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IEEE Recommended Practice for Nanoscale and Molecular Communication Framework

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IEEE Recommended Practice for Nanoscale and Molecular Communication Framework

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Abstract: A definition, terminology, conceptual model, and standard metrics for ad hoc network communication at the nanoscale are provided. Human-engineered networking is extended by the physical properties of nanoscale communication in ways beyond that defined in existing communication standards. These include in vivo, sub-cellular medical communication, smart materials and sensing at the molecular level, and the ability to operate in environments that would be too harsh for macroscale communication mechanisms to operate. Collaboration among a highly diverse set of disciplines with differing definitions and connotations for some terms is required by nanoscale communication, thus a common terminology is necessary in order to aid inter-discipline collaboration. A common framework for thinking abstractly about nanoscale communication can aid in defining and relating research and development effort. Components of the framework are independent enough to allow them to be developed in relative isolation, yet the components are also interoperable. To illustrate the recommended practice, example mappings between specific nanoscale communication use-cases and the common framework are included. Simulation code implementing the common framework for both wireless and molecular nanoscale communication is an embodiment of the common framework demonstrating precisely how the framework is applied.

Keywords: communication networks, communication standards, communication systems, 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, quantum mechanics, simulation, standards development

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Introduction

This introduction is not part of IEEE Std 1906.1-2015, IEEE Recommended Practice for Nanoscale and Molecular Communication Framework.

Nanoscale communication is expected to offer unprecedented benefits. For progress in the development of this technology to accelerate, clear, common definitions and a conceptual framework are needed to solidify and guide research toward practical systems. A conceptual framework is used to make conceptual distinctions and organize ideas. The word *framework* is a shortened form of *conceptual framework*. A conceptual framework provides the organization and structure required to develop conceptual models of nanoscale communication. Indeed, the lack of precise definitions and a general framework for nanoscale communication has resulted in limited impact and dissipated effort. The IEEE Std 1906.1 Recommended Practice for Nanoscale and Molecular Communication Framework provides this precise, common definition of nanoscale communication and a general framework that balances definitional precision with broad applicability. This includes metrics, use-cases, and a reference model implemented in a simulation environment. This effort is expected to facilitate research and development in nanoscale communication in a coherent manner that will enable collaboration and more rapid advancement.

The reference model is implemented in the form of Network Simulator-3 (ns-3) code that implements the IEEE 1906.1 framework. The code simulates the standard in several embodiments, one simulating molecular nanoscale communication, and another simulating electromagnetic (EM) nanoscale communication. In the EM nanoscale communication embodiment, the propagation model provides path loss and molecular absorption noise experienced in human tissue because medical applications are a promising application for nanoscale communication. These phenomena can be used to evaluate 1) the signal-to-interference ratio as a function of the power transmission and the distance between sender and receiver and 2) an upper bound on the channel capacity computed. In the molecular nanoscale communication embodiment, it is assumed that molecules move into the medium following the omnidirectional Fick's law. Knowing the number of molecules released for each pulse and the diffusion coefficient (assumed constant), the model computes the molecular concentration as a function of distance and time, evaluates the propagation delay, and estimates the maximum channel capacity when a concentration-based receiver is used. In both cases, it is possible to execute simulations aimed at investigating the channel capacity experienced by a nanoscale communication link established between two devices, by changing physical detail (i.e., power transmission for the EM embodiment, diffusion coefficient and number of molecules for the molecular nanoscale communication embodiment). The simulator offers scripts to execute and process simulations as well as to generate graphs (e.g., channel capacity versus distance) via MATLAB®.[a] The ns-3 IEEE 1906.1 reference code is available from http://standards.ieee.org/downloads/1906/1906.1/P1906.1/.

[a] MATLAB is a registered trademark of The MathWorks, Inc.

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1. Overview

This recommended practice provides a definition, common framework, and common parameters for nanoscale communication networks. There is currently no standard or recommended practice that defines precisely what a nanoscale communication network is, nor how its components should be viewed in a conceptual framework, nor precise definitions of standardized parameters and components for interoperable simulation modules. The lack of a standard in these areas has hindered research and development of this technology. The goal of this recommended practice is to provide a general framework that partitions the problem in such a way as to allow research and development to focus on specific, individual components that interoperate with one another. It also allows researchers to focus on specific components while being able to make assumptions about the environment in which those components will reside.

To date, few academic papers claiming to contribute to nanoscale communication networking attempt to precisely define nanoscale communication. The lack of a well-defined problem prevents coherent advances in the technology. In effect, each researcher is chasing a different and often unrelated goal and the lack of a common framework and definition prevents progress from taking place by building upon previous results. One reason reaching a common definition for nanoscale communication is difficult is due in part to the need for researchers from diverse fields to reach a common understanding of the topic, ranging from information theorists and physicists to biologists; a common terminology and definition are required in order to avoid miscommunication of ideas. Researchers can be separated by the same terminology, for example *communication* might mean one thing to a biologist (entities in direct contact with one another) and something different to an information theorist (transmission of information measured via information entropy). These diverse fields also often have different overarching goals; for example, information theorists focus on information entropy, biologists focus on *mechanism,* that is, understanding and manipulating systems of causally interacting phenomena and processes that produce measurable effects, computer scientists are interested in computational and simulation models, and electrical engineers tend to build primarily electromagnetic (EM) systems.

Another motivation for the standard is to address the interoperability problem in which simulation components for a nanoscale and molecular communication network are being developed with different and non-interoperable interfaces with one another. This means that simulation modules cannot be entirely reused or easily validated, resulting in confusion and wasted effort. This standard addresses metrics and parameters suitable for simulation interoperability and demonstrates this through the release of an ns-3 simulation that implements the standard.

Motivation for the standard comes from concerted interest by both academia and industry in the form of optimizing research efforts, reducing time to prototype, and minimizing the risk in seeking profit from the technology. Ideas reach credibility to the extent that they realize profitability. Academia and industry partnerships, including clinical endeavors, help to realize the technology via use-cases developed in this standard. Each is also concerned with the ability to focus on developing real, interoperable components of nanoscale communication networks based on relevant expertise. In other words, all groups should be able to create different components of a nanoscale communication system and be confident that all components will successfully interoperate. This is vital for knowing how to step-wise advance current technologies versus offering full or partial replacements. This standard framework provides a step toward accomplishing precisely these objectives.

The scope of this standard includes the fundamental definition of, and the conceptual framework and common terminology for, nanoscale communication. The scope was strategically chosen in order to develop a standard that clearly specifies the unique features and challenges of nanoscale and molecular communication while promoting cross-disciplinary creativity in exploring unique features and addressing research challenges. It is also important to note what is *not* within scope. The scope does not include the specification of specific protocols, stacks or layering, or applications. One can readily imagine delay-tolerant networking or gossip protocols implemented within this framework (Bush [B1][1]). However, specific protocols and applications will be defined in future standards building upon this one.

1.1 Scope

This recommended practice contains a conceptual model and a standard terminology for ad hoc network communication at the nanoscale. More specifically, this recommended practice contains:

a) the definition of nanoscale communication networking

b) the conceptual model for ad hoc nanoscale communication networking

c) the common terminology for nanoscale communication networking, including:

   1) the definition of a nanoscale communication channel highlighting the fundamental differences from a macroscale channel

   2) abstract nanoscale communication channel interfaces with nanoscale systems

   3) performance metrics common to ad hoc nanoscale communication networks

   4) the mapping between nanoscale and traditional communication networks, including necessary high-level components such as a map of major components: coding and packets, addressing, routing, localization, layering, and reliability.

[1] The numbers in brackets correspond to those of the bibliography in Annex D.

1.2 Purpose

A common framework greatly aids in communicating ideas among researchers from diverse fields and developing useful simulators for nanoscale communication. This includes interconnecting systems of multiple types of nanoscale simulators. A common abstract model enables theoretical progress to proceed from different disciplines with a common language. This framework serves as a recommended practice for additional nanoscale communication networking standards as industry becomes more involved in commercial integration of the technology.

Nanoscale communication standards are needed by the biomedical industry to create break-through diagnostic and treatment methods. Technical discussions and establishment of standards in nanoscale communications are impaired by lack of a common conceptual model and common nomenclature. This standard will enable research and development in this area by focusing industry and academia on a common conceptual model, common language, and nomenclature for nanoscale communications. IEEE Std 1906.1 will allow a family of standards to be developed that will lead to creation of the nanoscale communications mechanisms for various applications.

The stakeholders are broad, including the telecommunications industry, computer industry, biological and medical devices industry, and material science-related industries as some of the most obvious beneficiaries.

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.

ISO/TS 27687:2008 Nanotechnologies—Terminology and definitions for nano-objects—Nanoparticle, nanofibre and nanoplate; definition 2.1.[2]

3. 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.[3]

active network: A network composed of packets flowing through a telecommunications pathway that dynamically modifies its operation. *See also:* **program**.

affinity: The tendency of an atom or compound to combine with atoms or other compounds. *See also:* **receiver**.

communication: The act of conveying a message from a transmitting party to a receiving party. *See also:* **message**.

component: A required element of the framework that provides a service for communication in a network.

[2]ISO publications are available from the ISO Central Secretariat (http://www.iso.org/). ISO publications are also available in the United States from the American National Standards Institute (http://www.ansi.org/).
[3]*IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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**.

false positive: Incorrect classification of an anticipated signal. A signal did not occur, but was erroneously detected as occurring.

hybridization: The process of establishing a non-covalent, sequence-specific interaction between two or more complementary strands of nucleic acids into a single complex.

interplanetary scale: Length scale at which the speed of light significantly impacts communication performance and the effects of relativity are negligible.

length scale: A particular length or distance determined with the precision of an order of magnitude, denoted by L.

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 must objectively have a pre-existing value for any possible measurement before the measurement is made.

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.

medium: The environment connecting the transmitter and receiver, which can include gas, gel, or liquid.

message carrier: A physical entity that conveys a message across the medium. *See also:* **message**; **medium**.

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.

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.

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

packet: A packet information encapsulated to be transported through a communication network. *See also:* **active network**.

Planck length scale: Length scale where concepts of size and distance break down.

program or **programmed:** A series of instructions to define and control outcome.

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.

quantum length scale: The length scale where properties are related to their de Broglie wavelength.

receiver: A device used to collect messages from a transmitter.

receptor: A component that receives signals.

reduced-length scale-area network: Communication whose performance is dominated by properties caused by a reduction in length scale.

regime change: Length scale at which a physical property relevant to communication changes the bandwidth-volume ratio by an order of magnitude.

relativistic scale: Length scale at which relativity impacts communication performance.

relay: A component that facilitates communication between a transmitter and the receiver. *See also:* **transmitter**; **receiver**.

sensitivity: A measure of the proportion of true positives, which are events that actually occurred and have been correctly detected. *See also:* **specificity**.

specificity: A measure of precision in matching between components. *See also:* **sensitivity**.

swarm: The collective behavior of a large number of entities that results in an emergent behavior which does not involve central coordination and arises from simple rules that are followed by individuals.

thrust: Force described by Newton's Second Law that induces motion when applied perpendicular to a plane. *See also:* **motion**.

transmitter: A device used to convey a message to a receiver.

true positive: The correct classification of a signal.

3.1 Acronyms and abbreviations

EGF	epidermal growth factor
EM	electromagnetic
CNT	carbon nanotube
SWNT	single-walled carbon nanotube
DWNT	double-walled carbon nanotube
MWNT	multi-walled carbon nanotube
DNA	deoxyribonucleic acid
RNA	ribonucleic acid
OSI	Open Systems Interconnection
SBML	Systems Biology Markup Language

4. Definition of a molecular and nanoscale communication network

4.1 Main definition

A nanoscale communication network is a human-designed system for communicating at or with the nanoscale, using physical principles that are suited to nanoscale systems.

4.2 Expanded definition

4.2.1 Definition of "human-designed"

"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.

4.2.2 Definition of "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 upon this definition of communication.

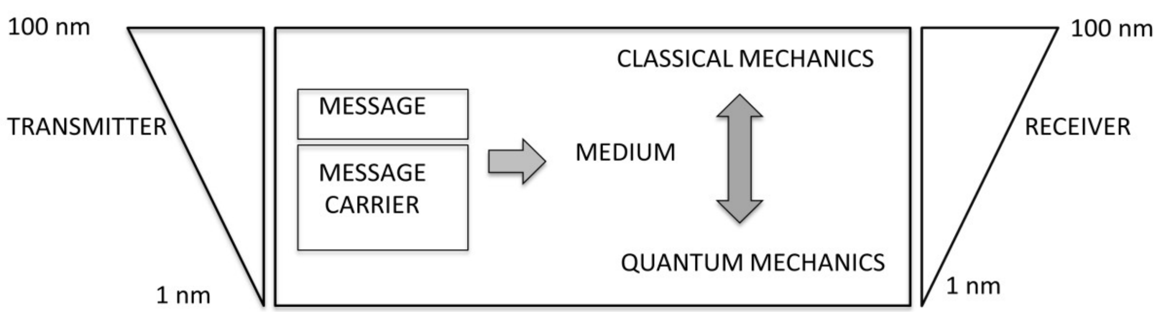

Figure 1—Illustration of single-hop nanoscale communication network

4.2.3 Definition of "at or with the nanoscale"

The definition of "at or with the nanoscale" breaks down as follows:

a) **At or with**. At least one of the following must have nanoscale dimensions: transmitter, receiver, medium, or message carriers; or one of their essential components must have nanoscale dimensions. We have defined *nanoscale* as dimensions of 1 nm to 100 nm as defined in ISO/TS 27687:2008, definition 2.1.

"At the nanoscale" refers to communication using essential components that reside at the nanoscale. "With the nanoscale" refers to communication using essential components at the nanoscale and with essential components at other scales that may reside at either larger or smaller length scales. For example, a macroscale communication network may interface to a microscale network that in turn interfaces with a nanoscale network. Example for illustration: In a human-made biosensor designed to measure the amount of signaling molecule needed to trigger a cell-specific response, the design of the device may have macro, micro, and nanoscale elements. Such a device applies a molecular communication network present in cells then transfers readout to micro or macroscale outputs. Human cells that may typically be on the order of 10 microns, or 100 times larger than 100 nm, are not at the nanoscale. The signaling molecules and cell surface receptor, acting as a message and receiver respectively, approach or at the nanoscale—such as the 150 nm epidermal growth factor (EGF) receptor and its 50 nm EGF ligand. This receptor-ligand complex must be engaged to generate a communication event. The ligand is an essential nanoscale component that enables transfer of information and communication at the nanoscale. Perturbation of the system at other scales is done to communicate with the nanoscale by targeting this molecular communication network.

