-information	bit	6.5.5.2.1
bandwidth	bit × s^{-1}	6.5.5.2.2
information-density	bit × m^{-x}	6.5.5.2.3
bandwidth-delay-product	bit	6.5.5.2.4

6.2.11 Mathematics

Table 17 shows the structure of the YANG model and the relationship of the YANG object required to build equations used by the metrics defined by the IEEE 1906.1 framework.

Table 17—Mathematics YANG module definition

Name	YANG data type	Reference (subclause)
Optional formal YANG data types		
equation	extension	6.5.2
expression	extension	6.5.2
name	extension	6.5.2

6.2.12 Function

Table 18 shows the structure of the YANG model and the relationship of the YANG object required to build equations used by the metrics defined by the IEEE 1906.1 framework.

Table 18—Function YANG module definition

Name	YANG data type	Reference (subclause)
name	annotation	6.5.2
number	typedef	6.5.2
variable-name	typedef	6.5.2
variable	typedef	6.5.2

6.3 Relationship to other YANG modules

6.3.1 Overview

Nanoscale and molecular communications are designed to operate within classical networks. The YANG modules defined in this standard are designed to operate in conjunction with YANG modules defined by the IETF, IEEE Std 802™, and other standards bodies.

6.3.2 Relationship to YANG data modeling language

Language extension is a feature used by the framework. The IEEE 1906.1 framework defines a new set of statements, for example to link a symbol to a physical dimension (such as "A" for ampere), or to associate a physical value to a SI unit. Extensions are being defined by the framework so that the corresponding keyword may be imported in and reused by other YANG modules.

6.3.3 Relationship to metadata with YANG

This framework implements IETF RFC 7952 regarding the use of metadata with YANG. Metadata is used to enrich the data model of IEEE Std 1906.1 by providing physical dimensions as YANG types regardless of the unit. By default, *units* statement in YANG (IETF RFC 7950) is the fundamental unit of the associated physical dimension, however, it is possible to express a value *si:unit* in XML or JSON format associated to the corresponding YANG type in any of the valid SI units associated to that physical dimension (e.g., nanometer, micrometer, millimeter).

CAUTION

Please note that YANG statement is *units*, and this standard, IEEE Std 1906.1.1, uses *unit* as YANG extension. XML and JSON annotations specifying SI units shall use *unit* to pass YANG validation.

XML RPCs and JSON RPCs should provide metadata specifying relevant units to IEEE Std 1906.1-2015, when required. For use of metadata, please refer to IETF RFC 7951 and IETF RFC 7952.

6.3.4 Relationship to IETF YANG modules

ieee-1906-dot1-components.yang is the YANG module providing augmentation to IETF interfaces. The YANG framework explicitly infers YANG *augment* statement to add nanoscale-related parameter to existing IETF interface YANG module. YANG *when* statement controls that the nanoscale system declares itself as an IANA-registered interface type (see 6.3.5) in order to accept augmentation to existing module.

6.3.5 Relationship to IANA YANG modules

The following entry has been made to the IANA ifType and transmission number registries:

Decimal: 299
Name: ieee19061nanocom
Description: Nanoscale and Molecular Communication
Reference: [IEEE Std 1906.1-2015][Stephen F Bush]

NOTE 1—Please see https://www.iana.org/assignments/smi-numbers.

NOTE 2—Please see the corresponding management information base (MIB) and YANG modules: https://www.iana.org/assignments/ianaiftype-mib and https://www.iana.org/assignments/yang-parameters.

6.4 Security considerations for quantum communications−based YANG modules

The YANG modules defined in Clause 6 are designed to be accessed via a network configuration protocol, e.g., NETCONF protocol (IETF RFC 6536). In the case of NETCONF, the lowest NETCONF layer is the secure transport layer and the mandatory-to-implement secure transport is SSH. The NETCONF access control model provides the means to restrict access for particular NETCONF users to a preconfigured subset of all available NETCONF protocol operations and content.

It is the responsibility of a system's implementor and administrator to ensure that the protocol entities in the system that support NETCONF, and any other remote configuration protocols that make use of these YANG modules, are properly configured to allow access only to those principals (users) that have legitimate rights to read or write data nodes. This standard does not specify how the credentials of those users are to be stored or validated.

6.5 Nanoscale and molecular communication YANG snippets

6.5.1 Introduction

NOTE—The YANG text in this document shall be the text of the YANG module. Thus, edits made to the YANG text in this document shall be reflected in any YANG modules claiming to conform with this standard. This note shall be removed once the YANG model has been completed.

6.5.2 Definition of numbers, symbols, and variables

```
typedef number{
    type string
    {
        pattern '[-+]?[0-9]*\.?[0-9]+([eE][-+]?[0-9]+)?(\s*[-+]\s*[0-
                 9]*\.?[0-9]+([eE][-+]?[0-9]+)?[ij])?';
    }

    description "A generic representation of a number. This type does
                 not make assumptions about precision
                 (simple, double etc., decimal32, 64) on the target
                 computer.

                 The number format is a string; the implementation
                 is expected to have parsing options to convert this
                 value into an appropriate format on the target system.
                 For example, Python is flexible enough to
                 convert such a string to a float.

                 Examples of numbers that can be represented with this
                 type:
                 -1, 2, 0, +4.5e4, -.5e4, -1.2e-5, 0.34, -5.6e-4 –16e3j


                 This generic representation of a number is designed
                 to express any physical measure without the need for
                 specifying numerical representation (such as
                 fraction-digit in the decimal64 type). This enables
                 reuse of 'mass' to express 'mass of the Sun' or a
                 'mass of a proton' by keeping the same fundamental
                 unit.";
  }

extension symbol {
    argument symbol-name;
```

```
    description "To provide a name that represents this type.
                 Adds nothing to a NETCONF server.
                 Refer to RFC 7950 for description of the
                 'extension' keyword";
}

typedef variable {
    type union
    {
      type number;
      type string {  pattern '[A-Za-z._:][A-Za-z0-9._:]*';  };
    }

    description "A variable is a mathematical or physical entity that
                 refers to either a number for constants, or a
                 name for variables.

                 This union helps assign or retrieve values based on
                 numbers or abstract names. Namespace design requires
                 special care as name conflict mitigation is outside
                 the scope of this YANG model. For example, a namespace
                 conflict shall be solved by using dots or underscores
                 (see YANG 1.1 instance-reference for XPath resolution).

                 The NETCONF server should return an <rpc-error> with
                 an error of type 'bad-element' if the variable name
                 cannot be retrieved.";
}
```

6.5.3 Definitions of SI units

6.5.3.1 Overview

The following YANG snippets provide definitions of the International System of Units.

6.5.3.2 Definition of YANG extensions and annotations

These snippets extend the use of YANG beyond the generic “units” statement to help metamodeling by adding attributes to data format elements (i.e., XML or JSON), to validate that equations are well balanced, and to let implementations define their units while keeping only one definition of a unit.

For instance, an astronomical and a nanoscale length cover the same SI dimension. However, to improve user friendliness, nanoscale lengths would redefine units as a nanometer rather than using fundamental units as meter. If no unit is provided, or the implementation does not support this YANG extension, then the SI fundamental unit is assumed. An XML snippet redefining the length and making use of YANG annotation follows:

`<length units = "nanometer">12</length>` or `<length units = "nm">12</length>`

```
extension units {
    argument name;
    description "To provide a unit to logical functions, such as
                 groupings, a container made of leaves, and have
                 a unit of its own.";
```

```
}

extension derived-units {
    argument name;
    description "This extension allows the use of an SI (or even a non-
                 SI) unit for a physical concept.

                 This helps a NETCONF server accept different scales
                 or orders of magnitude with the same meaning. For
                 example, length can be expressed as 'astronomical-
                 units' or 'picometers'. If the NETCONF server supports
                 the translation between units this should not
                 raise an <rpc-error>. A server fails to perform
                 this translation either:
                   1. Because it does not support the corresponding
                      mapping,
                   2. Because the unit provided is wrong (a client
                      specifying a distance in kg).

                 The NETCONF node SHALL return an <rpc-error> with a
                 <bad-attribute> element specifying that it could not
                 perform the conversion.

                 YANG nodes allowing this extension should be a leaf or
                 list-leaf only. When using this extension in the
                 YANG leaf or list-leaf definition:
                   1. Use unit names only, not symbols.
                   2. Do not add prefixes as they should be
                      implicitly understood by the NETCONF server.
                   3. Do not add neper, bel, and decibel unless you
                      want to be explicit. For example, loss is
                      unitless and unit should be 'one'. You do not
                      need to use this extension to accept 'dB' as it
                      makes sense for a loss. However, dBm shall be
                      defined in this extension to provide a ratio over
                      1 mW.
                   3. Do not use this extension if the leaf has no unit
                      substatement defined.

                 This extension should not be part of a container or a
                 list because there can be inconsistency between
                 the leaves and the container.

                 This extension helps the user only to use different SI
                 and non-SI units for the same YANG type. This
                 extension does not provide conversion between the
                 units and the NETCONF server should not rely on this
                 extension to perform validation.

                 This extension should be used with an annotation,
                 allowing the client to insert an XML attribute
                 specifying the unit attached to the value it provides.
                 If the attribute is not specified, then the
                 fundamental unit expressed in the unit substatement of
                 the containing YANG leaf shall be used.

                 When the client uses an XML attribute requesting a
```

```
                 change of units, the client should use names, but may
                 use symbols. The client should use SI prefix names,
                 but may use SI prefix symbols instead (the charset for
                 Greek letters may not be supported on the server).";
}

md:annotation unit{
    type string;
    description "This annotation defines the unit of the containing
                 type if it is not the unit specified in the units
                 substatement of the corresponding type. For instance,
                 an astronomical distance can be expressed in 'au'
                 (astronomical units), or in 'pm' or even in petameter.

                 A pattern is not provided for this annotation because
                 it is suggested to follow the SI recommendation.
                 Units:
                   1. Should have an SI or non-SI unit name
                   2. May have an SI or non-SI symbol name
                   3. Should have (if needed) SI prefix names (only if
                      unit names are used)
                   4. Might have SI prefix symbols (only if symbol
                      names are used)
                   5. Can be (if needed) np (neper logarithm), bel,
                      decibel, or dB.

                 Several examples lead to the same definition:
                 <transmitter nc:operation='create'>
                   <axial-length>1.2e-11</axial-length>
                 </transmitter>

                 <transmitter nc:operation='create'>
                   <axial-length sc:unit='nanometer'>12</axial-length>
                 </transmitter>

                 <transmitter nc:operation='create'>
                   <axial-length sc:unit='nm'>12</axial-length>
                 </transmitter>";
}
```

6.5.3.3 SI prefix definitions

```
identity si-prefix {
    description "An SI prefix appended to a unit to denote a factor
                 value to apply to the corresponding type.
                 NOTE: Do not use this identity directly. Instead, use
                 this identity as a base for any SI prefix.";
}

identity deca {
    base "si-prefix";
    ieee1906-dot1-math:symbol "da";
    description "Factor 10";
}

identity hecto {
    base "si-prefix";
```

```
        ieee1906-dot1-math:symbol "h";
        description "Factor 1e2";
    }

    identity kilo {
        base "si-prefix";
        ieee1906-dot1-math:symbol "k";
        description "Factor 1e3";
    }

    identity mega {
        base "si-prefix";
        ieee1906-dot1-math:symbol "M";
        description "Factor 1e6";
    }

    identity giga {
        base "si-prefix";
        ieee1906-dot1-math:symbol "G";
        description "Factor 1e9";
    }

    identity tera {
        base "si-prefix";
        ieee1906-dot1-math:symbol "T";
        description "Factor 1e12";
    }

    identity peta {
        base "si-prefix";
        ieee1906-dot1-math:symbol "P";
        description "Factor 1e15";
    }

    identity exa {
        base "si-prefix";
        ieee1906-dot1-math:symbol "E";
        description "Factor 1e18";
    }

    identity zetta {
        base "si-prefix";
        ieee1906-dot1-math:symbol "Z";
        description "Factor 1e21";
    }

    identity yotta {
        base "si-prefix";
        ieee1906-dot1-math:symbol "Y";
        description "Factor 1e24";
    }

    identity deci {
        base "si-prefix";
        ieee1906-dot1-math:symbol "d";
        description "Factor 1e-1";
    }
```

```
identity centi {
    base "si-prefix";
    ieee1906-dot1-math:symbol "c";
    description "Factor 1e-2";
}

identity milli {
    base "si-prefix";
    ieee1906-dot1-math:symbol "m";
    description "Factor 1e-3";
}

identity micro {
    base "si-prefix";
    ieee1906-dot1-math:symbol "µ";
    description "Factor 1e-6";
}

identity nano {
    base "si-prefix";
    ieee1906-dot1-math:symbol "n";
    description "Factor 1e-9";
}

identity pico {
    base "si-prefix";
    ieee1906-dot1-math:symbol "p";
    description "Factor 1e-12";
}

identity femto {
    base "si-prefix";
    ieee1906-dot1-math:symbol "f";
    description "Factor 1e-15";
}

identity atto {
    base "si-prefix";
    ieee1906-dot1-math:symbol "a";
    description "Factor 1e-18";
}

identity zepto {
    base "si-prefix";
    ieee1906-dot1-math:symbol "z";
    description "Factor 1e-21";
}

identity yocto {
    base "si-prefix";
    ieee1906-dot1-math:symbol "y";
    description "Factor 1e-24";
}
```

6.5.3.4 Definition of SI dimensions

```
identity meter {
    ieee1906-dot1-math:symbol "m";
    description "Fundamental unit of distance.";
}

identity gram {
    ieee1906-dot1-math:symbol "g";
    description "Unit of mass.";
}

identity second {
    ieee1906-dot1-math:symbol "s";
    description "Fundamental unit of time.";
}

identity ampere {
    ieee1906-dot1-math:symbol "A";
    description "Fundamental unit of electric current.";
}

identity kelvin {
    ieee1906-dot1-math:symbol "K";
    description "Fundamental unit of thermodynamic temperature.";
}

identity mole {
    ieee1906-dot1-math:symbol "mol";
    description "Fundamental unit of amount of substance.";
}

identity candela {
    ieee1906-dot1-math:symbol "cd";
    description "Fundamental unit of luminous intensity.";
}
```

6.5.3.5 Definition of SI base units

```
typedef length {
    type ieee1906-dot1-function:variable;
    units meter;
    ieee1906-dot1-si-units:derived-units  "astronomical-unit  bohr-radius
angstrom nautical-mile";
    description "The meter is the length of the path travelled by light
                 in vacuum during a time interval of 1/299 792 458 of a
                 second.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.1";
}

typedef mass {
    type ieee1906-dot1-function:variable;
    units kilogram;
    ieee1906-dot1-si-units:derived-units "tonne dalton electron-mass";
    description "The kilogram is the unit of mass; it is equal to the
```

```
                 mass of the international prototype of the kilogram.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.2";
}

typedef time {  // duration
    type ieee1906-dot1-function:variable;
    units second;
    ieee1906-dot1-si-units:derived-units "day hour minute quantum-of-
                                          time atomic-unit-of-time";
                                          // natural unit of time,
                                          planck time
    description "The second is the duration of 9 192 631 770 periods of
                 the radiation corresponding to the transition between
                 the two hyperfine levels of the ground state of the
                 cesium 133 atom.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.3";
}

typedef electric-current {
    type ieee1906-dot1-function:variable;
    units ampere;
    description "The ampere is that constant current which, if
                 maintained in two straight parallel conductors of
                 infinite length, of negligible circular cross-section,
                 and placed 1 meter apart in vacuum, would produce
                 between these conductors a force equal to 2 × 10^-7
                 newton per meter of length.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.4";
}

typedef thermodynamic-temperature {
    type ieee1906-dot1-function:variable;
    units kelvin;
    description "The kelvin, unit of thermodynamic temperature, is the
                 fraction 1/273.16 of the thermodynamic temperature of
                 the triple point of water.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.5";
}

typedef amount-of-substance {
    type ieee1906-dot1-function:variable;
    units mole;
    description "1. The mole is the amount of substance of a system
                 which contains as many elementary entities as there
                 are atoms in 0.012 kilogram of carbon 12; its symbol
                 is 'mol.'
                 2.  When  the  mole  is  used,  the  elementary  entities
shall
                    be specified and may be atoms, molecules, ions,
                    electrons, other particles, or specified groups of
                    such particles.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.6";
```

```
}

typedef luminous-intensity {
    type ieee1906-dot1-function:variable;
    units candela;
    description "The candela is the luminous intensity, in a given
                 direction, of a source that emits monochromatic
                 radiation of frequency 540 × 10^12 hertz and that has
a
                 radiant intensity in that direction of 1/683 watt per
                 steradian.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.1.1.7";
}
```

