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TeraSim: An *ns-3* extension to simulate Terahertz-band communication networks

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ABSTRACT

In the quest of higher wireless data-rates, Terahertz (THz)-band (0.1-10 THz) communication is envisioned as a key wireless technology of the next decade. In parallel to the development of THz transceivers and antennas, simulation tools are needed to expedite the development of communication and networking protocols tailored to this novel networking paradigm, at a fraction of the cost. The few simulation platforms developed to date for THz communication networks do not capture the peculiarities of the THz channel or the capabilities of THz devices. In this paper, TeraSim, i.e., an open source network simulation platform for THz communication networks is presented. TeraSim is built as an extension for *ns-3*, which is one of the most widely used teaching and education network simulation software. The simulator has been developed considering two major types of application scenarios, namely, nanoscale communication networks (average transmission range usually below one meter) and macroscale communication networks (distances larger than one meter). The simulator consists of a common channel module, separate physical and link layers for each scenario, and two assisting modules, namely, THz antenna module and energy harvesting module, originally designed for the macroscale and nanoscale scenario, respectively. The structure, relations and content of each module are presented in detail. Extensive simulation and test results are provided to validate the functionalities of the implemented modules. TeraSim is expected to enable the networking community to test THz networking protocols without having to delve into the channel and physical layers.

1. Introduction

Over the last decade, wireless data traffic has drastically increased due to a change in the way today's society creates, shares and consumes information. This change has been accompanied by an increasing demand for higher speed wireless communication anywhere, anytime. For example, uncompressed Ultra High Definition (UHD) and a 3D uncompressed UHD video transmission would require 24 Gigabit-per-second (Gbps) and 100 Gbps links respectively [1]. Following this trend, wireless multi-Gbps and Terabit-per-second (Tbps) links are expected to become a reality within the next five to ten years. While millimeter-wave (30–300 GHz) communication is the way to go, the limited available consecutive bandwidth (<10 GHz), will limit the feasibility of Tbps links. In this context, THz band communication is envisioned as a key technology to satisfy the need for such very high data-rates, both in traditional networking paradigms as well as in novel nanoscale communication networks or nanonetworks [2–5].

For many years, the lack of compact and efficient ways to generate and detect THz band signals has limited the feasibility of such communication systems. However, within the last decade, outstanding progress has been achieved towards the development of compact THz-band transceivers and antennas. For example, on the one hand, in an *electronic approach*, III–V semiconductor technologies have demonstrated record performance in terms of output power, noise figure, and energy efficiency at sub-THz frequencies, and are quickly approaching the 1 THz mark [6–8]. On the other hand, in an *optics or opto-electronic approach*, Quantum Cascade Lasers are rising as potential candidates for high-power THz-band signal generation, in addition to photomixing-based and photoconductive antenna approaches [9–11]. More recently, the use of nanomaterials such as graphene is enabling the development of plasmonic transceivers, antennas and antenna arrays, which intrinsically operate in the THz-band [12–14].

The huge bandwidth in the THz band comes at the expense of a very high spreading loss, mainly due to the very small size of THz antennas. In addition, THz signals induce internal vibrations in gaseous molecules, which leads to molecular absorption loss. While for millimeter-wave band, oxygen molecules cause the most absorption, at THz-band frequencies, water vapor is the main absorber. Molecular absorption not only increases the path-loss,

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but it also limits the available transmission bandwidth [15]. The very high path loss motivates the use of directional antennas to establish communication links beyond several meters (macroscale applications). While this problem is not present in nanoscale applications, other issues arising from the miniaturization of the device affects the communication at nanoscale. For example, the very small size of nano-batteries motivates the use of energy-harvesting nano-systems [16]. These unique characteristics of this radically different communication paradigm of THz band necessitates the design and analysis of new channel models, communication algorithms, and networking protocols.

In parallel to the development of experimental testbeds [6,17–19], simulation tools are needed to expedite the development, validation and refinement of the communication and networking solutions. In this direction, a few simulator platforms have been developed to date for THz-band communication networks. For example in [20], the authors developed Nano-Sim, an *ns-3* extension to simulate electromagnetic nanoscale communication networks in the THz band. However, Nano-Sim implements only the nanoscale scenario of the THz band communication and uses a simplified channel model that uses the nano-node transmission range as its single parameter. In addition, it does not capture the energy harvesting requirements of nano-devices. In [21], the authors developed a THz propagation model for *ns-3* at frequencies up to 2 THz. Although this propagation model provides accurate THz path loss for a single frequency, it does not take into account the fact that a real signal consists of a band of frequencies. In addition, this is not a complete network simulator in the sense that it does not implement any physical (PHY) layer or medium access control (MAC) layer. To the best of our knowledge, there is no complete simulation platform for THz communication networks.

In this paper, we present TeraSim [22], the first simulation platform for THz communication networks which captures the capabilities of THz devices and the peculiarities of the THz channel, and which implements recently proposed MAC and PHY layer solutions tailored to both nanoscale and macroscale THz scenarios. More specifically, in terms of channel, we have developed a common channel module that implements the frequency selective channel model introduced in [15]. At the PHY and MAC layers, two parallel set of modules for nanoscale and macroscale scenarios have been developed [23,24]. In relation to the capabilities of THz devices, we have implemented an energy harvesting model and a THz directional antenna model. We have thoroughly validated the functionalities of the models by comparing the simulation outputs to the analytical and numerical results available in the literature. TeraSim is built as an extension for *ns-3*, which is one of the most widely used teaching and education network simulation software. Also, *ns-3* has a rich collection of existing source code that can be reused for minimizing the efforts in building a new simulator. TeraSim is designed in a way that it can be incorporated in *ns-3* base without any modification to the existing packages. Ultimately, our goal is to provide a starting point for the networking research community to both develop new solutions for THz networks and contribute to the development of the simulation platform.