4.2.4 Definition of "physical principles that are suited to nanoscale systems"

Classical physical principles are typically used to describe standardized macroscale or macroscale communication systems and can even apply to larger nanometer scale systems. Change in scale impacts nanoscale communication via change in scale as listed in Annex C or changes that can only be explained by quantum phenomena. As the atomic scale is approached, quantum principles must be applied that are suited to quantum-scale mechanics. These mechanics do not scale or, if so, they have significantly different properties at the macroscale. Physical principles that operate at the lower end of nanoscale (1 nm to 3 nm) include changes in the properties of materials. The ability of these properties to change even within the nanoscale range defined herein (1 nm to 100 nm) means that it is possible to fine-tune nanoscale size for desired outcomes different from larger nanoscale properties.

As properties of materials change from the macroscale to larger end of the nanoscale to atomic nanoscale, their behavior in nanoscale communication networks will also be altered. At the atomic nanoscale, changes include an increase in surface-to-volume ratio, gravitational forces become negligible, EM forces dominate, and random molecular motion becomes significant. These changes alter properties that are optical (such as color, transparency), electrical conductivity, physical properties such as hardness or boiling point, and chemical reactivity and reaction rates. How each impacts a particular communication network or application should be considered. For example, increased surface-to-volume ratio allows an increase in reaction rates that may permit lower dosage of medicines delivered in hybrid biosynthetic nanoparticles and reduce side effects related to toxicity.

a) *Physical principles included in this definition.* This definition includes (without limitation) nanoscale communication based on molecular communication and carbon nanotubes, as both of these types of systems are suitable for communication at the nanoscale, but have significantly different behavior at the macroscale. A carbon nanotube (CNT) can be single-walled (SWNT) and is typically one-atom-layer thick of graphite rolled into a tube of 1 nm diameter versus a multi-walled carbon nanotube (MWNT) that can be 5 nm to 50 nm in diameter. This includes double-walled nanotubes (DWNT).

b) *Physical principles excluded in this definition.* For clarity, macroscale electronic components (having dimensions greater than 100 nm) and electrical and/or EM message carriers using macroscale technologies are excluded from this definition, as their physical operation utilizes macroscale phenomena rather than nanoscale phenomena.

5. Framework of a molecular and nanoscale communication network

5.1 Goals

The goals of the framework are:

a) Division: Components are described independently to allow components to be researched and developed independently to the extent possible. Where interfaces or data exchange functions are involved, the components are to be tested independently and then with other components with which interfaces and data exchanges are identified.

b) Creativity: Components are general enough to avoid restricting new ideas.

c) Clarity: Components are defined well enough to allow a degree of interaction between components by independent developers.

d) Interoperability:

   1) Multiple components are able to interoperate to form a single communication system.

   2) Components from one system are able to operate in a different system of compatible physics with a minimum amount of change.

   3) Different IEEE 1906 systems are able to interoperate with one another.

5.2 Framework

This clause defines the components of the IEEE 1906 framework and provides examples. Length scale is partitioned, based upon regime change, into Planck length scale, quantum length scale, nanoscale, microscale, macroscale, interplanetary length scale, and relativistic length scale. The Message Carrier and Message are defined in 4.2 and serve as components within the framework. The IEEE 1906 framework **shall** be composed of the following components:

a) Component 0: Message Carrier

   1) A fundamental component introduced in 4.2.2 and includes its volume, mass, and energy

      i) The Message Carrier provides the service of transporting the Message.

      The message carrier may be either particle or wave. Similar to quantum mechanics, the message carrier may also be a simultaneous combination of both particle and wave. Examples: Molecular structure may encode information transported by the Message Carrier from a transmitter to a receiver. Wave-like changes in message concentration may also encode information.

      While IEEE 1906.1 message carriers may be either particle-based or wave-based, today's message carriers are primarily wave-based: acoustic, RF, optical, visible light, power-line carrier, etc. utilize waves whose characteristics and performance are defined by their wavelength. Figure 2 illustrates nanoscale message carriers within the context of wave-based message carriers at the time this standard was developed in 2015. If one considers usable wavelengths to be from 10^5 km to 0.1 mm, then that defines the communication-length scale prior to the introduction of nanoscale communication. Optical communication takes us closer to the nanoscale in wavelength; optical communication also allows for quantum effects to be utilized, such as for quantum key distribution. Thus, nanoscale communication potentially fills the gap between classical physics and quantum physics in communication.

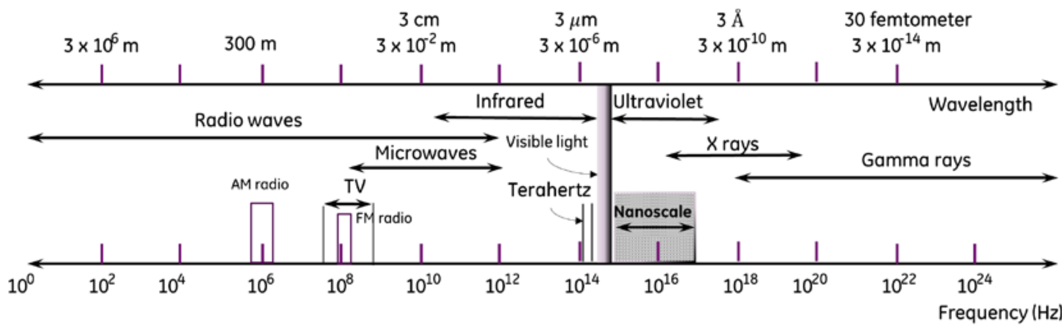

Figure 2—Nanoscale message carriers are illustrated to show their length scale within the context of prior technology wave-message carriers

b) Component 1: Motion

1) Defines the movement capability for Component 0 (Message Carrier)

i) The Motion Component provides the service of movement for the Message Carrier (in any direction) caused by force or thrust applied to the Message Carrier. Motion provides the necessary potential to transport information through a communication channel.

NOTE—Message Carriers can be active, generating their own motion, or passive, being propagated by the Media. Active or passive Message Carrier motion is separate and independent from whether there exists Active Network Programmability, explained in 6.17.[4]

ii) Examples: Molecules diffusing through fluids, Brownian motion, self-propelled motion

c) Component 2: Field

1) Defines organized movement of Component 1 (Motion)

i) The Field Component provides the service of organized motion for Message Carriers. It can be thought of as a virtual waveguide in communications. The Field may be implemented internally or externally relative to the Medium.

ii) Examples: An internal implementation includes swarm motion or flocking behavior; external implementations are non-turbulent fluid flow, EM field, chemical gradient released to guide movement of bacteria, molecular motors guided by microtubules

d) Component 3: Perturbation

1) Defines the signal transported by Component 0 (Message Carrier)

i) The Perturbation Component provides the service of varying Message Carriers as needed to represent a signal. This may be thought of as modulation (signal impression).

ii) Examples: Signals based on the number of received message carriers, controlled dense-versus-sparse concentrations of molecules, simple on-versus-off flow of signal molecules, using different types of message carriers, modifying the conformation of molecules (e.g., deoxyribonucleic acid [DNA]) to represent multiple states

The Margolus–Levitin theorem provides a fundamental limit on quantum computation and on perturbation for nanoscale communication. The upper bound on perturbation rate is 6×10^{33} operations per second per joule of energy. A quantum system of energy, E, needs at least a time of $h/(4 \times E)$, where $h = 6.626 \times 10^{34}$ J × s is Planck's constant, to transition to an orthogonal state.

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

e) Component 4: Specificity

1) Defines targeted reception of Component 3 (Perturbation)

i) The Specificity Component provides the service of sensing or reception of a message carrier by a target. This can be mapped to addressing in classical communication systems.

ii) Example: The shape or affinity of a molecule to a particular target, complementary DNA for hybridization

An illustration of the framework constructed from 4.2.2 and showing the relationship among the components is shown in Figure 3. Reference code that implements the components is located in http://standards.ieee.org/downloads/1906/1906.1/P1906.1/.

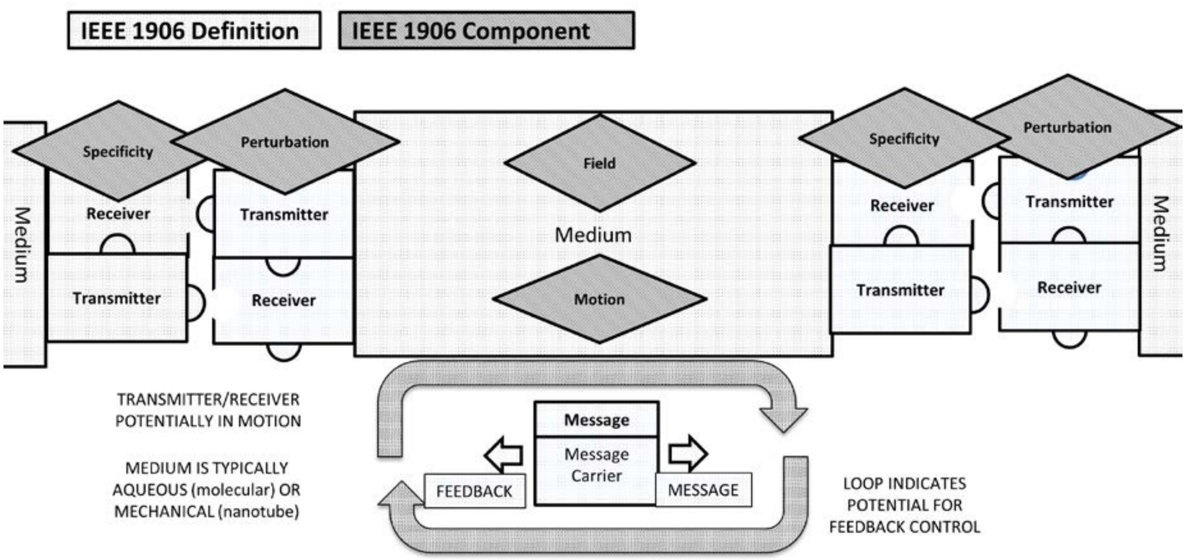

Figure 3—Reference model: A node is composed of a transmitter and receiver. Perturbation represents a Message, Motion conveys the Message, Field physically orients Messages, and Specificity regulates Message reception

5.3 Framework components

The term *component* is purposely used to discourage the classical notion of a protocol stack or layering. However, components are dependent upon the services provided by other components. Thus, a protocol stack view **might** be considered as shown in Table 1.

Table 1—Example nanoscale communication network components

Layer name	Explanation	Example (molecular)	Example (nanotube/terahertz)
Specificity	Correctly detect true versus false messages	Shape or affinity of molecule to a particular target, complementary DNA for hybridization, etc.	Antenna aperture, resonant frequency, impedance match
Perturbation	Vary concentration or motion as needed for signal (shockwave)	Dense versus sparse concentrations of molecules, on versus off flow of signal molecules or motors, conformational changes in molecules, etc.	Amplitude, frequency, or phase modulation
Field	Organized flow direction	Flowing liquid, applied EM field, motors attached to microtubules, concentration gradient of chemical molecules, swarm motion, etc.	Omni or directed with multiple CNTs
Motion	Potential communication channel in the wild (semi-random)	Molecules diffusing through liquid, unattached molecular motors, Brownian motion, self-propelled motion, etc.	Wave propagation and phase velocity
Message Carrier	Mass and energy	Molecular chain, etc.	EM wave

5.3.1 Component service equations

Each component provides a service that shall be described as follows:

a) Message Carrier

1) This component provides the service of containing and transporting a message.

NOTE—In a classical communication system, the Message Carrier is typically a wave described by approximations of wave propagation. In a nanoscale communication system, the Message Carrier can be a particle whose motion is described by diffusion.

2) Its service is described by bit-density, defined as bits per unit volume of carrier.

3) The motivation for this service is to provide a higher efficiency by transporting more bits per unit volume.

4) The ability to follow an efficient path is important as defined by motion metrics described in 5.3.1.b).

5) The ability to be received, or bind, to the proper target is defined by the specificity metrics defined in 5.3.1.e).

b) Motion

1) This component provides the ability of the message carrier to change position efficiently. It involves the volume and mass of the message carrier and the forces applied without regard to an intended direction.

2) Its service can be described by the mass flow rate defined in Equation (1).

$$\dot{m} = \rho \times \dot{V} = \rho \times v \times A = j_m \times A \tag{1}$$

where

m is mass of the message carrier

$\dot{V}$ is volume flow rate of the message carrier

ρ is mass density of the fluid

v is flow velocity of the mass of the message carriers

A is cross-sectional vector area/surface

j_m is mass flux of the message carriers

3) A motivation might be to improve the bandwidth of the channel by increasing the flux of Message Carriers, thus enabling greater information flow.

c) Field

1) The service provided by this component is the ability to direct a message carrier to its target. This involves the ability to control message carrier direction.

2) A vector field V defined on a set S is called a gradient field or a conservative field if there exists a real-valued function (a scalar field) f on S such that Equation (2) holds.

$$V = \nabla f = \left(\frac{\partial f}{x_1}, \frac{\partial f}{x_2}, \frac{\partial f}{x_3}, \cdots, \frac{\partial f}{x_n} \right) \tag{2}$$

where

V is a vector field

f is a function

x_n is a set of dimensions

The motion and field components can appear in a single equation such as the Langevin Noise (versus a typical radio propagation model, for example), shown in Equation (3).

$$m \times \frac{d^2 x}{dt^2} = -\lambda \times \frac{dx}{dt} + \eta(t) \tag{3}$$

where

x is the position of a message carrier

m is the mass of the message carrier

t is time

λ is the systematic part of the molecular force (field component)

η is random component of force (motion component)

3) The motivation is to achieve higher channel capacity by more efficiently routing a message carrier toward its target receiver.

d) Perturbation

1) The service provided by this component is the ability to turn signals on or off efficiently, for example, the modification of the conformation of molecules (e.g., DNA) to represent multiple states.

2) The motivation behind this component is the ability to utilize the channel effectively by enabling rapid changes that form signals to take place in the medium.

e) Specificity

1) Ability to improve message carrier connectivity with their intended receivers.

2) As an example, this service can be measured by the docking/hybridization probability and by how sensitive docking and hybridization are to the characteristics of message carriers.

3) The motivation behind this metric is to measure the efficiency with which message carriers reach their intended receivers and are thus able to decode their message.

5.3.2 Miscellaneous elements

Other communication elements, such as a relay, may be included in the network. These elements shall be described by fundamental IEEE 1906 components. For example, the service provided by a relay is the ability to increase message concentration or modify motion to increase message deliverability. The motivation behind this network element is to enable messages to travel longer distances and increase the likelihood of message deliverability. This might be thought of as a form of signal amplification. An example is calcium ion concentration in a biological cell that can be amplified when the ions bind to protein channels which induces the release of calcium ions from these channels. A relay can recognize what it should amplify (Specificity component), the relay amplifies it (e.g., creates more Messages/Message Carriers), or perhaps modifies the Motion or Field (Perturbation). The IEEE 1906 components provide the minimum set of building blocks required to construct nanoscale communication network elements.