6.5.3.6 Definition of SI-derived units

```
typedef area {
    type ieee1906-dot1-function:variable;
    units meter^2;
    ieee1906-dot1-si-units:derived-units "hectare barn";
    description "A measure of the total area occupied by the surface of
                 a physical body";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef volume {
    type ieee1906-dot1-function:variable;
    units meter^3;
    ieee1906-dot1-si-units:derived-units "liter";
    description "A measure of the total volume within the surface of a
                 physical body.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef velocity {  // speed
    type ieee1906-dot1-function:variable;
    units meter/second;
    ieee1906-dot1-si-units:derived-units knot;
    description "A measure of the length of the path travelled by a
                 physical body during a time interval of 1 second.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef acceleration {
    type ieee1906-dot1-function:variable;
    units meter/second^2;
    ieee1906-dot1-si-units:derived-units gal;
    description "A measure of the change in velocity of a physical body
                 during a time interval of 1 second.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}
```

```
typedef wavenumber {
    type ieee1906-dot1-function:variable;
    units meter^-1;
    description "Derived unit expressed in terms of base units: m^-1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef mass-density { //density
    type ieee1906-dot1-function:variable;
    units kilogram/meter^3;
    description "Derived unit expressed in terms of base units: kg m^3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef surface-density {
    type ieee1906-dot1-function:variable;
    units kilogram/meter^2;
    description "Derived unit expressed in terms of base units: kg m^-2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef specific-volume {
    type ieee1906-dot1-function:variable;
    units meter^3/kilogram;
    description "Derived unit expressed in terms of base units: m^3 kg^-
1";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef current-density {
    type ieee1906-dot1-function:variable;
    units ampere/meter^2;
    description "Derived unit expressed in terms of base units: A m^-2";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef magnetic-field-strength {
    type ieee1906-dot1-function:variable;
    units ampere/meter;
    ieee1906-dot1-si-units:derived-units oersted;
    description "Derived unit expressed in terms of base units: A m^-1. ";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef amount-concentration { // concentration
    type ieee1906-dot1-function:variable;
    units mole/meter^3;
    description "Derived unit expressed in terms of base units: mol m^-3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}
```

```
typedef mass-concentration {
    type ieee1906-dot1-function:variable;
    units kilogram/meter^3;
    description "Derived unit expressed in terms of base units: kg m^-3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
  }

typedef luminance {
    type ieee1906-dot1-function:variable;
    units candela/meter^2;
    ieee1906-dot1-si-units:derived-units stilb;
    description "Derived unit expressed in terms of base units: cd m^-2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}

typedef refractive-index {
    type ieee1906-dot1-function:variable;
    units one;
    description "Derived unit expressed in terms of base units: 1.
[v]alues of quantities with unit one, are expressed simply as
numbers.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
  }

typedef relative-permeability {
    type ieee1906-dot1-function:variable;
    units one;
    description "Derived unit expressed in terms of base units: 1.
[v]alues of quantities with unit one, are expressed simply as
numbers.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.1";
}
```

6.5.3.7 Definition of SI-derived units with special names and symbols

```
typedef plane-angle {
    type ieee1906-dot1-function:variable;
    units one;
    ieee1906-dot1-si-units:derived-units "radian degree minute second";
    description "Derived unit expressed in terms of base units: 1.
[V]alues of quantities with unit one, are expressed simply as
numbers. [P]lane angle, radian, rad = m/m.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef solid-angle {
    type ieee1906-dot1-function:variable;
    units one;
    ieee1906-dot1-si-units:derived-units steradian;
    description "Derived unit expressed in terms of base units: 1.
[V]alues of quantities with unit one, are expressed simply as
```

```
numbers. [S]olid angle, steradian, sr = m^2/m^2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef frequency {
    type ieee1906-dot1-function:variable;
    units second^-1;
    ieee1906-dot1-si-units:derived-units hertz;
    description "Derived unit expressed in terms of base units: s^-1.
[F]requency, hertz, Hz = s^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
  }

typedef force {
    type ieee1906-dot1-function:variable;
    units kilogram.meter/second^2;
    ieee1906-dot1-si-units:derived-units "newton dyne";
    description "Derived unit expressed in terms of base units: kg m
s^-2. [F]orce, newton, N = kg m s−2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef pressure { // stress
    type ieee1906-dot1-function:variable;
    units kilogram/meter.second^2;
    ieee1906-dot1-si-units:derived-units "pascal bar mmHg";
    description "Derived unit expressed in terms of base units: kg m^-1
s^2. [P]ressure, stress, pascal, Pa = kg m−1 s−2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef energy { //work, amount-of-heat
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^2;
    ieee1906-dot1-si-units:derived-units "joule electronvolt hartree-
                                          energy erg";
    description "Derived unit expressed in terms of base units: kg m^2
s^-2. [E]nergy, work, joule, J = kg m^2 s^−2 N m.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef power { //radiant-flux
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^3;
    ieee1906-dot1-si-units:derived-units watt;
    description "Derived unit expressed in terms of base units: kg m^2
s^-3. [P]ower, radiant flux, watt, W = kg m^2 s^−3 J/s.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-charge {  //amount-of-electricity
```

```
    type ieee1906-dot1-function:variable;
    units ampere.second;
    ieee1906-dot1-si-units:derived-units "coulomb elementary-charge";
    description "Derived unit expressed in terms of base units: A s.
                [C]harge, coulomb, C = A s.";
                reference "The International System of Units: 8th
                Edition 2006. Clause 2.2.2";
}

typedef electric-potential-difference { //electromotiveForce
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^3.ampere;
    ieee1906-dot1-si-units:derived-units volt;
    description "Derived unit expressed in terms of base units: kg m^2
s^-3 A^-1. [E]lectric potential difference, volt, V = kg m^2 s^−3 A^−1,
W/A.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef capacitance {
    type ieee1906-dot1-function:variable;
    units ampere^2.second^4/kilogram.meter^2;
    ieee1906-dot1-si-units:derived-units farad;
    description "Derived unit expressed in terms of base units: A^2 s^4
kg^-1 m^-2. [C]apacitance, farad, F = kg^−1 m^−2 s^4 A^2, C/V.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-resistance {
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^3.ampere^2;
    ieee1906-dot1-si-units:derived-units ohm;
    description "Derived unit expressed in terms of base units: kg m^2
s^-3 A^-2. [E]lectric resistance, ohm, Ω = kg m^2 s^−3 A^−2, V/A.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-conductance {
    type ieee1906-dot1-function:variable;
    units second^3.ampere^2/kilogram.meter^2;
    ieee1906-dot1-si-units:derived-units siemens;
    description "Derived unit expressed in terms of base units: s^3 A^2
kg^-1 m^-2. [E]lectric conductance, siemens, S = kg^−1 m^−2 s^3 A^2,
A/V.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef magnetic-flux {
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^2.ampere;
    ieee1906-dot1-si-units:derived-units "weber maxwell";
    description "Derived unit expressed in terms of base units: kg m^2
s^-2 A^-1. [M]agnetic flux, weber, Wb = kg m^2 s^−2 A^−1, V s.";
```

```
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef magnetic-flux-density {
    type ieee1906-dot1-function:variable;
    units kilogram/second^2.ampere;
    ieee1906-dot1-si-units:derived-units "tesla gauss";
    description "[M]agnetic flux density, tesla, T = kg s^-2 A^-1,
Wb/m^2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef inductance {
    type ieee1906-dot1-function:variable;
    units kilogram.meter^2/second^2.ampere^2;
    ieee1906-dot1-si-units:derived-units henry;
    description "[I]nductance, henry, H = kg m^2 s^-2 A^-2, Wb/A.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef temperature {
    type ieee1906-dot1-function:variable;
    units kelvin;
    ieee1906-dot1-si-units:derived-units "celsius fahrenheit";
    description "Celsius temperature, degree Celsius, deg C = K.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef luminous-flux {
    type ieee1906-dot1-function:variable;
    units candela.steradian;
    ieee1906-dot1-si-units:derived-units lumen;
    description "[L]uminous flux, lumen, lm = cd sr, cd sr.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef illuminance {
    type ieee1906-dot1-function:variable;
    units candela.steradian/meter^2;
    ieee1906-dot1-si-units:derived-units "lux phot";
    description "[I]lluminance, lux, lx = cd sr m^-2, lm/m^2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef activity { //(referred to a radionuclide)
    type ieee1906-dot1-function:variable;
    units second^-1;
    ieee1906-dot1-si-units:derived-units becquerel;
    description "[A]ctivity referred to a radionuclide, becquerel, Bq =
s^-1.";
    reference "The International System of Units: 8th Edition 2006.
```

```
                Clause 2.2.2";
}

typedef absorbed-dose { //specific dose, kerma
    type ieee1906-dot1-function:variable;
    units meter^2/second^2;
    ieee1906-dot1-si-units:derived-units gray;
    description "[A]bsorbed dose, kerma, gray, Gy = m^2 s^-2, J/kg.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}

typedef dose-equivalent {
    type ieee1906-dot1-function:variable;
    units meter^2/second^2;  // Sievert (J/kg)
    ieee1906-dot1-si-units:derived-units sievert;
    description "[D]ose equivalent, sievert, Sv = m^2 s^-2, J/kg.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}

typedef catalytic-activity {
    type ieee1906-dot1-function:variable;
    units mole/second;
    ieee1906-dot1-si-units:derived-units katal;
    description "[C]atalytic activity, katal, kat = mol s^-1.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}

typedef dynamic-viscosity {
    type ieee1906-dot1-function:variable;
    units kilogram/second;
    ieee1906-dot1-si-units:derived-units "pascal.second poise";
    description "[D]ynamic viscosity, pascal second, Pa s, kg m^-1
s^-1.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}

typedef moment-of-force {
    type ieee1906-dot1-function:variable;
    units meter^2.kilogram/second^2; //N.m
    ieee1906-dot1-si-units:derived-units "newton.meter";
    description "[M]oment of force, newton meter, N m, kg m^2 s^-2.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}

typedef surface-tension {
    type ieee1906-dot1-function:variable;
    units kilogram/second^2;
    ieee1906-dot1-si-units:derived-units "newton/meter";
    description "[S]urface tension, newton per meter, N m^-1, kg s^-2.";
    reference "The International System of Units: 8th Edition 2006.
                Clause 2.2.2";
}
```

```
typedef angular-velocity {
    type ieee1906-dot1-function:variable;
    units s^-1;
    ieee1906-dot1-si-units:derived-units "radian/second";
    description "[A]ngular velocity, angular frequency, radian per
second, rad s^−1, s^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef angular-acceleration {
    type ieee1906-dot1-function:variable;
    units s^-2;
    ieee1906-dot1-si-units:derived-units "radian/second^2";
    description "[A]ngular acceleration, radian per second squared,
rad/s^2, s−2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef heat-flux-density { // irradiance
    type ieee1906-dot1-function:variable;
    units kilogram/s^3;
    ieee1906-dot1-si-units:derived-units "watt/meter^2";
    description "[H]eat flux density, irradiance, watt per square
meter, W/m^2, kg s^−3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef heat-capacity {     // entropy
    type ieee1906-dot1-function:variable;
    units meter^2.kilogram/second^2.K;
    ieee1906-dot1-si-units:derived-units "joule/kelvin";
    description "[H]eat capacity, entropy, joule per kelvin, J K^−1, kg
m^2 s^−2 K^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef specific-heat-capacity {     // specific-entropy
    type ieee1906-dot1-function:variable;
    units meter^2/second^2.K;
    ieee1906-dot1-si-units:derived-units "joule/kilogram.kelvin";
    description "[S]pecific heat capacity, specific entropy, joule per
kilogram kelvin, J K^−1 kg^−1, m^2 s^−2 K^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef specific-energy {
    type ieee1906-dot1-function:variable;
    units meter^2/second^2;
    ieee1906-dot1-si-units:derived-units "joule/kilogram";
    description "[S]pecific energy, joule per kilogram, J kg^−1, m^2
s^−2.";
```

```
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef thermal-conductivity {
    type ieee1906-dot1-function:variable;
    units meter.kilogram/second^3.K;
    ieee1906-dot1-si-units:derived-units "watt/meter.kelvin";
    description "[T]hermal conductivity, watt per meter kelvin, W m^-1
K^-1, kg m s^-3 K^-1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef energy-density {
    type ieee1906-dot1-function:variable;
    units kilogram/meter.second^2;
    ieee1906-dot1-si-units:derived-units "joule/meter^3";
    description "[E]nergy density, joule per cubic meter, J m^-3, kg
m^-1 s^-2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-field-strength {
    type ieee1906-dot1-function:variable;
    units meter.kilogram/second^3.ampere;
    ieee1906-dot1-si-units:derived-units "volt/meter";
    description "[E]lectric field strength, volt per meter, V m^-1, kg
m s^-3 A^-1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-charge-density {
    type ieee1906-dot1-function:variable;
    units second.ampere/meter^3;
    ieee1906-dot1-si-units:derived-units coulomb/meter^3;
    description "[E]lectric charge density, coulomb per cubic meter, C
m^-3 A s m^-3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef surface-charge-density {
    type ieee1906-dot1-function:variable;
    units second.ampere/meter^2;
    ieee1906-dot1-si-units:derived-units coulomb/meter^2;
    description "[S]urface charge density, coulomb per square meter, C
m^-2, A s m^-2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef electric-flux-density{  //electricDisplacement
    type ieee1906-dot1-function:variable;
    units second.ampere/meter^2;
```

```
    ieee1906-dot1-si-units:derived-units coulomb/meter^2;
    description "[E]lectric flux density, electric displacement,
coulomb per square meter, C m^−2, A s m^−2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef permittivity {
    type ieee1906-dot1-function:variable;
    units second^4.ampere^2/meter^3.kilogram;
    ieee1906-dot1-si-units:derived-units farad/meter;
    description "[P]ermittivity, farad per meter, F m^−1, kg^−1 m^−3
s^4 A^2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef permeability {
    type ieee1906-dot1-function:variable;
    units meter.kilogram/second^2.ampere^2;
    ieee1906-dot1-si-units:derived-units henry/meter;
    description "[P]ermeability, henry per meter, H m^−1, kg m s^−2
A^−2.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
  }

typedef molar-energy {
    type ieee1906-dot1-function:variable;
    units meter^2.kilogram/second^2.mole;
    ieee1906-dot1-si-units:derived-units joule/mole;
    description "[M]olar energy, joule per mole. J mol^−1, kg m^2 s^−2
mol^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef molar-heat-capacity {  //molarEntropy
    type ieee1906-dot1-function:variable;
    units meter^2.kilogram/second^2.mole.kelvin;
    ieee1906-dot1-si-units:derived-units joule/mole.kelvin;
    description "[M]olar entropy, molar heat capacity, joule per mole
kelvin, J K−1 mol−1, kg m^2 s^−2 mol^−1 K^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef exposure { //(x and gamma rays)
    type ieee1906-dot1-function:variable;
    units second.ampere/kilogram;
    ieee1906-dot1-si-units:derived-units coulomb/kilogram;
    description "[E]xposure (x- and γ-rays), coulomb per kilogram, C
kg^−1, A s kg^−1.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}
```

```
typedef absorbed-dose-rate {
    type ieee1906-dot1-function:variable;
    units meter^2/second^3;
    ieee1906-dot1-si-units:derived-units gray/second;
    description "[A]bsorbed dose rate, gray per second, Gy s^−1, m^2
s^−3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef radiant-intensity {
    type ieee1906-dot1-function:variable;
    units meter^2.kilogram/second^3;
    ieee1906-dot1-si-units:derived-units watt/steradian;
    description "[R]adiant intensity, watt per steradian, W sr^−1, kg
m^2 s^−3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef radiance {
    type ieee1906-dot1-function:variable;
    units kilogram/second^3;
    ieee1906-dot1-si-units:derived-units watt/meter^2.steradian;
    description "[R]adiance, watt per square meter, steradian W sr^−1
m^−2, kg s^−3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}

typedef catalytic-activity-concentration {
    type ieee1906-dot1-function:variable;
    units mol/second^3.second;
    ieee1906-dot1-si-units:derived-units katal/meter^3;
    description "[C]atalytic activity concentration, katal per cubic
meter, kat m^−3, mol s^−1 m^−3.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 2.2.2";
}
```

6.5.3.8 Definition of non-SI units

```
identity speed-of-light {
    description "The speed of light in vacuum which is equal to 299 792
                 458 m/s (exact).";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1";
}

identity reduced-planck-constant {
    description "It equals 1.054 571 68 (18) × 10^−34 J s.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}
```

```
identity electron-mass {
    description "It equals 9.109 3826 (16) × 10^−31 kg.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

identity Planck-time {
    description "It equals 1.288 088 6677 (86) × 10^−21 s.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

identity elementary-charge {
    description "It equals 1.602 176 53 (14) × 10−19 C.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

identity bohr-radius {
    description "It equals 0.529 177 2108 (18) × 10^−10 m.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

identity hartree-energy {
    description "It equals 4.359 744 17 (75) × 10^−18 J.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

identity atomic-unit-of-time {
    description "It equals 2.418 884 326 505 (16) × 10^−17.s";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1
               P.J. Mohr and B.N. Taylor, Rev. Mod. Phys., 2005, 77, 1-
               107";
}

typedef kinematic-viscosity {
    type ieee1906-dot1-function:variable;
    units meter^2/second;            //  1 stokes (1 St) = 10^-4 m^2 s^-
1
    description "[K]inematic viscosity, square meter per second, m^2/s.";
    reference "The International System of Units: 8th Edition 2006.
               Clause 4.1";
}
```

6.5.3.9 Keywords for declaring SI-derived units within the nanoscale system

The following identities shall be reused in properties (see 5.5.5) to identify specifically the derived SI units described by the nanoscale system to redefine its unit (for example, change frequency from Hertz to Terahertz).

```
identity si-derived-unit{
  description "Logical placeholder. You should not use this.";
}

identity area{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity volume{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity velocity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity acceleration{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity wavenumber{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity mass-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity surface-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity specific-volume{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity current-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity magnetic-field-strength{
  base si-derived-unit;
```

```
    description "See corresponding typedef";
  }

  identity amount-concentration{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity mass-concentration{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity luminance{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity refractive-index{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity relative-permeability{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity plane-angle{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity solid-angle{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity frequency{
    base si-derived-unit;
    description “See corresponding typedef”;
  }

  identity force{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity pressure{
    base si-derived-unit;
    description "See corresponding typedef";
  }

  identity energy{
    base si-derived-unit;
    description "See corresponding typedef";
  }
```

```
identity power{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-charge{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-potential-difference{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity capacitance{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-resistance{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-conductance{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity magnetic-flux{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity magnetic-flux-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity inductance{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity temperature{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity luminous-flux{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity illuminance{
```

```
  base si-derived-unit;
  description "See corresponding typedef";
}

identity activity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity absorbed-dose{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity dose-equivalent{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity catalytic-activity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity dynamic-viscosity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity moment-of-force{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity surface-tension{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity angular-velocity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity angular-acceleration{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity heat-flux-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity heat-capacity{
  base si-derived-unit;
  description "See corresponding typedef";
```

```
}

identity specific-heat-capacity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity specific-energy{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity thermal-conductivity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity energy-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-field-strength{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-charge-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity surface-charge-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity electric-flux-density{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity permittivity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity permeability{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity molar-energy{
  base si-derived-unit;
  description "See corresponding typedef";
}
```

```
identity molar-heat-capacity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity exposure{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity absorbed-dose-rate{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity radiant-intensity{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity radiance{
  base si-derived-unit;
  description "See corresponding typedef";
}

identity catalytic-activity-concentration{
  base si-derived-unit;
  description "See corresponding typedef";
```

6.5.4 Definitions for types of components and definitions

6.5.4.1 Overview

The following YANG snippets follow the recommendations of Clause 5 and provide a valid implementation of component types and definitions.