The rest of our paper is organized as follows. In Section 2, we provide overview of the design and functionalities of the TeraSim modules. In Section 3, we describe the details of the common modules. In Section 4 and Section 5, we describe the specific modules for the nanoscale and macroscale scenarios respectively. We describe the flow of a packet through the protocol stack of the simulator in Section 6. In Section 7, we provide some testing and validation results for the implemented modules and the performance of the MAC protocols we implemented. Finally, we conclude our paper in Section 8.

2. TeraSim: Structure overview

The way in which TeraSim has been structured is motivated by the physics of the THz band and the envisioned application scenarios. In particular, the THz band provides wireless communication devices with an unprecedentedly large bandwidth, ranging from several tens of GHz up to a few THz. The main phenomena affecting the propagation of THz-band signals are the spreading loss and the absorption loss due to water vapor molecules [15]. The molecular absorption peaks widen up with the increasing transmission distance and consequently shrink the available bandwidth. Considering this phenomenon, THz-band communication can be categorized into two scenarios:

- **Nanoscale scenario:** Over short distances, usually below 1 m, the THz band can be considered a single transmission window, almost 10 THz wide. In this scenario, impulse-radio type communications based on the transmission of femtosecond-long pulses has been proposed [23]. As the path loss is very small at this short distance, nodes can rely on omnidirectional antennas to communicate. However, due to the very small size of the nano-devices, they might need to harvest energy from the environment to operate over extended periods of time [25].
- **Macroscale scenario:** For longer distances, molecular absorption divides the THz band in to multiple transmission windows, tens of GHz wide each. In this scenario, the transmission of ultra-broadband pulses is no longer the preferred option, but, instead, power should be focused in the different windows by utilizing (multi) carrier modulations [26]. A highly directional antenna or beamforming antenna array is needed to overcome the severe path loss in this scenario. Energy harvesting might not be required.

Motivated by this observation, the structure of TeraSim is divided in the following way:

- TeraSim implements one common channel module for the upper layer protocols both for nanoscale and macroscale application scenarios.
- TeraSim implements different physical layers tailored to nano and macro scenarios, namely, pulse-based communications for the nanoscale scenario and continuous-wave for the macroscale scenario.
- At the link layer, TeraSim implements two well-known MAC protocols, namely, ALOHA and CSMA, both tailored to leverage the peculiarities of the different physical layers.
- Finally, TeraSim implements some assisting modules that capture the device peculiarities, including the directional antenna module and energy harvesting module to be used mainly for macroscale and nanoscale scenario respectively. However, these modules can be used for either scenario with minor adaptation at the MAC layer.

In Fig. 1, we illustrate the structure of TeraSim and its relation with the existing *ns-3* code base. A THz-band communication network consists of *ns-3* `Node` objects. Each `Node` can have one or more `THzNetDevice` objects that are derived from *ns-3* `NetDevice` class. Similar to an NIC (Network Interface Card) implementing PHY and MAC protocol, `THzNetDevice` has pointers to `THzMAC` and `THzPhy` objects. `THzMAC` and `THzPhy` can be subclassed to create new MAC and PHY layer solutions. `THzPhy` uses `THzSpectrumValueFactory` to generate pulse for nanoscale scenario and carrier waveform for macroscale scenario. In addition, a `Node` uses `THzNetDevice` to communicate to another `Node` through `THzChannel`. `THzChannel` uses `THzSpectrumPropagationLoss` to calculate both spreading loss and absorption loss

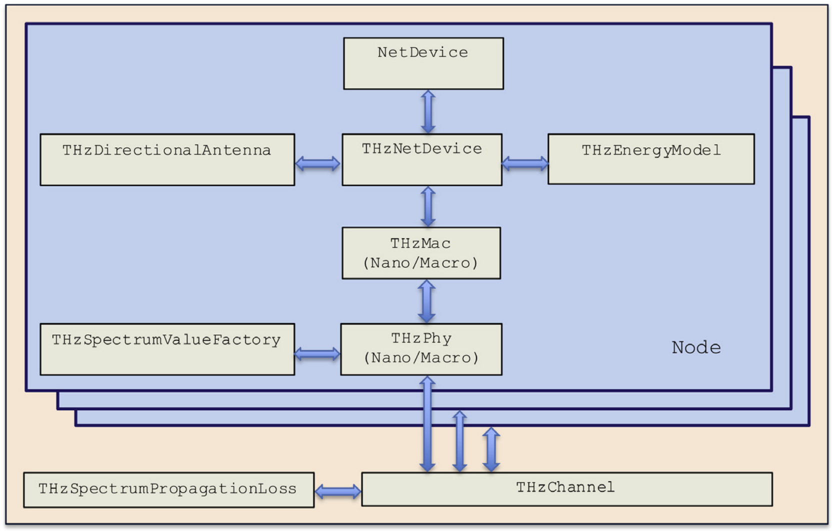


Fig. 1. TeraSim block diagram.

of different frequency bands. In order to accurately reproduce the real life behavior of energy harvesting system for nanonetwork, a `THzEnergyModel` is aggregated to each `Node`. `THzNetDevice` controls the `THzDirectionalAntenna`, which can be also configured to work as an omnidirectional antenna (e.g., for nanoscale scenarios). In the following discussion, we first present the modules that are common to both macroscale and nanoscale scenarios. Then we present the modules that are designed specifically for each of the scenarios.