5.3.3 Relation to other frameworks

The IEEE 1906 framework can be compared, or mapped into, communication protocols. There have been many attempts to map nanoscale communication networks to the Open Systems Interconnection (OSI) model (ISO/IEC standard 7498-1:1994) in different ways. As an informative example, see Table 2. Due to their size, nanoscale communication systems are simpler and less-easily programmed than macroscale systems. The IEEE 1906 framework is representative of those found in natural, small-scale settings, such as biological systems. The result is less control with which to implement the details of OSI logical layers. For example, perturbation is simpler and has a tendency to be more mechanical in implementation. Motion is more random, for example, subject to Brownian forces. Some type of gradient or field is required to improve motion. There is also less control over specificity (addressing).

Table 2 —Example OSI to nanoscale communication network mapping

<table>
<tr><th>OSI model</th><th colspan="3">IEEE 1906 component mapping</th><th>Explanation</th></tr>
<tr><td>Application</td><td colspan="3"></td><td>No 1906 component</td></tr>
<tr><td>Presentation</td><td colspan="3"></td><td>No 1906 component</td></tr>
<tr><td>Session</td><td colspan="3"></td><td>No 1906 component</td></tr>
<tr><td>Transport</td><td colspan="3"></td><td>No 1906 component</td></tr>
<tr><td>Network</td><td></td><td rowspan="2">Field</td><td></td><td>Field may enable Message Carrier transport across multiple nodes</td></tr>
<tr><td rowspan="2">Data Link</td><td rowspan="2">Specificity</td><td rowspan="2"></td><td rowspan="2">Motion, enhanced by Field and Specificity, enable Message Carrier to reach next-hop node</td></tr>
<tr><td rowspan="2">Motion</td></tr>
<tr><td>Physical</td><td>Message Carrier</td><td>Perturbation</td><td>Perturbation creates the signal transported by the Message Carrier using Motion</td></tr>
</table>

A problem with using the OSI model is that it does not provide a framework that is detailed enough to allow a nanoscale communication network to be described in mathematical detail. The IEEE 1906 framework is designed to encourage such detail as a prerequisite to designing protocols and applications.

OSI model (ISO/IEC 7498-1 [B7]) defines the traditional seven layer protocol stack. The IEEE 1906 framework can be considered to reside within the lowest layers of the OSI stack.

More specifically:

a) Message relates approximately to a classical frame, packet, or protocol data unit (PDU).

b) Message Carrier (Component 0) relates to a wave (the characteristic of a wave that encodes information).

c) Motion (Component 1) relates approximately to the classical physical layer (wave propagation).

d) Field (Component 2) relates approximately to the classical data link and network layers (ensuring node-to-node information flow).

e) Perturbation (Component 3) relates approximately to classical modulation at the physical layer.

f) Specificity (Component 4) relates approximately to classical addressing at the data link layer.

5.3.4 Relation to active network

The IEEE 1906 framework shall not preclude components from interacting in such a manner that they intentionally influence one another in a cross-layer or cross-component manner. Construction of the network infrastructure may have to be "bootstrapped," that is, refined or grown by the communication network itself utilizing self-assembly. For example, message carriers (Component 0) can be programmed to modify the communication channel in order to improve channel capacity as shown in Figure 4 where X and Y are random variables representing input and output of the channel. The program within the message carrier is reflected via changes to the medium. Programming will take a simpler, more native form, for example, chemical programming. Within an active network, a frame or packet X can be composed of data X' and a program X'' that can be deposited within the communication channel and thus execute within the network (Bush [B1]). From channel-coding perspective, $p_{x,y}(x, y)$ is the joint distribution of X and Y and $p_{x|y}(x \mid y)$ is the conditional probability of Y given X. The signal set to be transmitted X can be engineered to be the distribution that is least impacted by noise from the channel. The joint distribution of signals is $p_{x,y}(x,y)$ and thus the optimal distribution of signals can be determined. The maximum mutual information between X and Y is the channel capacity. Concisely stated, the goal is to choose the static information X' and a program X'' so that the received information Y has the greatest likelihood of matching the transmitted data X'. The Active Network Programmability metric, described in 6.17, defines the degree to which a nanoscale communication network is active.

a) Information transported might be designed to improve the physical operation of the channel e.g.,

   1) Message carriers might be designed to intentionally change the viscosity, concentration, etc. of the channel, thus impacting the Motion component.

   2) Molecular motors carrying microtubules can be designed to intentionally change the shape of the microtubule network, thus impacting the Field component.

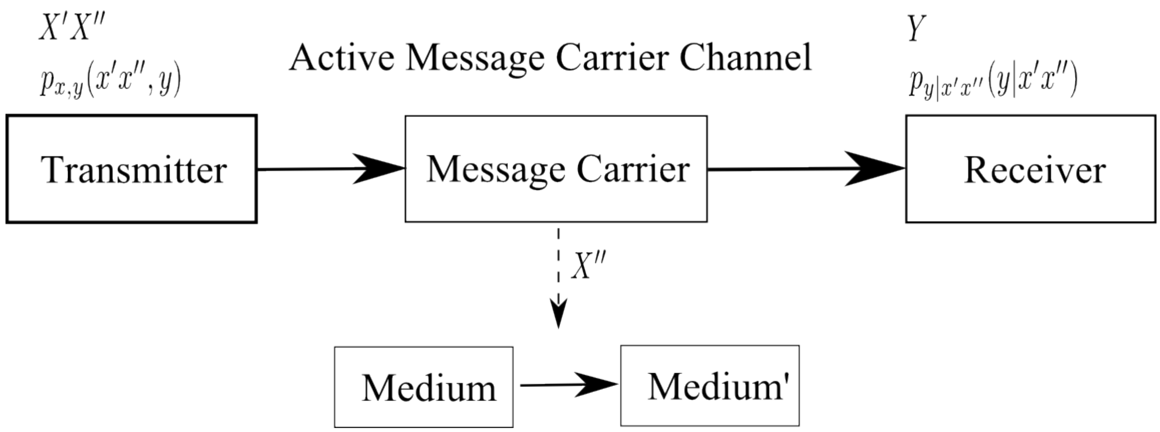

Figure 4—Active (cross-layer) approaches are not excluded from the framework

5.3.5 Component interfaces

Each component shall have a general, but clearly defined interface to the components for which it provides service. Examples include:

— Message-to-Message Carrier (encoding)

— Message Carrier-to-Motion (range of motion)

— Motion-to-Field (controlled motion)

— Field-to-Perturbation (rapid control of field)

— Perturbation-to-Specificity (ability to dynamically change Specifity to encode a message)

— Specificity-to-Message Carrier (Message Carrier and binding capability)

— Message Carrier-to-Receiver (decoding)

The matrix shown in Table 3 shows the metrics, defined in Clause 6, that define the interfaces between components in more detail.

Table 3—IEEE 1906 component interface matrix

Row impacts column	Message	Message Carrier	Motion	Field	Perturbation	Specificity
Message	N/A	Message Deliverability Message Lifetime Information Density Bandwidth-Delay Product Information and Communication Energy	Active Network Programmability	Active Network Programmability	Message Encoding	Specificity Sensitivity Affinity
Message Carrier	Specificity Sensitivity Affinity	Message exchange between carriers Collision Behavior	Collision Behavior	Active Network Programmability	Active Network Programmability	Specificity Sensitivity Affinity
Motion		Mass Displacement Positioning Accuracy of Message Carriers	N/A	Persistence Length Diffusive Flux Langevin Noise	Perturbation Rate	Angular Spectrum Delay Spectrum
Field			Persistence Length Diffusive Flux Langevin Noise	N/A	Perturbation Rate	
Perturbation	Message Encoding	Perturbation Rate Supersystem Degradation Bandwidth-Volume Ratio	Perturbation Rate	Perturbation Rate	N/A	Perturbation Rate
Specificity		Specificity Sensitivity Affinity				N/A

5.4 Nanoscale communication network description

Nanoscale communication networks shall describe their physical layer by denoting: transmitter, receiver, message, medium, components that have a dimension from 1 nm to 100 nm, the communication physics suited to the nanoscale, message carrier, motion, field, perturbation, and specificity. Examples of the last five components are shown Table 4 and more detailed examples can be found in the annexes.

Table 4—IEEE 1906.1 framework examples

IEEE 1906 component	Example 1: Calcium waves	Example 2: Receptor-ligand	Example 3: Molecular motor	Example 4: Nanotube network	Example 5: Flagellated bacteria	Example 6: THz waves
Message Carrier	Calcium ion concentration	Ligand concentration	Molecular motor and cargo	Charge	Bacterium and cargo	EM wave
Motion	Diffusion	Diffusion	Walking and directed diffusion	Potential difference	Goal-driven (food/light)	Radiating and waveguide
Field	Directed concentration gradient or compartmentalization	Directed concentration gradient or receptor clustering	Microtubule polarity and connectivity	Nanotube orientation	Chemical concentration of food particles, and intensity of light	Intensity/ directional antenna
Perturbation	Transmission rate or concentration change	Transmission rate or concentration change	Change in number and types of molecules inside the cargo	Current (amperage) variation	Change in number and types of molecules inside the bacteria	RF modulation
Specificity	Calcium sensing receptor sensitivity to Ca+	Receptor sensitivity to ligand	Receptor sensitivity to cargo	Receiver sensitivity to charge	Receptor sensitivity to bacterium or cargo	Receptor sensitivity/ antenna aperture

6. Metrics

This clause contains common metrics that nanoscale communication networks and nanoscale communication network simulations shall compute in order to present interoperable information among components of the system as well as to compare the performance of different systems. Nanoscale communication networks shall report the following metrics, which are categorized by component below:

— Message component: 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.

  a) Message Deliverability (see 6.1)
  b) Message Lifetime (see 6.2)
  c) Information Density (see 6.3)
  d) Bandwidth-Delay Product (see 6.4)
  e) Information and Communication Energy (see 6.5)

— 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.

  a) Collision Behavior (see 6.6)
  b) Mass Displacement (see 6.7)
  c) Positioning Accuracy of Message Carriers (see 6.8)

— 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.

a) Persistence Length (see 6.9)

b) Diffusive Flux (see 6.10)

c) Langevin Noise (see 6.11)

— 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.

a) Specificity (see 6.12)

b) Affinity (see 6.13)

c) Sensitivity (see 6.14)

d) Angular (angle-of-arrival) Spectrum (see 6.15)

e) Delay (time-of-arrival) Spectrum (see 6.16)

— System: These metrics relate to and impact all components. All of the metrics in this category shall be implemented.

a) Active Network Programmability (see 6.17)

b) Perturbation Rate (see 6.18)

c) Supersystem Degradation (see 6.19)

d) Bandwidth-Volume Ratio (see 6.20)

6.1 Message Deliverability

Message Deliverability measures whether a Message Carrier survives long enough to deliver its information to the intended receiver. Deliverability is defined as the ability of the transmitter to increase the likelihood that the transmitted message can be delivered to the receiver through the medium before it expires (in time when the receiver can utilize the message contents or before the message expires or the motion/flow/channel is altered), and is measured as a probability that the message can be delivered to the intended receiver before it expires, assuming an error-free transmission. The units are a probability value.

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

6.2 Message Lifetime

Message Lifetime measures the lifetime of a Message Carrier. A Message Carrier can be designed to disintegrate or become ineffective after a specified time-to-live (TTL). Lifetime is defined as the amount of time that a message persists before degrading or turning over and being unable to deliver information as originally intended. Thus a communication network should provide timely delivery of some messages while others might have a longer lifetime (durability). TTL is used in 6.1.

6.3 Information Density

Information Density is the amount of information encoded within a Message Carrier per volume. Shannon information is assumed by default, but this could also include other forms of information measurement such as Kolmogorov Complexity or those based upon Algorithmic Information Theory. The volume includes both the volume of the Message and the Message Carrier. The units of this metric are bits per cubic nanometer.

Information Density relates to Bandwidth-Volume Ratio, defined in 6.20, because greater information density transported by a message carrier can allow for greater bandwidth within a smaller volume.

6.4 Bandwidth-Delay Product

Bandwidth-Delay Product is proportional to the maximum number of Message Carriers capable of fitting within the physical channel. It is important for communication protocols and algorithms to know this in order to design optimal communication control. The units are bits. Bandwidth-Delay Product is intuitively the maximum amount of bits the nanoscale communication pipe can hold at any instant in time. As the name implies, it is BD where B is the bandwidth measured in bits-per-second and D is the transmission delay (in seconds) through the communication pipe.

NOTE—IEEE 1906.1 systems will likely tend to have a very large Bandwidth-Delay Product. Individual Message Carriers can move relatively slowly, and each individual Message Carrier might only encode small number of bits, but there will be large numbers of them, on the order of Avogadro's constant.

A larger Bandwidth-Delay Product indicates a greater number of potential message carriers residing in the media at the same time and may impact the operation of some protocols as well as physical and biological mechanisms that are influenced by residual message carriers in the system.

6.5 Information and Communication Energy

The Message Carrier requires energy for its movement, propulsion (if active motion is used), and steering. If passive motion is utilized, energy is required in order to cause surrounding fluid flow or to create the gradient in the field. Moreover, energy can be required at the transmitter and receiver for the release and reception of the Message Carrier. This energy might be the result of Message Carrier synthesis at the transmitter or reception characteristics at the receiving parties. This is the metric that quantifies energy used in nanoscale communication. This is energy per bit of information conveyed by the Motion Component. It can be considered the efficiency of the Message Carrier. It is defined in Equation (4).

$$\frac{E_{mc}}{I_{mc}} \tag{4}$$

where

E_{mc} is the energy expended to deliver a message

I_{mc} is the information per Message Carrier in bits

Mass and energy are equivalent via relativity while energy and information are related via concepts such as entropy and Maxwell's Daemon. Thus, mass and information are related. Information and Communication Energy can be broken down into separate values for each IEEE 1906 framework component.

6.6 Collision Behavior

Collision Behavior measures the physical result of collision between Message Carriers. Upon impact, they can join, merge, or absorb one another or they can bounce or reflect away from one another. This metric has a significant impact upon whether and how Message Carriers disperse and their efficiency in reaching their target receivers. Collision Behavior is a measure of the interaction of colliding Message Carriers.

NOTE—Collisions can be designed to accomplish more sophisticated actions, such as the exchange of Messages when collision occurs, for example, as part of a gossip-like communication routing protocol (Bush [B1]). In such a design, other metrics such as Specificity and Affinity between Message Carrier and Message can be relevant.

