Body-Centric Terahertz Networks: Prospects and Challenges

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Nasir Saeed
King Abdullah University of Science and Technology

Hadi Sarieddeen
King Abdullah University of Science and Technology

Tareq Y. Al-Naffouri
King Abdullah University of Science and Technology

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Nasir Saeed, *Senior Member, IEEE,* Mohamed Habib Loukil, *Student Member, IEEE,*
Hadi Sarieddeen, *Member, IEEE,* Tareq Y. Al-Naffouri, *Senior Member, IEEE,*
and Mohamed-Slim Alouini, *Fellow, IEEE*

***Abstract*—Following recent advancements in Terahertz (THz) technology, THz communications are currently being celebrated as key enablers for various applications in future generations of communication networks. While typical communication use cases are over medium-range air interfaces, the inherently small beamwidths and transceiver footprints at THz frequencies support nano-communication paradigms. In particular, the use of the THz band for in-body and on-body communications has been gaining attention recently. By exploiting the accurate THz sensing and imaging capabilities, body-centric THz biomedical applications can transcend the limitations of molecular, acoustic, and radio-frequency solutions. In this paper, we study the use of the THz band for body-centric networks, by surveying works on THz device technologies, channel and noise modeling, modulation schemes, and networking topologies. We also promote THz sensing and imaging applications in the healthcare sector, especially for detecting zootonic viruses such as Coronavirus. We present several open research problems for body-centric THz networks.**

***Index Terms*—THz communications, body-centric networks, channel modeling, modulation, coding, networking, sensing, imaging, Coronavirus**

I. Introduction

As the deployment of the fifth-generation (5G) of wireless mobile communications is in full swing, the research community is moving forward, looking into beyond 5G. The common topic across different research projects is the usage and applications of higher frequencies in the millimeter-wave (mmWave) and terahertz (THz) frequency bands. While mmWave communications are already defining 5G [1], [2], THz-band communications are expected to play a vital role in the upcoming sixth-generation (6G) wireless technology [3]–[22]. Therefore, THz-related research has attracted significant funding and standardization efforts are already underway [23]–[25].

The THz band between the microwave and optical bands is the only piece of the radio-frequency (RF) spectrum that remains unutilized for communication purposes. Therefore, both the microwave and optical bands' wireless communication technologies are expected to stretch to support THz communications. From the RF communications perspective, THz frequencies start with 100 GHz, below which is the mmWave band. From the optical communication perspective, THz frequencies are below 10 THz (the far-infrared) (see Fig. 1). According to the IEEE 802.15 Terahertz Interest Group (IGthz), the THz range is 300 GHz-10 THz [26].

Besides enabling high-speed wireless communications, the THz band has numerous medical applications, such as in characterizing tablet coatings, investigating drugs, dermatology, oral healthcare, oncology, and medical imaging [27]. Another promising use of the THz band is to enable connectivity in body-centric networks (BCNs). Due to the unique THz propagation properties and sensing capabilities, and due to the THz radiation's relative safety on biological tissues [28], the THz spectrum can improve the performance of existing BCNs, thus enabling various medical applications [29]. The BCN paradigm consists of connected bio-nano sensors and devices that compute various physical and physiological phenomena, such as heart rate and glucose level, as shown in Fig. 2. These networks can operate inside the human body in real-time for health monitoring and medical implant communication [30]. Also, BCNs can feature in e-drug delivery systems [31].

BCNs can further be classified into two categories, on-body and in-body networks (OBNs and IBNs). OBNs utilize wearable devices or implanted nano-sensors that provide continuous monitoring of patients. OBN devices principally use the radio-frequency (RF) technology to disseminate information; however, the main disadvantages of this technology are high-energy consumption and electromagnetic interference. On the contrary, IBNs consist of tiny-devices, also called nano-machines, that patrol within the body and collect critical health-related information [32]. Primitively, nature-inspired molecular communication is used to connect such nano-machines [33]. Other technologies are investigated for BCN applications such us acoustic solutions [34], [35]. Furthermore, researchers are currently investigating a wide range of electromagnetic frequencies [36], [37], where the optical and THz bands are considered as promising alternatives. In addition, there are some attempts to use hybrid systems for communicating inside the human body [38], [39]. To better understand different BCN paradigms, the interested readers are referred to [31], [32] that briefly discuss these wireless technologies for nano communications. In Table I, we enlist the literature on promising wireless technologies for IBNs.