6.5.4.2 Generic concept definition

```
identity concept {
    description "A root keyword as placeholder for IEEE Std 1906.1-
                 2015. Just for logical convenience. It does not bear
                 any meaning and third-party identities should not
                 derive from this identity directly.";
}

identity component{
    base concept;
    description "A required element of the framework that provides a
                 service for communication in a network.";
}

identity definition{
    base concept;
    description "A required element of the definition of a molecular
```

```
                and nanoscale communication network.”;
}
```

6.5.4.3 Definition of the framework component

```
identity message-carrier {
    base component;
    description "The message carrier provides the service of
                 transporting the message.";
}

identity motion {
    base component;
    description "Defines the movement capability for Message Carrier.";
}

identity field {
    base component;
    description "Defines organized movement of Motion.";
}

identity perturbation {
    base component;
    description "Defines the signal transported by Message Carrier.";
}

identity specificity {
    base component;
    description "Defines targeted reception of Perturbation.";
  }
```

6.5.4.4 Definition of types of message-carrier

```
identity calcium-ion {
    base message-carrier;
    description "Calcium ion.";
}

identity ligand {
    base message-carrier;
    description "Ligand-receptor system.";
}

identity motor {
    base message-carrier;
    description "Molecular motor.";
}

identity charge {
    base message-carrier;
    description "Electrical charge.";
}

identity bacterium {
    base message-carrier;
    description "Bacterium.";
```

```
}

identity electromagnetic-wave {
    base message-carrier;
    description "Electromagnetic wave.";
}
```

6.5.4.5 Definition of types of motion

```
identity diffusion {
    base motion;
    description "Diffusion.";
}

identity walking {
    base motion;
    description "Walking.";
}

identity potential-difference {
    base motion;
    description "Electrical potential difference.";
}

identity wave-guided {
    base motion;
    description "Follows a wave guide.";
}
```

6.5.4.6 Definition of types of field

```
identity concentration-gradient {
    base field;
    description "Concentration gradient.";
}

identity compartmentalized {
    base field;
    description "Compartmentalized.";
}

identity microtubule {
    base field;
    description "Microtubule.";
}

identity nanostructure-orientation {
    base field;
    description "Nanostructure orientation, e.g., nanotube
                 orientation.";
}

identity directional-antenna {
    base field;
    description "directional antenna";
}
```

6.5.4.7 Definition of types of perturbation

```
identity transmission-rate {
    base perturbation;
    description "Transmission rate is varied to create bits.";
}

identity concentration-change {
    base perturbation;
    description "Concentration is varied to create bits.";
}

identity molecular-structure {
    base perturbation;
    description "Molecular structure is changed to represent bits.";
}

identity electrical-current-variation {
    base perturbation;
    description "Electrical current is varied to create bits.";
}

identity electromagnetic-wave-variation {
    base perturbation;
    description "The electromagnetic wave is varied to create bits.";
}
```

6.5.4.8 Definition of types of specificity

```
identity receptor-sensitivity {
    base specificity-type;
    description "Receptor sensitivity.";
}

identity electrical-charge {
    base specificity-type;
    description "Electrical charge or voltage sensitivity threshold is
                 exceeded.";
}

identity antenna-aperture {
    base specificity-type;
    description "Antenna aperture and orientation control
                 specificity.";
}
```

6.5.4.9 Definition of IEEE 1906.1 definitions

```
identity transmitter {
    base definition;
    description "A device used to convey a message to a receiver.";
}

identity receiver {
    base definition;
    description "A device used to collect messages from a
```

```
                 transmitter.";
}

identity medium {
    base definition;
    description "The environment connecting the transmitter and
                 receiver, which includes gas, gel, or liquid.";
}

identity message {
    base definition;
    description "The information to be conveyed that is known to the
                 transmitting party interfacing with a receiver, and
                 unknown, but recognizable, to the receiving party.";
}

identity non-standard-physics{
  base definition;
  description "This identity represents any non-standard physics that
               need to be included to the model.";
}

identity component-less-than-100nm{
  base definition;
  description "Identifies the components that have a dimension from 1nm
               to 100nm.";
}

identity system-definition{
  base definition;
  description "Identifies the intended system type. For IEEE1906.1-
               2015, please consider 'nanoscale communication'.";
}

identity nanoscale-communication{
  base system-definition;
  description "Identifies the intended system type. For IEEE1906.1-
               2015, please consider 'nanoscale communication'.";
}
```

6.5.5 Definition of metrics

6.5.5.1 Definition of thermodynamic metrics

6.5.5.1.1 Definition of diffusion coefficient

```
typedef diffusion-coefficient{
    type ieee1906-dot1-function:variable;
    units meter^2.second^-1;
    description "Diffusivity or diffusion coefficient is a
                 proportionality constant between the molar flux due to
                 molecular diffusion and the gradient in the
                 concentration of the species (or the driving force for
                 diffusion).";
```

```
}
```

6.5.5.1.2 Definition of flow velocity

```
grouping flow-velocity {
    uses ieee1906-dot1-math:vector;
    ieee1906-dot1-si-units:units meter/second;
    description "The flow velocity of the mass of the message
                 carriers.";
}
```

6.5.5.1.3 Definition of mass flux

```
grouping flow-velocity {
    type ieee1906-dot1-function:variable;
    ieee1906-dot1-si-units:units kilogram second^-1 meter^-2;
    description "A reusable mass flux equation.";
}
```

6.5.5.1.4 Definition of volumetric flow rate

```
grouping volumetric-flow-rate {
    ieee1906-dot1-math:equation volumetric-flow-rate {
        ieee1906-dot1-math:symbol "Vdot Q";
        ieee1906-dot1-math:value;
        units "meter^3 second^-1";

        ieee1906-dot1-math:expression {
            uses flow-velocity;
            uses ieee1906-dot1-math:vector-area;
        }

        description "Volume of fluid which passes per unit time. The
                     volume flow rate of the message carrier.";
        }

    description "A volumetric flow rate equation.";
}
```

6.5.5.1.5 Definition of mass flow rate

```
grouping mass-flow-rate {
    ieee1906-dot1-math:equation mass-flow-rate {
        ieee1906-dot1-math:symbol mdot;
        ieee1906-dot1-math:value;
        units kilogram.second^-1;

        ieee1906-dot1-math:expression {
            leaf density {
                ieee1906-dot1-math:symbol rho;
                type ieee1906-dot1-si-units:mass-density;
                description "A mass density.";
            }
        uses volumetric-flow-rate;
    }
```

```
    ieee1906-dot1-math:expression{
        leaf density {
            ieee1906-dot1-math:symbol rho;
            type ieee1906-dot1-si-units:mass-density;
            description "A mass density.";
        }
        uses flow-velocity;
        uses ieee1906-dot1-math:vector-area;
    }

    ieee1906-dot1-math:expression {
        uses mass-flux;
        uses ieee1906-dot1-math:vector-area;
    }

    description "A reusable mass flow rate equation.";
  }
```

6.5.5.2 Definition of information

6.5.5.2.1 Definition of amount of information

```
typedef amount-of-information {
    type ieee1906-dot1-math:scalar;
    ieee1906-dot1-si-units:units bit;
    description "The amount of information of a system in bits.";
}
```

6.5.5.2.2 Definition of bandwidth

```
typedef bandwidth {
    type ieee1906-dot1-math:scalar;
    ieee1906-dot1-si-units:units bit/second;
    description "Bandwidth in bits per second of a communication
                 channel.";
  }
```

6.5.5.2.3 Definition of information density

```
grouping information-density {
    ieee1906-dot1-math:equation information-density {
        ieee1906-dot1-si-units:units m^-X;  // This is a surface, it
        can have two or more dimensions, hence the 'X'
        ieee1906-dot1-math:value;

        ieee1906-dot1-math:expression {
            uses ieee1906-dot1-math:surface;
            leaf amount-of-information {
                type amount-of-information;
                description "Amount of information.";
            }
        }
    }

    description "A reusable equation representing information
```

```
                 density.";
  }
```

6.5.5.2.4 Definition of bandwidth-delay product

```
grouping bandwidth-delay-product {
    ieee1906-dot1-math:equation bandwidth-delay-product {
        ieee1906-dot1-si-units:units bit;
        ieee1906-dot1-math:value;

        ieee1906-dot1-math:expression {
            leaf bandwidth {
                type bandwidth;
              description "The bits per second transported by the
                           nanoscale communication channel.";
            }

            leaf delay {
                type ieee1906-dot1-si-units:time;
                description "The time for a message to propagate from
                             one end of a channel to the other.";
            }
        }
    }

    description "A reusable equation representing bandwidth delay
                 product.";
  }
```

6.5.5.3 Definition of message metrics

```
grouping message-metrics{
  description "These metrics deal with the information encoded within a
               Message and how the Message is impacted by the channel
               and intended target. Metrics a) through d) shall be
               implemented. Metric e) may be implemented.";
  reference "IEEE Std 1906.1-2015 Clause 6";

  container message-metrics{
    when "derived-from-or-self(../type-of-definition,
          'ieee1906-dot1-types:message')";
    description "The parent definition shall have a leaf of type
                'message' in order to be eligible to use this
                container.";

  leaf message-deliverability{
    type ieee1906-dot1-math:probability;
    description "Message Deliverability measures whether a Message
                 Carrier survives long enough to deliver its
                 information to the intended receiver.

                  Message Deliverability (MD) assumes messages have a
                  finite time-to-live (TTL). Thus, MD = P(tr < TTL)
                  where tr is the age of the message at the time of
                  reception by the destination to which the message was
                  addressed. TTL is in 6.2 of IEEE Std 1906.1-2015.
```

```
                  This leaf can be named.";

      reference "IEEE Std 1906.1-2015 subclause 6.1";
  }

  leaf message-lifetime{
    type ieee1906-dot1-si-units:time;
    description "Message Lifetime measures the lifetime of a Message
                Carrier. TTL is used in 6.1 of IEEE Std 1906.1-2015.";

    reference "IEEE Std 1906.1-2015 subclause 6.2";
  }

  uses ieee1906-dot1-information:information-density;

  container bandwidth-delay-product{
  leaf channel-bandwidth {
    type ieee1906-dot1-function:variable;
    description "The bits per second transported by the nanoscale
                 communication channel.";
  }
  leaf channel-delay {
    type ieee1906-dot1-function:variable;
    description "The time for a message to propagate from one end of a
                 channel to the other.";
  }
  description "Bandwidth-Delay Product is proportional to the maximum
               number of message carriers capable of fitting within the
               physical channel.";
  reference "IEEE Std 1906.1-2015 subclause 6.4";
  }

  container information-and-communication-energy {
    leaf energy-message-delivery {
      type ieee1906-dot1-function:variable;
      description "The energy used to transport a message across a
                   channel.";
    }
    leaf information-message-delivery {
      type ieee1906-dot1-function:variable;
      description "The amount of information in a message.";
    }
    description "This is the metric that quantifies energy used in
                 nanoscale communication. This is energy per bit of
                 information conveyed by the Motion Component.";
    reference "IEEE Std 1906.1-2015 subclause 6.5";
  }
}
```

6.5.5.4 Definition of the motion metric

```
grouping motion-metrics
{
  description "Motion component: These metrics are strongly related to
               the Motion Component, which describes Message Carrier
               motion. Either both a) and b) shall be implemented or c)
```

```
             shall be implemented.";

container motion-metrics
{
  when "derived-from-or-self(../type-of-component,
        'ieee1906-dot1-types:motion')";
  description "The parent component shall have a leaf of type 'motion'
               in order to be eligible to use this container.";

container collision-behavior {
  leaf coefficient-of-restitution {
    type ieee1906-dot1-math:proper-fraction;
    units "unitless";
    description "A measure of the 'restitution' of a collision
                 between two objects: how much of the kinetic energy
                 remains for the objects to rebound from one another
                 vs. how much is lost as heat, or work done deforming
                 the objects. The coefficient is defined as the ratio
                 of relative speeds after and before an impact, taken
                 along the line of the impact.";
  }
  leaf speed-before-collision {
    type ieee1906-dot1-si-units:velocity;
    description "The speed of a message carrier loaded with message
                 before collision.";
  }
  leaf speed-after-collision {
    type ieee1906-dot1-si-units:velocity;
    description "The speed of a message carrier loaded with message
                 after collision.";
  }
  reference "IEEE Std 1906.1-2015 subclause 6.6";
  description "Collision Behavior measures the physical result of
               collision between message carriers.";
}

container mass-displacement {
  leaf mass-displacement {
    type ieee1906-dot1-function:variable;
    description "Value of the mass displacement.";
  }
  leaf x {
    type ieee1906-dot1-si-units:mass;
    units "kilogram";
    description "Mass at time t.";
  }
  leaf T {
    type ieee1906-dot1-si-units:time;
    units "second";
    description "Sample period (the time between each sample).";
  }
  leaf tau {
    type ieee1906-dot1-si-units:time;
    units "second";
    description "Sample time";
  }
  leaf M {
```

```
      type ieee1906-dot1-function:variable;
      units "unitless";
      description "Number of samples";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.7";
    description "Molecular communication assumes message carriers
                 are composed of mass and move from one location to
                 another.";
  }

  container positioning-accuracy-of-message-carriers {
    leaf radius {
      type ieee1906-dot1-si-units:length;
      units "nanometer";
    }
    leaf position {
      type ieee1906-dot1-si-units:length;
      description "The location of the center of mass of the message
                   carriers.";
    }
    leaf accuracy-percent {
      type ieee1906-dot1-math:percent;
      description "Then number of message carriers located within the
                   given area or volume.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.8";
    description
      "Multiple swarms of message carriers can be controlled like
       unified organisms to swim along predetermined paths toward the
       receiver by an external macro-unit (e.g., an agglomeration of
       flagellated magnetotactic bacteria can be utilized as efficient
       carriers of nanoloads and guided toward an aggregation zone by a
       magnetic field generated in custom-made magnetic resonance
       imaging systems). It is defined as the radius of the circle hat
       has its center at the mean and contains a given percentage of
       half the realizations of the location estimates (i.e., the
       performance measure of circular error probable in the classical
       geolocation context).";
  }
}
```

6.5.5.5 Definition of the field metric

```
grouping field-metrics
{

  description "Field component: These metrics relate to the degree to
               which Message Carrier motion can be controlled such that
               it follows an intended gradient. Diffusive Flux is used
               in Brownian motion and can be modeled by Levy or Weiner
               processes and can also be described by the Langevin
               Noise. At least one of a), b), or c) shall be
               implemented in order to describe Message Carrier
               motion.";

  container field-metrics
  {
```

```
    when "derived-from-or-self(../type-of-component,
          'ieee1906-dot1-types:field')";
    description "The parent component shall have a leaf of type 'field'
                 in order to be eligible to use this container.";

  container persistence-length {
    list unit-tangent-vectors {
      key "segment-index";
      leaf segment-index {
        type uint32;
        description "A segment index.";
      }
      leaf s {
        type ieee1906-dot1-si-units:length; // Vector?
          description "The position of a unit tangent sample.";
      }
      container u-s {
        uses ieee1906-dot1-math:nabla;
        description "The unit tangent vector at point s in set of
                     connected segments.";
      }
    }
    container u-0 {
      uses ieee1906-dot1-math:nabla;
      description "Unit tangent vector at the origin or beginning of
                   the chain of connected segments";
    }
    leaf zeta-p {
      type ieee1906-dot1-si-units:length;
      units "nanometer";
      description "The persistence length.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.9";
    description "Persistence Length is a measure of the degree to which
                 a chain-like structure is either soft (like strings of
                 cooked spaghetti) or rigid (like metal rods).";
  }
  container diffusive-flux {
    uses ficks-1-law {
      description "This metric is derived from Fick's First Law.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.10";
    description "Fick’s First Law is one of the standard laws of
                 diffusion.";
    }
  container langevin-noise {
    uses langevin-equation {
      description "Langevin noise is a term in the general Langevin
                   equation.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.11";
    description "Random motion has a significant impact upon the
                 performance of message carriers, in particle form, to
                 reach their target receivers.";
  }
}
```

6.5.5.6 Definition of the specificity metric

```
grouping specificity-metrics
{

description "Specificity component: These metrics are related to the
             ability of a Message Carrier to deliver a Message to its
             intended target. Metrics a), c), and e) shall be
             implemented; metrics b) or d) may be implemented.";

  container specificity-metrics
  {
    when "derived-from-or-self(../type-of-component,
          'ieee1906-dot1-types:specificity')";
    description "The parent component shall have a leaf of type
                 'specificity' in order to be eligible to use this
                 container.";

  leaf specificity {
    type ieee1906-dot1-math:percent; //specificity;
    reference "IEEE Std 1906.1-2015 subclause 6.12";
    description "A measure of precision in matching between components.
                 See also: sensitivity.";
  }
  leaf affinity {
          type ieee1906-dot1-function:variable;
    units "d/dG";
    reference "IEEE Std 1906.1-2015 subclause 6.13";
    description "Affinity is a standard measure of chemical affinity;
                 however, it is applied to the broader IEEE 1906
                 framework and the affinity of message carriers to
                 their intended targets, media, and other message
                 carriers.";
  }
  leaf sensitivity {
    type ieee1906-dot1-math:percent;  //sensitivity;
    reference "IEEE Std 1906.1-2015 subclause 6.14";
    description "A measure of the proportion of true positives, which
                 are events that actually occurred and have been
                 correctly detected. See also: specificity.";
  }
  container angular-spectrum {
    uses probability-density;
    reference "IEEE Std 1906.1-2015 subclause 6.15";
    description "Angular Spectrum quantifies the distribution of the
                 intensity of nanoscale communication signals received
                 at the receiver as a function of angle-of-arrival.";
  }
  container delay-spectrum {
    uses probability-density;
    reference "IEEE Std 1906.1-2015 subclause 6.16";
    description "Delay Spectrum quantifies the distribution of the
                 intensity of nanoscale communication signals received
                 at the receiver as a function of time-of-arrival.";
  }
}
```