Collisions can either be elastic, meaning they conserve both momentum and kinetic energy, or inelastic, meaning they conserve momentum but not kinetic energy. An inelastic collision can also be called a plastic collision. A perfectly inelastic collision (e.g., perfectly plastic) is a limiting case of inelastic collision in which the two bodies stick together after impact. The degree to which a collision is elastic or inelastic is quantified by the coefficient of restitution, a value that generally ranges between zero and one. A perfectly elastic collision has a coefficient of restitution of one; a perfectly inelastic collision has a coefficient of restitution of zero, which is defined in Equation (5).

$$C_R = \frac{V_{AC}}{V_{BC}} \tag{5}$$

where

C_R is the coefficient of restitution

V_{AC} is the relative speed (energy, mass) between colliding Message Carriers after collision

V_{BC} is the relative speed (energy, mass) between colliding Message Carriers before collision

Collision Behavior is unique to IEEE 1906 channels; it differs from the notion of collision in macroscopic communication. The information in message carriers undergoing collision assumes physical properties such as kinetic and potential energy as well as momentum.

6.7 Mass Displacement

Molecular communication can assume Message Carriers are composed of mass and move from one location to another. Although small, there is a continuous change of mass, or mass oscillation, which occurs among communicating entities during communication. This metric quantifies the relative changes in mass of the communicating entities due to communication and is related to the notion of clock synchronization. Thus, a measure of mass displacement would be useful. Mass Displacement is defined as the skew in mass over time of communicating entities within the nanoscale communication network. This is likely, but not always, related to the amount of information conveyed from one node to another. Here we simply utilize Allan variance, a measure of frequency stability, but apply it to mass instead of time. The standard deviation of mass frequency fluctuations $\sigma_y(M,T,\tau)$, or M-sample variance, is defined in Equation (6).

$$\sigma_y^2(M,T,\tau) = \frac{1}{M-1}\left\{\sum_{i=0}^{M-1}\left[\frac{x(iT+\tau)-x(iT)}{\tau}\right]^2 - \frac{1}{M}\left[\sum_{i=0}^{M-1}\frac{x(iT+\tau)-x(iT)}{\tau}\right]^2\right\} \tag{6}$$

where

$x(t)$ is the mass at time t

T is the sample period (the time between each sample)

τ is the sample time

M is the number of samples

The average fractional mass frequency time series is shown in Equation (7).

$$\sigma_y^2(M,T,\tau) = \frac{1}{M-1}\left\{\sum_{i=0}^{M-1}\bar{y}_i^2 - \frac{1}{M}\left[\sum_{i=0}^{M-1}\bar{y}_i\right]^2\right\} \tag{7}$$

where

M is the number of frequency samples used to compute variance

T is the time between each frequency sample

τ is the time-length of each frequency estimate

An important aspect is that of M-sample variance model counter dead-time, which exists when the value of T differs from that of τ. The Allan variance is defined in Equation (8).

$$\sigma_y^2(\tau) = \left\langle \sigma_y^2(2,\tau,\tau) \right\rangle \tag{8}$$

where

τ is the observation period

$\langle x \rangle$ is commonly used to denote the expectation value of a variable x

The Allan variance is conveniently expressed as shown in Equation (9).

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle \left(\bar{y}_{n+1} - \bar{y}_n\right)^2 \right\rangle = \frac{1}{2\tau^2}\left\langle \left(x_{n+2} - 2x_{n+1} + x_n\right)^2 \right\rangle \tag{9}$$

where

τ is the observation period

$\bar{y}_n$ is the nth fractional mass frequency average over the observation time τ

$\langle x \rangle$ is commonly used to denote the expectation value of a variable x

The samples are taken with no dead-time between them, which is achieved by letting $T = \tau$.

Sampling of message carrier mass occurs through a plane normal to the flow through the medium. It may also be sampled through an arbitrary surface as defined in 6.17, and illustrated in Figure 5. Clearly, Mass Displacement relates to Diffusive Flux as defined in 6.10 and there is inherent uncertainty as noted in 6.8.

6.8 Positioning Accuracy of Message Carriers

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 will be beneficial to locate the message carrier swarms from the macro-unit. This location information can be used to adaptively control the future movement of the swarms to improve their message delivery efficiency by reducing propagation delay and environmental uncertainty. The location information can also be used to assess the remote controllability and trackability of the swarms. This metric quantifies the positioning accuracy of the message carrier swarms, which is defined as the radius of the circle that 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). All the location coordinates should be measured with reference to a global frame encompassing the supersystem where the IEEE 1906 network resides. The units of this metric are standard length units. Implementation of this metric requires detailed information about the controlling and tracking mechanisms utilized by the macro-unit.

Fluorescent labeling can be applied to message carriers for tracking purposes at the macro-unit. For in vivo nanoscale communication, specific types of message carriers capable of enhancing the imaging contrast of aqueous medium within the body can be employed (e.g., superparamagnetic nanoparticles in contrast-enhanced thermoacoustic molecular tomography, magnetic resonance imaging, microwave medical imaging, etc.). The macro-unit performs contrast-enhanced imaging to track the message carriers.

6.9 Persistence Length

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). This has a significant impact upon Message Carriers that ride along such track-like strands. If no chain-like structures compose the media, then this value returns zero (0). Persistence Length is in units of nanometers, where longer lengths define stiffer structures (Bush and Goel [B2]). Persistence Length is the rate at which the tangents taken along each segment of a linear chain in a network become decorrelated from one another. If *R(s)* is a point on a segment *s*, then let *u(s)* be the unit tangent vector in Equation (10).

$$u(s) = \frac{\partial R}{\partial s} \tag{10}$$

where

R(s) is a point on a segment *s*

The orientations of the unit tangent vectors for all segments *s* are quantified by the inner product in Equation (11).

$$\langle u(s) \times u(0) \rangle = e^{-s/\xi_p} \tag{11}$$

where

$\langle x \rangle$ is commonly used to denote the expectation value of a variable x

$u(s)$ is the unit tangent vector at point s in set of connected segments

$u(0)$ is the unit tangent vector at the origin or beginning of the chain of connected segments

ξ_p is the persistence length

For longer persistence lengths, or for shorter tubes, the linear chain will tend to be straighter. For longer tubes or shorter persistence lengths, the impact of de-correlation along the chain tangent tends to become more significant. Longer persistence length, by definition, implies straighter tubes. However, tubes that are shorter in length are typically able to hold up better under physical stress in situ and thus are able to maintain a straighter shape as well. They also typically have less opportunity to curl given their shorter length. However, keep in mind that this applies only to segments that compose a tube and does not imply that the tubes themselves are aligned in any particular pattern. We can approximate the curved chains as many smaller random chains that happen to be connected end-to-end, but with de-correlated alignment. Thus, shorter persistence lengths will tend to decrease the percolation threshold, which is important in the explanation of network conductance. Persistence length becomes important in applications of nanotubes in developing photovoltaic cells, fuel cells and electronic components such as transistors, primarily due to longer lengths having greater electrical resistance. The persistence length of a microtubule has been estimated to range from 0.2 mm to 5.2 mm, while the persistence length at the tip of a microtubule has been found to be much shorter. The rigidity and persistence length of microtubules has been found to be sensitive to various chemicals and related to various diseases. An advantage of persistence length over other metrics is that it relates to the physical nature of the tube structure. Persistence length is actually a basic mechanical property that measures not only the shape of a tube but also its stiffness. The usefulness of persistence length is that it extends beyond the shape of a tubular structure to infer its stress and strain. The persistence length is related the bending stiffness by Equation (12).

$$\xi_p = \frac{B_S}{k_B \times T} \tag{12}$$

where

B_S	is the bending stiffness
k_B	is Boltzmann's constant
T	is temperature

The bending stiffness is related to Young's Modulus as $B_S = Y \times I$

where

Y	is Young's Modulus
I	is the area moment of inertia

Note that the area moment of inertia is $I = \frac{\pi \times r^4}{64}$ $I = \frac{\pi r^4}{64}$ where r is the radius of the area moment of inertia. Thus, Young's Modulus is related to persistence length by Equation (13) where all variables have been previously defined.

$$Y = \frac{64 \times K_B \times T}{\xi_p \times \pi \times r^4} \tag{13}$$

Young's Modulus is the ratio of stress (pressure) to strain (dimensionless) and thus it has units of pressure. Knowledge of Young's Modulus allows an estimate of the degree to which a tube will extend with tension or buckle under compression.

A typical technique to estimate the persistence length is to use image analysis of electron micrographs. Persistence Length is related to message carrier motion, in particular Langevin Noise in 6.11 and Diffusive Flux in 6.10.

6.10 Diffusive Flux

Fick's First Law is one of the standard laws of diffusion. Diffusion is common in many molecular communication use-cases. Fick's First Law relates the diffusive flux, the main metric of interest, to the concentration under the assumption of steady state. It postulates that the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient (spatial derivative), or in simplistic terms the concept that a solute will move from a region of high concentration to a region of low concentration across a concentration gradient. In one spatial dimension, the law is expressed in Equation (14).

$$J = -D \times \partial / \partial x \tag{14}$$

where

- J is the *diffusion flux*, which is the amount of substance per unit area per unit time, for example (mol/m^2 × s); J measures the amount of substance that will flow through a small area during a small time interval
- D is the diffusion coefficient or mass diffusivity in dimensions of length^2 × time^{-1}, for example (m^2/s)
- ϕ for ideal mixtures is the concentration in dimensions of amount of substance per unit volume, for example (mol/m^3)
- x is the position (length), for example, in meters

D is proportional to the squared velocity of the diffusing particles, which depends on the temperature, viscosity of the fluid and the size of the particles according to the Einstein relation (kinetic theory) and Stokes-Einstein relation.

In dilute aqueous solutions the diffusion coefficients of most ions are similar and have values that at room temperature are in the range of 0.6×10^{-9} to 2×10^{-9} m^2/s. For biological molecules the diffusion coefficients normally range from 10^{-11} to 10^{-10} m^2/s. In two or more dimensions we use ∇, the del or gradient operator, which generalizes the first derivative, yielding Equation (15) where the variables have been previously defined.

$$J = -D \times \nabla \phi \tag{15}$$

The driving force for one-dimensional diffusion is the quantity in Equation (16) where all variables have been previously defined.

$$-\frac{\partial \phi}{\partial x} \tag{16}$$

For ideal mixtures Equation (16) is the concentration gradient. In chemical systems other than ideal solutions or mixtures, the driving force for diffusion of each species is the gradient of chemical potential of this species. Then Fick's First Law (one-dimensional case) can be written as Equation (17).

$$J_i = -\frac{D \times c_i}{R \times T} \times \frac{\partial \mu_i}{\partial x} \tag{17}$$

where

- i is an index that denotes the ith species

c is the concentration (mol/m^3)

R is the universal gas constant J/K × mol

T is the absolute temperature K

μ is the chemical potential J/mol

If the primary variable is mass fraction (y_i, given, for example, in kg/kg), then the equation changes to that shown in Equation (18).

$$J_i = -\rho \times \nabla y_i \tag{18}$$

where

ρ is the fluid density, for example in kg/m^3

Density is outside the gradient operator. Diffusive Flux is the rate of flow through an area and assumes this is due to a concentration difference. Thus, it is a passive component of motion. Activation energy is the minimum energy that must be added to cause diffusion to occur.

6.11 Langevin Noise

Random motion has a significant impact upon the performance of Message Carriers, in particle form, to reach their target receivers. For example, random motion impacts the extent to which a random walk (Brownian motion, Langevin Equation) implies a Levy process, which thus implies a Poisson process, which allows classical queuing theory to provide valid results. The specific metric of interest is the noise term, $\eta(t)$, explained below. The Langevin Noise describes the random movement of a particle in a fluid due to collisions with the molecules of the fluid expressed in Equation (19).

$$m \times \frac{d^2x}{dt^2} = -\lambda \times \frac{dx}{dt} + \eta(t) \tag{19}$$

where

m is mass

t is time

x is position

λ is a damping coefficient

The force acting on the particle is written as a sum of a viscous force proportional to the particle's velocity (Stokes' Law), and a noise term $\eta(t)$ (the name given in physical contexts to terms in stochastic differential equations which represent stochastic processes) representing the effect of the collisions with the molecules of the fluid. The force $\eta(t)$ has a Gaussian probability distribution with correlation function is shown in Equation (20).

$$\left\langle \eta_i(t) \times \eta_j(t') \right\rangle = 2 \times \lambda \times k_B \times T \times \delta_{ij} \times \delta(t - t') \tag{20}$$

where

$\langle x \rangle$ is commonly used to denote the expectation value of a variable x

k_B is Boltzmann's constant

T is the temperature

δ is the δ-function form of the correlations in time and indicates that the force at a time t is assumed to be completely uncorrelated with the force at any other time

This is an approximation; the actual random force has a nonzero time-correlation with the collision time of the molecules. However, the Langevin Noise is used to describe the motion of a "macroscopic" particle at a much longer time scale, and in this limit the δ-correlation and the Langevin Noise become exact. Thus, increasing temperature or the damping coefficient increases the random component.

NOTE 1—A relatively large value of $\eta(t)$ can provide a distinction between classical and nanoscale physics mentioned in the definition that requires physical principles suited to nanoscale systems.

NOTE 2—Message Carriers flowing through turbulence, which is a type of flow characterized by chaotic property changes, are expected to be a fertile source of Motion research. Explicit use of turbulence can also serve as a distinction in physical principle between classical and nanoscale communication.

Langevin Noise is used to describe motion in this definition, thus it relates to Diffusive Flux defined in 6.10 and Positioning Accuracy of Message Carriers in 6.8. Langevin Noise is the random portion of motion. Langevin Noise is also related to Persistence Length in 6.9 because both describe motion; Langevin Noise focuses on the random portion and Persistence Length focuses on the non-random.

6.12 Specificity

Specificity, sensitivity, and affinity are often confused, but are very different metrics. Specificity (sometimes called the true negative rate) measures the proportion of negatives which are correctly identified as such (e.g., the percentage of Message Carriers not addressed to an intended target node that are not accepted by the intended target node). Sensitivity (also called the true positive rate, or the recall rate in some fields) measures the proportion of true positives which are correctly identified (e.g., the percentage of Message Carriers addressed to an intended target node that are recognized and accepted by the correct intended target node). These two measures are complementary to the false positive rate and the false negative rate, respectively. A perfect predictor would be described as 100% sensitive (i.e., all intended targets nodes accept correct Message Carriers) and 100% specific (i.e., no Message Carriers are accepted by incorrect, not-intended targets nodes or other entities that can be within the Media or the Media itself). Affinity is the attraction between entities and is defined in 6.13. Specificity is defined in Equation (21).

$$\frac{T_N}{T_N + F_P} \tag{21}$$

where

T_N is the number of true negatives
F_P is the number of false positives

NOTE—The specificity metric can be used as a measure of the ability for a Message to be properly addressed to its intended Receiver as well as an indication of the loss of Messages to unintended binding with entities other than the intended target receiver.

Specificity differs from Sensitivity in 6.14 and is related to Affinity in 6.13.