3. TeraSim: Common modules

3.1. Terahertz net device module

`THzNetDevice` is derived from the base class `NetDevice` provided by *ns-3* to create new MAC protocols. It performs as the joint point which connects the `THzChannel` module, `THzPhy` module, `THzMac` module and the assistant modules such as the `THzDirectionalAntenna` and `THzEnergyModel` together.

3.2. Terahertz channel module

The function of `THzChannel` module is to provide a general THz band channel that can be used by any future upper layer protocol design. It considers both the omnidirectional antenna and directional antenna cases to provide necessary functionality of the nanoscale and macroscale scenario respectively. One of the novelties of our channel module is that it takes into account waveforms with realistic bandwidth and applies the frequency selective propagation behavior of the THz channel. When the waveform generated by `THzSpectrumValueFactory` is passed down to the channel, `THzChannel` first obtains the antenna gains of the transmitter and receiver from the `THzDirectionalAntenna` module accounting for the directions of the beams at that moment. Then it passes the waveform, total antenna gain and the mobility model to `THzSpectrumPropagationLoss` which applies the frequency and distance dependent spreading and absorption loss to the waveform. `THzSpectrumPropagationLoss` then calculates the received power by integrating over the received signal power spectral density (p.s.d.). `THzChannel` then passes the packet along with the received power to the physical layers of all the receivers to simulate the wireless broadcast channel. `THzChannel` module allows the users to set some attributes of the channel such as noise floor (i.e., detection threshold).

In the macroscale scenario, the sender antenna and receiver antenna perform differently during communication, specifically transmitter antenna always points the beam towards the receiver while the receiver antenna periodically sweeps the entire area to avoid the deafness problem. The `THzChannel` module is designed to be able to distinguish the identity of the transceiver (i.e., directional for macroscale and omnidirectional for nanoscale) so that it can feedback the correct antenna gain to the calculation of the received signal power.

3.3. Terahertz spectrum waveform module

For the reason that the molecular absorption loss is frequency dependent in the THz band, `THzSpectrumValueFactory` creates a THz spectrum waveform using `SpectrumModel` class provided by the *ns-3* source. The use of `SpectrumModel` enables the absorption loss calculation from one sub-band to another within the THz band.

`THzSpectrumValueFactory` module lets the user set the number of samples as attribute. The ability to sample the frequency band helps to see the tradeoff between speed and accuracy of the results. For the macroscale scenario, the `THzSpectrumValueFactory` module lets the user select the preferred frequency window as well by specifying the central frequency and the 3 dB bandwidth of this window. After the frequency sub-bands are designed, the transmitted signal power is masked in these bands to generate the transmitted signal p.s.d., which is used by the `THzChannel`, more specifically by the `THzSpectrumPropagationLoss` module, to calculate the spreading loss and absorption for each sub-band.

3.4. Terahertz directional antenna module

We develop the `THzDirectionalAntenna` module based on `CosineAntennaModule`, which is provided in the *ns-3* platform. The antenna gain of the cosine model is determined as [27]:

$$g(\phi, \theta) = \cos^{\alpha}\left(\frac{\phi - \phi_0}{2}\right), \qquad (1)$$

where θ refers to the inclination angle, ϕ_0 is the azimuthal orientation of the antenna and the exponent α determines the desired 3 dB beamwidth $\phi_{3\text{ dB}}$, which can be calculated as:

$$\alpha = -\frac{3}{20\log_{10}\left(\cos\frac{\phi_{3\text{ dB}}}{4}\right)}. \qquad (2)$$

In our design, we extend the cosine antenna model with the ability of turning. Along with specifying the turning/non-turning property of a directional antenna, we can also set other attribute parameters such as the turning speed, initial angle, maximum gain and beamwidth. Note that `THzDirectionalAntenna` can be used as omnidirectional antenna by setting the beamwidth to 360° and the maximum gain to 0 dB. The design of directional antenna parameters will not be introduced in this paper. In the end, the antenna gain of both transmitter and receiver will be feedbacked to the channel when the `THzChannel` calls as illustrated before.

3.5. Terahertz spectrum propagation loss module

The propagation of electromagnetic waves at THz-band frequencies is mainly affected by molecular absorption, which results in both molecular absorption loss and molecular absorption noise. In particular, based on the THz-band channel model introduced in [15], the signal power at a distance d from the transmitter, P_r is given by:

$$P_r(d) = \int_B S_t(f)\,|H_c(f,d)|^2 G_t(f)\,G_r(f)\,df, \tag{3}$$

where S_t is the single-sided p.s.d. of the transmitted signal, B stands for its bandwidth and f refers to frequency. H_c refers to the THz channel frequency response, which is given by:

$$H_c(f,d) = \left(\frac{c}{4\pi f d}\right) \exp\left(-\frac{k_{abs}(f)\,d}{2}\right), \tag{4}$$

where c refers to the speed of light and k_{abs} is the molecular absorption coefficient of the medium. This parameter depends on the molecular composition of the transmission medium, i.e., the type and concentration of molecules found in the channel and is computed as in [15]. G_t and G_r refer to the gain of transmitter antenna and receiver antenna respectively. Similarly, the molecular absorption noise power N_r at a distance d from the transmitter, which can be modeled as additive, Gaussian, colored and correlated to the transmitted signal [23], is given by:

$$N_r(d) = \int_B \left(S_{N^B}(f) + S_{N^I}(f,d)\right) |H_r(f)|^2 df, \tag{5}$$

where it is taken into account that the total molecular absorption noise is contributed by the background atmospheric noise p.s.d., S_{N^B} and the self-induced noise p.s.d., S_{N^I}, and are computed as described in [23]. H_r refers to the receiver frequency response. As of now, we have not implemented the molecular absorption noise as it is relatively low compared to the electronic thermal noise which we capture as noise floor.

