# Defining Communication at the Bottom

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***Abstract*—Nanoscale communication is expected to offer unprecedented benefits. However, lack of a precise definition and general framework for nanoscale communication has resulted in limited impact and dissipated effort. The IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework provides the precise, common definition of nanoscale communication and a standard, general framework.**

**The definition of nanoscale communication must carefully depict the field so that it captures the unique aspects of small-scale physics with respect to communication. Both the definition and framework must be broad enough to cover the scope of cross-disciplinary technologies that may be utilized while simultaneously be precise enough to allow for interoperable and reusable components.**

**The implication for the field is significant. The IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework will enable diverse disciplines to have a common language and reference for making lasting contributions. A lasting impact will be possible because others can now build upon these results through rational design and synthesis.**

***Index Terms*— Nanoscale communication networks, Molecular communication, Nanotechnology, Nanoelectromechanical systems, Nanoscale devices, Communication systems, Communication networks, Nanobioscience, Nanobiotechnology, Nanomedicine, Nanowires, Communication standards, IEEE standards, Standards development, Simulation, Carbon nanotubes, Quantum mechanics.**

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## I. Introduction: The Need for a Common Framework

Nanoscale communication networks have been discussed actively since the turn of the millennium as a compelling area of exploration in communication. However, progress over the last decade has had little impact. This is due, in part, to the lack of a coherent effort to define the field and allow researchers to build upon one another's work. Hardware instantiations similar to [5] are needed, particularly if they help to validate simulations developing as part of the standard reference model, discussed in Section V. New technologies require industry support and acceptance to develop and survive; the same is true for nanoscale communication. Realistic "killer applications" must be envisioned. These are applications so necessary or desirable that they prove the core value of nanoscale communication. Ensuring that all issues are addressed begins with reaching consensus as to the precise definition of nanoscale communication and then developing a common conceptual framework; that is the accomplishment of IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework. This paper reviews the contributions to the draft standard and provides insight into the decisions that went into developing it. The standard document takes precedent over information in this paper and should be referred to for further detail.

## I. Motivation and Scope: Working Together

One of the motivations for the standard is that few academic articles claiming to contribute to nanoscale communication attempt to precisely define it. The lack of a well-defined problem prevents a coherent development process. Results become more scattered such that progress and results remain dispersed. In effect, each researcher is chasing a different and often unrelated goal. The lack of a common framework and definition prevents directed follow-up by different groups. Reaching a common definition for nanoscale communication has been difficult in part due to the need to bring researchers from diverse fields, ranging from information theorists and physicists to biologists, together in discussion to develop and embrace a common understanding of the topic thereby avoiding miscommunication of ideas. Sometimes researchers are separated by the same terminology. "Communication" may mean one thing to a biologist (molecular entities in direct contact with one another) and something different to an information theorist (transmission of information measured via information entropy). Diverse fields may also have different overarching goals. As an example, information theorists are focused upon information entropy, biologists are focused upon "mechanism," that is, understanding and manipulating systems of causally interacting phenomena and processes that produce measurable effects, computer scientists are interested in simulating such systems, and electrical engineers tend to want to build them.

Another motivation for the standard is to address the problem in which nanoscale communication network simulation components are being developed with different but non-interoperable interfaces. Simulation modules that cannot be entirely reused will result in propagated confusion and wasted effort.

Motivation for IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework comes from a concerted interest by both academia and industry in the form of optimizing research effort, reducing time to prototype, and minimizing risk in seeking profit from this technology. Ideas attain greatest credibility through their obtainable value. Academia and industry partnerships, including clinical endeavors in human health applications, come together in use-cases that help to realize the need for the technology and which have been developed in the IEEE P1906.1/Draft 1.0 standard. Each group 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 with confidence that all components will interoperate successfully. This is vital for knowing how to advance current technologies step-wise versus offering full or partial replacements. The IEEE P1906.1/Draft 1.0 standard provides a step toward accomplishing this objective.

The scope of the 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 communication while promoting creativity across disciplines in addressing the implementation. It is also important to note what is *not* within the scope. The scope does not include the specification of a particular protocol or application. However, the notion of specific protocols and applications are mentioned as examples for what can be defined by future standards that build upon IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework.