Inter-connecting the nano-devices to form a network that can exchange information and achieve a common goal is vital and challenging in BCNs. Since nano-devices are quite dif-

The authors are with the Department of Computer, Electrical and Mathematical Sciences and Engineering (CEMSE), King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Kingdom of Saudi Arabia, 23955-6900 (e-mail: nasir.saeed@kaust.edu.sa; mohamedhabib.loukil@kaust.edu.sa; hadi.sarieddeen@kaust.edu.sa; tareq.alnaffouri@kaust.edu.sa; slim.alouini@kaust.edu.sa). This work was supported by the KAUST Office of Sponsored Research.

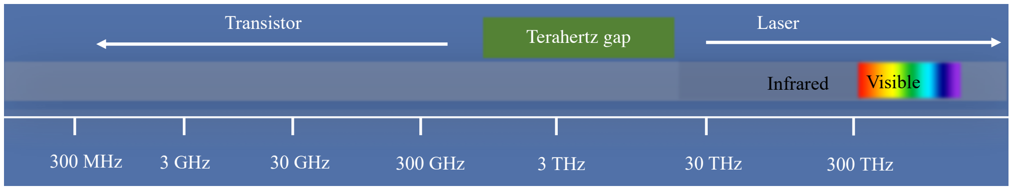


Fig. 1: The THz gap.

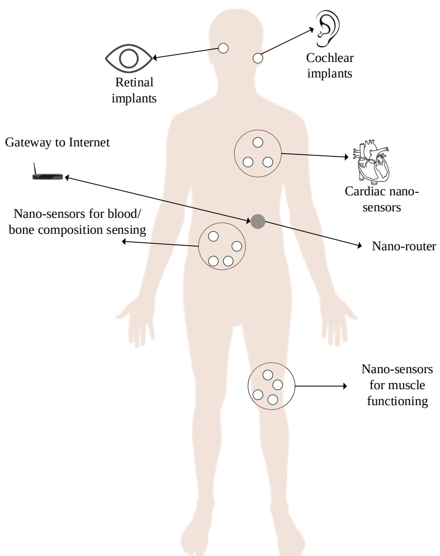


Fig. 2: Illustration of BCN architecture with nano-scale devices.

ferent from conventional sensing devices, the communication technologies that interconnect them need to be re-evaluated. The most obvious solution seems to be RF technologies; however, nano-devices' distinct properties require modifying the existing channel models, communication protocols, and networking architectures. Nevertheless, the RF technology is not suitable for BCNs due to its lack of compactness, high complexity, and power consumption [29]. Therefore, recent research has shown that the THz band has the potential to enable low complexity, power-efficient, and high-bandwidth point-to-point links in BCNs [32].

THz communications still face various challenges, such as high path loss due to atmospheric losses and spreading, limiting their communication range [129]. For example, to communicate at distances of a few millimeters, the entire THz band is available due to negligible atmospheric loss. However, to establish links in the order of meters without the support of additional antenna and power gains, only sub-THz frequencies in the order of tens of gigahertz (GHz) can be used. Furthermore, direct single-hop long distances are difficult to achieve with THz frequencies due to the high attenuation. As a result of such constraints, novel THz-specific transceiver designs are required, that should be of compact size, high-sensitivity, low-power, and low-noise figure. Carbon nanotubes [130], complementary metal-oxide-semiconductor (CMOS), [131], silicon-germanium (BiCMOS) [132], and graphene-based [133] transceivers are potential candidates.

Connecting the nano-devices in BCNs is thus crucial, and can be achieved using various wireless communication technologies. For OBNs, there are multiple options to connect wearable devices, such as RF, optical, and THz paradigms. However, in IBNs, the possibilities are limited to molecular and THz communications, due to the aforementioned limitations of in-vivo RF communications [134]. Hence, the

TABLE I: Literature on promising wireless technologies for IBNs.

Issues addressed	**Electromagnetic**			**Molecular**	**Acoustic**
	RF	**THz**	**Optical**		
Channel modeling	[40]–[56]	[57]–[66]	[67]–[71]	[33], [72]–[78]	[34], [35] [79], [80]
Noise modeling	[46], [56], [81]	[58], [82]–[87]	[67]	[88]–[91]	[35]
Performance analysis	[41], [46], [56] [92], [93]	[59], [86] [83], [94]	[67]–[71]	[72], [95] [91], [96]–[98]	[35], [79]
Experimental demonstration	[81], [93], [99]	[100], [94]	-	[101], [102]	[80]
Modulation and coding schemes	[56]	[28], [94], [103]–[105]	[68], [69], [106]	[107]–[112]	[79], [80] [113]
Networking	[114]	[115]–[117]	[70]	[74], [78] [118]	[79], [80] [119]
Security	[120], [121]			[120]–[123]	[120], [121]
Testbeds	[92], [124]–[126]	[62], [63], [100]	-	[127], [128] [77]	[79], [113]

research on THz BCNs is promising where novel transceiver designs, antennas, channel models, modulation and coding schemes, and networking topologies are still in progress. Since several research challenges still face THz BCNs, it is crucial to review these networks' various aspects and highlight promising research directions. Towards this end, this tutorial aims at outlining the physical and network layer considerations for implementing THz BCNs. This tutorial also highlights the importance of THz sensing and imaging in biomedical applications, especially for detecting zootonic diseases such as the Coronavirus disease (COVID-19).