6.13 Affinity

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. It is a key component of the IEEE 1906 Specificity component. Affinity is the phenomenon whereby certain atoms or molecules have the tendency to aggregate or bond. The International Union of Pure and Applied Chemistry (IUPAC) definition for affinity A is the negative partial derivative of Gibb's free energy G with respect to extent of reaction ξ at constant pressure and temperature shown in Equation (22).

$$A = -\left(\frac{\partial G}{\partial \xi}\right)_{P,T} \tag{22}$$

where

A is the affinity

G is the Gibb's free energy

ξ is the reaction at constant pressure and temperature

The extent of reaction is a quantity that measures the extent in which the reaction proceeds. It is usually denoted by the Greek letter ξ. The extent of a reaction has units of amount (moles). Gibb's free energy is a thermodynamic potential that measures the usefulness or process-initiating work obtainable from a thermodynamic system at a constant temperature and pressure (isothermal, isobaric). The Gibb's free energy (SI units J/mol) is the maximum amount of non-expansion work that can be extracted from a closed system. Affinity is positive for spontaneous reactions. A spontaneous process is the time-evolution of a system in which it releases free energy (usually as heat) and moves to a lower, more thermodynamically stable energy state.

High-affinity binding results from greater intermolecular force between the message carrier and its receiver while low-affinity binding involves less intermolecular force. High-affinity binding involves a longer residence time for the message carrier at its receiver binding site than is the case for low-affinity binding. High-affinity binding can be important when some of the binding energy can be used to cause a conformational change in the receiver, resulting in altering its behavior to implement detection and subsequent decoding of the message. Thus, affinity plays a key role in Sensitivity, 6.14, and Specificity, 6.12.

6.14 Sensitivity

Sensitivity, Specificity, and Affinity are often confused, but are very different metrics. Please refer to the discussion in the introduction of the Specificity metric, 6.12. Sensitivity is defined in Equation (23).

$$\frac{T_P}{T_N + T_P} \tag{23}$$

where

T_N is the number of true negatives

T_P is the number of true positives

NOTE—This metric can be a function of time; molecular receiver sensitivity might be reduced in the presence of a large number of bound molecules. Sensitivity might return to a heightened state after the bound molecules are released from the receptor. This can have a significant effect on communication performance.

6.15 Angular (angle-of-arrival) Spectrum

Angular Spectrum quantifies the distribution of the intensity of nanoscale communication signals received at the receiver as a function of angle-of-arrival. For EM nanoscale communications, this metric is identical to the power angular spectrum used in classical wireless channels. For molecular communications, this metric is defined as follows. Consider a generic two-dimensional receiver defined as a curve enclosing a connected area of points, which includes a reference point (center) of the receiving area. Define delay τ and azimuth φ as the time-of-arrival and angle-of-arrival of a message carrier at the receiver. The delay is with reference to the time when the message carrier was emitted from the transmitter, and the azimuth is with reference to the center of the receiving area. The received signal strength given by the number of message carriers absorbed by the receiver is a random variable over the receiving space and time due to uncertainties during the propagation process caused by random Brownian motions, unexpected degeneration of message carriers, etc. A spatial-temporal description of molecular communication channels is developed by introducing the delay-azimuth spectrum $\Xi_{\tau,\varphi}(\tau,\varphi)$, defined as the ensemble average of received signal strength at specific τ and φ over multiple realizations of the propagation process. The azimuth spectrum is derived as shown in Equation (24).

$$\Xi_{\varphi}(\varphi) = \int_{\tau} \Xi_{\tau,\varphi}(\tau,\varphi)d\tau \tag{24}$$

where

τ	is the time-of-arrival at the receiver
φ	is the angle-of-arrival at the receiver
$\Xi_{\tau,\varphi}(\tau,\varphi)$	is the delay-azimuth spectrum defined as the average received signal strength at specific τ and φ

This metric can be measured empirically or derived theoretically. It can also be used to extract other nanoscale communication channel parameters such as the angle spread, which quantifies the amount of signal dispersion in the angular domain. The angle spread is given by Equation (25).

$$\sigma_{\varphi} = \sqrt{\int_{\varphi} \left|\exp(j\varphi) - \mu_{\varphi}\right|^2 \times \Xi_{\varphi}(\varphi)d\varphi} \tag{25}$$

where

$$\mu_{\varphi} = \int_{\varphi} \exp(j\varphi) \times \Xi_{\varphi}(\varphi)d\varphi \tag{26}$$

$\Xi_{\varphi}(\varphi)$	is the azimuth spectrum given in Equation (24).

This metric is a probability density function. For molecular communications, implementation of this metric requires averaging the number of received message carriers within a differential angle over a sufficient number of realizations of the propagation process. For EM nanoscale communications, implementation of this metric follows the classical power angular spectrum. The above formulations can be readily extended to three-dimensional propagation scenarios.

The computation of Angular Spectrum requires the position information of message carriers when they have crossed the circumference of the receiving area. It is related to Positioning Accuracy of Message Carriers in 6.8.

6.16 Delay (time-of-arrival) Spectrum

Delay Spectrum quantifies the distribution of the intensity of nanoscale communication signals received at the receiver as a function of time-of-arrival. Similar to the angular spectrum, the delay spectrum is derived in Equation (27).

$$\Xi_{\tau}(\tau) = \int_{\varphi} \Xi_{\tau,\varphi}(\tau,\varphi) d\varphi \tag{27}$$

where

$\Xi_{\tau,\varphi}(\tau,\varphi)$ is the delay-azimuth spectrum

This metric can be measured empirically or derived theoretically. It can also be used to extract other nanoscale communication channel parameters such as the delay spread, which quantifies the amount of signal dispersion in the temporal domain. If the delay spectrum is a non-increasing function with delay, the delay spread is given by Equation (28).

$$\sigma_{\tau} = \sup \left\{ \Delta\tau \in [0, \tau_{\max} - \tau_{\min}] : \int_{\tau_{\min}}^{\tau_{\min}+\Delta\tau} \Xi_{\tau}(\tau) d\tau < \varepsilon \right\} \tag{28}$$

where

$\tau_{\min}$ is the minimum delay

$\tau_{\max}$ is the maximum delay

$\Delta\tau$ is the possible value of delay spread in the range between 0 and $\tau_{\max} - \tau_{\min}$

$\Xi_{\tau}(\tau)$ is the delay spectrum given in Equation (27)

ε is a pre-specified sufficiently large percentage

This metric is a probability density function. For molecular communications, implementation of this metric requires averaging the number of received message carriers within a differential delay over a sufficient number of realizations of the propagation process. For EM nanoscale communications, implementation of this metric follows the classical power delay spectrum.

The computation of Delay Spectrum requires the trajectory information of message carriers. It is related to Positioning Accuracy of Message Carriers in 6.8.

6.17 Active Network Programmability

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). When specifically designed to do this in order to cause either a transient or permanent change in the Media, they are known as *active message carriers*. This metric provides a standard measure for how "active" a message carrier is. If Message Carriers do not change the underlying media, then the value of this metric is zero. The units are change in Message Carrier flux through a given surface over a given time. An active network is designed to intentionally allow messages and information being transmitted to modify and improve the network itself. The Message

Carrier might be designed to modify the network. Because this is a self-referential design (network elements constructing/improving the network that changes the motion/behavior of network elements constructing/improving the network etc.), it has been notoriously challenging to study and quantify. Active network programmability is based upon the amount and duration of change in network state that an individual Message Carrier can impart upon the network topology. This is illustrated in Figure 5 and quantified in Equation (29).

$$A = \oint_S \int_t \Delta f(t)\,dt\,dS \tag{29}$$

where

- t is time
- S is a virtual surface that defines the volume through which the change in flux of Message Carriers should be clearly specified
- $f(t)$ is the flux of Message Carriers as a function of time where flux is the rate of flow through a unit area
- $\Delta f(t)$ is the change in $f(t)$ intentionally caused by a programmed Message Carrier through a surface S

Symbol	Meaning
●	Message Carrier (e.g. molecular motor)
———	Field Component (e.g., microtubule, nanotube)
-------->	Motion Component (e.g., instantaneous direction of motion)
○	Surface (S) over which surface integral is computed

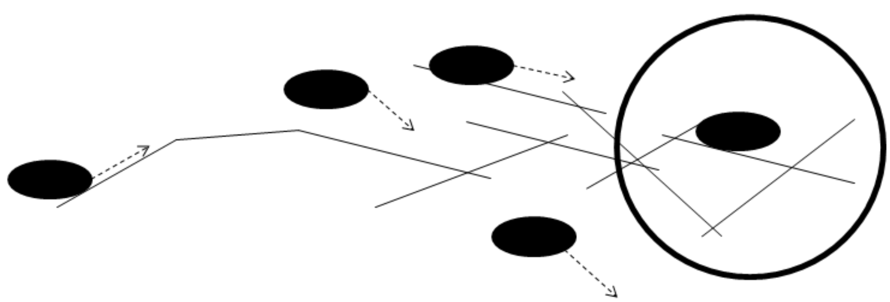

Figure 5—Message Carrier flux defined by flow through a surface integral

The impact of the change in Message Carrier flux can take time to implement and might not be permanent, thus the integral over time captures temporal aspects of the change. A discrete version of this metric is simply the change in Message Carrier flow through space as a change in network topology occurs intentionally caused by a Message Carrier, e.g., a Message Carrier causes microtubule or CNT network partitions to join together, split apart, or otherwise re-orient themselves. This effect can be measured by graph theoretic means such as the change in the graph Laplacian, a discrete form of the concept represented by this metric. Since A is the accumulated message carrier flow through a given surface area for a given time, and if we know the bits transported per message carrier, then A can be used to derive the bandwidth through a defined surface area within the media. Multiply A by the bits per message carrier and divide by the time over which the integration was performed. If the surface bisects the media, then it reduces to the bandwidth of the channel. The function $f(t)$ may be substituted by any of the metrics defined for the Field component, for example Persistence Length, 6.9. The units of the function shall be stated along with the value of the Active Network Programmability.

Active Network Programmability is the change in flux due to change in the medium structure caused by message carriers. It is related to Persistence Length in 6.9, Diffusive Flux in 6.10, and Langevin Noise in 6.11.

6.18 Perturbation Rate

Perturbation Rate is a measure of both the rate and control of any type of perturbation used to send a signal in the system. It is designed to quantify the ability to control signal generation; typically, signal quality degrades as perturbation rate increases. This metric captures change in signal quality as a function of rate. The term *perturbation* is used to be purposely broad in its application. It refers to changes in any of the other IEEE 1906 components with the intent of transmitting a signal. A larger rate of perturbation might allow for more communication bandwidth, however, this can come at a loss of accuracy in control of the perturbation or cause ill effects such as unintended resonance with other components of the system. This metric is a rate versus accuracy curve. Perturbation error is the difference between the intended perturbation rate and the actual perturbation rate.

Error in reception of the signal is also dependent upon receiver settings defined by Sensitivity, 6.14, and Specificity, 6.12. However, perturbation rate accuracy is measured assuming perfect sensitivity and specificity in order to distinguish transmission from reception problems.

6.19 Supersystem Degradation

The supersystem is the system in which the IEEE 1906 network resides. This can be a biological organism. This metric quantifies the impact of the 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. Supersystem Degradation is a measure of the impact of implementing nanoscale communication within a system. This metric captures the negative impact of the implementation upon the larger system. This metric is simply the percent reduction in function of the system's main function due to the nanoscale implementation within the system. As an example, if nanoscale communication is implemented as action potentials within a neuron that are shared with the neuron's normal operation, then we need to measure any loss or disruption of primary function due to the implemented nanoscale system. The metric is defined in Equation (30).

$$d_s = \frac{s_{pn}}{s_p} \tag{30}$$

where

d_s is the supersystem degradation

s_{pn} is the supersystem performance with the embedded nanoscale communication network

s_p is the native supersystem performance (without the embedded nanoscale communication network).

Typically, we expect to see this metric as a function of the embedded nanoscale communication network bandwidth, $s_{pn}(bw)$ shown in Equation (31) where all variables have been defined.

$$d_s(bw) = \frac{s_{pn}(bw)}{s_p} \tag{31}$$

Supersystem Degradation is related to Bandwidth-Volume Ratio, 6.20, because bandwidth is a performance measure of the communication system and volume of the communication components may impact the supersystem's performance.

6.20 Bandwidth-Volume Ratio

The Bandwidth-Volume Ratio takes into account and combines two fundamental essences of molecular and nanoscale communication, namely its size and bandwidth. The Bandwidth-Volume Ratio is defined as the bandwidth in bits per second that the system offers divided by the total system volume including transmitter, receiver, and message carrier and its context is illustrated in Figure 6 in which there exist length scales, denoted by L, at which physical properties relevant to communication performance change by an order of magnitude known as regime change. The impact of changes in length scale is quantified in Annex C. Communication examples of regime change are:

— the length scale at which mechanical oscillation bandwidth (perturbation) approaches commercial EM frequencies (mechanical frequency scales by L^{-1})

— the length scale at which Brownian motion dominates message carrier motion (diffusion time scales by L^2)

Industry will seek to leverage physical changes that impact communication due to reduction in length scale.

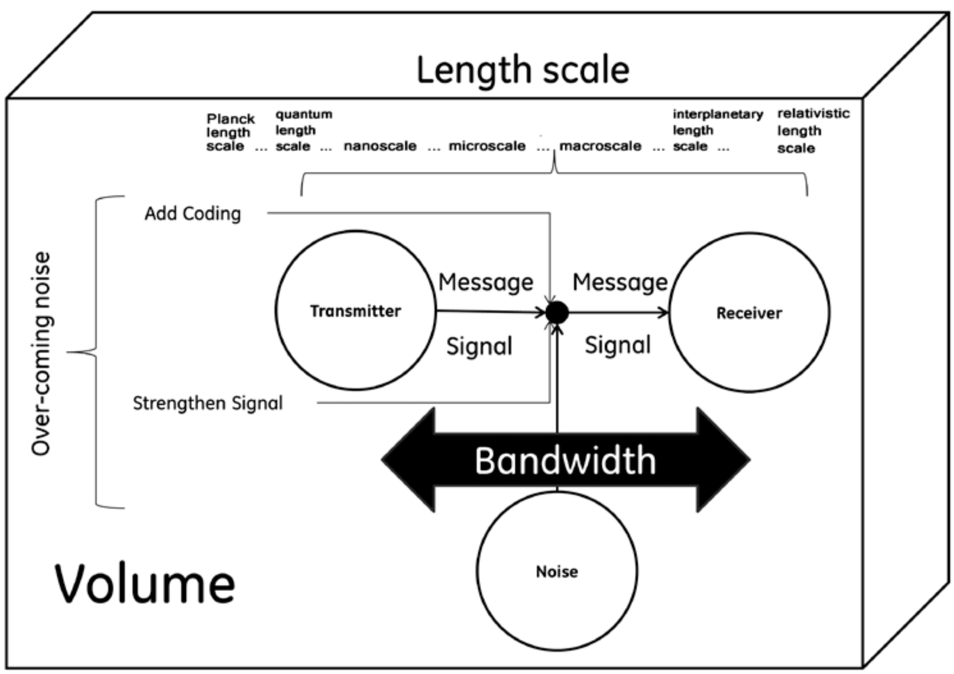

Figure 6—An illustration of the Bandwidth-Volume Ratio showing a spectrum of length scales composed of Planck length scale, quantum length scale, nanoscale, microscale, macroscale, interplanetary length scale, and relativistic length scale with respect to the signal and noise

The objective for nanoscale communication is to obtain a small total volume (V) and high bandwidth (BW), thus the ratio (BW/V) of an ideal system should approach infinity. V can be broken into the terms shown in Equation (32).

$$V = V_{tranmitter} + V_{receiver} + V_{message\ carriers} \tag{32}$$

where

$V_{tranmitter}$	is the volume of the transmitter
$V_{receiver}$	is the volume of the receiver
$V_{message\ carriers}$	is the volume of the Message Carrier

Bandwidth (BW) can be broken down into various channel capacity equations. Designers can increase this metric by choosing which IEEE 1906 component volume to reduce versus increasing bandwidth in order to increase the value of this metric. Note that this metric applies equally well to macroscale systems including wireless, where the message carrier component is wavelength. The units are bits/(second ×nm^3).