## II. Definition: Capturing the Essence

The standard begins by defining nanoscale communication in a manner to position the technology to leverage its unique aspects. This requires a mindset of working with unique characteristics at smaller scales and the manner in which they impact communication. One principle that should be apparent is that this technology involves the nanoscale and utilizes the definition of nanoscale as defined in ISO/TS 27687:2008 definition 2.1 [12], a size ranging from 1 to 100 nm. One nanometer is chosen as the lower limit to avoid including single or small groups of atoms as nanoscale objects; for perspective the size of a hydrogen atom is 0.5 nanometers. The upper limit is the size at which material properties change significantly from their macroscopic size, the size at which a person can directly perceive them without the aid of magnification. A key requirement of a nanoscale communication system is that it must have an essential component that exists at the nanoscale in at least one dimension.

Among the changes in material properties at the nanoscale are an increase in surface area per unit mass and the fact that quantum effects become significant. Reducing mass yields particles driven by forces that are typically considered weak at the macroscale. When atoms residing at the surface become a large proportion of the total number of atoms, material properties change and the nanoparticle becomes more chemically active at its interfaces. Examples enabled by these changes include multi-component protein structures such as molecular motors (active motion) and Brownian motion (passive motion). Quantum effects can change a particle's electromagnetic properties including its optical characteristics. For example, quantum confinement occurs when the quantum wave function is constrained within a nanoparticle due to its small size. If one of the three dimensions is confined, a quantum well results; if two dimensions are confined, the structure is known as a quantum wire; if all three dimensions are confined, then a quantum dot is the result. Carbon nanotubes serve as a well-known example of quantum wire [3]. A key requirement of nanoscale communication as defined in IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework is that it must leverage physical properties that differ from the macroscopic scale.

Another requirement to meet the definition of nanoscale communication in IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework is that the proposed system must map to the basic elements of communication theory. This includes a *transmitter*, *receiver*, *medium*, *message carrier*, and *message*. Most of these elements are intuitively obvious; however, message and message carrier may need further explanation. Message is essentially the information to be transmitted, however, "information" is a loaded term defined differently in different fields. Message carrier refers to the physical instantiation used to transport the message.

The final requirement is that at least one component of the nanoscale communication network must be synthetic. This is included in order to facilitate commercial development and not simply describe a natural phenomenon. Next we consider the framework as defined by the standard.

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## III. Framework: A Division of Labor

The IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework standard specifies a framework rather than a protocol. Many nanoscale communication protocols are anticipated in the future. What is required to catalyze such protocols is a framework that defines the common services that a nanoscale communication protocol will utilize. The framework must be broad enough to encompass the possible types of message transport that leverage properties exhibited at the nanoscale. It must also be broad enough to anticipate academic and industry needs to develop individual components of a nanoscale network and allow them to interoperate. Simulation modules will likely develop along similar lines; such modules must be able to interoperate and allow code to be easily reused.

The components of the framework build upon the definition and include: *message carrier*, *motion*, *field*, *perturbation*, and *specificity*. The message carrier was mentioned in the definition as the physical entity that carries the message; similar to quantum mechanics, it may take a particle or wave form. The motion component refers to the service that provides the force that enables the message carrier to move. The field component provides the service of guiding the message carrier. Motion may be random while the field component provides directionality [2]. The field component may be applied externally. Perturbation is the component that provides controlled change in order to create a signal. It is analogous to modulation in telecommunications; it is the process of varying an aspect of the message carrier or its flow such that a valid message is formed. Perturbation can take many forms including changing the molecular structure, varying the concentration of message carriers, varying a voltage level through a nanowire, or changing the specificity of the receiver. Finally, the specificity component controls the affinity of the receiver to the message carrier. These component and their relationships are known as simply as the *standard model*.

The five components must interoperate through a well-defined interface. This allows a division of labor such that one organization could develop message carriers while another develops field components and everyone can be confident that the components will work successfully together.

The message carrier component transports the message. Specificity provides the ability for addressing and thus may reside at the data link layer as a means of ensuring the message carrier binds only to the intended target. The motion component represents the physical operation of the application of force to the message carrier; it ensures that the message carrier travels from one node to another across a data link. The field component provides a level of directionality to the motion of the message carrier and can help it cross a data link as well as a complete network path. Finally, the perturbation component applies to variations of any subset of components in order to form a signal recognized by the intended receiver.