6.5.5.7 Definition of system metrics

```
grouping system-metrics
{
  description
"System metrics relate to and impact all components.
All of the metrics in this category shall be implemented.";

  container system-metrics
  {
    description "Metrics that can be used by nanoscale systems only.";

  container active-network-programmability {
    leaf t {
      type ieee1906-dot1-si-units:time;
      units "second";
      description "The current time.";
    }
    container S {
      uses math-expression {
      description "A virtual surface that defines the volume through
                  which the change in flux of message carriers should
                  be clearly specified.";
      }
    }
    leaf f {
      type ieee1906-dot1-function:variable;
      units "second^-1 meter^-2";
      description "The flux of message carriers as a function of time
                   where flux is the rate of flow through a unit
                   area.";
    }
    leaf delta-f {
      type ieee1906-dot1-function:variable;
      units "second^-1 meter^-2";
      description "The change in f(t) intentionally caused by a
                  programmed message carrier through a surface.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.17";
    description
      "Message carriers can be programmed or coded such they change the
      underlying media (e.g., microtubules, nanotubes, etc.) as they
      transport information (see 5.3.4).";
  }
  container perturbation-rate {
    leaf rate-of-perturbation {
      type derivative;
      units "second^-1";
      description "Rate of change of the component representing bits of
                   information in the channel. There is typically a
                   tradeoff with error-of-perturbation.";
    }
    leaf error-of-perturbation {
      type derivative;
      units "second^-1";
      description
        "Rate of error in the component representing bits of
```

```
        information
        in the channel. There is typically a tradeoff with rate-of-
        perturbation";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.18";
    description "Perturbation rate is a measure of both the rate and
                 control of any type of perturbation used to send a
                 signal in the system.";
  }
  container supersystem-degradation {
    leaf performance-attribute {
      type string;
      description
        "A descriptive name of the performance-attribute.";
    }
    leaf ds {
      type ieee1906-dot1-math:percent;
      units "percent";
      description
        "The supersystem degradation of the performance-attribute.";
    }
    leaf spn {
      type ieee1906-dot1-math:percent;
      units "percent";
      description
        "The supersystem performance of the performance-attribute with
        the embedded nanoscale communication network.";
    }
    leaf sp {
      type ieee1906-dot1-math:percent;
      units "percent";
      description "The native supersystem performance (without the
                   embedded nanoscale communication network).";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.19";
    description "The supersystem is the system in which the IEEE 1906.1
                 network resides. Can be a biological organism. This
                 metric quantifies the impact of the network upon the
                 supersystem with regard to its normal operation.";
  }
  container bandwidth-volume-ratio {
    leaf bandwidth {
      type ieee1906-dot1-information:bandwidth;
      units "bit second^-1";
      description "The bandwidth of the nanoscale communication
                   channel.";
    }
    leaf volume {
      type ieee1906-dot1-si-units:volume;
      units "nanometer^3";
      description "The sum of the volume of the transmitter and
                   receiver pair for a communication system.";
    }
    reference "IEEE Std 1906.1-2015 subclause 6.20";
    description "The Bandwidth-Volume Ratio takes into account
                 and combines two essences of molecular and nanoscale
                 communication, namely its size and bandwidth.";
```

```
  }
}
```

6.5.6 Definition of the nanoscale and molecular communication component

```
grouping component {
    list component {
        key identifier;

        leaf name {
            type string;
            description "An optional name to describe the IEEE 1906.1
                         component in the corresponding biological
                         implementation or simulation.

                         For example, a neuron model conforming to the
                         IEEE 1906.1 framework could use 'axon' as
                         a name for one of its components.";
        }

        leaf description {
            type string;
            description "An optional string to describe the
                         IEEE 1906.1 component in the
                         corresponding biological implementation or
                         simulation.

                         For example, a neuron model conforming to the
                         IEEE 1906.1 framework could specify what
                         this 'axon' is supposed to do in its
                         corresponding model.";
        }

        leaf identifier {
        type string;
       }
        description "A unique identifier for this component to be
                     associated to the non-IEEE 1906.1 model. Using URN
                     notation.

                     For example, a neuron axon can be composed of
                     Multiple sections. Each of the section should be
                     uniquely identified by the underlying model to
                     store statistics or retrieve configuration,
                     simulate a fault, etc.";
        }

      leaf human-designed {
        type boolean;
        description "'Human-designed' means a system that occurs as a
                     result of conscious human intervention. For
                     clarity, human-designed may include naturally
                     occurring components in an arrangement or for a
                     purpose that is not otherwise naturally
                     occurring.";
        default false;
      }
```

```
container properties
  uses properties:property;
  description "This container stores the list of optional
               properties that provide extra definition of the
               component, or make this component attribute
               supersedes corresponding system (or parent
               component) corresponding attribute.";
}

  leaf type-of-component {
      type identityref { base 'ieee1906-dot1-types:component'; }
      mandatory true;
      description "Identifies this component from the non-IEEE
                   1906.1 model to an IEEE 1906.1 compatible
                   component.

                   For example, a neurotransmitter can be
                   considered a 'message-carrier'. This leaf
                   automatically selects the correct type of
                   metric to display.

               See the following list of 'uses'. The underlying
               Metrics define a 'when' statement making them
               valid and usable if the type-of-components matches
               them.";
  }

leaf-list sub-definition
{
  type instance-identifier { require-instance false; }
  description "Identifies the list of child definitions that are
               part of this definition. There shall be 0 or more
               child definition and child definition shall be of
               any type.";
}

leaf-list next-definition
{
  type instance-identifier { require-instance false; }
  description "Identifies the list of sibling definitions
               attached to this definition in a unidirectional
               way. There shall be 0 or more next definitions and
               next definition shall be of any type.

               This leaf-list helps identify the components along
               the data path of a message, and shall help build a
               tree or a bus.";
}
  leaf-list sub-component {
    type instance-identifier { require-instance false; }
    description "Identifies the list of child components that
                 are part of this component. There shall be zero
                 or more child components and child component
                 shall be of any type.

                 For example, a nanoscale interface can be
```

```
                     composed of a transmitter and a receiver sub-
                     component, and a transmitter can be composed
                     of a perturbation and a field sub-component
                     while the receiver is made of a specificity
                     sub-component.";
      }

      leaf-list next-component {
        type instance-identifier { require-instance false; }
          description "Identifies the list of sibling components
                      attached to this component in a
                      unidirectionally. There shall be zero or more
                      next components and next components shall be of
                      any type.

                      This leaf-list helps identify the components
                      along the data path of a message, and shall help
                      build a tree or a bus.

                      For example, an axon is a set of microtubules.
                      In its simple form, this model can help
                      identify that microtubule identified MT_00 is
                      connected to the soma (a perturbation
                      component) and MT_01 is connected to MT_00
                      helping the simulation or a remote tool to
                      build the hierarchy of the biological model
                      from that YANG module.";
      }

      uses ieee1906-dot1-metrics:motion-metrics;
      uses ieee1906-dot1-metrics:field-metrics;
      uses ieee1906-dot1-metrics:specificity-metrics;
      uses ieee1906-dot1-metrics:system-metrics;

      description "A list of IEEE Std 1906.1-2015 compatible objects
                  in any nanoscale model.";
    }

      description "This is the main grouping of the IEEE 1906.1
                  framework. This helps link conceptual objects to a
                  'component' and access to metrics and
                  configuration data.";
}
```

6.5.7 Definition of the nanoscale and molecular communication property

```
grouping property{
  leaf timestamp{
    type ieee1906-dot1-si-units:time;
    description "Gives a timestamp for a snapshot of the system,
                relating metrics to a reference in simulation time.";
  }

  leaf length{
    type empty;
    description "Gives users options to annotate this leaf, thus
                declaring to the system which SI unit is used to
```

```
                describe length for this and its child nodes (e.g., for
                this XML element and its children).

                All derived units shall depend on this property. If for
                instance, length is in nanometer, and time is in
                second, then it is expected that speed shall be in
                nanometer.second-1, unless annotation of the specific
                leaf tells something different.

                If omitted, defaults to 'meter'.

                The implementation of the framework shall ensure
                annotation matches a length, otherwise it shall ensure
                NETCONF server sends back appropriate rpc-error, like
                maybe bad attribute.";
}

leaf scale
{
  type union
  {
    type enumeration
    {
       enum Planck;
       enum quantum;
       enum nanoscale;
       enum microscale;
       enum macroscale;
       enum interplanetary;
       enum relativistic;
    }
    type enumeration
    {
       enum less-than-1um;
       enum less-than-100nm;
       enum less-than-10nm;
    }
  }
  default nanoscale;
  description "Defines a generic scale for this system. If omitted,
               it is understood that it is a nanoscale system
               (<1um).";
}

leaf mass{
  type empty;
  description "Gives users options to annotate this leaf, thus
               declaring to the system which SI unit is used to
               describe mass for this component and its child nodes
               (e.g., for this XML element and its children).

               All derived units shall depend on this property.

               If omitted, defaults to 'kilogram'.

               The implementation of the framework shall ensure
               annotation matches a length, otherwise it shall ensure
```

```
                   NETCONF server sends back appropriate rpc-error, like
                   maybe bad attribute.";
    }

    leaf time{
      type empty;
      description "Gives users options to annotate this leaf, thus
                   declaring to the system which SI unit is used to
                   describe time for this component and its child nodes
                   (e.g., for this XML element and its children).

                   All derived units shall depend on this property.

                   If omitted, defaults to 'second'.

                   The implementation of the framework shall ensure
                   annotation matches a length, otherwise it shall ensure
                   NETCONF server sends back appropriate rpc-error, like
                   maybe bad attribute.";
    }

    leaf duration{
      type empty;
      description "It is simply another way of naming time. If time is
                   already defined as property with its SI unit
                   annotated, then it shall be treated as an error if this
                   leaf is also present as property.";
    }

    leaf electric-current{
      type empty;
      description "Gives users options to annotate this leaf, thus
                   declaring to the system which SI unit is used to
                   describe electric current for this component and its
                   child nodes (e.g., for this XML element and its
                   children).

                   All derived units shall depend on this property.

                   If omitted, defaults to 'ampere'.

                   The implementation of the framework shall ensure
                   annotation matches a length, otherwise it shall ensure
                   NETCONF server sends back appropriate rpc-error, like
                   maybe bad attribute.";
    }

    leaf thermodynamic-temperature{
      type empty;
      description "Gives users options to annotate this leaf, thus
                   declaring to the system which SI unit is used to
                   describe temperature for this component and its child
                   nodes (e.g., for this XML element and its children).

                   All derived units shall depend on this property.

                   If omitted, defaults to 'kelvin'.
```

```
                The implementation of the framework shall ensure
                annotation matches a length, otherwise it shall ensure
                NETCONF server sends back appropriate rpc-error, like
                maybe bad attribute.";
}

leaf amount-of-substance{
  type empty;
  description "Gives users options to annotate this leaf, thus
                declaring to the system which SI unit is used to
                describe amount of substance for this
                component and its child nodes (e.g., for this XML
                element and children).

                All derived units shall depend on this property.

                If omitted, defaults to 'mole'.

                The implementation of the framework shall ensure
                annotation matches a length, otherwise it shall ensure
                NETCONF server sends back appropriate rpc-error, like
                maybe bad attribute.";
}

leaf luminous-intensity{
  type empty;
  description "Gives users options to annotate this leaf, thus
                declaring to the system which SI unit is used to
                describe luminous intensity for this component and its
                child nodes (e.g., for this XML element and its
                children).

                All derived units shall depend on this property.

                If omitted, defaults to 'candela'.

                The implementation of the framework shall ensure
                annotation matches a length, otherwise it shall ensure
                NETCONF server sends back appropriate rpc-error, like
                maybe bad attribute.";
}

leaf-list derived-unit{
  type identityref { base 'ieee1906-dot1-si-units:si-derived-unit'; }
  description "Gives users options to annotate this specific SI
                derived unit, thus declaring to the system which SI
                unit is used the said unit for this component and its
                child nodes (e.g., for this XML element and its
                children).

                All derived units shall depend on this property.

                The list does not have to be complete. Omitted derived
                units default to their SI definitions, or derive from
                base units if they are defined. For example, the
                annotation may contradict its base unit: if system
```

```
                 defines time in millisecond, frequency is in kilohertz;
                 if not specified, or if this derived-unit refers to
                 frequency, any other units, such as Terahertz, can be
                 used.
                 However, tools and plugins checking balance of units
                 may raise errors.

                 The implementation of the framework shall ensure
                 annotation matches corresponding derived SI unit,
                 otherwise it shall ensure NETCONF server sends back
                 appropriate rpc-error, like maybe bad attribute.";
  }

  description "This is a convenience grouping for the IEEE 1906.1
               framework.
               This relates any conceptual object to a 'property'.";
}
```

6.5.8 Definition of the nanoscale and molecular communication definition

```
grouping definition{
  list definition{
    key identifier;

    leaf name{
      type string;
      description "An optional name to describe what is this definition
                   in the non-1906.1 model.";
    }

    leaf description{
      type string;
      description "An optional string to describe what does this
                   definition in the non-1906.1 model.";
    }

    leaf identifier{
      type string;
      description "A unique identifier for this definition to be
                   associated to the non-1906.1 model.";
    }

    leaf human-designed{
      type boolean;
      description "'Human-designed' means a system that occurs as a
                   result of conscious human intervention. For clarity,
                   human-designed systems may include naturally
                   occurring components in an arrangement or for a
                   purpose that is not otherwise naturally occurring.";
      default false;
    }

    container properties{
      uses properties:property;
      description "This containers stores the list of optional
                   properties that provide extra definition of the
                   component, or make this component attribute
```

```
                  supersedes corresponding system (or parent
                  component) corresponding attribute.";
   }

   leaf type-of-definition{
      type identityref { base 'ieee1906-dot1-types:definition'; }
      mandatory true;
      description  "Identifies the IEEE 1906.1 definition
                    extended in this model.";
   }

   leaf-list sub-definition{
     type instance-identifier { require-instance false; }
     description "Identifies the list of child definitions that are
                  part of this definition. There shall be 0 or more
                  child definition and child definition shall be of any
                  type.";
   }

   leaf-list next-definition{
     type instance-identifier { require-instance false; }
     description "Identifies the list of sibling definitions attached
                  to this definition in a unidirectional way. There
                  shall be 0 or more definitions and next definition
                  shall be of any type.

                  This leaf-list helps identify the components along
                  the data path of a message, and shall help build a
                  tree or a bus.";
   }

   leaf-list sub-component{
     type instance-identifier { require-instance false; }
     description "Identifies the list of child components that are
                  part of this definition. There shall be 0 or more
                  child components and child components shall be of any
                  type.";
   }

   leaf-list next-component{
     type instance-identifier { require-instance false; }
     description "Identifies the list of next components that are
                  interfaced to this definition. There shall be 0 or
                  more next components and next components shall be of
                  any type. However, model shall clearly identify next
                  components that make valid interfaces from IEEE
                  1906.1 perspective.

                  For example, if this definition is of type
                  'message', then suitable 'next-component' would be
                  of type 'message-carrier'";
   }

   uses ieee1906-dot1-metrics:message-metrics;

   description "A list of IEEE 1906.1 compatible objects.";
 }
```

```
  description "This is the main grouping for the IEEE 1906.1
               framework. This relates any conceptual object to a
               'definition'.";
}
```

6.5.9 Definition of the nanoscale and molecular communication system

```
grouping system{
    description "This is an API for nanoscale systems. You can use it
                 in your own modules and refine it.";

    leaf identifier{
      type types:urn;
      description "Identifying the system to make it a resource
                   available online.";
    }

    leaf title{
      type string;
      description "A short, optional title for this nanoscale system.
                   Can be the name of the product.";
    }

    leaf-list organization{
      type string;
      description "The name of the vendor or the authority providing
                   standards.";
    }

    leaf-list contact{
      type string;
      description "List of contact names. It is recommended to append
                   the email address of the contact as well.";
    }

    leaf description{
      type string;
      description "An optional leaf describing what this nanoscale is
                   expected to do.";
    }

    leaf version{
      type string;
      default "1.0";
      description "The version number of this document. No pattern
                   control for this leaf is defined. User may use
                   simple numbering or provide a date and time, or a
                   mix of them.";
    }

    leaf license{
      type string;
      description "The name of the license controlling rights to this
                   document";
    }
```

```
leaf human-designed{
  type boolean;
  description "'Human-designed' means a system that occurs as a
               result of conscious human intervention. For clarity,
               human-designed systems may include naturally
               occurring components in an arrangement or for a
               purpose that is not otherwise naturally occurring.";
  default false;
}

leaf system-type{
  type identityref { base 'types:system-definition'; }
  description "Define the system type being described. Defaults to
               nanoscale-communication.

               Communication is the act of conveying a message from
               a transmitting party to a receiving party. This
               includes the components of message, transmitter,
               receiver, medium, and message carriers. In nanoscale
               communication at one to a few nanometers (nm), in
               the atomic range, local realism may be
               altered by quantum principles and include quantum
               entanglement.

               Communication includes systems with many
               transmitters and
               many receivers, for example broadcast (one to-all),
               multicast (many-to-one), and network (many-to-many)
               communication systems. The definition of a message
               includes signals transmitted for control purposes.
               The definition of a nanoscale communication network
               is illustrated in Figure 1 with a single-hop
               network. The framework discussed in Clause 5 builds
               on this definition of communication.";
  default 'types:nanoscale-communication';
}

container definitions
{
  uses definitions:definition;
  description "This container stores the list of definitions that
               are part of the system.";
}

container components
{
  uses components:component;
  description "This containers stores the list of components that
               are part of the system.";
}

container properties
{
  uses properties:property;
  description "This containers stores the list of optional
               properties that provide extra definition of the
               system.";
```

```
    }

    uses metrics:system-metrics;
  }
```

6.5.10 Definition of the nanoscale system

```
container nanoscale-system{
    description "This is a nanoscale system. It can be used as is in
                 any of your XML or JSON files. It is also convenient
                 as debugging to represent the data tree.";
    uses system;
  }
```

6.5.11 Definition of the nanoscale interface

```
augment "/if:interfaces/if:interface"{
  container nanoscale-interface{
    when "derived-from-or-self(/if:interfaces/if:interface/if:type,
          'ieee1906-dot1-types:nanoscale-communication-interface')";
    if-feature ieee1906-dot1-types:nanoscale-interface;

    container definitions{
      uses ieee1906-dot1-definitions:definition;
      description "This containers stores the list of definitions that
                   are part of the system.";
      }

    container components{
      uses  component;
      description "This container stores the list of components that
                   are part of the system.";
      }

    container properties{
      uses properties:property;
      description "This containers stores the list of optional
                   properties that provide extra definition of the
                   system.";
      }

    uses ieee1906-dot1-metrics:system-metrics;
    description "Addition of data nodes for the nanoscale communication
                 interface to the standard Interface data model, for
                 interfaces of the type 'nanoscale-communication-
                 interface'.";
    }

  description "Augment IETF interface when the nanoscale system can
               coexist within a classical network. Otherwise, the
               system can be a pure scientific 'self-contained' 1906.1
               nanoscale system which cannot augment ietf-interface.";
  }
```

Annex A

(informative)

Use cases

A.1 Introduction

Annex A presents four use cases illustrating the production of Extensible Markup Language (XML) and JavaScript Object Notation (JSON) files to describe nanoscale communication systems and experiments in conformance with IEEE Std 1906.1-2015. Table A.1 summarizes the use cases and presents specific parts of the framework that are covered.