In the `THzSpectrumPropagationLoss` module, the medium absorption coefficient k_{abs} is a frequency adaptive value and is calculated from `data_AbsCoe.txt` file which lists molecular absorption coefficient for the THz band based on the HITRAN (HIgh resolution TRANsmission molecular absorption database) database and the channel model in [15]. Therefore, the module can directly call the medium absorption coefficient of the corresponding frequency sub-band. Also `THzSpectrumPropagationLoss` obtains the distance between the sender and the receiver from the mobility models of the sender and the receiver. In this module, we compute the path loss and apply it to transmitted signal p.s.d. on each sub-band to obtain received signal p.s.d. Then we integrate the received signal p.s.d over the signal bandwidth to obtain the received signal power.

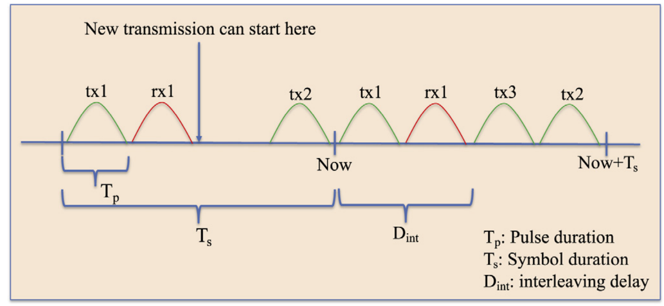


Fig. 2. Pulse interleaving illustration.

4. TeraSim: Nanoscale scenario modules

4.1. THz PHY nano module

The physical layer (`THzPhyNano`) for the nanoscale transmit by using TSOOK, a modulation scheme based on the transmission of one-hundred-femtosecond-long pulses by following an on–off keying modulation spread in time [23]. In masking the power, `THzSpectrumValueFactory` uses the first derivative of the Gaussian pulse modeled in [23] as:

$$p(t) = \frac{a_0}{\sqrt{2\pi}\sigma} e^{\frac{-(t-\mu)^2}{2\sigma^2}}, \tag{6}$$

where a_0 is a normalizing constant to adjust the pulse total energy, σ is the standard deviation of the Gaussian pulse in seconds, and μ is the location in time for the center of the pulse in seconds. The p.s.d. of the time derivate of a femtosecond-long pulse is also Gaussian-shaped, but the frequency position of its main components increases with the derivative order n:

$$S_p(f) = (2\pi f)^{2n} a_0^2 e^{-(2\pi\sigma f)^2}. \tag{7}$$

The p.s.d. of such pulses is mainly contained between 0.1 and 4 THz. The technological limitation forces the consecutive pulses to be far away from each other (100–1000 times). `THzPhyNano` allows the users to easily adjust pulse duration T_p and symbol duration T_s before the simulation starts i.e., at the configuration time. The use of these short time spread pulses provides several advantages. For example, the collision probability among simultaneous users of the channel becomes very small. In addition, a node can interleave multiple transmissions and receptions at the same time. `THzPhyNano` generates the femtosecond-long-pulse using `THzSpectrumValueFactory` module at the beginning of a simulation. When `THzPhyNano` receives the packet from MAC layer, it maps the pulses of the ongoing transmissions and receptions into one symbol time. Then it starts transmission of the first pulse from the next empty pulse position. Fig. 2 depicts how the interleaving is done for a new transmission.

At the same time it creates the data structure for the packet including the transmission start time, transmission duration, and others using `THzSpectrumSignalParameters` which is a subclass of *ns-3* `SpectrumSignalParameters`. These information are stored both at the sender and the receiver sides to detect collision, interleave transmissions, etc. The data structure is then passed to the channel along with the pulse p.s.d. to apply the channel affects. While receiving a data structure from the channel, the `THzPhyNano` checks if the packet collided with the existing transmissions or receptions. A collision happens when two pulses of different receptions overlap in time. If the pulse in reception overlaps with the pulse of an ongoing transmission, the reception is dropped. If there is an overlap with another reception, the Signal to Interference plus Noise Ratio (SINR) is calculated. The packet is then delivered to upper layer if SINR is greater than another threshold which depends on the user requirement. The data structure is deleted at the sender side after transmission duration and at the receiver side after the packet processing is over.

4.2. THz MAC nano module

Since the transmissions are interleaved, there is not much contention for the channel in nanoscale scenario. Hence the channel does not need be reserved using Network Allocation Vector (NAV). When a packet is enqueued in the `THzMacNano`, `THzMacNano` checks if it has enough energy. If it does have sufficient energy to complete a transmission, it passes the packet over to PHY layer for 0-way (ALOHA) handshake protocol. A node receive the packet if it has enough energy. The desired receiver then sends an acknowledgment (ACK) packet to the sender. If the desired receiver does not have sufficient energy and does not reply with an ACK, the sender considers it as a failure and retransmits the packet if the number of retransmissions has not reached the threshold yet. When the maximum number of retransmissions is reached, the packet is dropped. For 2-way (CSMA) handshake protocol, the communication starts by sending a request to transmit (RTS) packet. The desired receiver replies back with an clear to send (CTS) packet if it has enough energy to complete the reception. An RTS transmission failure counts towards the number of retransmissions as well. The transmission can fail either due to packet error or lack of energy at the receiver.