Bandwidth-Volume Ratio is related to Supersystem Degradation, 6.19, because it is a function of bandwidth and may be impacted by the volume of the communication system embedded within it.

Annex A

(informative)

Reference model

The reference code has been implemented as an extension of NS-3, i.e., a discrete-event and open source network simulator, designed for replacing the popular NS-2 in both research and educational fields (see https://www.nsnam.org/). It has been written in C++ by exploiting both event-driven and object-oriented paradigms. At the time of this writing, it comprises 27 classes, 57 files, and more than 11 000 lines of code, which can be downloaded from http://standards.ieee.org/downloads/1906/1906.1/P1906.1/ [B6] and Bush [B1].

The simulator has been designed by following a hierarchical structure. Its core models, components, and entities described within the communication framework providing basic parameters and functionality common to all the communication schemes available for the nanoscale and it supports the interaction of components and entities during the exchange of a given message. The core of the simulator should be upgraded for implementing specific communication paradigms. As a first step in this direction, examples of both EM and molecular communication schemes have been developed.

A.1 Implementation detail

Figure A.1 shows the Unified Modeling Language (UML) diagram of the most important classes that comprise the core of the simulator emphasizing the relationship they have with the NS-3 core. Such a diagram only reports the most important data members and functions; some detail regarding relationships among objects has been omitted.

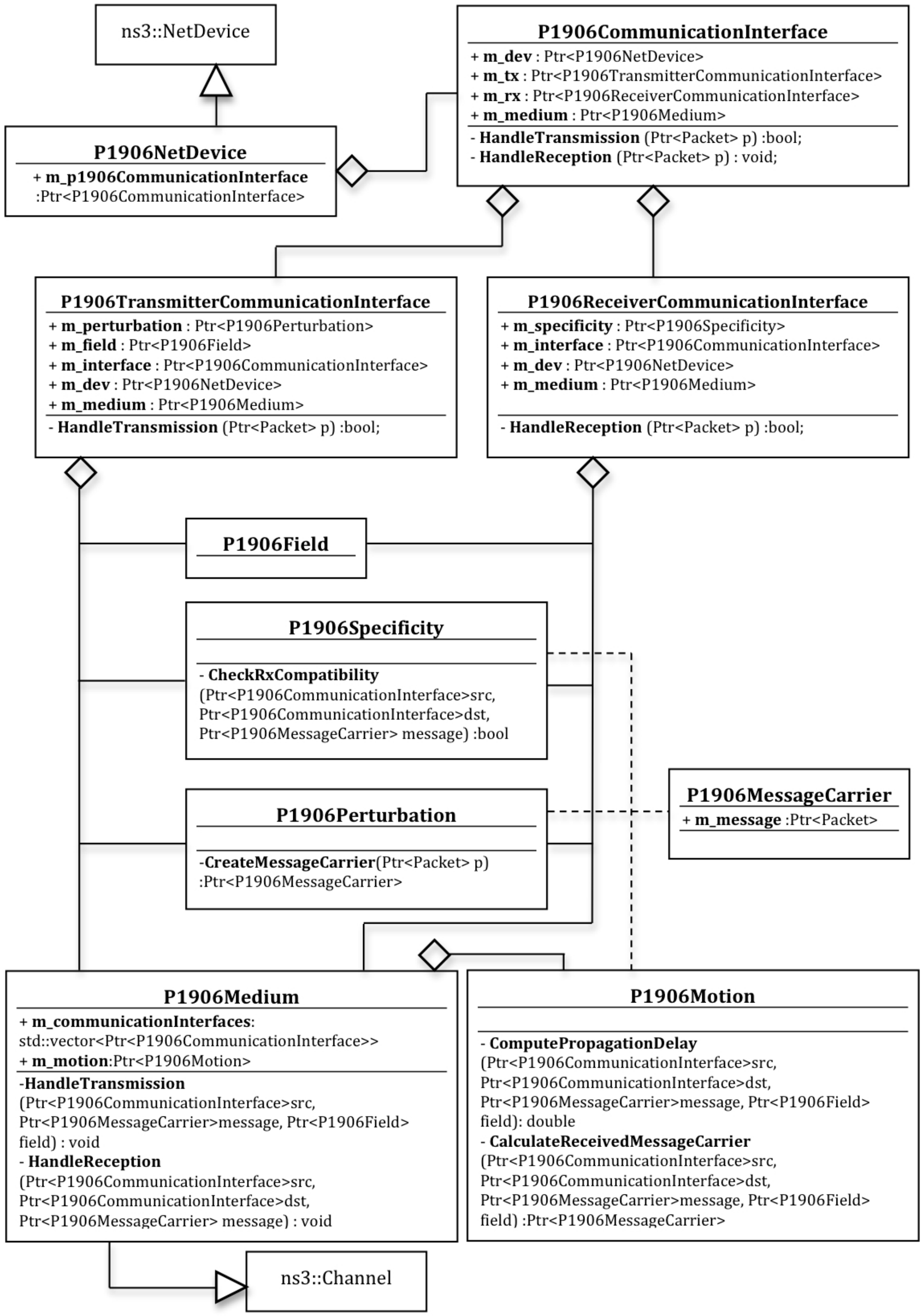

Figure A.1—The UML diagram of the implemented communication framework

All the implemented classes shown in Figure A.1 can be classified in two main groups:

1) Classes implementing components of the IEEE 1906 framework:

   — `P1906MessageCarrier`
   — `P1906Motion`
   — `P1906Field`
   — `P1906Perturbation`
   — `P1906Specificity`

2) Classes implementing other entities that, despite being involved in the communication process, are not classified as "components":

   — `P1906CommunicationInterface`
   — `P1906TransmitterCommunicationInterface`
   — `P1906ReceiverCommunicationInterface`
   — `P1906Medium`
   — `P1906NetDevice`

The message that can be generated and exchanged among devices is implemented in the `P1906MessageCarrier` class. As a default, this component has only one data member, a pointer to the ns3:Packet object, that represents the string of bits (packet) stored with the message itself. Additional parameters should be added for customizing the definition of the Message Carrier component for a specific communication model and for a target use-case.

The `P1906NetDevice` class models the network device that participates in the communication process. It has been conceived as a container for the entire protocol stack and the physical interface. By extending the general `ns3::NetDevice` class available in the official NS-3 release, it already has the basic methods that manage: i) uniquely identifying the device in the network, ii) handling mobility, iii) providing the interface to the application layer, and iv) offer direct access to any portion of the protocol stack and the physical layer of the modeled device. All of these features are very useful for building target applications on top of the general communication framework devised by the IEEE 1906.1 working group.

As highlighted in the UML diagram, an important data member defined within the `P1906NetDevice` class is `m_interface`, which represents the physical interface modeled by the `P1906CommunicationInterface` class handling transmission and reception of messages. It contains a pointer to the `P1906TransmitterCommunicationInterface` and `P1906ReceiverCommunicationInterface` classes, which handle transmission and reception procedures, respectively.

The key element of the communication process is the Medium, modeled by the `P1906Medium` class, which manages delivery of messages among the devices attached to it. This class inherits from the `ns3::Channel` class, already available in the official release of NS-3. All the entities involved in both transmission and reception procedures contain a pointer to the medium object, thus enabling access to its main functions implementing the aforementioned task. At the same time, the medium stores the list of attached physical interfaces, the `m_communicationInterfaces` variable, in order to be cognizant of the group of devices toward which messages are being delivered.

As anticipated, the Medium should deliver the received message to all the attached devices (stored within the `m_communicationInterfaces` data member), by using its `HandleTransmission` procedure.

In general, the transmission of a message through a non-ideal medium leads to the modification of some properties of the message itself. Consider, for example, the transmitted power in EM-based communication and the delay in delivery of the Message. To introduce both of these effects, the medium exploits the `P1906Motion` class, which models properties and functionalities of the Motion component. Also in this case, the implementation of this class should be properly extended by considering the communication model and the chosen use-case. By default, it does not introduce any modification of the Message Carrier component and calculates a null propagation delay.

Obviously, the Perturbation, Specificity, and Field components modeled by the `P1906Motion`, `P1906Perturbation`, `P1906Specificity`, and `P1906Field` classes are fully involved during the execution of the communication process.

Transmission is initiated by the `P1906TransmitterCommunicationInterface` entity through its `HandleTransmission` procedure. This function receives as input a string of bits coding the information to be transmitted (packet) and exploits the perturbation component stored in the `m_perturbation` variable for generating the message carrier component. This last functionality is provided by the `CreateMessageCarrier` procedure of the `P1906Perturbation` class, whose implementation should be customized according to the communication model and the chosen use-case. Then the created message and the field components, stored within the `P1906TransmitterCommunicationInterface` class within the `m_field` data members respectively, are passed to the Medium.

The Medium uses the motion component for modifying properties of the transmitted message carrier. Then, for each attached device, it triggers the reception procedure through the `HandleReception` function. In particular, it verifies that the remote physical interface is able to correctly receive and interpret the transmitted message. To this end, it calls the `CheckRxCompatibility` method of the `P1906Specificity` class associated to the remote device. In case the `CheckRxCompatibility` method returns TRUE, the packet stored within the message carrier component is delivered to the upper layers of the destination device through its `P1906ReceiverCommunicationInterface`.

To summarize, Figure A.2 illustrates the main steps that comprise the aforementioned communication process. They are:

1) The `NetDevice` receives a message from the upper layers. The message is delivered to the Transmitter Communication Interface.
2) The Perturbation component is used to create the Message Carrier.
3) The Transmitter Communication Interface triggers the propagation in the medium by passing Message Carrier, Perturbation, and Field components.
4) The Motion component modify properties of the Message Carrier, for example, propagation loss and delay.
5) The Message Carrier is delivered to the receiver and the Specificity component verifies compatibility.
6) When compatible, the message is delivered to the upper layers.
7) The message is received by upper layers.

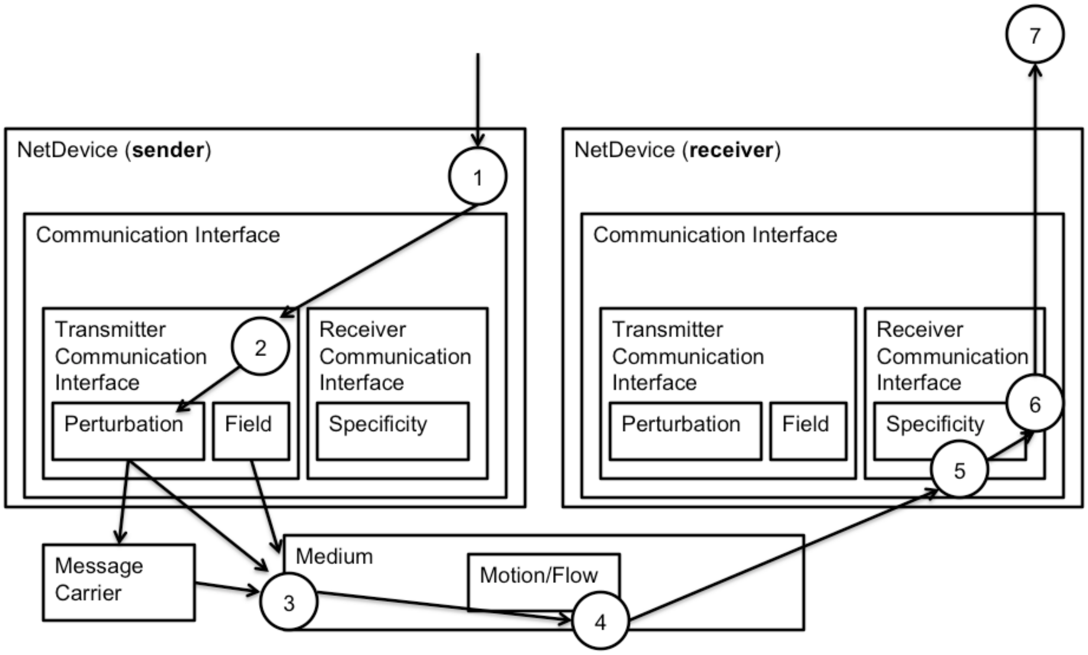

Figure A.2—Summary of steps comprising the communication process as modeled within the implemented simulation framework

A.2 Electromagnetic (EM) communication

The aforementioned core of the simulator has been extended to model the communication among nanoscale devices based on the exchange of EM waves. Figure A.3 shows the UML diagram of classes modeling the EM example. Also in this case, the diagram only reports the most important data members and functions, whereas some details about relationships among objects have been omitted.