Table A.1—Description of use cases and their relationship to the IEEE 1906.1 framework

Use case name	Description	Reference (subclause)
Generic nanoscale system	Shows the generic XML/JSON template generated from YANG modules of the IEEE 1906.1 framework, including the use of comprehensive sets of definitions, components, interfaces, and metrics.	A.2
Lab-on-chip	Represents a case where the framework is augmented to reflect specific needs of a third-party nanoscale model.	A.3
Wireless nanosensor network	Illustrates an example in which the nanoscale system is an Internet Engineering Task Force (IETF) interface.	A.4
Neuron model	Illustrates the use of a component hierarchy to model substructures of neurons, demonstrating detailed metrics.	A.5

A.2 Generic nanoscale system

A.2.1 Overview

The goal of this example is to demonstrate the generation of XML and JSON files from the YANG framework and to describe the mandatory definitions, components, interfaces, and metrics to comply with IEEE Std 1906.1-2015. Note that the values provided in this example are not intended to describe any particular real system, but are merely for illustrative purposes only. It is believed that nanoscale communication systems and interfaces shall share the same overall hierarchy as this example. For this reason, the mentioned components are filled with generic types, and all the metrics exhibit random values. This example also shows redefinition of SI units. For an explicit illustration on how to use SI units in a nanoscale communication XML or JSON file, please see Annex B.

A.2.2 Generic nanoscale system definition in XML format

```
<?xml version="1.0"?>
<nanoscale-system xmlns="urn:ieee:std:1906.1:yang:ieee1906-dot1-system"
             xmlns:types="urn:ieee:std:1906.1:yang:ieee1906-dot1-types"
             xmlns:si="urn:ieee:std:1906.1:yang:ieee1906-dot1-si-units"
        xmlns:metrics="urn:ieee:std:1906.1:yang:ieee1906-dot1-metrics">
  <identifier>urn:ieee:std:1906.1:xml:example-model</identifier>
  <title>Example IEEE Std 1906.1.1 Model</title>
```

```
<organization>IEEE Standards Association</organization>
<contact>IEEE P1906.1 Working Group
         Chair: Stephen F Bush (bushsf@research.ge.com)
         Secretary: Guillaume Mantelet
                    (gmantelet@voltigeurnetworks.com)</contact>
<description>This example demonstrates how the IEEE 1906.1.1 YANG
             model conforms with IEEE Std 1906.1-2015.</description>
<version>1.0</version>
<license>IEEE Standards Association</license>
<system-type>types:nanoscale-communication</system-type>
<!-- IEEE Std 1906.1-2015 Clause 4 Formal definition of a nanoscale
     communication system -->
<definitions>
  <definition>
    <identifier>Transmitter</identifier>
    <!-- Clause 4.2.1: shall be human-engineered (describe which part
         is "human-engineered") NOTE: If all the components and
         definitions of the system are human engineered, then a lazy
         description of human-engineered at the system level is
         allowed.-->
    <human-designed>true</human-designed>
    <name>Generic Transmitter</name>
    <description>IEEE Std 1906.1-2015 subclause 4.2.2: requires the
                transmitter shall be clearly defined.</description>
    <type-of-definition>types:transmitter</type-of-definition>
    <!-- Eventually, you can create your own YANG model that augments
         framework and insert message metrics there, or, why not, tx
         counts. -->
  </definition>
  <definition>
    <identifier>Receiver</identifier>
    <!-- subclause 4.2.1: shall be human-engineered (describe which part
         is "human-engineered") -->
    <human-designed>true</human-designed>
    <name>Generic Receiver</name>
    <description>IEEE Std 1906.1-2015 subclause 4.2.2 requires explicit
                definition of the nanoscale receiver</description>
    <type-of-definition>types:receiver</type-of-definition>
    <!-- Eventually, you can create your own YANG model that augments
         framework and insert message metrics there, or, why not, rx
         counts. -->
  </definition>
  <definition>
    <identifier>Medium</identifier>
    <!-- Clause 4.2.1: shall be human-engineered (describe which part
         is "human-engineered") -->
    <human-designed>true</human-designed>
    <name>Generic Medium</name>
    <description>IEEE Std 1906.1-2015 subclause 4.2.2 requires explicit
                definition of the nanoscale medium</description>
    <type-of-definition>types:medium</type-of-definition>
    <!-- Eventually, you can create your own YANG model that augments
         framework and insert message metrics there, or, why not,
         channel loss, BER etc. -->
  </definition>
  <definition>
    <identifier>Message</identifier>
```

```
      <!-- Clause 4.2.1: shall be human-engineered (describe which part
           is "human-engineered") -->
      <human-designed>true</human-designed>
      <name>Generic Message</name>
      <description>IEEE Std 1906.1-2015 subclause 4.2.2 requires explicit
                   definition of the nanoscale message</description>
      <type-of-definition>types:message</type-of-definition>
      <!-- Next line defines interface (encoding) to our model.
           Component MessageCarrier should follow (IEEE Std 1906.1-2015
           subclause 4.3)-->
      <next-component>"/nanoscale-system/components/component
                      [identifier='MessageCarrier']"</next-component>
      <message-metrics>
        <!-- IEEE Std 1906.1-2015 subclause 6.1 Message Deliverability -->
        <message-deliverability>0.8</message-deliverability>
        <!-- IEEE Std 1906.1-2015 subclause 6.2 Message Lifetime -->
        <message-lifetime si:unit="milliseconds">10</message-lifetime>
        <!--IEEE Std 1906.1-2015 subclause 6.3 Information Density -->
        <information-density si:unit="bit.nanometer-3">
          <surface>
            <!-- List order is important. First scalar for 'x', second
                 scalar for 'y' -->
            <scalar>0</scalar>
            <scalar>10</scalar>
          </surface>
          <amount-of-information>10</amount-of-information>
        </information-density>
        <!-- IEEE Std 1906.1-2015 subclause 6.4 Bandwidth-Delay Product
         -->
        <bandwidth-delay-product>
          <channel-bandwidth>10</channel-bandwidth>
          <channel-delay si:unit="milliseconds">10</channel-delay>
        </bandwidth-delay-product>
        <!-- IEEE Std 1906.1-2015 subclause 6.5 Information and
             Communication Energy -->
        <information-and-communication-energy>
          <energy-message-delivery>10</energy-message-delivery>
          <information-message-delivery>10</information-message-delivery>
        </information-and-communication-energy>
      </message-metrics>
    </definition>
    <definition>
      <identifier>Nanoscale Communication System</identifier>
      <!-- Subclause 4.2.1: shall be human-engineered (describe which
           part is "human-engineered") -->
      <human-designed>true</human-designed>
      <name>Nanoscale System</name>
      <description>IEEE Std 1906.1-2015 subclause 4.2.3: requires a
                   fundamental, essential component of the system shall
                   reside at the nanoscale and be clearly defined
                   here.</description>
      <type-of-definition>types:component-less-than-100nm</type-of-
definition>
    </definition>
    <definition>
      <identifier>BrownianMotion</identifier>
      <name>Brownian Motion</name>
```

```
    <description>IEEE Std 1906.1-2015 subclause 4.2.4: requires that
                 physics unique to the nanoscale regime be leveraged and
                 clearly defined. We define this as atypical, or non-
                 standard-physics, for communication.</description>
    <type-of-definition>types:non-standard-physics</type-of-definition>
    <!-- Eventually, this is your entry point to put your custom
         metrics. See A.2 and A.3 in IEEE Std 1906.1-2015 -->
  </definition>
</definitions>
<components>
  <component>
    <identifier>MessageCarrier</identifier>
    <!-- Subclause 4.2.1: shall be human-engineered (describe which
         part is "human-engineered") -->
    <human-designed>true</human-designed>
    <name>Message Carrier</name>
    <description>IEEE Std 1906.1-2015 subclause 4.2.2 requires explicit
                 definition of the message carrier.</description>
    <!-- An example of a property, it is purely optional, here it
         would override corresponding property from parent component,
         which is, here, the system itself -->
    <properties>
      <derived-unit si:unit="terahertz">si:frequency</derived-unit>
    </properties>
    <type-of-component>types:message-carrier</type-of-component>
    <!-- Next line defines interface (range of motion) to our model.
         Component Motion should follow (See IEEE Std 1906.1-2015
         subclause 4.3)-->
    <next-component>"/nanoscale-
system/components/component[identifier='Motion']"</next-component>
    <!-- Next line defines interface (decoding) to our model.
         Component Receiver should have been defined -->
    <next-definition>"/nanoscale-
system/definitions/definition[identifier='Receiver']"</next-definition>
    <!-- Message carrier has no metrics associated by default, but
         you can specify set of metrics -->
  </component>
  <component>
    <identifier>Motion</identifier>
    <!-- Subclause 4.2.1: shall be human-engineered (describe which part
         is "human-engineered") -->
    <human-designed>true</human-designed>
    <name>Motion</name>
    <description>IEEE Std 1906.1-2015 requires clear definition of the
                 movement capability for Message
                 carrier.</description>
    <properties>
      <derived-unit si:unit="terahertz">si:frequency</derived-unit>
    </properties>
    <type-of-component>types:motion</type-of-component>
    <!-- Next line defines interface (controlled motion) to our
         model. Component Field should follow -->
    <next-component>"/nanoscale-
system/components/component[identifier='Microtubule']"</next-component>
    <motion-metrics>
      <!-- IEEE Std 1906.1-2015 subclause 6.6 Collision Behavior -->
      <collision-behavior>
```

```
          <coefficient-of-restitution>1/2</coefficient-of-restitution>
          <speed-before-collision
si:unit="nanometers/millisecond">10</speed-before-collision>
         <speed-after-collision
si:unit="nanometers/millisecond">10</speed-after-collision>
        </collision-behavior>
        <!-- IEEE Std 1906.1-2015 subclause 6.7 Mass Displacement -->
        <mass-displacement>
          <mass-displacement>10</mass-displacement>
          <x si:unit="nanograms">10</x>
          <!-- Here, component time unit was in microsecond.
               Exceptionally, this leaf overrides property and uses
               milliseconds instead. It is more tractable than 1e-2,
               for embedded system that do not necessarily have complex
               number notation, or even floating point arithmetic
               units. -->
          <T si:unit="milliseconds">10</T>
          <tau si:unit="millisecond">10</tau>
          <M>10</M>
        </mass-displacement>
        <!-- IEEE Std 1906.1-2015 subclause 6.8 Positioning Accuracy of
             Message Carriers -->
        <positioning-accuracy-of-message-carriers>
          <radius si:unit="nanometers">10</radius>
          <position si:unit="nanometers">10</position>
          <accuracy-percent>10</accuracy-percent>
        </positioning-accuracy-of-message-carriers>
      </motion-metrics>
    </component>
    <component>
      <identifier>Microtubule</identifier>
      <!-- Subclause 4.2.1: shall be human-engineered (describe which part
           is "human-engineered") -->
      <human-designed>true</human-designed>
      <name>Microtubule</name>
      <description>IEEE Std 1906.1-2015 requires clear definition of the
                  field component: microtubule organizes movement of
                  motion.</description>
      <type-of-component>types:microtubule</type-of-component>
      <!-- Next line defines interface (rapid control of field) to our
           model. Component Perturbation should follow -->
      <next-component>"/nanoscale-system/components/component[identifier
                     ='Perturbation']"</next-component>
      <field-metrics>
        <!-- IEEE Std Std 1906.1-2015 subclause 6.9 Persistence Length -->
        <persistence-length>
          <unit-tangent-vectors>
            <segment-index>1</segment-index>
            <s si:unit="nanometers">10</s>
            <u-s>
              <nabla>
                <coordinate>0</coordinate>
                <coordinate>0</coordinate>
                <coordinate>0</coordinate>
              </nabla>
            </u-s>
          </unit-tangent-vectors>
```

```
          <u-0>
            <nabla>
              <coordinate>5.10</coordinate>
              <coordinate>1.02</coordinate>
              <coordinate>2.04</coordinate>
            </nabla>
          </u-0>
          <zeta-p si:unit="nanometers">10</zeta-p>
        </persistence-length>
        <!-- IEEE Std 1906.1-2015 subclause 6.10 Diffusive Flux -->
        <diffusive-flux>
          <J>10.1</J>
          <D>10e6</D>
          <phi>10e-5</phi>
          <x>10</x>
        </diffusive-flux>
        <!-- IEEE Std 1906.1-2015 subclause 6.11 Langevin Noise -->
        <langevin-noise>
          <m si:unit="nanograms">10</m>
          <x>10</x>
          <t>10</t>
          <lambda>10</lambda>
          <eta>10</eta>
        </langevin-noise>
      </field-metrics>
    </component>
    <component>
      <identifier>Perturbation</identifier>
      <!-- Subclause 4.2.1: shall be human-engineered (describe which
           part is "human-engineered") -->
      <human-designed>true</human-designed>
      <name>Perturbation</name>
      <description>IEEE Std 1906.1-2015 requires clear definition of
                  perturbation defining the signal transported by
                  message-carrier.</description>
      <type-of-component>types:perturbation</type-of-component>
      <!-- Next line defines interface to our model. Component
           Specificity should follow -->
      <next-component>"/nanoscale-
system/components/component[identifier='Specificity']"</next-component>
    </component>
    <component>
      <identifier>Specificity</identifier>
      <!-- Subclause 4.2.1: shall be human-engineered (describe which
           part is "human-engineered") -->
      <human-designed>true</human-designed>
      <name>Specificity</name>
      <description>IEEE Std 1906.1-2015 requires definition of specificity
                  defining targeted reception of perturbation
                  signal.</description>
      <type-of-component>types:specificity</type-of-component>
      <!-- Next line defines interface to our model. Component
           MessageCarrier should have been defined -->
      <next-component>"/nanoscale-
system/components/component[identifier='MessageCarrier']"</next-
component>
      <specificity-metrics>
```

```
        <!-- IEEE Std 1906.1-2015 subclause 6.12 Specificity -->
        <specificity>80</specificity>
        <!-- IEEE Std 1906.1-2015 subclause 6.13 Affinity -->
        <affinity>10</affinity>
        <!-- IEEE Std 1906.1-2015 subclause 6.14 Sensitivity -->
        <sensitivity>50</sensitivity>
        <angular-spectrum>
          <density-function>
            <probability-sample>0.7</probability-sample>
          </density-function>
          <!-- IEEE Std 1906.1-2015 subclause 6.15 Angular (angle-of-
               arrival) Spectrum -->
        </angular-spectrum>
        <!-- IEEE Std 1906.1-2015 subclause 6.16 Delay (time-of-arrival)
             Spectrum -->
        <delay-spectrum>
          <density-function>
            <probability-sample>0.6</probability-sample>
          </density-function>
        </delay-spectrum>
      </specificity-metrics>
    </component>
  </components>
  <!-- And now to the system metrics itself-->
  <system-metrics>
    <!-- IEEE Std 1906.1-2015 subclause 6.17 Active Network
         Programmability -->
    <active-network-programmability>
      <t si:unit="nanoseconds">10</t>
      <S>
        <math-formula>
          <expression>10X^2</expression>
          <package>Mathematica</package>
          <version>12.0</version>
        </math-formula>
      </S>
      <f>10</f>
      <delta-f>10</delta-f>
    </active-network-programmability>
    <!-- IEEE Std 1906.1-2015 subclause 6.18 Perturbation rate -->
    <perturbation-rate>
      <rate-of-perturbation>10</rate-of-perturbation>
      <!-- should these derivatives have annotations? Yes, especially
           if we use variables. Are derivatives sort of ratio? Is speed,
           for example, derivative of position? -->
      <error-of-perturbation>10</error-of-perturbation>
    </perturbation-rate>
    <!-- IEEE Std 1906.1-2015 subclause 6.19 Supersystem degradation --
>
    <supersystem-degradation>
      <performance-attribute>The supersystem is the system in which the
IEEE 1906 nanoscale network resides. This metric quantifies the
potential impact of the nanoscale network upon the supersystem with
regard to its normal operation. In other words, this metric quantifies
how much the IEEE 1906 network reduces the performance of the original
system.</performance-attribute>
      <ds>10</ds>
```

```
      <spn>10</spn>
      <sp>10</sp>
    </supersystem-degradation>
    <!-- IEEE Std 1906.1-2015 subclause 6.20 Bandwidth-Volume Ratio -->
    <bandwidth-volume-ratio>
      <bandwidth>10^9</bandwidth>
      <volume si:unit="nanometers^3">10</volume>
    </bandwidth-volume-ratio>
  </system-metrics>
</nanoscale-system>
```