4.3. THz energy model

`THzEnergyModel` is installed in the `Node` by object aggregation provided in the classes derived from *ns-3* `Object`. For the energy harvesting model, we implement an energy harvester that harvests energy at a constant rate and provides interfaces to consume certain amount of energy. Among other attributes, user can set the initial energy in the battery, amount of energy harvested each time and the energy harvesting interval. For quantifying the energy consumed in transmission and reception of a packet, we use the analysis provided in [25]. If we denote the energy consumed in transmitting an L bits packet as E_{tx}^{L} and energy consumed in receiving the same packet as E_{rx}^{L}, we obtain the following expressions:

$$E_{tx}^{L} = LWE_{tx}^{pulse}, E_{rx}^{L} = LE_{rx}^{pulse}, \quad (8)$$

where E_{tx}^{pulse} and E_{rx}^{pulse} are the energy consumed in transmission and reception of a pulse respectively and W refers to the coding weight, i.e., the probability of transmitting a pulse instead of being silent. Whenever MAC layer sends or receives a packet, an appropriate amount of energy is consumed through the interfaces provided by the `THzEnergyModel`. The energy unit is defined to be the amount required to receive one control packet.

5. TeraSim: Macroscale scenario modules

5.1. Terahertz PHY macro module

In the macroscale scenario, where we do not have energy limitation, nodes can use traditional carrier waveform based signals to send information. We consider that nodes transmit a conventional carrier modulated signal over a 100 GHz-wide transmission window at the central frequency of 1.05 THz. This is done to overcome the very high molecular absorption loss over long distances [15]. The modulated signal p.s.d is constructed at the beginning of the simulation with the `THzSpectrumValueFactory` module.

Here, we mainly consider the time duration of a packet being propagated in the THz channel and check if the receiver is able to receive the signal with enough power strength by comparing with the SINR threshold.

5.2. Terahertz MAC macro module

For the macroscale scenario, the nodes are capable to switch between transmission mode and receiving mode. `THzMacMacro` module controls these operation modes by setting the corresponding attribute defined in `THzDirectionalAntenna` module. When a node is in transmission mode, it points the beam towards the intended receiver. On the other hand, a node in receiving mode keeps turning the beam to sweep the entire area to meet the potential transmitters. We apply the NAV mechanism in `THzMacMacro` module. For both 0-way handshake and 2-way handshake cases, in which the communication starts with a data or a RTS packets respectively, the header of each packet has a duration field that declares the needed transmission duration of this packet. Nodes listen to the wireless medium and set their NAV based on the duration field information they read from the header of any received packet, and defer accessing channel for that duration. The carrier-sense indication will be marked as "idle" if the NAV counts down to zero or if there is no one occupying the medium at all. The transmission starts when nodes sense the "idle" channel.

6. TeraSim: Packet flow

Having described how each module is designed and implemented, we illustrate next the flow of a packet through the protocol stack to provide the reader a holistic view of the simulator. In Fig. 3, we illustrate a diagram of the packet flow through the protocol stack of our simulator. As can be seen from the figure, A node in our simulator has all layers of a classical wireless network protocol stack. For the transport and network layers, we use the *ns-3* provided TCP and IP protocol respectively, which ensures that any future protocols for these layers can be added easily to our simulator.

For packet generation, we build our application modules that generate packets using the Poisson distribution. The packet length and the mean inter-arrival time of packets can be adjusted by the user at configuration time. This packet is then passed to the transport layer using standard UDP socket provided by *ns-3*. After all the processing in the transport layer and network layer are finished, the packet is passed to the `THzNetDevice` which calls the `Enqueue()` method of the corresponding MAC protocol. `Enqueue()` method creates a data structure of the packet information that includes the packet, enqueue time, the destination, sequence number among others and adds it to the list of data structures of ongoing transmissions. This information is used to calculate the throughput of a packet when an acknowledgment is received. Depending on the application scenario, the `THzMac` may pass the packet to `THzPhy` if it has enough energy (by calling `CheckResources()` method in nanoscale scenario) or if the channel is available (in macroscale scenario where carrier based communication is available). If there is enough resource available (energy for nanoscale and channel for macroscale) in the respective scenario, MAC layer may behave in two different ways depending on the protocols implemented. For the 0-way handshake protocol, MAC layer directly passes the data packet to the PHY layer, while for the 2-way handshake protocol, the MAC layer first checks the availability of the receiver by an RTS/CTS handshake. In the nanoscale scenario, the receiver is available if it has sufficient energy to receive the packet whereas in macroscale scenario, if the receiver directional beam is facing the transmitter. The packets are passed to the PHY layer by calling `SendPacket()` method of `THzPhy`.

`THzPhy` creates its own data structure for the packet and adds it to the list of ongoing transmissions. If a new transmission or reception comes while a transmission is going on, `THzPhy` will use the information to interleave in nanoscale scenario and check for

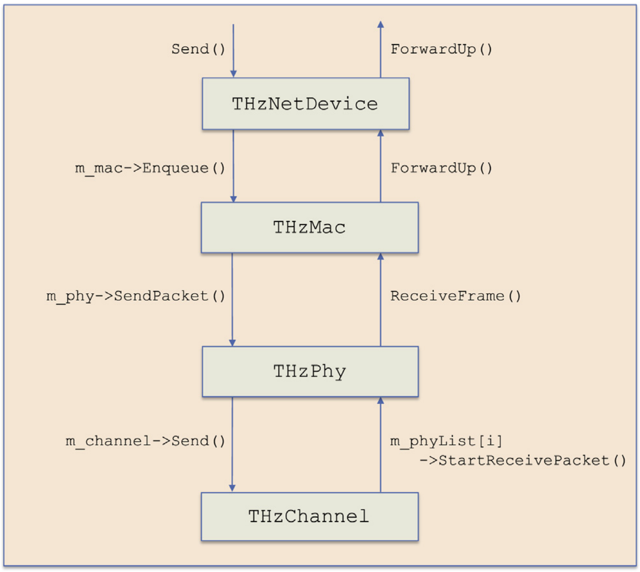


Fig. 3. Packet flow through TeraSim protocol stack.