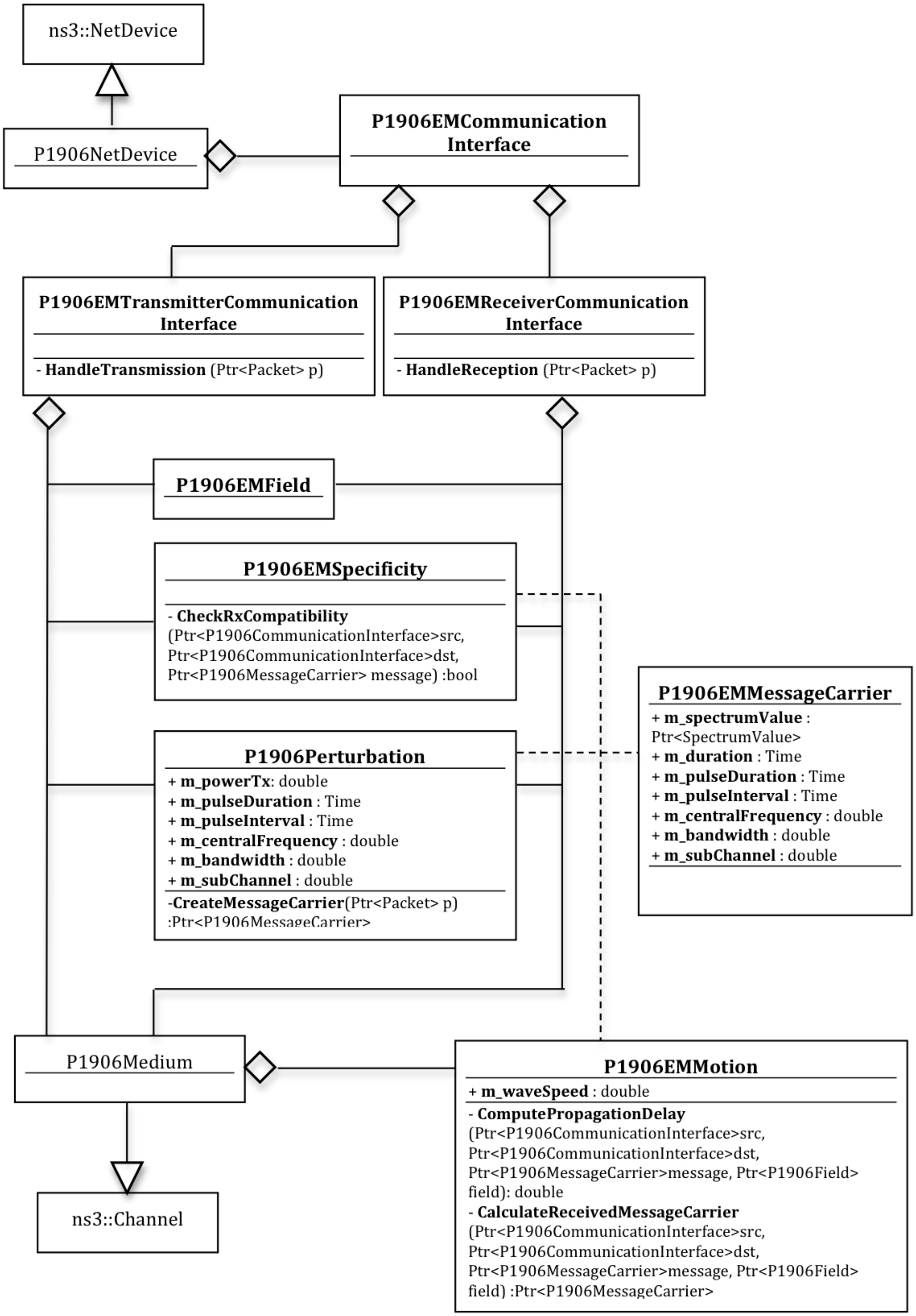

Figure A.3—The UML diagram of the EM example

The implemented example has been developed assuming transmission of the message carrier into the THz channel (i.e., by using the bandwidth 0.55 THz to 1.55 THz, an omnidirectional antenna, and a physical layer based on the Time-Spread On-Off Keying (TS-OOK) modulation scheme). TS-OOK uses a very simple technique that reduces implementation complexity; it represents a logical one by transmitting a short pulse and a logical zero by silence.

As reported in Figure A.3, the `P1906EMPerturbation` class has been created by extending the `P1906Perturbation` class reported in Figure A.2 by including all parameters characterizing the EM transmission, such as transmission power, pulse duration, pulse interval, central frequency of the bandwidth adopted during the transmission, bandwidth size, and the size of each sub-channel.

The `P1906EMMessageCarrier` class integrates all parameters reported within the `P1906EMPerturbation` object (note that these parameters are set by the perturbation component during generation of the message carrier itself). In addition, the `m_spectrumValue` data member has been created to store the power spectral density of the transmitted signal. This member is set by the Perturbation component by uniformly dividing the transmitted power over all available subchannels. Then, it is updated by the Motion component, implemented by the `P1906EMMotion` class, according to the propagation model.

The `P1906EMMotion` component models the propagation of EM waves within the human body. It integrates path loss and thermal noise provided by (Yang, Alomainy, and Hao [B13] and Yang, et al. [B14]), plotted in Figure A.4, and considers a constant message propagation speed stored within the `m_waveSpeed` member variable.

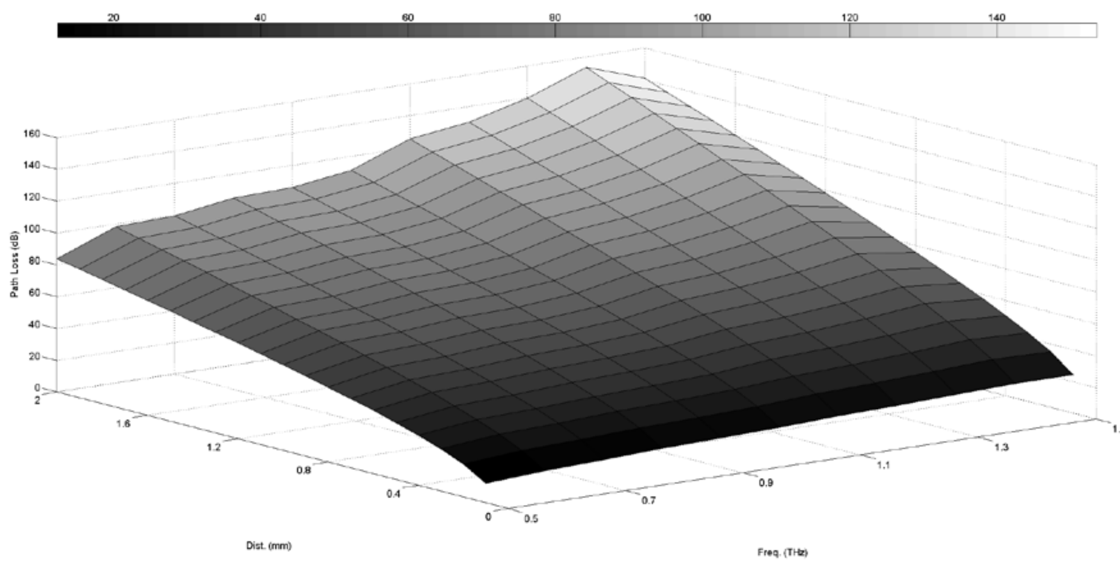

Figure A.4—Path loss model provided by Yang, Alomainy, and Hao [B13] and Yang, et al. [B14]

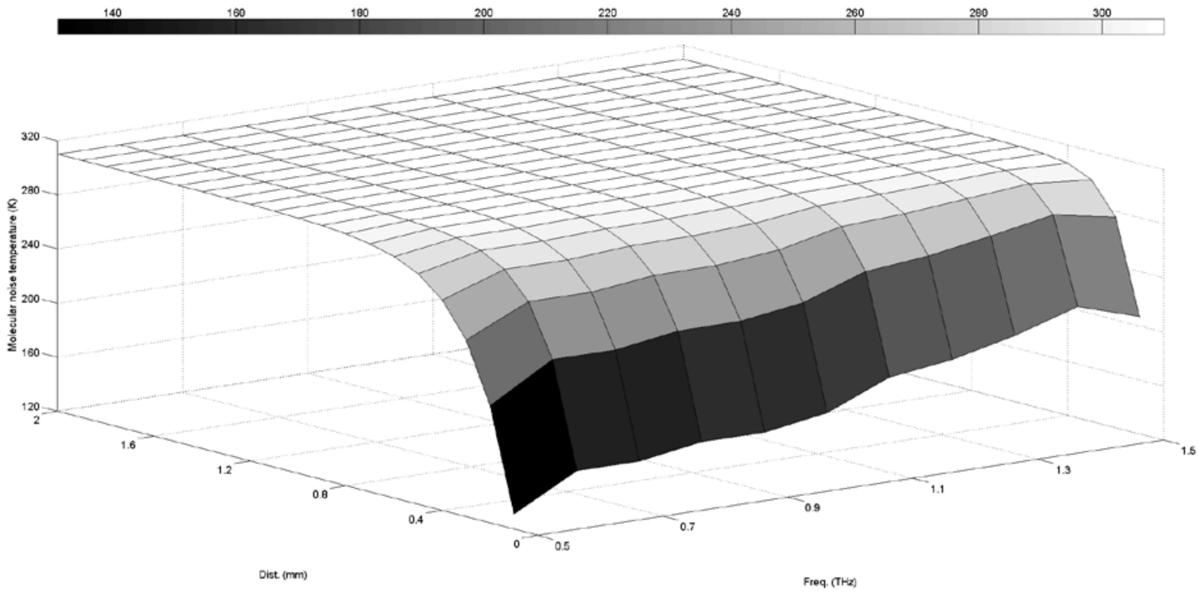

Figure A.5—Thermal noise model provided by Yang, Alomainy, and Hao [B13] and Yang, et al. [B14]

The communication procedure follows the same steps described in A.1.

During the reception process the specificity component, implemented within the `P1906EMSpecificity` class, verifies the compatibility between the received message carrier and the receiver. To this end, it verifies that all the parameters stored within the received message carrier are equal to those stored within the perturbation component.

When the Message carrier and Receiver are compatible, the Specificity verifies that the channel capacity is greater than (or equal to) the physical data rate. The physical data rate is computed as the inverse of the pulse interval. The channel capacity is computed by using the Shannon theorem expressed in Equation (A.1).

$$C(d) = \sum_i \Delta f \times \log_2 \left[1 + \frac{S(f_i) \times A^{-1}(f_i, d)}{N(f_i, d)} \right] \tag{A.1}$$

where

d	is the distance between the sender and the receiver
$C(d)$	is theoretical channel capacity
Δf	is the size of the subchannel
f_i	is the central frequency of the ith subchannel
$S(f_i)$	is the power of the transmitted signal
$A(f_i, d)$	is the attenuation due to the path loss model
$N(f_i, d)$	is the noise power

A.3 Molecular communication

The core of the simulator has been also extended to model molecular communications based on the pure diffusion process. Figure A.6 shows the UML diagram of classes modeling the Molecular example. Also in this case, the diagram only reports the most important data members and functions, whereas some details about relationships among objects have been omitted.

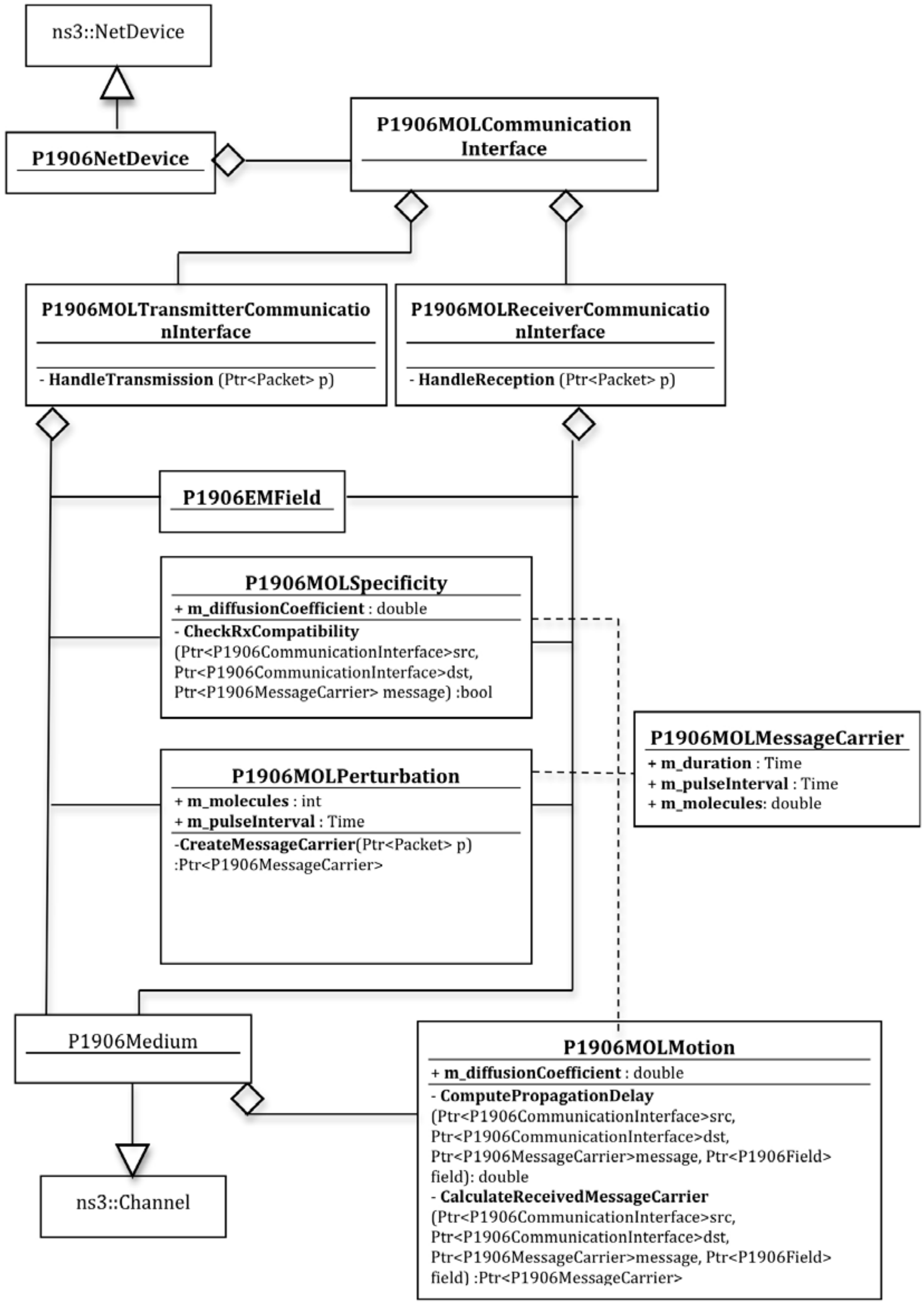

Figure A.6—The UML diagram of the Molecular example

It is assumed that molecules diffuse into the medium according to Brownian motion. In that hypothesis propagation of this pulse can be analytically modeled by Fick's laws of diffusion, which expresses the concentration of molecules as a function of distance and time. In particular, the molecular concentration at any point in space is expressed in Equation (A.2).

$$c(r,\ t) = \frac{Q}{(4 \times \pi \times D \times t)^{3/2}} \times e^{-r^2/4 \times D \times t} \tag{A.2}$$

where

- c is the molecular concentration
- r is the distance between sender and receiver
- Q is the number of molecules released by the sender
- D is the diffusion coefficient
- t is the time variable

The `P1906MOLPerturbation` class has been created by extending the `P1906Perturbation` class reported in Figure A.2 by including all parameters characterizing the molecular communication, such as pulse interval and number of molecules released for each pulse.

The `P1906MOLMessageCarrier` class integrates all parameters reported within the `P1906MOLPerturbation` object (note that these parameter are set by the perturbation component during generation of the message carrier itself).