A.2.3 Generic nanoscale system definition in JSON format

```
{
  "ieee1906-dot1-system:nanoscale-system": {
    "identifier": "urn:ieee:std:1906.1:xml:example-model",
    "title": "Example IEEE 1906.1.1 Model",
    "organization": [
      "IEEE Standards Association"
    ],
    "contact": [
      "IEEE P1906.1 Working Group
       Chair: Stephen F Bush (bushsf@research.ge.com)
       Secretary: Guillaume Mantelet (gmantelet@voltigeurnetworks.com)"
    ],
    "description": "This example demonstrates how the IEEE 1906.1.1
                    YANG model conforms with IEEE Std 1906.1-2015.",
    "version": "1.0",
    "license": "IEEE Standards Association",
    "system-type": "ieee1906-dot1-types:nanoscale-communication",
    "definitions": {
      "definition": [
        {
          "identifier": "Transmitter",
          "human-designed": true,
          "name": "Generic Transmitter",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.2: requires
                          the transmitter shall be clearly defined.",
          "type-of-definition": "ieee1906-dot1-types:transmitter"
        },
        {
          "identifier": "Receiver",
          "human-designed": true,
          "name": "Generic Receiver",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.2
           requires explicit definition of the nanoscale receiver",
          "type-of-definition": "ieee1906-dot1-types:receiver"
        },
        {
          "identifier": "Medium",
          "human-designed": true,
          "name": "Generic Medium",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.2 requires
                          explicit definition of the nanoscale medium",
          "type-of-definition": "ieee1906-dot1-types:medium"
        },
        {
```

```
          "identifier": "Message",
          "human-designed": true,
          "name": "Generic Message",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.2 requires
                     explicit definition of the nanoscale transmitter",
          "type-of-definition": "ieee1906-dot1-types:message",
          "next-component": [
            "\"/nanoscale-
system/components/component[identifier='MessageCarrier']\""
          ],
          "message-metrics": {
            "message-deliverability": "0.8",
            "message-lifetime": "10",
            "@message-lifetime": {
              "ieee1906-dot1-si-units:unit":"milliseconds"
            },
            "information-density": {
              "@": {
                "ieee1906-dot1-si-units:unit":"bit.nanometer-3"
              },
              "surface": {
                "scalar": [
                  "0",
                  "10"
                ]
              },
              "amount-of-information": "10"
            },
            "bandwidth-delay-product": {
              "channel-bandwidth": "10",
              "channel-delay": "10",
              "@channel-delay": {
                "ieee1906-dot1-si-units:unit":"milliseconds"
              }
            },
            "information-and-communication-energy": {
              "energy-message-delivery": "10",
              "information-message-delivery": "10"
            }
          }
        },
        {
          "identifier": "Nanoscale Communication System",
          "human-designed": true,
          "name": "Nanoscale System",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.3:
           requires a fundamental, essential component of the system
           shall reside at the nanoscale and be clearly defined here.",
          "type-of-definition":"ieee1906-dot1-types:component-less-than-100nm"
        },
        {
          "identifier": "BrownianMotion",
          "name": "Brownian Motion",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.4: requires
                          that physics unique to the nanoscale regime be
                          leveraged and clearly defined. We define this
                          as atypical, or non-standard-physics, for
```

```
                       communication.",
          "type-of-definition": "ieee1906-dot1-types:non-standard-physics"
        }
      ]
    },
    "components": {
      "component": [
        {
          "identifier": "MessageCarrier",
          "human-designed": true,
          "name": "Message Carrier",
          "description": "IEEE Std 1906.1-2015 subclause 4.2.2 requires
                       explicit definition of the message carrier.",
          "properties": {
            "derived-unit": [
              "ieee1906-dot1-si-units:frequency"
            ],
            "@derived-unit": [
              { "ieee1906-dot1-si-units:unit":"terahertz"
              }
            ]
          },
          "type-of-component": "ieee1906-dot1-types:message-carrier",
          "next-component": [
            "\"/nanoscale-
system/components/component[identifier='Motion']\""
          ],
          "next-definition": [
            "\"/nanoscale-
system/definitions/definition[identifier='Receiver']\""
          ]
        },
        {
          "identifier": "Motion",
          "human-designed": true,
          "name": "Motion",
          "description": "IEEE Std 1906.1-2015 requires clear definition
                      of the movement capability for message carrier.",
          "properties": {
            "derived-unit": [
              "ieee1906-dot1-si-units:frequency"
            ],
            "@derived-unit": [
              { "ieee1906-dot1-si-units:unit":"terahertz"
              }
            ]
          },
          "type-of-component": "ieee1906-dot1-types:motion",
          "next-component": [
            "\"/nanoscale-
system/components/component[identifier='Microtubule']\""
          ],
          "motion-metrics": {
            "collision-behavior": {
              "coefficient-of-restitution": "1/2",
              "speed-before-collision": "10",
              "@speed-before-collision": {
```

```
                "ieee1906-dot1-si-units:unit":"nanometers/millisecond"
              },
              "speed-after-collision": "10",
              "@speed-after-collision": {
                "ieee1906-dot1-si-units:unit":"nanometers/millisecond"
              }
            },
            "mass-displacement": {
              "mass-displacement": "10",
              "x": "10",
              "@x": {
                "ieee1906-dot1-si-units:unit":"nanograms"
              },
              "T": "10",
              "@T": {
                "ieee1906-dot1-si-units:unit":"milliseconds"
              },
              "tau": "10",
              "@tau": {
                "ieee1906-dot1-si-units:unit":"millisecond"
              },
              "M": "10"
            },
            "positioning-accuracy-of-message-carriers": {
              "radius": "10",
              "@radius": {
                "ieee1906-dot1-si-units:unit":"nanometers"
              },
              "position": "10",
              "@position": {
                "ieee1906-dot1-si-units:unit":"nanometers"
              },
              "accuracy-percent": "10"
            }
          }
        },
        {
          "identifier": "Microtubule",
          "human-designed": true,
          "name": "Micro tubule",
          "description": "IEEE Std 1906.1-2015 requires clear definition of
                          the field component: microtubule organizes
                          movement of motion.",
          "type-of-component": "ieee1906-dot1-types:microtubule",
          "next-component": [
            "\"/nanoscale-
system/components/component[identifier='Perturbation']\""
          ],
          "field-metrics": {
            "persistence-length": {
              "unit-tangent-vectors": [
                {
                  "segment-index": 1,
                  "s": "10",
                  "@s": {
                    "ieee1906-dot1-si-units:unit":"nanometers"
                  },
```

```
                "u-s": {
                  "nabla": {
                    "coordinate": [
                      "0",
                      "0",
                      "0"
                    ]
                  }
                }
              }
            ],
            "u-0": {
              "nabla": {
                "coordinate": [
                  "5.10",
                  "1.02",
                  "2.04"
                ]
              }
            },
            "zeta-p": "10",
            "@zeta-p": {
              "ieee1906-dot1-si-units:unit":"nanometers"
            }
          },
          "diffusive-flux": {
            "J": "10.1",
            "D": "10e6",
            "phi": "10e-5",
            "x": "10"
          },
          "langevin-noise": {
            "m": "10",
            "@m": {
              "ieee1906-dot1-si-units:unit":"nanograms"
            },
            "x": "10",
            "t": "10",
            "lambda": "10",
            "eta": "10"
          }
        }
      },
      {
        "identifier": "Perturbation",
        "human-designed": true,
        "name": "Perturbation",
        "description": "IEEE Std 1906.1-2015 requires clear definition of
                        perturbation defining the signal transported
                        by message-carrier.",
        "type-of-component": "ieee1906-dot1-types:perturbation",
        "next-component": [
          "\"/nanoscale-
system/components/component[identifier='Specificity']\""
        ]
      },
      {
```

```
          "identifier": "Specificity",
          "human-designed": true,
          "name": "Specificity",
          "description": "IEEE Std 1906.1-2015 requires definition of
                          specificity defining targeted reception of
                          perturbation signal.",
          "type-of-component": "ieee1906-dot1-types:specificity",
          "next-component": [
            "\"/nanoscale-
system/components/component[identifier='MessageCarrier']\""
          ],
          "specificity-metrics": {
            "specificity": "80",
            "affinity": "10",
            "sensitivity": "50",
            "angular-spectrum": {
              "density-function": [
                {
                  "probability-sample": "0.7"
                }
              ]
            },
            "delay-spectrum": {
              "density-function": [
                {
                  "probability-sample": "0.6"
                }
              ]
            }
          }
        }
      ]
    },
    "system-metrics": {
      "active-network-programmability": {
        "t": "10",
        "@t": {
          "ieee1906-dot1-si-units:unit":"nanoseconds"
        },
        "S": {
          "math-formula": {
            "expression": "10X^2",
            "package": "Mathematica",
            "version": "12.0"
          }
        },
        "f": "10",
        "delta-f": "10"
      },
      "perturbation-rate": {
        "rate-of-perturbation": "10",
        "error-of-perturbation": "10"
      },
      "supersystem-degradation": {
        "performance-attribute": "The supersystem is the system in
which the IEEE 1906 nanoscale network resides. This metric quantifies
the potential impact of the nanoscale network on the supersystem with
```

```
regard to its normal operation. In other words, this metric quantifies
how much the IEEE 1906 network reduces the performance of the original
system.",
        "ds": "10",
        "spn": "10",
        "sp": "10"
      },
      "bandwidth-volume-ratio": {
        "bandwidth": "10^9",
        "volume": "10",
        "@volume": {
          "ieee1906-dot1-si-units:unit":"nanometers^3"
        }
      }
    }
  }
}
```

A.3 Lab-on-chip application: nano-intravital device

A.3.1 Introduction

Further description of this use case is available in Annex B of IEEE Std 1906.1-2015. The mapping between the nano-intravital device (NANIVID) components to the IEEE 1906.1 framework is recalled as a reference in Table A.2.

Table A.2—Mapping NANIVID components to the IEEE 1906.1 framework

IEEE 1906.1 component	Corresponding components in NANIVID
Transmitter	Hydrogel (loaded with epidermal growth factor [EGF])
Receiver	R-EGF (R = receptor) or membrane surface of cells
Message	EGF (epidermal growth factor)
Medium	Growth media
Message carrier	Diffusion from concentrated source
Component < 100 nm	R-EGF on cancer cells
Non-standard physics	Brownian motion
Motion	Diffusion based
Field	Gradient based
Perturbation	Loading hydrogel with EGF and insertion in the NANIVID device
Specificity	High

A.3.2 Derived component

The NANIVID model describes component types that are not defined in 5.4.2, and therefore that are not included in the IEEE 1906.1 framework. The component types shall be defined to refine the set of metrics used by these NANIVID components. The following excerpt is an example of an addition to the framework as defined in 5.4.2.

```
identity diffusion-from-concentrated-source {
    base types:message-carrier;
    description "A transmitter emits a time-sensitive amount of solute
                 that defines the intensity of a signal. Above a
```

```
                 certain concentration, the transmitter signals a
                 'one', 'on' or 'true' message, otherwise it shall be
                 considered 'zero', 'off', or 'false'. The signal moves
                 through the medium by diffusion and the receiver
                 measures the corresponding 'concentration' as a
                 function of time.";
}
```

A.3.3 Non-standard physics property

The Brownian motion identity declares the “non-standard” physics applying to the communication system. It is a property similar to the declared size of component (< 100 nm), which is a length scale property:

```
identity brownian-motion {
    base types:diffusion;
    base types:non-standard-physics;
    description "A diffusion-based motion ruled by the laws of Brownian
                 movement. Because it inherits from diffusion which
                 itself inherits from motion, a component pointing to
                 this type shall have access to motion metrics.";
}
```

A.3.4 Potential new metrics

Annex B of IEEE Std 1906.1-2015 provides a description of nanoscale experiments and considers the definition of metrics for these examples out of scope. This annex does not provide further detail for these metrics. However, if metrics for Brownian motion were utilized in the NANIVID experiment, the following grouping could be used:

```
grouping brownian-motion-metrics{
  container brownian-motion-metrics{
    when "derived-from-or-self(../type-of-component, 'brownian-motion')";
    description "The parent component shall have a leaf of type
                 'brownian-motion' in order to be eligible to use this
                 container.";
  }

  description "This is a placeholder for Brownian motion metrics being
               used as non-standard physics in this model.";
}
```

A.3.5 NANIVID description container

All NANIVID model definitions are included in the framework, and there is no need to augment it. However, to make use of the framework, a container specifying the NANIVID experiment may be defined, making use of the groupings provided by the framework defined by this standard:

```
feature nanivid{
  description "This nanoscale system is part of nanivid experiment.";
}

container nanivid{
    description "Redefined nanoscale-system for our nanivid experiment,
                 in which we provide an extra subtree.";

  uses system:system{
```

```
    augment components/component{
      if-feature nanivid;
      uses brownian-motion-metrics;

      description "Augment nanoscale system with the brownian motion
                   defined in NANIVID example.";
    }
  }
}
```

A.3.6 NANIVID description in XML format

The NANIVID biological model shall reuse the YANG model described in Clause 6, and specifically the snippet in 6.5.5. No addition to the framework is required. The following XML snippet is a valid biological IEEE 1906.1 model:

```
<?xml version="1.0"?>
<nd:nanivid xmlns:nd="urn:ieee:std:1906.1:yang:ieee1906-dot1-nanivid">
  <nd:identifier>urn:ieee:std:1906.1:xml:nanivid</nd:identifier>
  <nd:title>NANIVID</nd:title>
  <nd:organization>IEEE  1906.1.1  - Recommended  Practice  for  Nanoscale
and Molecular Communication Framework Working Group</nd:organization>
  <nd:description>Nano-intravital device</nd:description>
  <nd:definitions>
    <nd:definition>
      <nd:description>R-EGF on cancer cells</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">tod:component-
less-than-100nm</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier  xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">tod:non-standard-physics</nd:identifier>
      <nd:type-of-definition
xmlns:n="urn:ieee:std:1906.1:yang:ieee1906-dot1-nanivid">n:brownian-
motion</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier>transmitter</nd:identifier>
      <nd:description>Hydrogel (loaded with EGF)</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">tod:transmitter</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier>receiver</nd:identifier>
      <nd:description>Rhodamine-EGF on membrane surface of
cells</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">tod:receiver</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier>message</nd:identifier>
```

```
      <nd:description>Epidermal-Growth-Factor on cancer
cells</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">tod:message</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier>medium</nd:identifier>
      <nd:description>growth media</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">tod:medium</nd:type-of-definition>
    </nd:definition>
  </nd:definitions>
  <nd:components>
    <nd:component>
      <nd:identifier>urn:ieee:std:1906.1:xml:diffusion</nd:identifier>
      <nd:type-of-component  xmlns:n="urn:ieee:std:1906.1:yang:ieee1906-
dot1-nanivid">n:diffusion-from-concentrated-source</nd:type-of-
component>
    </nd:component>
    <nd:component>
      <nd:identifier>urn:ieee:std:1906.1:yang:motion</nd:identifier>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:diffusion</nd:type-of-component>
      <nd:motion-metrics/>
    </nd:component>
    <nd:component xmlns:n="urn:ieee:std:1906.1:yang:ieee1906-dot1-nanivid">
      <nd:identifier>urn:ieee:std:1906.1:yang:brownian-
motion</nd:identifier>
      <nd:type-of-component>n:brownian-motion</nd:type-of-component>
      <n:brownian-motion-metrics/>
    </nd:component>
    <nd:component>
      <nd:identifier>urn:ieee:std:1906.1:yang:concentration-
gradient</nd:identifier>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:concentration-gradient</nd:type-of-component>
      <nd:field-metrics/>
    </nd:component>
    <nd:component>
      <nd:identifier>urn:ieee:std:1906.1:yang:concentration-
change</nd:identifier>
      <nd:description>Loading hydrogel with EGF and insertion in the
NANIVID device</nd:description>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:concentration-change</nd:type-of-component>
    </nd:component>
    <nd:component>
      <nd:identifier>urn:ieee:std:1906.1:yang:receptor-
sensitivity</nd:identifier>
      <nd:description>High</nd:description>
```

```
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">toc:receptor-
sensitivity</nd:type-of-component>
      <nd:specificity-metrics/>
    </nd:component>
  </nd:components>
  <nd:system-metrics/>
</nd:nanivid>
```

A.3.7 NANIVID description in JSON format

```
{
  "ieee1906-dot1-nanivid:nanivid": {
    "identifier": "urn:ieee:std:1906.1:xml:nanivid",
    "title": "NANIVID",
    "organization": [
      "IEEE Std 1906.1.1 - IEEE Standard Data Model for Nanoscale
Communication Systems"
    ],
    "description": "Nano-intravital device",
    "definitions": {
      "definition": [
        {
          "description": "R-EGF on cancer cells",
          "type-of-definition": "ieee1906-dot1-types:component-less-than-100nm"
        },
        {
          "identifier": "tod:non-standard-physics",
          "type-of-definition": "brownian-motion"
        },
        {
          "identifier": "transmitter",
          "description": "Hydrogel (loaded with EGF)",
          "type-of-definition": "ieee1906-dot1-types:transmitter"
        },
        {
          "identifier": "receiver",
          "description": "Rhodamine-EGF on membrane surface of cells",
          "type-of-definition": "ieee1906-dot1-types:receiver"
        },
        {
          "identifier": "message",
          "description": "Epidermal-Growth-Factor on cancer cells",
          "type-of-definition": "ieee1906-dot1-types:message"
        },
        {
          "identifier": "medium",
          "description": "growth media",
          "type-of-definition": "ieee1906-dot1-types:medium"
        }
      ]
    },
    "components": {
      "component": [
        {
          "identifier": "urn:ieee:std:1906.1:xml:diffusion",
```

```
          "type-of-component": "diffusion-from-concentrated-source"
        },
        {
          "identifier": "urn:ieee:std:1906.1:yang:motion",
          "type-of-component": "ieee1906-dot1-types:diffusion"
        },
        {
          "identifier": "urn:ieee:std:1906.1:yang:brownian-motion",
          "type-of-component": "brownian-motion"
        },
        {
          "identifier": "urn:ieee:std:1906.1:yang:concentration-gradient",
         "type-of-component": "ieee1906-dot1-types:concentration-gradient"
        },
        {
          "identifier": "urn:ieee:std:1906.1:yang:concentration-change",
          "description": "Loading hydrogel with EGF and insertion in
the NANIVID device",
          "type-of-component": "ieee1906-dot1-types:concentration-change"
        },
        {
          "identifier": "urn:ieee:std:1906.1:yang:receptor-sensitivity",
          "description": "High",
          "type-of-component": "ieee1906-dot1-types:receptor-
sensitivity"
        }
      ]
    }
  }
}
```

A.3.8 Triggering action in the NANIVID experiment

To trigger cell migration, an action on the perturbation component is performed by changing metric parameters. For example, Raja et al. [B5][10] uses 0 uM, 4.5 uM, 5 uM, 6 uM, 7 uM, and 7.4 uM concentrations of EGF:

```
..
&lt;component&gt;
  &lt;identifier&gt;urn:ieee:std:1906.1:yang:perturbation&lt;/identifier&gt;
  &lt;perturbation-metrics&gt;
    &lt;molar-concentration units="micromol.l-1"&gt;7.4&lt;/molar-concentration&gt;
  &lt;/perturbation-metrics&gt;
&lt;/component&gt;
..
```

NOTE—Units for molar concentration can be a system property.