IEEE P1906.1 components are more general than the Open Systems Interconnection (OSI) model and apply equally well to an active network as illustrated in Fig. 1. In this case, the message carrier is "programmed" to make persistent changes to the underlying network channel medium that impact subsequent future message carriers traveling over the channel [1]. Thus, if $X$ and $Y$ are random variables representing the input and output of the channel respectively, then channel operation is modified by some function $f(X)$ that impacts the conditional probability of $Y$ being recognized correctly when $X$ is transmitted. While an active network is a powerful paradigm, it also violates the strict separation of layers enforced by the OSI model.

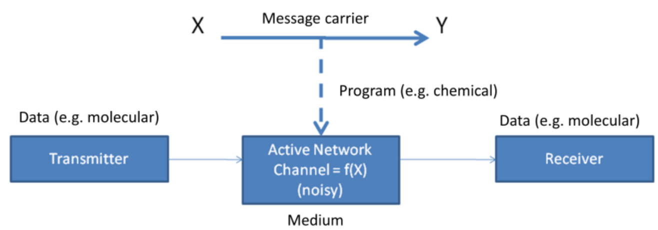


Fig. 1. The relationship between IEEE P1906.1/Draft 1.0 and active networks is illustrated. The message carrier may be "active" in the sense that it generates programmed changes within the underlying network as it moves through the network. This optimization changes the probability of $Y$, and thus the channel output being correctly received when $X$ is sent.

## IV. Use-Cases: Reaping The Benefits

In this section we briefly discuss use-cases that provide example applications that make use of the IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework. These use-cases map onto the framework and definitions. As mentioned, IEEE P1906.1/Draft 1.0 does not specify a particular protocol or an application. Instead, use-cases serve to illustrate how the standard may be used for various protocols and provide ideas for future protocol and application development. Example technologies include the Carbon Nanotube (CNT) radio and molecular communication (active and passive) are described next.

The CNT radio illustrated in Fig. 2 meets the definition of a nanoscale communication network because it has an essential component, the CNT that is one-dimensional with a diameter on the order of a nanometer [7]. It meets the size requirement and exhibits quantum confinement with regard to having nanoscale physical properties. Finally, the CNT radio has elements that map to a transmitter, receiver, medium, message, and message carrier, thus meeting all the requirements for the definition of nanoscale communication. IEEE P1906.1/Draft 1.0 components and definitions map to the CNT radio. The message carrier component is the carrier wave, the perturbation component is modulation of the signal with the carrier wave, the message is encoded in the signal wave form, the specificity component is the antenna length, the field component is the directionality of the electromagnetic (EM) wave, and the motion component is EM wave propagation.

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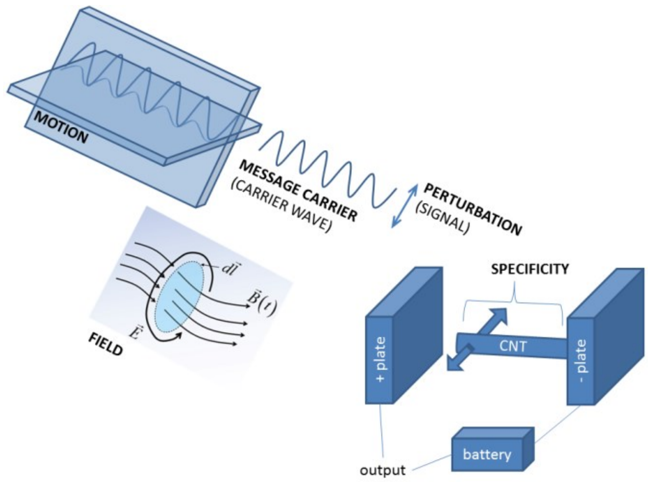


Fig. 2. The CNT radio IEEE P1906.1/Draft 1.0 components map to a transmitter, receiver, medium, message, and message carrier. It also meets the size requirement and exhibits quantum confinement with regard to having nanoscale physical properties.

A ligand-receptor molecular communication example is shown in Fig. 3 [9]. This meets the definition of nanoscale communication because the ligand is an essential component of the system and is on the order of tens of nanometers. The small size of ligands causes them to be impacted by physical forces that differ from macroscale forces, including those involved in Brownian motion. There are also elements that map to transmitter, receiver, medium, message, and message carrier, thus meeting all the requirements for the definition of nanoscale communication when incorporated into a human-made biosensor.