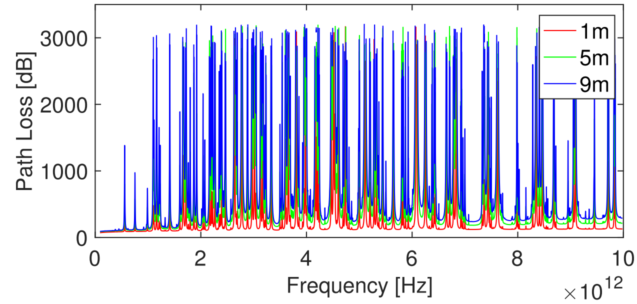


Fig. 4. Path loss as a function of frequency and distance.

collision in both of the scenarios. Then the packet is passed to the THzChannel by calling the SendPacket() method of the channel through the handle (pointer to THzChannel).

The channel then calculates the received power for every other node connected to it and schedules ReceivePacket() of the THzChannel after the corresponding propagation time. The RecivePacket() method of the channel invokes the RecivePacket() method of the THzPhy using the pointer to it. After the packet transmission time, the RecivePacket() method of the THzChannel schedules the ReceivePacketDone() method, which in turn invokes the ReceivePacketDone() method of the corresponding PHY layer. The ReceivePacket() method of the THzPhy checks for the collision and calculates the SINR every time there is a new interfering signal. Then it marks the packet as collided if the SINR value is less than the threshold, otherwise it marks the packet as not collided. The ReceivePacketDone() of the PHY then checks the completely received packet to see if it was collided i.e., the SINR was less than the threshold at

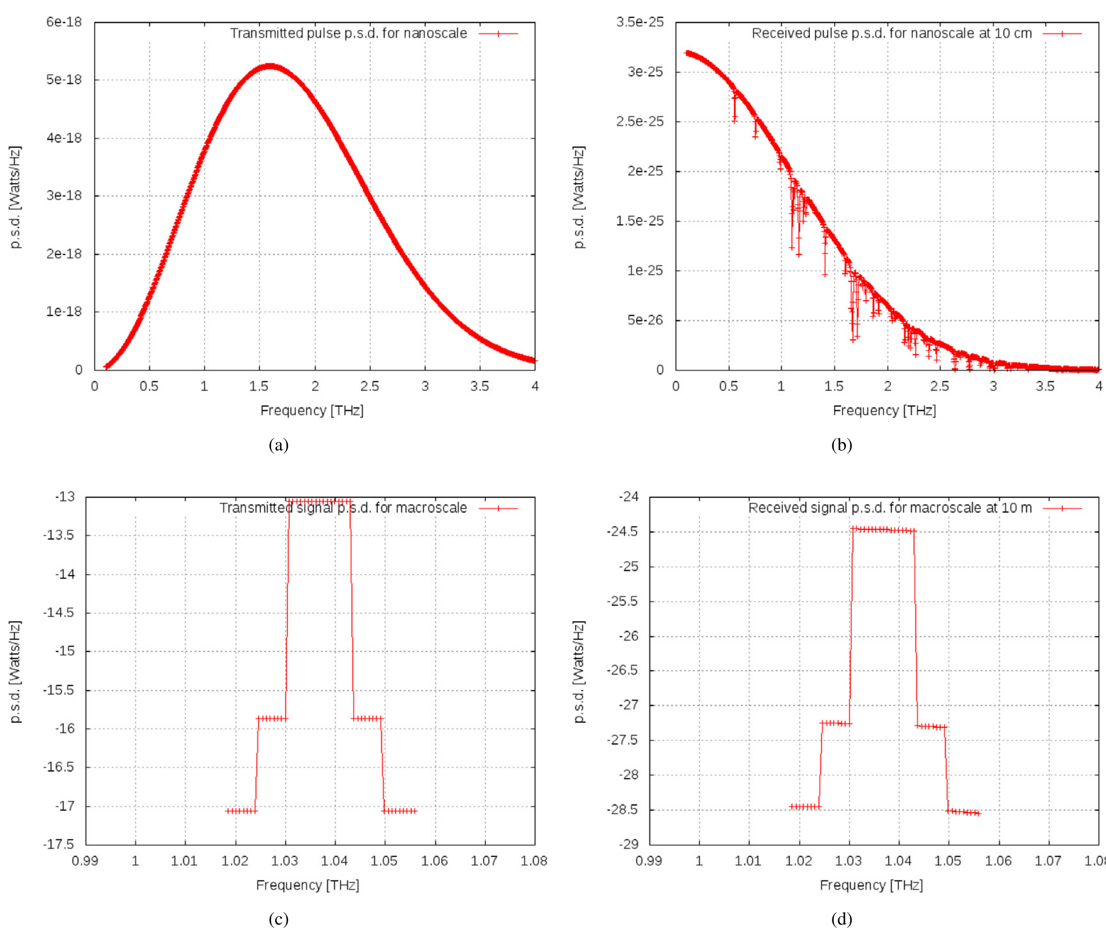


Fig. 5. Power spectral density of nanoscale and macroscale signal generated by TeraSim.