[10] The numbers in brackets correspond to those of the bibliography in Annex E.

A.4 Wireless nanosensor networks

A.4.1 Introduction

Further description of this use case is available in Annex B of IEEE Std 1906.1-2015. The mapping between the set of nanosensor components and the IEEE 1906.1 framework is recalled in Table A.3:

Table A.3—Mapping wireless nanosensor network components to the IEEE 1906.1 framework

IEEE 1906.1 component	Corresponding components in NANIVID
Transmitter	Carbon nanotube (CNT)–based nanoantenna
Receiver	CNT-based nanoantenna
Message	Sodium concentration
Medium	Air
Message carrier	Electromagnetic (EM) wave
Component < 100 nm	Sensor, message carrier (THz frequency wave)
Non-standard physics	Impact of scale on resonance
Motion	Radiation and wave guide
Field	Intensity/directional antenna
Perturbation	RF modulation
Specificity	Receptor sensitivity/antenna aperture

A.4.2 Derived component

The wireless nanosensor model describes component types that are not defined in 5.4.2, and therefore that are not included in the IEEE 1906.1 framework. The component types are defined, as required, to refine the set of metrics used by these components. The following excerpt serves as an example of an addition to the framework as defined in 5.4.2.

```
identity radio-frequency-modulation {
    base types:perturbation;
    description "The instantaneous frequency deviation in carrier
                waves transport message acting in our model as a
                perturbation. In this model, modulation is performed
                over oscillations in the range of 20 Khz to 300 GHz,
                and beyond.";
}
```

A.4.3 Non-standard physics property

The impact of scale on resonance identity declares the non-standard physics that applies to this system. In addition, resonance metrics could lead to the development of new metrics as described in A.3:

```
identity impact-of-scale-on-resonance{
  base types:non-standard-physics;
  description "Apparently, scale of the system has an impact on its
               resonance its motion.";
}
identity radio-frequency-modulation {
  base types:perturbation;
  description "The instantaneous frequency deviation in carrier waves
               transport message acting in our model as a perturbation.
```

```
               In this model, modulation is performed over oscillations
               in the range of 20 Khz to 300 GHz, and beyond.";
```

A.4.4 Potential new metrics

Annex B of IEEE Std 1906.1-2015 provides descriptions of nanoscale experiments and considers the definition of metrics for these examples out of scope. This annex does not provide further detail for these metrics. However, if metrics for resonance were utilized in nanosensor devices, the following grouping would be provisioned:

```
grouping resonance-metrics{
  container resonance-metrics{
    when "derived-from-or-self(../definitions:type-of-definition,
          'impact-of-scale-on-resonance')";
    description "The parent component shall have a leaf of type
                 'impact-of-scale-on-resonance' in order to be eligible
                 to use this container.";
  }

  description "This is a placeholder for Resonance metrics being used
               as non-standard physics in this model.";
```

A.4.5 Nanosensor description container

The nanosensor model definitions can be incorporated into an IETF interface: here an antenna acts as both transmitter and receiver. The framework defined by this standard offers a container augmenting ietf-interface that that is reused as-is to describe a wireless nanosensor. Thus, with this model, one can access the nanoscale along with classical parameters such as packet statistics, bytes in error, etc.

```
feature nanosensor{
  description "This nanoscale interface is a nanosensor.";
}

augment "/if:interfaces/if:interface/components:nanoscale-
interface/definitions:definitions/definitions:definition"{
  if-feature nanosensor;
  uses resonance-metrics;

  description "Augment nanoscale interface with the resonance defined
               in nanosensor example.";
}
```

A.4.6 Wireless nanosensor description in XML format

The wireless nanosensor can reuse the YANG model described in Clause 6, and specifically the snippet of 6.5.5. No addition to the framework is required and the following XML snippet is a valid biological IEEE 1906.1 model. Metrics and mandatory components are omitted for the sake of brevity. Please refer to A.2 for the comprehensive set of components that this nanosensor XML file should provide to comply with IEEE Std 1906.1-2015:

```
<?xml version="1.0"?>
<if:interfaces xmlns:if="urn:ietf:params:xml:ns:yang:ietf-interfaces">
  <if:interface>
    <if:name>nano0</if:name>
```

```
    <if:type xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:nanoscale-communication-interface</if:type>
    <ni:nanoscale-interface
xmlns:ni="urn:ieee:std:1906.1:yang:ieee1906-dot1-components">
      <ni:definitions>
        <ni:definition>
          <ni:description>Sensor, message carrier</ni:description>
          <ni:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">tod:component-
less-than-100nm</ni:type-of-definition>
        </ni:definition>
        <ni:definition xmlns:n="urn:ieee:std:1906.1:yang:ieee1906-dot1-
nanosensor">
          <ni:identifier xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-
dot1-types">toc:non-standard-physics</ni:identifier>
          <ni:type-of-definition>n:impact-of-scale-on-
resonance</ni:type-of-definition>
          <n:resonance-metrics/>
        </ni:definition>
      </ni:definitions>
      <ni:components>
        <ni:component xmlns:ns="urn:ieee:std:1906.1:yang:ieee1906-dot1-
nanosensor">
          <ni:identifier>ns:perturbation</ni:identifier>
          <ni:type-of-component>ns:radio-frequency-modulation</ni:type-
of-component>
        </ni:component>
      </ni:components>
    </ni:nanoscale-interface>
  </if:interface>
</if:interfaces>
```

A.4.7 Wireless nanosensor description in JSON format

```
{
  "ietf-interfaces:interfaces": {
    "interface": [
      {
        "name": "nano0",
        "type": "ieee1906-dot1-types:nanoscale-communication-
interface",
        "ieee1906-dot1-components:nanoscale-interface": {
          "definitions": {
            "definition": [
              {
                "description": "Sensor, message carrier",
                "type-of-definition": "ieee1906-dot1-types:component-
less-than-100nm"
              },
              {
                "identifier": "toc:non-standard-physics",
                "type-of-definition": "ieee1906-dot1-nanosensor:impact-
of-scale-on-resonance"
              }
            ]
          },
```

```
          "components": {
            "component": [
              {
                "identifier": "ns:perturbation",
                "type-of-component": "ieee1906-dot1-nanosensor:radio-
frequency-modulation"
              }
            ]
          }
        }
      }
    ]
  }
}
```


A.5 Model of a neuron

A.5.1 Introduction

The component hierarchy as described in 5.5.3 manages message carriers as their state changes as described by subcomponents of the model and is used to provide computational models of events to understand disease progression. In 5.5.3, the effect of internal calcium concentration in the neuron soma on brain-derived neurotrophic factor (BDNF) transport in vesicles by Kinesin along multiple axon microtubule (MT) segments is described. The full published model also describes the upstream amyloid-beta effect on membrane receptors and as pores, that impact soma calcium levels, that are events in the calcium-amyloid beta model of Alzheimer's disease. This clause demonstrates one part of that full multipart model. The model in this example is described in Banerjee et al. [B1].

Table 19—Mapping neuron model components to the IEEE 1906.1 framework

IEEE 1906.1 component	Corresponding components in neuron model (Banerjee et al. [B1])
Transmitter	Memoryless discrete source of BDNF and Ca^{2+}
Receiver	Positive polarity ends of the last set of microtubules
Message	Brain-derived neutron factor (BDNF)
Medium	MT tracks
Message carrier	Dense core vesicle (DCV)-BDNF (molecular motor-vesicle cargo loaded with DCV-BDNF)
Component < 100 nm	Microtubule diameter, gaps between microtubule sets, etc.
Component < 10 um	Microtubule length
Non-standard physics	Poisson process generating BDNF and Ca^{2+} ions
Motion	Diffusion (passive) and walking (active, molecular motor on MT tracks)
Field	Microtubule
Perturbation	Concentration change (stimuli producing Ca^{2+} influx)
Specificity	Receptor sensitivity (receptors for DCV-BDNF molecules on kinesins)

During this simulation, the concentration of BDNF molecules is recorded. Interfaces between subcomponents of the neuron record the concentration of BDNF molecules entering or leaving associated model components.

A.5.2 Component hierarchy

In this generic model, shown in Figure A.1, a neuron comprises:

a) A soma acting as a transmitter

b) The BDNF molecules acting as messages

c) An axon comprising three microtubules sets. Each set contains five microtubules acting as the IEEE 1906.1 field for the propagation of the BDNF molecules

d) Optionally, the dendrite terminating the axon is the receiver

The following excerpt presents an example of IEEE Std 1906.1.1 applied to a neuron. Note that the hierarchy provides the relationship among the microtubule sets, the transmission path between the microtubules, and their relationship within the neuron.

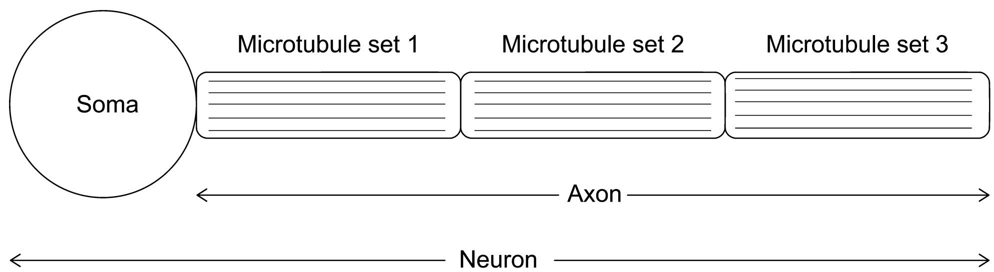

Figure A.1—Model of a neuron

Models simulating life and death cycles benefit from this hierarchy. In this iteration of the model, however, microtubules are considered parallel and have the same length. Each microtubule in future iterations of the model, for example:

— Can be associated to a position, a shape, or an orientation

— Can lead to the creation of other microtubules

— Can vary over time in their position, shape, and orientation

A.5.3 Derived component

The model described in Banerjee et al. [B1] defines a vesicle-cargo as a specialized molecular motor (which derives from message carrier). In this case, a new specialized identity is deemed relevant:

```
identity dcv-bdnf{
  base types:motor;
  description "It is a molecular motor-vesicle cargo loaded with DCV-BDNF";
}
```

A.5.4 Non-standard physics

BDNF molecules and Ca^{2+} ions are generated in the model using a Poisson process. This is the non-standard physics at stake in this model:

```
identity poisson-process
{
```

```
  base types:non-standard-physics;
  description "The Poisson process can be used to simulate the
               generation of message, or something that acts to the
               message, such as perturbation.";
}
```

A.5.5 Potential new metrics

Banerjee et al. [B1] further defines metrics to express the impact of aberrant induction of Ca^{2+} within the neuron. These new metrics would be reflected in a YANG module enhancing the IEEE 1906.1 framework defined by the experiment. This YANG module would import modules from the IEEE 1906.1.1 YANG framework:

```
grouping unrealized-dcv-bdnf-percentage
{
  description "This is defined as the percentage of DCV-BDNF molecules
               lost during neuronal transport.";
  reference "B1";
  leaf value {
    type percentage;
    description "The corresponding message deliverability of the
                 system".
  }
}

grouping average-traversal-time-per-bdnf-molecule
{
  description "This is a measure of latency or response time of a
               system";
  reference "B1";
  leaf average-time-due-to-diffusion {
    type time;
    description "A function of the distance between the point of
                 consideration and generation and the diffusion
                 coefficient".
  }
  leaf average-clearance-time {
    type time;
    description "Average clearance time of BDNF through microtubule
                 gates using gate selection process.".
  }
}
```

These groupings may also restrict types of components or definition that may use them.

A.5.6 Neuron model container

The new neuron model wraps the IEEE 1906.1 framework system into a dedicated container and adds the two defined metrics to their specified location. The first one applies to components, while the second one augments system metrics.

```
container neuron-model{
  description "Redefined nanoscale-system for our neuron model, which
               is enriched with new metrics, and this is only the
               beginning.";
```

```
  uses system:system{
    augment components/component{
      uses unrealized-dcv-bdnf-percentage;
      description "Augment nanoscale system with the Poisson process
                   defined in neuron model.";
    }

    augment system-metrics{
      uses average-traversal-time-per-bdnf-molecule;
      description "Augment system metrics to add our neuron-wide
                   average results";
    }
  }
}
```

A.5.7 Neuron model description in XML format


```
<?xml version="1.0"?>
<nd:neuron-model xmlns:nd="urn:ieee:std:1906.1:yang:ieee1906-dot1-
neuron">
  <nd:identifier>urn:ieee:std:1906.1:xml:neuron-model</nd:identifier>
  <nd:title>Neuron Model</nd:title>
  <nd:organization>IEEE Std 1906.1.1 - IEEE Standard Data Model for
Nanoscale Communication Systems</nd:organization>
  <nd:description>Description of a neuron with an axon comprising three
                  microtubule sets, each set
                  containing five parallel
                  microtubules of the same length.</nd:description>
  <nd:definitions>
    <nd:definition>
      <nd:description> Microtubule length </nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">tod:component-
less-than-10um</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:description> Microtubule diameter, gaps between Microtubule
sets etc.</nd:description>
      <nd:type-of-definition
xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">tod:component-
less-than-100nm</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier xmlns:tod="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:non-standard-physics</nd:identifier>
      <nd:type-of-definition>nd:poisson-process</nd:type-of-definition>
    </nd:definition>
    <nd:definition>
      <nd:identifier>SOMA_01</nd:identifier>
      <nd:type-of-definition
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:transmitter</nd:type-of-definition>
      <nd:sub-definition>/nd:nanoscale-
system/nd:definitions/nd:definition[nd:identifier='AXON_01']</nd:sub-
definition>
```

```
      <nd:description>Soma</nd:description>
    </nd:definition>
    <nd:definition>
      <nd:identifier>DENDRITE_01</nd:identifier>
      <nd:type-of-definition
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:receiver</nd:type-of-definition>
      <nd:sub-definition>/nd:nanoscale-
system/nd:definitions/nd:definition[nd:identifier='BDNF']</nd:sub-
definition>
      <nd:description>Dendrite</nd:description>
    </nd:definition>
    <nd:definition>
      <nd:identifier>BDNF</nd:identifier>
      <nd:type-of-definition
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:message</nd:type-of-definition>
      <nd:description>Brain-derived neurotrophic
factor</nd:description>
      <nd:message-metrics>
        <nd:message-deliverability>0.92543260</nd:message-
deliverability>
        <nd:message-lifetime
xmlns:si="urn:ieee:std:1906.1:yang:ieee1906-dot1-si-units"
si:unit="milliseconds">10</nd:message-lifetime>
        <nd:information-density
xmlns:si="urn:ieee:std:1906.1:yang:ieee1906-dot1-si-units"
si:unit="bit.nanometer-3">
          <nd:surface>
            <nd:scalar>0</nd:scalar>
            <nd:scalar>10</nd:scalar>
          </nd:surface>
          <nd:amount-of-information>10</nd:amount-of-information>
        </nd:information-density>
        <nd:bandwidth-delay-product/>
      </nd:message-metrics>
    </nd:definition>
    <nd:definition>
      <nd:identifier>AXON_01</nd:identifier>
      <nd:type-of-definition
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:medium</nd:type-of-definition>
      <nd:next-definition>/nd:nanoscale-
system/nd:definitions/nd:definition[nd:identifier='DENDRITE_01']</nd:ne
xt-definition>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_STAGE_01']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_STAGE_02']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_STAGE_03']</nd:sub-
component>
      <nd:description>axon</nd:description>
    </nd:definition>
    <nd:definition>
```

```
      <nd:type-of-definition
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:medium</nd:type-of-definition>
      <nd:description>Air</nd:description>
    </nd:definition>
  </nd:definitions>
  <nd:components>
    <nd:component>
      <nd:description> molecular motor-vesicle cargo loaded with DCV-
BDNF </nd:description>
      <nd:type-of-component>nd:dcv-bdnf</nd:type-of-component>
      <nd:unrealized-dcv-bdnf-percentage>1.6</nd:unrealized-dcv-bdnf-
percentage>
    </nd:component>
    <nd:component>
      <nd:description> active motion, molecular motor on MT tracks
</nd:description>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:walking</nd:type-of-component>
    </nd:component>
    <nd:component>
      <nd:description> passive motion, diffusion of BDNF
</nd:description>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:diffusion</nd:type-of-component>
    </nd:component>
    <nd:component>
      <nd:identifier>MT_STAGE_01</nd:identifier>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:compartmentalized</nd:type-of-component>
      <nd:next-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_STAGE_02']</nd:next
-component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_01_01']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_01_02']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_01_03']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_01_04']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_01_05']</nd:sub-
component>
      <nd:field-metrics>
        <nd:persistence-length>
          <nd:u-0>
            <nd:nabla>
              <nd:coordinate>10</nd:coordinate>
            </nd:nabla>
```

```
        </nd:u-0>
      </nd:persistence-length>
      <nd:diffusive-flux>
        <nd:D>8.1367e-012</nd:D>
      </nd:diffusive-flux>
      <nd:langevin-noise/>
    </nd:field-metrics>
  </nd:component>
  <nd:component>
    <nd:identifier>MT_STAGE_02</nd:identifier>
    <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:compartmentalized</nd:type-of-component>
    <nd:next-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_STAGE_03']</nd:next
-component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_02_01']</nd:sub-
component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_02_02']</nd:sub-
component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_02_03']</nd:sub-
component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_02_04']</nd:sub-
component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_02_05']</nd:sub-
component>
    <nd:field-metrics>
      <nd:persistence-length>
        <nd:u-0>
          <nd:nabla>
            <nd:coordinate>10</nd:coordinate>
          </nd:nabla>
        </nd:u-0>
      </nd:persistence-length>
      <nd:diffusive-flux>
        <nd:D>8.1367e-012</nd:D>
      </nd:diffusive-flux>
      <nd:langevin-noise/>
    </nd:field-metrics>
  </nd:component>
  <nd:component>
    <nd:identifier>MT_STAGE_03</nd:identifier>
    <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:compartmentalized</nd:type-of-component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_03_01']</nd:sub-
component>
    <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_03_02']</nd:sub-
component>
```

```
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_03_03']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_03_04']</nd:sub-
component>
      <nd:sub-component>/nd:nanoscale-
system/nd:components/nd:component[nd:identifier='MT_03_05']</nd:sub-
component>
    </nd:component>
    <nd:component>
      <nd:identifier>MT_01_01</nd:identifier>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:microtubule</nd:type-of-component>
    </nd:component>
    <!-- And so on with MT 01 02 ... MT 03 05 -->
    <nd:component>
      <nd:description> stimuli producing Ca2+ influx </nd:description>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-
types">toc:concentration-change</nd:type-of-component>
    </nd:component>
    <nd:component>
      <nd:description> Receptors for DCV-BDNF molecules on kinesins
</nd:description>
      <nd:type-of-component
xmlns:toc="urn:ieee:std:1906.1:yang:ieee1906-dot1-types">toc:receptor-
sensitivity</nd:type-of-component>
    </nd:component>
  </nd:components>
  <nd:system-metrics>
    <!-- Usual system metrics, not shown here, the augmented metrics
             are here of primary interest. -->
    <nd:average-traversal-time-per-bdnf-molecule>
      <nd:average-time-due-to-diffusion
xmlns:si="urn:ieee:std:1906.1:yang:ieee1906-dot1-si-units"
si:unit="milliseconds">1.23</nd:average-time-due-to-diffusion>
      <nd:average-clearance-time
xmlns:si="urn:ieee:std:1906.1:yang:ieee1906-dot1-si-units"
si:unit="milliseconds">1.23</nd:average-clearance-time>
    </nd:average-traversal-time-per-bdnf-molecule>
  </nd:system-metrics>
</nd:neuron-model>
```