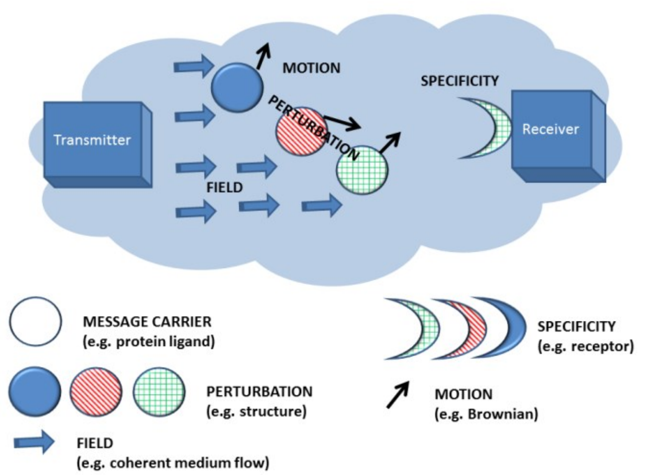


Fig. 3. In molecular communication the message carrier may be a protein ligand that in this diagram is always found in a perturbed state instantiated in the different types of ligands shown.

While the previous example describes the definition and framework in general, consider a specific application of such communication in practice for nanotherapeutics. The goal is to deliver drugs directly to malignant tissue while minimizing toxicity throughout the body. In gastric cancer, the inhibition of DNA topoisomerase I (Topo-1) that is necessary for DNA replication, recombination and transcription using the compound Camptothecin (CPT) blocks growth of the cancerous cells in vitro [17]. However, CPT is not in clinical use because of its poor solubility and high systemic toxicity.

We can visualize nanoscale communication here. Considering CPT as a message, a message carrier is required to transport it to the malignant tissue. To begin anticancer activity the carrier has to transmit this message to receptors on cancerous gastric cells.

The CRLX101 nanopharmaceutical can selectively target tumor cells due to their leaky vasculature and an enhanced permeability and retention (EPR) effect [4]. CRLX101 contains a cyclodextrin-based polymer (CDP) molecule that can be used to carry CPT. CPT conjugates with CDP to form nanoparticles 30-40 nm in size. The process of conjugation of CPT with CDP on CRLX101 can be seen as the process of perturbation. This conjugation additionally increases the solubility and also reduces toxicity.

The message carrier (CDP) in CRLX101 transports the message (CPT) to its target location. It also must transmit the message to the receivers that are receptors on gastric cancer cells. The transmission takes place when the conjugation linkage hydrolyzes. The message is delivered through diffusion into cells with a gradient-based field and has been demonstrated in a cell culture medium. The specificity is considered low since CRLX101 may accumulate at tumor tissues other than the desired one due to the EPR effect. This nanoscale communication, mapped to the IEEE P1906.1/Draft 1.0 standard, is readily understandable and modifiable within the framework. Its components are shown in Table I adapted from [16].

TABLE I
IEEE P1906.1/DRAFT 1.0 APPLIED TO TARGETED DRUG DELIVERY.

| Standard Component | Instantiation |
|---|---|
| Transmitter | CDP |
| Receiver | Receptor on gastric cancer cell line |
| Message | CPT |
| Medium | Cell culture media |
| Message (nano-)carrier | CDP |
| Motion | Diffusion based |
| Field | Gradient based |
| Perturbation | Loading CRLX101 with CPT |
| Specificity | Low |

Another biomedical application of nanoscale communications is lab-on-chip. To study the tumor microenvironment and effects of particular chemical gradients on different cell types, assays are typically performed with a chemoattractant to create a gradient. This gradient attracts the cancerous cells. However, even the best known assay, needle-based assay, can sustain the chemoattractant gradient only for a few hours. Therefore, a device called *NANIVID* (Nano-intravital device) has been developed [15]. The device contains a customized hydrogel blend that can be loaded with epidermal growth factor (EGF). Nanoscale communication exists between the hydrogel in NANIVID and the receptor EGF (R-EF) on the tumor cells. NANIVID releases the encapsulated materials over several days. The transmitter is the hydrogel, which expands when hydrated, and passively releases the message (EGF) into the environment through the outlet of the device. In contrast to a typical communication setup where the message moves towards the receiver, here the EGF creates a chemotactic gradient to attract *receivers* that are the tumor cells that have R-EGF on their cell surface. The cells move through diffusion in a gradient-based field. Perturbation is the process of loading the hydrogel with EGF on the NANIVID device. *Specificity* is high since only motile cells with R-EGF are attracted to the device. This process of communication is shown in Fig. 4. Real-time cell migration into the NANIVID can be monitored through a scaled-down electrode system.