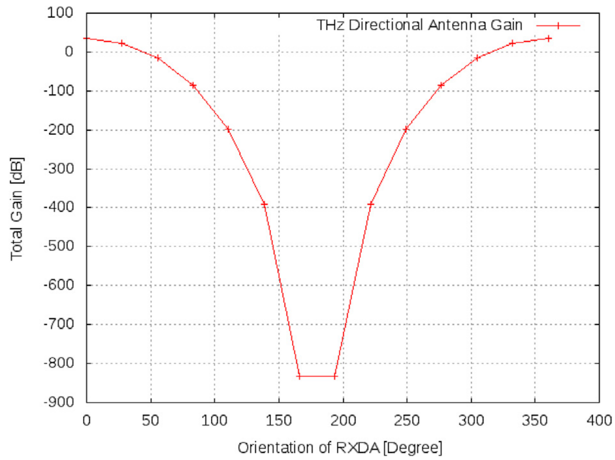


Fig. 6. Directional antenna pattern.

some point during reception. If it did collide, the packet is dropped. Otherwise, the packet is passed to the MAC layer. The MAC layer first checks if it is the intended receiver of the packet by looking into the destination address. If it is the intended receiver and the packet is received correctly, The MAC layer schedules an ACK packet for the corresponding source node and passes the packet to the upper layer.

7. TeraSim: Model testing and validation

In this section, we validate our TeraSim by comparing the values of different parameters generated by TeraSim simulation with that produced by analytical models. Specifically, we have compared important parameters like path loss, channel behavior, received power, directional antenna gain and MAC protocol performance among others.

7.1. Path loss

Path loss is the most important part of the THz channel as it has molecular absorption loss in addition to the regular spreading loss. We created a separate script to produce the path loss plot from TeraSim channel module. The path loss generated by TeraSim is shown as a function of frequency and distance in Fig. 4. As can be seen from the figure, the path loss generated over the THz band by our channel indeed matches the THz channel model developed in [15]. Indeed, the molecular absorption loss is significant beyond one meter and defines multiple windows several gigahertz wide.

7.2. Signaling, antenna gain and received power

For the PHY layer, we have different physical layers for macroscale and nanoscale scenario. In Fig. 5(a), we show the power spectral density of the first derivative of the Gaussian pulse generated by our `THzSpectrumValueFactory` module using a transmission power of 10 μW. In Fig. 5(b), we show the p.s.d. of the corresponding received signal at a distance of 10 cm. As can be seen from these figures, the p.s.d. of the Gaussian pulse spans the frequency band between 0.1 and 4 THz. These figures also show that the TeraSim accurately implements the THz channel.

The p.s.d. of transmitted signal for macroscale scenario is shown in Fig. 5(c). A 100 GHz bandwidth window with the central frequency of 1.05 THz was chosen to mask the transmitted signal. We made this choice since this is the first absorption defined transmission window above 1 THz. The corresponding received signal p.s.d. at a distance of 10 m with an antenna gain of 17.27 dB is depicted in Fig. 5(d). In this case, we do not see the effects of absorption peaks as the bandwidth was selected as 3 dB window. In Fig. 6, the radiation pattern of TeraSim directional antenna module is shown as a function of azimuth angle. The figure proves that our directional antenna can indeed provide high directivity. In our design, the maximum antenna gain is 17.3 dB per transceiver antenna with antenna 3 dB beamwidth of 27.7°.

The received signal strength for the specific signaling used is also compared to that produced by MATLAB simulation to validate the TeraSim simulator. In Table 1, the received signal strength for macroscale scenario is shown for a transmission power of −20 dBm and with the test condition that transmitter and receiver antennas are facing each other. As can be seen from the table, the TeraSim results are very close to the MATLAB simulation results. The little difference is caused by the dynamic 3 dB bandwidth used in MATLAB, while a fixed bandwidth has been used in the *ns-3* module.

The received signal strength for nanoscale scenario is shown in Table 2 for a transmission power of −20 dBm. The TeraSim results are very close to the MATLAB simulation results as can be seen from the table. An important point to note here is that the received signal power shown here do not incorporate any interference from the neighboring nodes.

7.3. MAC protocol

As an example use case, we have implemented slightly modified versions of two popular MAC protocols namely, 0-way and 2-way handshake. We place the nodes uniformly in a circular disk of radius 10 m and 0.01 m for macroscale and nanoscale scenario respectively. To illustrate the performance of the MAC protocols, we show the impact of the node density on the throughput and the packet discarding rate with fixed packet generation rate. The packet generation follows the Poisson distribution with rate in unit of packets/second.

For the nanoscale scenario, nano-nodes communicate by utilizing TS-OOK with pulse length $T_p = 100$ fs, and spreading factor $T_s/T_p = 100$. The transmission power is set as described in Section 7.2. The attributes of the energy harvesting module are setup as follows. We define the energy harvesting interval $1/\lambda_{harv} = 8$ μs per energy unit and energy required to transmit a pulse and receive a pulse as 0.125 units (equivalent to 1 attoJoule) and 0.0125 units, respectively. The coding weight is chosen to be 0.5 for a data packet size of 128 bytes and a control packet size of 17 bytes. The mean packet generation interval is 550 μs between two successive packets. A maximum retransmission of 5 times is allowed before the packet is dropped. In the 2-way case, an RTS transmission failure counts towards the number of retransmissions as well. The throughput performance of the two protocols is shown in Fig. 7(b) and the discarding rate is shown in Fig. 7(a). As can be seen from the figures, the 0-way handshake protocol has lower discard probability than the 2-way case. The reason for this is that 2-way protocol counts the RTS failure towards the maximum number of retransmissions before dropping a packet. For the 0-way protocol, the retransmission happens due only to failed data packet transmission. As a result for every transmission wasted, the time duration before the next retransmission is very long for 0-way than that of the 2-way protocol. Therefore, the throughput is less for the 0-way than the 2-way protocol. In addition, the throughput decreases and the discarding rate increases with the increasing node density for both of the protocols. The reason for this behavior is that with increased node density, a node needs to receive packets from more transmitters with the same energy harvesting rate.