A. Related Surveys

Several surveys address THz communications in general, providing insights on both the device and communication aspects [3]–[8], [22], [135]. The communication aspects mainly target channel modeling paradigms, signal processing techniques, novel routing protocols, and supporting experimentation. There are also a few dedicated review articles that discuss THz communications for nano-networks (NNs). Among these is the pioneering work of Akyildiz et al. [136], that discusses various possibilities of communication in NNs, and introduces the architecture for nano-networks, consisting of nano-nodes, nano-routers, and micro/nano-interfaces. Similar insights can be found in [137], with a better focus on molecular communications. The work in [138] further surveys the literature on big data analytics for future healthcare systems. Moreover, [135] discusses the medium access control (MAC) layer protocols for NNs and compares the performance of various MAC protocols in terms of transmission distance, collision probability, and energy consumption.

Several other contributions [139]–[143] target different aspects of NNs, converging at a common idea of two possible communication options, namely, molecular and THz communications. The former is more suitable for IBNs, whereas THz can be used for both IBNs and OBNs. Among these contributions, [142] is more relevant to our work, as it summarizes various requirements of IBNs, including functional (purpose of communication), technical (reliability, security, safety, etc.), and legal (e.g., implantability of the devices and duration of the body contact) aspects. Table II summarizes these relevant articles.

TABLE II: Comparison of relevant review articles.

Ref.	Year	Area of Focus
Akyildiz *et al* [3]	2010	Presents THz communications for NNs, channel modeling, and routing protocols
Jornet *et al.* [137]	2012	Introduces the internet of multimedia nano-things (IoMNT), a possible architecture for IoMT, and networking protocols
Rikhtegar *et al.* [144]	2013	Studies molecular and electromagnetic communications, nano-devices, and networking for NNs
Balasubramaniam *et al.* [139]	2013	Presents various applications of NNs and how to connect the NNs with the outside world
Akyildiz *et al.* [3], [4]	2014	Focuses on THz applications at the nano and macro levels and presents possible THz band transceivers and antennas
Miraz *et al.* [141]	2015	Overviews connecting the NNs with the internet of things (IoT) and its applications
Dressler *et al.* [142]	2015	Focuses on healthcare applications using in-body NNs and presents various networking architectures
Petrov *et al.* [145]	2016	Presents an overview of the THz band for future wireless communication networks
Rizwan *et al.* [138]	2018	Focuses on big data analytics, such as data gathering, processing, feature extraction, and predictive modeling for healthcare applications
Ghafoor *et al.* [135]	2019	Presents applications of the THz band and various MAC layer protocols for THz communications
Lemic *et al.* [146]	2019	Focuses on THz communications for NNs and its applications
Sarieddeen *et al.* [22]	2020	Presents an overview of THz communication, sensing, imaging, and localization along with their applications
This paper	2020	Focuses on the issues of THz devices, communications, and networking for THz-band body centric networks, highlighting various applications in the health industry

B. Contributions of this Paper

In the context of the surveys mentioned above, we can see that most of the contributions are outdated. i.e., dating back to 2016, except [22], [135], [138] and [146], which are more generic, focusing on the THz band and its usage for future wireless communication networks. Therefore, these recent works do not focus on the prospects of the THz band for body-centric networks. Hence, we believe that it is quite important to articulate a tutorial on THz communications for BCNs, which can help both academia and industry. Unlike the existing works, our tutorial focuses on the critical aspects of THz-based BCNs, including device technologies, channel and noise modeling, modulation and networking algorithms, and applications in the healthcare industry. Moreover, we also present the latest research highlighting that THz-band communications can help in pandemic response management by detecting the Coronavirus disease (COVID-19). We further present various future research challenges for THz-band BCNs and their applications.

C. Organization

The rest of this tutorial is organized as follows. In Section II, we present an overview of the THz signal sources and antennas, such as electronic, photonic, integrated hybrid devices, and graphene-based THz antennas. Section III presents the current research work on various communications technologies for BCNs, focusing more on THz band channel modeling for IBNs. Section IV then covers various modulation schemes for THz-based IBNs. Moreover, in Section V, we discuss numerous network topologies and routing protocols for BCNs. Section VI further highlights the THz band's importance for sensing and imaging applications, including detection of COVID-19. Then, in Section VII, we illustrate the latest consensus on the health effects of THz radiation. Finally, in Section VIII, we focus on future research challenges for THz-based BCNs, followed by Section IX, which concludes this tutorial.