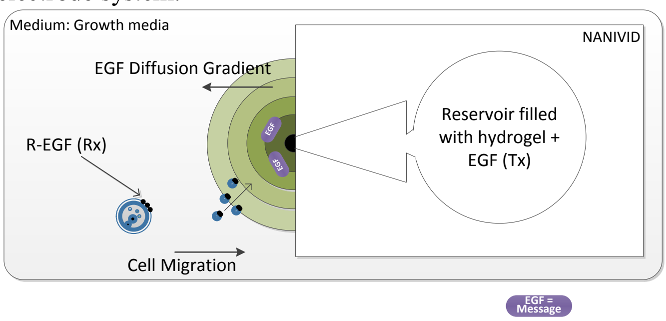


Fig. 4. An illustration of the nanoscale communication process involved with NANIVID [16]. Source: Adapted from IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework.

## V. Reference Code: A Working Model

A modular and free simulation platform will be useful to enable research to converge toward common goals through a standard nanoscale communication simulation environment. While preliminary tools modeling molecular [6][11] and electromagnetic [13] communication paradigms are available, none captures all the features characterizing the communication framework envisaged in this contribution. To bridge this gap, a novel, open-source, and extensible simulation tool has been developed and elected as a reference model within the IEEE P1906.1 working group. Implemented on top of ns-3, it is available online [14].

The core of the simulator models the components described within the communication framework. Simulator models provide basic parameters and functionality common to all communication schemes and support the interaction of components during the exchange of a message.

The message that can be generated and exchanged among devices is implemented in the P1906MessageCarrier class. By default, this component has only one data member (i.e., a pointer to the ns3:Packet object), that represents the string of bits (i.e., a packet) stored within the message. Additional parameters should be added for customizing the definition of the message carrier component for a specific model and use-case. The P1906NetDevice class models the network device that participates in the communication process. It stores within the m_interface data member the communication interface (i.e., modeled by the P1906CommunicationInterface class), which is composed of P1906TransmitterCommunicationInterface and P1906ReceiverCommunicationInterface classes handling transmission and reception procedures, respectively. A 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. It adopts the P1906Motion class for implementing propagation and delay models. Perturbation, Specificity, and Field components are modeled by the P1906Motion, P1906Perturbation, P1906Specificity, and P1906Field classes.

Operation of nanoscale communication is illustrated in Fig. 5: (1) the NetDevice receives a message from 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 the Message Carrier, Perturbation, and Field components (4) the Motion component modifies 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 and (7) the message is received by upper layers.

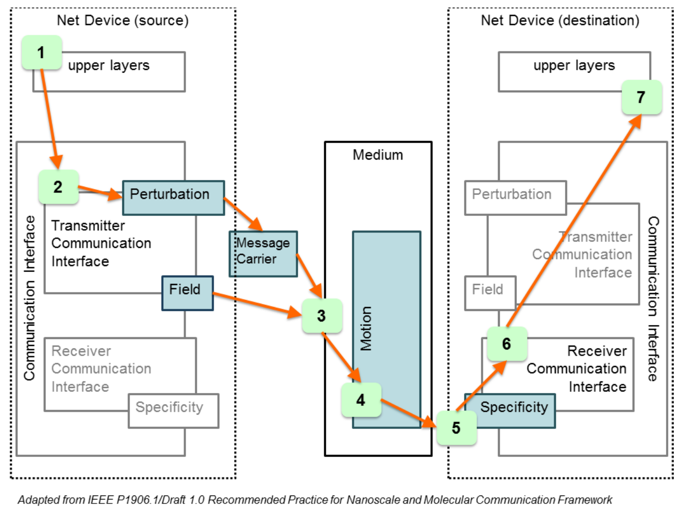


Fig. 5. Summary of steps comprising communication as modeled using the simulation software tool within the implemented simulation framework. Source: Adapted from IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework.

## VI. Example Simulations of Electromagnetic and Molecular Communication

The core of the simulator has been extended to model communication among nanoscale devices based on the exchange of both electromagnetic waves (EM) and molecules.