The `P1906MOLMotion` component models the diffusion of molecules. The `m_diffusionCoefficient` member variable stores the diffusion coefficient of the considered medium (it is passed to the receiver's Specificity component for evaluating the channel capacity).

The communication procedure follows the same steps described in A.1.

During the reception process the Specificity component, implemented within the `P1906MOLSpecificity` class, verifies the compatibility between the received message carrier and the receiver. In the affirmative case, Specificity verifies that the channel capacity is greater than (or equal to) the physical data rate. The physical data rate is computed as the inverse of the pulse interval. The channel capacity is computed by assuming to use an amplitude detection scheme, as described by Chen, et al. [B3].

In nature both compartmental reaction-diffusion as well as discrete, well-defined communication events, need to be considered. This P1906 extension of the ns-3 simulator builds from the IEEE P1906.1 draft standard. It offers an exciting opportunity to evaluate in detail discrete event-based processes critical at nano- and microscales. The future challenge is to combine the capabilities of the aforementioned ns-3 extension with realistic computational models from other domains and scales, such as systems biology, represented via machine-readable languages such as Systems Biology Markup Language (SBML) in user-friendly environments (SBML [B11]). This will require reconciling continuous differential equations with discrete events to create a synergistically powerful computational approach.

Annex B

(informative)

Use-cases

B.1 Lab-On-Chip application: nano-intravital device

Cancer cells create a microenvironment that induces chemotaxis and hypoxia under which the tumor progresses. In order to understand the tumor microenvironment, monitoring of interactions between different cell types and the effects of particular chemical gradients is required. Thus, special tools and devices are required to obtain a deeper understanding of the processes involved in tumor progression. These tools should be capable of monitoring the cellular microenvironment both *in vitro* and *in vivo*.

Many chemotaxi assays have been developed to understand cellular migration. The best of them are needle-based assays since they can be easily used both *in vitro* and *in vivo*. However, this assay can sustain the chemoattractant gradient for only for a few hours and *in vivo* imaging of the tumor during the assay is not possible.

The nano-intravital device (NANIVID) (Raja, et al. [B10]) illustrated in Figure B.1 has been developed to replace the needle-based assay. The NANIVID is made of biocompatible, optically transparent materials. A customized hydrogel is loaded with a chemoattractant such as epidermal growth factor (EGF).

Nanoscale communication exists between the NANIVID and the EGF receptors on the tumor cells. A sustained release of encapsulated materials over several days can be achieved with this device. The hydrogel expands and passively releases the loaded factor, when hydrated, into the environment through the outlet of the device. EGF creates a chemotactic gradient to attract cells toward the device. Real-time cell migration into the device can be monitored through a scaled-down electrode system. The NANIVID can be modified to initiate controlled changes to the microenvironment including the induction of hypoxia.

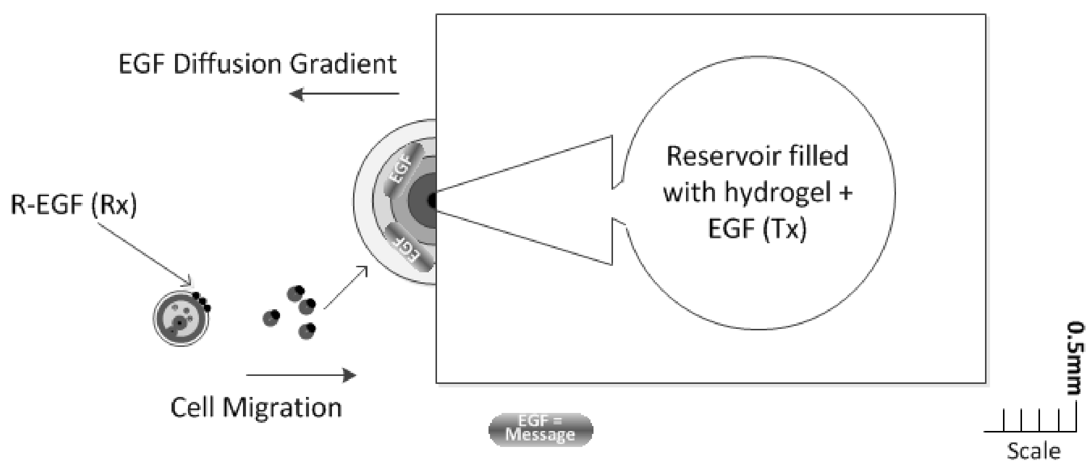

Figure B.1–A 2-D representation of in vitro NANIVID in an experimental setup. The transmitter (hydrogel with EGF), receiver (R-EGF on cancer cells) and the message (EGF) are shown. The direction of EGF diffusion and cell migration are also shown.

The communication in terms of IEEE 1906 components can be seen in Table B.1.

Table B.1—Mapping NANIVID components to the IEEE 1906 framework

IEEE 1906 component	Corresponding components in NANIVID
Transmitter	Hydrogel (loaded with EGF)
Receiver	R-EGF (R = Receptor) on 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

B.2 Targeted drug delivery with CRLX101

Delivery of drugs directly to malignant tissue while minimizing toxicity has been an important goal in nanotherapeutics. Camptothecin (CPT) exhibits anti-cancer activity against several types of cancer cells including gastric cancer and animal tumors. This is due to the inhibition of DNA topoisomerase I (Topo-1) causing cell death because Topo-1 is essential for basic cellular processes including DNA replication, recombination and transcription. Topo-1 is up-regulated in rapidly dividing tumor cells. CPT was not used clinically because of its poor solubility and high systemic toxicity before CRLX101.

CRLX101 (Weiss, et al. [B12]) is a dynamically tumor-targeted nanopharmaceutical consisting of a cyclodextrin-based polymer (CDP) molecule and CPT, which conjugates with CDP forming 30 nm to 40 nm nanoparticles. This conjugation increases the solubility and also reduces toxicity when the drug is administered systematically.

CRLX101 selectively targets tumor cells because of leaky vasculature (enhanced permeability and retention [EPR] effect). Nanoscale communication is evident here. CRLX101 slowly releases CPT when the linkage is hydrolyzed. The receptors on the gastric cell lines receive CPT, which then starts the antitumor activity. The mapping of this use-case to the IEEE 1906.1 framework is shown in Table B.2. The specificity is considered low since CRLX101 can accumulate at tumor tissues other than the desired one due to the EPR effect.

Table B.2—Mapping targeted drug delivery use-case to IEEE 1906 framework

IEEE 1906.1 component	Corresponding components
Transmitter	CDP
Receiver	Receptor on gastric cancer cell lines (MCG803)
Message	CPT
Medium	Cell-culture media
Message carrier	CDP
Component < 100 nm	CDP-CPT nanoparticles
Non-standard physics	Brownian motion
Motion	Diffusion based
Field	Gradient based
Perturbation	Loading CRLX101 with CPT
Specificity	Low

B.3 Contrast-enhanced medical imaging

Contrast-enhanced medical imaging (CMI) has been widely studied and adopted in clinical practice, not only for improving the contrast of the acquired images but also for functional and molecular imaging, e.g., targeting specific biomolecules, gene expression, etc. For example, superparamagnetic nanoparticles have been used as the contrast agent in various CMI modalities for targeted tumor detection, including thermoacoustic molecular tomography, magnetic resonance imaging, microwave medical imaging, etc. However, only a low concentration of contrast agent is able to reach cancer cells by using currently available targeting techniques.

A new technique has been developed to improve CMI performance, where biocompatible and biodegradable microbots (e.g., magnetotactic bacteria or MTB (Martel, et al. [B9]) monitored by an external controlling and tracking system are employed as micro-vehicles to transport the contrast agent for more effective contrast-agent delivery (Chen, Kosmas, Anwar, and Huang [B3] and Chen, Kosmas, and Martel [B4]). There are various strategies for loading the microbots. For example, in the case of MTB, loading inside the cell or attaching nanoparticles to the cell can be applied. The loading strategies can utilize antibodies specific to MTB cells or other methods based on chemical bonding. The nanoparticles (contrast agent) can be functionalized by means of proper molecular groups such as peptides or antibodies, which are able to bind to cancer cell receptors. The MTB release the nanoparticles when they encounter the cancer. Figure B.2 illustrates the system highlighting the IEEE 1906 components.

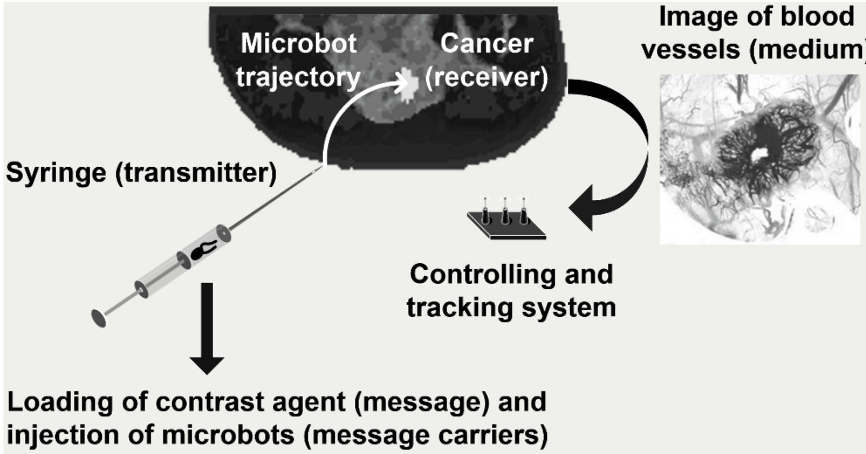

Figure B.2—A 2-D representation of microbot-assisted, touch-communication model of CMI in which microbots are loaded with contrast agent and monitored by an external controlling-and-tracking system. The transmitter (syringe), receiver (cancer), and message carriers (microbots and contrast agent) are shown. The microbot's trajectory and the angiogram on which the CMI process is displayed are also shown.

A molecular communication system can be visualized in this application. The contrast agent nanoparticles and the microbots are message carriers. The path of the microbots in the vascular tree is the communication channel. The loading/injection and unloading of the contrast agent correspond to the transmitting and receiving processes, respectively. In this way, a touch-communication model of CMI is achieved, which provides a visual display of the CMI process in an angiogram by tracking the microbots and enables the external system to adaptively control the movement of microbots by "touching" the tangible microbot-maneuvering space with a magnetic guiding field (Chen, Kosmas, Anwar, and Huang [B3]). Table B.3 shows the relation of this use-case to the 1906.1 framework.

Table B.3—CMI use-case mapping to the IEEE 1906.1 framework

IEEE 1906 component	Corresponding components
Transmitter	Injection syringe
Receiver	Receptors on cancer cell lines
Message	Number or type of contrast agent molecules
Medium	Blood
Message carrier	Microbots (e.g., MTB) and contrast agent
Component < 100 nm	Contrast agent molecules (~30 nm to 50 nm)
Non-standard physics	Biased random walks on vascular tree
Motion	Magnetotaxis
Field	External magnetic field
Perturbation	Change in number of type of contrast agent molecules
Specificity	Receptor sensitivity to contrast agent

B.4 Wireless nanosensor networks

It is envisioned that the concentration of sodium, glucose, and other ions in a person's body can be monitored by means of nanoscale sensors or nanosensors. A nanosensor network can be formed in which several such sensors are distributed around the body to collect relevant data. Each sensor node is equipped with a CNT-based nanoantenna that acts as the transceiver, which uses a THz frequency band to communicate. The mapping of this EM-based communications to the IEEE 1906 framework is given in Table B.4.

Table B.4—Wireless nanosensor networks use-case mapping to the IEEE 1906.1 framework

IEEE 1906 component	Corresponding components
Transmitter	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 waveguide
Field	Intensity/directional antenna
Perturbation	RF modulation
Specificity	Receptor sensitivity/antenna aperture

Annex C

(informative)

Scaling Laws

Table C.1—Microfluidic Scaling Laws

Property	Scaling Law
Acceleration	L
Area	L^2
Capillary force	L
Centrifugal force	L^4
Diffusion time	L^2
Distance	L
Electrostatic force	L^2
Gravitational force	L^3
Hydrostatic pressure	L^1
Inertial force (with constant velocity)	L^2
Marangoni stress (spatial gradient of surface tension)	L^{-1}
Mass	L^3
Mass flow rate (with constant velocity)	L^2
Pressure drop along a channel (with constant length and flow rate)	L^{-4}
Pressure drop along a channel (with constant length and velocity)	L^2
Pressure drop along a channel (with scaled length and constant velocity)	L^{-1}
Pressure force	L^2
Stokes drag force	L
Time	L^0
Van der Waals force	L^{-7}
Velocity	L
Viscous force (with constant velocity)	L^1
Volume	L^3
Volume flow rate (with constant velocity)	L^2

Table C.2—Electromechanical Scaling Laws

Property	Scaling Law
surface/volume	L^{-1}
speed	L^{0}
acceleration	L^{-1}
force = mass × acceleration	L^{2}
total strength = force = area	L^{2}
shear stiffness = stretching stiffness = area/length	L
bending stiffness = radius^4/length^3	L
deformation = force/stiffness	L
mass = volume	L^{3}
acceleration = force/mass	L^{-1}
frequency = acoustic speed/length	L^{-1}
frequency = (stiffness/mass)$^{-0.5}$	L^{-1}
time = frequency^{-1}	L
speed = acceleration × time	constant
frequency = speed/length	L^{-1}
power = force × speed	L^{2}
power density = power/volume	L^{-1}
viscous stress @ constant speed = shear rate = speed/thickness	L^{-1}
frictional force = force	L^{2}
frictional power = force × speed	L^{2}
wear life = thickness/erosion rate	L
thermal speed = (thermal energy/mass)$^{-0.5}$	$L^{-3/2}$
voltage = electrostatic field × length	L
electrostatic force = area × (electrostatic field)^2	L^{2}
resistance = length/area	L^{-1}
ohmic current = length/area	L^{2}
field emission current = area	L^{2}
electrostatic energy = volume × (electrostatic field)^2	L^{3}
capacitance = electrostatic energy/(voltage)^2	L
electrostatic power density = electrostatic power/volume	L^{-1}
resistance power density = (current density)^2	constant
motor current density = (charge/area) frequency	L^{-1}
motor resistive power density = (motor current density)^2	L^{2}
magnetic field = current/distance	L
magnetic force = area × (magnetic field)^2	L^{4}
magnetic energy = volume × (magnetic field)^2	L^{5}
inductance = magnet energy/(current)^2	L
inductive time constant = inductance/resistance	L^{2}
capacitive time constant resistance × capacitance	constant
oscillation frequency = (1/(inductance × capacitance))	L^{-1}
oscillation frequency = wave speed/length	L^{-1}
Q = oscillation frequency = inductance/resistance	L
heat capacity = volume	L^{3}
thermal conductance = area/length	L
thermal time constant = heat capacity/thermal conductance	L^{2}
temperature elevation = frictional power/thermal conductance	L

Annex D

(informative)

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