A.5.8 Neuron model description in XML format


```
{
  "ieee1906-dot1-neuron:neuron-model": {
    "identifier": "urn:ieee:std:1906.1:xml:neuron-model",
    "title": "Neuron Model",
    "organization": [
      "IEEE Std 1906.1.1 - IEEE Standard Data Model for Nanoscale
Communication Systems"
    ],
```

```
    "description": "Description of a neuron with an axon comprising
three microtubule sets, each set containing five parallel microtubules
of the same length.",
    "definitions": {
      "definition": [
        {
          "description": " Microtubule length ",
          "type-of-definition": "ieee1906-dot1-types:component-less-
than-10um"
        },
        {
          "description": " Microtubule diameter, gaps between
Microtubule sets etc.",
          "type-of-definition": "ieee1906-dot1-types:component-less-
than-100nm"
        },
        {
          "identifier": "toc:non-standard-physics",
          "type-of-definition": "poisson-process"
        },
        {
          "identifier": "SOMA_01",
          "type-of-definition": "ieee1906-dot1-types:transmitter",
          "sub-definition": [
            "/ieee1906-dot1-neuron:nanoscale-
system/definitions/definition[identifier='AXON_01']"
          ],
          "description": "Soma"
        },
        {
          "identifier": "DENDRITE_01",
          "type-of-definition": "ieee1906-dot1-types:receiver",
          "sub-definition": [
            "/ieee1906-dot1-neuron:nanoscale-
system/definitions/definition[identifier='BDNF']"
          ],
          "description": "Dendrite"
        },
        {
          "identifier": "BDNF",
          "type-of-definition": "ieee1906-dot1-types:message",
          "description": "Brain-derived neurotrophic factor",
          "message-metrics": {
            "message-deliverability": "0.92543260",
            "message-lifetime": "10",
            "@message-lifetime": {
              "ieee1906-dot1-si-units:unit":"milliseconds"
            },
            "information-density": {
              "@": {
                "ieee1906-dot1-si-units:unit":"bit.nanometer-3"
              },
              "surface": {
                "scalar": [
                  "0",
                  "10"
                ]
```

```
              },
              "amount-of-information": "10"
            }
          }
        },
        {
          "identifier": "AXON_01",
          "type-of-definition": "ieee1906-dot1-types:medium",
          "next-definition": [
            "/ieee1906-dot1-neuron:nanoscale-
system/definitions/definition[identifier='DENDRITE_01']"
          ],
          "sub-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_STAGE_01']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_STAGE_02']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_STAGE_03']"
          ],
          "description": "axon"
        },
        {
          "type-of-definition": "ieee1906-dot1-types:medium",
          "description": "Air"
        }
      ]
    },
    "components": {
      "component": [
        {
          "description": " molecular motor-vesicle cargo loaded with
DCV-BDNF ",
          "type-of-component": "dcv-bdnf",
          "unrealized-dcv-bdnf-percentage": "1.6"
        },
        {
          "description": " active motion, molecular motor on MT tracks
",
          "type-of-component": "ieee1906-dot1-types:walking"
        },
        {
          "description": " passive motion, diffusion of BDNF ",
          "type-of-component": "ieee1906-dot1-types:diffusion"
        },
        {
          "identifier": "MT_STAGE_01",
          "type-of-component": "ieee1906-dot1-types:compartmentalized",
          "next-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_STAGE_02']"
          ],
          "sub-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_01_01']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_01_02']",
```

```
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_01_03']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_01_04']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_01_05']"
          ],
          "field-metrics": {
            "persistence-length": {
              "u-0": {
                "nabla": {
                  "coordinate": [
                    "10"
                  ]
                }
              }
            },
            "diffusive-flux": {
              "D": "8.1367e-012"
            }
          }
        },
        {
          "identifier": "MT_STAGE_02",
          "type-of-component": "ieee1906-dot1-types:compartmentalized",
          "next-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_STAGE_03']"
          ],
          "sub-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_02_01']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_02_02']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_02_03']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_02_04']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_02_05']"
          ],
          "field-metrics": {
            "persistence-length": {
              "u-0": {
                "nabla": {
                  "coordinate": [
                    "10"
                  ]
                }
              }
            },
            "diffusive-flux": {
              "D": "8.1367e-012"
            }
          }
        },
        {
```

```
          "identifier": "MT_STAGE_03",
          "type-of-component": "ieee1906-dot1-types:compartmentalized",
          "sub-component": [
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_03_01']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_03_02']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_03_03']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_03_04']",
            "/ieee1906-dot1-neuron:nanoscale-
system/components/component[identifier='MT_03_05']"
          ]
        },
        {
          "identifier": "MT_01_01",
          "type-of-component": "ieee1906-dot1-types:microtubule"
        },
        {
          "description": " stimuli producing Ca2+ influx ",
          "type-of-component": "ieee1906-dot1-types:concentration-
change"
        },
        {
          "description": " Receptors for DCV-BDNF molecules on kinesins
",
          "type-of-component": "ieee1906-dot1-types:receptor-
sensitivity"
        }
      ]
    },
    "system-metrics": {
      "average-traversal-time-per-bdnf-molecule": {
        "average-time-due-to-diffusion": "1.23",
        "@average-time-due-to-diffusion": {
          "ieee1906-dot1-si-units:unit":"milliseconds"
        },
        "average-clearance-time": "1.23",
        "@average-clearance-time": {
          "ieee1906-dot1-si-units:unit":"milliseconds"
        }
      }
    }
  }
}
```

Annex B

(informative)

The SI units YANG module

B.1 Introduction

The purpose of the Système International (SI) units yet another next generation (YANG) module is to provide a central definition of physical dimensions. Domains of science cover different scales which could lead to separate definitions of the same dimension. For example, distance between two membranes, or two different planets could lead to two distinct YANG definitions in different modules because the units differ. For the biological model, one would use micrometer, whereas the astronomical model would use astronomical units. The same physical dimension ends up being incompatible between the two models for this unit difference (which is worsened by YANG type decimal64 and uint64). This module provides a unified definition of distance, by stating that distance is an SI base unit and letting each of model annotate its Extensible Markup Language (XML) or JavaScript Object Notation (JSON) file by allowing attributes to be added to elements that redefine the SI unit being used.

NOTE—The IEEE 1906.1.1 YANG modules ieee1906-dot1-function.yang, ieee1906-dot1-math.yang, and ieee1906-dot1-si-units.yang utilize YANG annotations. See RFC 7952.

B.2 Using SI unit types to define new metrics

When defining new YANG modules, for instance by augmenting the IEEE 1906.1 YANG framework and adding more metrics, it is recommended that corresponding YANG leaves use any of the SI unit YANG types. For instance, message-lifetime in message-metrics is a unit of time, or a duration, and it links to a corresponding SI base unit:

```
leaf message-lifetime{
  type ieee1906-dot1-si-units:time;
  description "Message Lifetime measures the lifetime of a Message
               Carrier. TTL is used in 6.1.";

  reference "IEEE Std 1906.1-2015 subclause 6.2";
}
```

Where time is defined as:

```
typedef time{
  type ieee1906-dot1-function:variable;
  units second;
  ieee1906-dot1-si-units:derivedUnits "day hour minute quantum-of-time
atomic-unit-of-time";
  description "The second is the duration of 9 192 631 770 periods of
               the radiation corresponding to the transition between
               the two hyperfine levels of the ground
               state of the cesium 133 atom.";
  reference "The International System of Units: 8th Edition 2006.
             Clause 2.1.1.3";
}
```

B.3 Using component-wide properties to redefine units of physical dimensions

B.3.1 Introduction

SI base units are assumed by default when parsing metrics in XML or JSON format. With nanoscale systems however this could lead to smaller numeric representation of physical dimensions. At the nanoscale, one would result in representing distances under the following format: 1e-9. It is assumed that models make use of high-level libraries to convert scientific number representation into data type that matches with the target hardware architecture. However, on some embedded systems with limited resources, use of these numbers should be avoided, and decimal64 should be kept in mind.

B.3.2 SI base unit redefinition

The properties YANG module allows a user to directly redefine SI base units. Users are encouraged to define length properties as "nanometer," when defining nanoscale communication systems. For example:

```
<property>
  <length si:unit="nanometer" />
</property>
```

Nanoscale systems may require milliseconds to represent time, duration, velocities, and accelerations.

B.3.3 SI-derived unit redefinition

In addition to redefining SI base unit, the properties YANG module allows users to redefine SI-derived units. For instance, consider the following snippet:

```
<property>
  <length si:unit="nanometer" />
  <time   si:unit="millisecond" />
  <derived-unit si:unit=”terahertz”>si:frequency</derived-unit>
  <derived-unit
si:unit="milligram.nanometer/second^2">si:force</derived-unit>
  ...
</property>
```

Metrics using length display values in nanometers, and velocities in nanometers per millisecond. Any derived unit that is linked to time is assumed to display milliseconds, unless they are specifically defined differently. If frequency were not listed among the properties, then frequency would be in kilohertz. However, as frequency is redefined here, it is in terahertz.

B.3.4 Property hierarchy

If an SI base or derived unit is not listed within the properties of a given component or definition, then it is assumed that the units used are defined by parent and ancestor components, and, if no definition is available in an ancestor, then SI base units are assumed. For example, component A is a subcomponent of definition B which is a definition of system C.

```
<nanoscale-system>  <!-- System C -->
  ...
  <properties>
```

```
    <length si:unit="nanometer" />
  </properties>
  <definitions>
    <definition>
      <identifier>B</identifier>
      <properties>
        <time si:unit="millisecond" />
      </properties>
      <sub-component>A</sub-component>
  ...
  <components>
    <component>
      <identifier>A</identifier>
      <properties />
```

In this example, if component C has a metric in which some values are velocities, then units are in nanometer per millisecond, because C would inherit the time unit from parent definition B and length from ancestor system C.

B.4 Using YANG annotations to locally redefine SI units of values

Alternatively, metadata can be provided to give an SI unit a specific value or scope:

```
<message-metrics>
  <message-deliverability>0.8</message-deliverability>
  <message-lifetime si:unit="milliseconds">10</message-lifetime>
  <information-density si:unit="bit.nanometer-3">
    <surface>
      <scalar>0</scalar>
      <scalar>10</scalar>
    </surface>
    <amount-of-information>10</amount-of-information>
  </information-density>
  ...
```

Implementations of the YANG framework are expected to validate units via dimensional analysis, namely, that expressions composed of multiple units on both sides of an equation reduce to the same fundamental unit.

Annex C

(normative)

Simulator integration

The vision for IEEE Std 1906.1.1 is that serves as the glue allowing simulation tools to interoperate at different scales and from different disciplines. Figure C.1 (a) shows a network simulator utilizing any number of different small-scale biological tools like Systems Biology Markup Language (SBML) Figure C.1 (c). The IEEE 1906.1.1 yet another next generation (YANG) module enables interoperation among these tools at different scales.

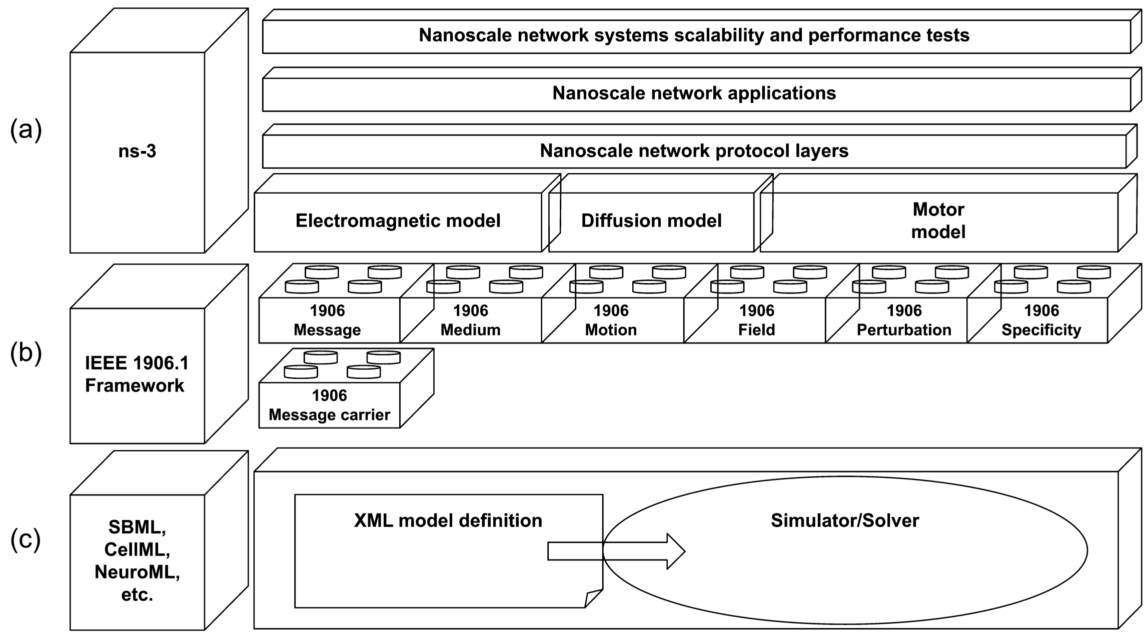

Figure C.1—Simulator integration use case where (a) is a network simulator, such as network simulator version 3 (ns-3), (b) is the IEEE 1906.1 standard, and (c) is a biological simulation tool, such as SBML

Annex D

(informative)

Tools and repository

IEEE Std 1906.1.1 enables a common, self-describing repository for nanoscale communication testing and experiments. The repository described above will be referenced simply as a *central repository* in the reminder of this annex and includes both storage and tools for managing the information. Test input, scenarios, and results should be described in a common format allowing others to confidently build on prior results, and will be referred to throughout this annex as the *experiment*.

NOTE—One example is https://ieee-dataport.org/ however, many other possibilities exist including a simple Git repository.

— The central repository may host a network configuration protocol (NETCONF)/RESTCONF server. Queries may be made to retrieve a specific experiment based on its URN, or to upload new results and dataset.

— The central repository may maintain the yet another next generation (YANG) module storing all the required identities augmenting the core IEEE 1906.1 framework. Definition of a new identity may be suggested to improve the existing taxonomy.

— The central repository may use existing YANG validators and run specific metadata processors to validate data consistency of uploaded datasets (for instance, conservation of energy, etc.).

— An interface other than NETCONF/RESTCONF may be provided, for example, aHypertext Markup Language (HTML) web page where the user can fillout a form providing all required IEEE Std 1906.1-2015 details to describe a nanoscale and molecular experiment (e.g., A.2 and A.3), and the tool may return and store data under Extensible Markup Language (XML) or JavaScript Object Notation (JSON) format.

— A taxonomy may be provided by the above interface while defining the experiment and the user may derive new metrics and identifiers to extend those of IEEE Std 1906.1-2015 (e.g., A.3).

— Sets of extra keywords outside the current scope of this draft document may be added to improve the relationship among experiments uploaded to the central repository, providing a consistent and directly comparable set of datasets.

— The central repository may convert data between XML and JSON, enabling the inclusion of MathML and Systems Biology Markup Language (SBML) models.

— The central repository may convert metrics into sets of input/outputs to implement simulations in tools such as MATLAB, COMSOL, ns-3, etc.

Annex E

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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[B2] IEEE Std 754™, IEEE Standard for Floating-Point Arithmetic.

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[B4] IETF RFC 6087, Guidelines for Authors and Reviewers of YANG Data Model Documents.

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