The EM example assumes transmission of the message carrier using a THz channel by using 0.45 through 1.55 THz spectrum divided into sub-channels of 0.1 THz each, an omnidirectional antenna, and a physical layer based on Time-Spread On-Off Keying (TS-OOK) modulation [8]. The perturbation component includes all parameters characterizing electromagnetic 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. During the generation of messages, such parameters are also stored in the Message Carrier component. In addition, the Message Carrier component also contains the m_spectrumValue data member 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 sub-channels. The Motion component models the propagation of electromagnetic waves within the human body and it is in charge of modifying the m_spectrumValue data member of the Message Carrier component during the delivery process. It integrates path loss and thermal noise provided in [18][19] and considers a constant message propagation speed stored within the m_waveSpeed member variable. During the reception process the Specificity component verifies the compatibility between the received message carrier and the receiver by checking the correspondence between parameters stored within the received message carrier and those stored within the Perturbation component. When the Message carrier and Receiver are compatible, the Specificity component verifies that the channel capacity is greater than or equal to the physical data rate. In the affirmative case, the message is delivered to the upper layers; otherwise it is discarded.

The molecular example considers the presence of a sender and a receiver that communicates by means of molecules released using OOK modulation. Modeling the movement of molecules through Brownian motion, molecular diffusion is characterized by Fick's law of diffusion that defines the concentration of molecules as a function of the distance from the sender and the time interval from the instant in which molecules have been sent [11]. Knowing the number of molecules sent by the sender $Q$ and the value of the diffusion coefficient $D$, Fick's law can be used to evaluate the propagation delay and the minimum distance between two consecutive pulses. Such mathematical models, as well as the data member storing the value of the diffusion coefficient, have been implemented within the Motion and the Specificity components. In the first case, Fick's law is exploited to evaluate the propagation delay; in the second case, it is used to verify that the transmission rate does not exceed the allowable value. Information about number of molecules transmitted for each pulse and the time interval between two consecutive pulses are stored in the Perturbation component and stored within the Message Carrier component.

To demonstrate the effectiveness of the simulation tool and the design of the IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework, an initial comparison between EM and molecular communication schemes, expressed in terms of maximum channel capacity, has been performed. For the EM case, the pulse energy and pulse duration are set to 500 pJ and 100 fs, respectively. For the molecular case, the number of molecules released for each pulse and the diffusion coefficient are set to 50,000 and 1.0 nm$^2$/ns, respectively. Fig. 6 plots the channel capacity as a function of the distance between sender and receiver, which has been computed by considering reference models in [10][11]. Results show that the EM-based communication ensures extremely high physical data rates until the distance between source and destination is lower than 10 mm. In contrast, the considered molecular communication scheme provides lower communication capabilities.

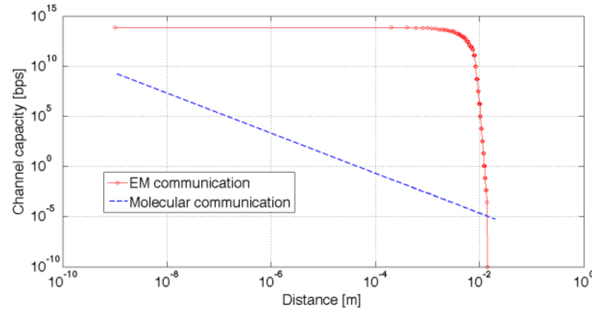


Fig. 6. Channel capacity versus distance comparison between electromagnetic and molecular communication schemes, both implemented in ns-3 facilitated by IEEE P1906.1/Draft 1.0.

## VII. Conclusion: Benefits of a Common Goal

The IEEE P1906.1/Draft 1.0 Recommended Practice for Nanoscale and Molecular Communication Framework provides a clear, common definition and framework for nanoscale communication that allows researchers to collaborate and build from previous work to focus upon rapidly developing solutions to the most impactful problems that need to be addressed to create practical and useful systems. The standard will serve as the unifying basis for future nanoscale communication network protocols and application standards. It is suggested that all future research projects should indicate mappings to the standard following the examples in Sections III and IV.

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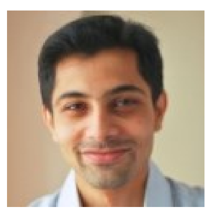

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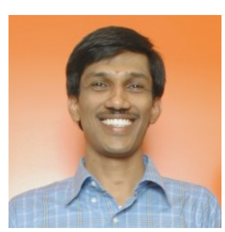

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