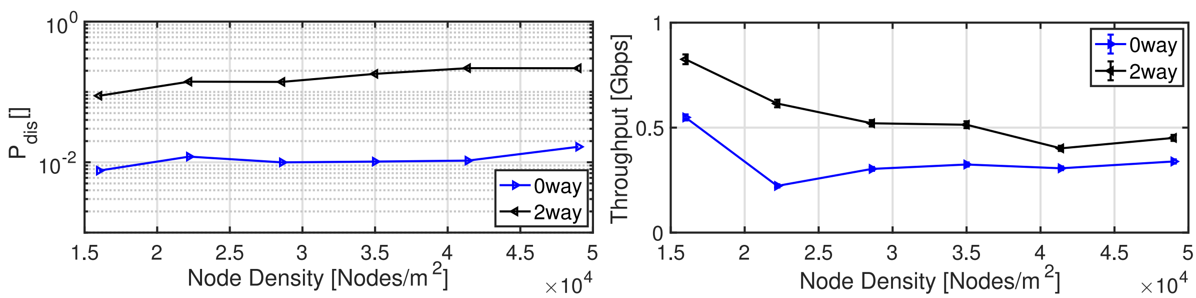
For the macroscale scenario, the attributes of THz directional antenna need to be set up. The directional antenna gain and the

Table 1
Macroscale scenario.

Distance [m]		1	5	10	15	20
MATLAB	P_{TX} [dB]	−50	−50	−50	−50	−50
	P_{RX} [dB]	−108.65	−123.31	−130.04	−134.25	−137.39
ns-3	P_{TX} [dB]	−50	−50	−50	−50	−50
	P_{RX} [dB]	−108.47	−122.43	−128.46	−131.98	−134.48

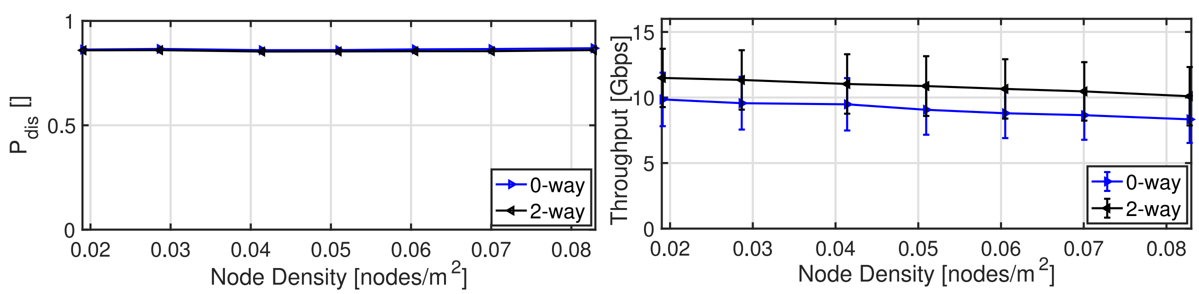
Table 2
Nanoscale scenario.

Distance [m]		0.0001	0.001	0.01	0.1	1
MATLAB	P_{TX} [dB]	−50	−50	−50	−50	−50
	P_{RX} [dB]	−66.01	−86.49	−106.5	−126.80	−148.1
ns-3	P_{TX} [dB]	−50	−50	−50	−50	−50
	P_{RX} [dB]	−63.74	−83.77	−103.40	−124.90	−146.63



(a) Packet discard probability (b) Throughput

Fig. 7. Performance of MAC protocols in nanoscale ad hoc scenario.



(a) Packet discard probability (b) Throughput

Fig. 8. Performance of MAC protocols in macroscale centralized scenario.

beamwidth are set as described in Section 7.2 and the antenna turning speed at the receiver node is set as 91032.04 rounds per second [24]. The nodes generate packets of length 15 000 bytes with the mean value of inter-packet interval as 22 μs. As shown in Fig. 8(a), the packet discard probabilities of both 0-way and 2-way cases are extremely high. The main reason for this is that many retransmission attempts are wasted when the receiver is not facing the transmitter. As the cost of very high discard probability, the achieved throughput is also affected. In Fig. 8(b), the throughput is illustrated as a function of node density. With increasing node density, more collisions occur and thus leads to decreasing throughput. Also, the 2-way case performs better than the 0-way case for the reason that it is much faster to process retransmissions of RTS other than DATA, meaning it is easier for the 2-way case to dump redundant packets from the buffer when the receiver is not ready and thus reduce queueing delay for all the packets waiting in queue. The performances of the MAC protocols described above match with the analytical results presented in [24].

8. Conclusions

In this paper, we have presented TeraSim, the first comprehensive THz band communication network simulator that captures the peculiarities of the frequency selective THz band channel and the capabilities of the THz devices and implements recently proposed communication and networking solutions. The simulator implements the detailed frequency dependent behavior of the THz band channel accounting for the molecular absorption loss and the spreading loss. In addition, TeraSim incorporates separate physical layers tailored to the two application scenarios, namely, nanoscale and macroscale scenarios. Finally, to show the use cases, TeraSim implements two popular MAC protocols that have been adapted to both of the aforementioned scenarios. Along with the details of *ns-3* implementations, we have validated the functionalities of TeraSim by comparing the results from TeraSim with that generated from MATLAB simulation of analytical results. By contributing TeraSim to an open repository, we encourage the community to test and validate THz networking solutions with high modeling accuracy, without having to being heavily familiar with the channel physics and the physical layer.

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