II. THz Signal Sources, Antennas, and Detectors

The main contributions to THz technology are still at the device level rather than the system level. High-frequency electromagnetic radiation is perceived as waves that are treated via electronic devices (the mmWave realm) or as particles that are processed via photonic devices (the optical realm). Novel solutions are considering the use of both electronic and photonic materials for THz transceiver design.

On the electronic side, silicon-based systems [147], [148] that have been used for mmWave applications are being pushed for THz communication usage. Typical solutions include silicon complementary metal-oxide-semiconductor (CMOS) and silicon-germanium (SiGe) BiCMOS technologies [131], [132], [149], [150], which demonstrate incredible compactness and compatibility with existing fabrication processes. Furthermore, higher operating frequencies have been noted using heterojunction bipolar transistors (HBTs) [151], [152], III-V-based semiconductors [153], high electron mobility transistors (HEMTs) [154]–[156], and Schottky diodes [157]. In [150], SiGE-HBT devices are shown to operate at 720 GHz. Other experimental demonstrations with different frequencies and transmission powers are highlighted in [158]–[161].

The main design driver for photonic solutions, on the other hand, is data rate [162], where higher carrier frequencies are supported, but the degrees of integration and output power are both low. Frequencies beyond 300 GHz have been supported using optical downconversion systems [162], quantum cascade lasers [163], photoconductive antennas [164], and uni-traveling carrier photodiodes [165]. The use of resonant tunneling diodes (RTDs) is also shown to deliver oscillation frequencies up to 2 THz [166]–[169]. Moreover, hybrid photonic-electronic solutions are also emerging [170]. These developments have improved the generation, modulation, and radiation of THz waves [162], [170]–[172]. While photonic devices can be used for OBNs, their prospect use in IBNs is more challenging due to their relatively bulky structures.

The use of plasmonic materials for THz communications is also gaining popularity [129], [173]. In particular, graphene is considered the best choice for nano-antennas that support EM nano communications, high electron mobility, and reconfigurability [174]–[177]. Plasmonic solutions are capable of directly generating waves in the true THz range in much more compact (order of μm) and flexible designs, by supporting the propagation of surface plasmon–polariton (SPP) waves [178]. For instance, [179] proposes a THz transceiver made of graphene that can be utilized for nano communications. In fact, graphene can be used to develop direct THz signal sources, modulators (that manipulate amplitude, frequency, and phase), and on-chip THz antenna arrays [180]. Graphene-based designs are further favored for IBN applications for their low electronic noise temperature and their ability to generate short pulses that save energy [103].

III. Channel and Noise Modeling

As a pre-requisite for understanding THz technology's role in BCN applications, it is essential to investigate the propagation and noise models of THz transmissions inside the human body. This section summarizes the studies performed to characterize the in-body THz channel and noise models, taking into account several phenomena such as molecular absorption caused by human tissues, spreading resulting from the expansion of the wave, and reflection and scattering of signals. By taking these factors into account, we shape a comprehensive understanding of THz BCNs that defines the achievable propagation distances, assists in performance analysis, and predicts communications scenarios.

A. Channel Modeling

Being the pioneers to introduce the concept of THz transceivers for nano-communications [29], Akyildiz *et al.* introduced the channel model for THz propagation in the air [129], which was later adopted by the research community for different applications. In this work, we illustrate how IBNs can benefit from nano-scale components operating in the THz band, where transmissions are less vulnerable to propagation losses, especially scattering [181]. Since the propagation medium for IBNs is the human tissue, it is vital to understand this medium by acquiring its parameters before modeling the propagation at THz frequencies. Building on multiple studies on THz channel modeling over the air [129], [182], the works in [59], [60], [183] adopt a similar propagation loss model for modeling in-body THz channels.

The path loss in human skin consists of two components: absorption and spreading losses [59]. In [83], [183], [184], the IBN path loss is modeled using the modified Friis equation as

$$\mathrm{PL}(f,d)[dB] = \mathrm{PL}_{\mathrm{abs}}(f,d)[dB] + \mathrm{PL}_{\mathrm{spr}}(f,d)[dB], \quad (1)$$

where $\mathrm{PL}_{\mathrm{spr}}$ denotes the spread loss due to the expansion and the propagation of the wave in the medium, d is the total length of the path, f is the operating frequency, and $\mathrm{PL}_{\mathrm{abs}}$ represents the absorption loss. The spreading loss can be further expressed as

$$\mathrm{PL}_{\mathrm{spr}}(f,d)[dB] = 20\log_{10}\left(\frac{4\pi d n_r}{\lambda_0}\right),$$

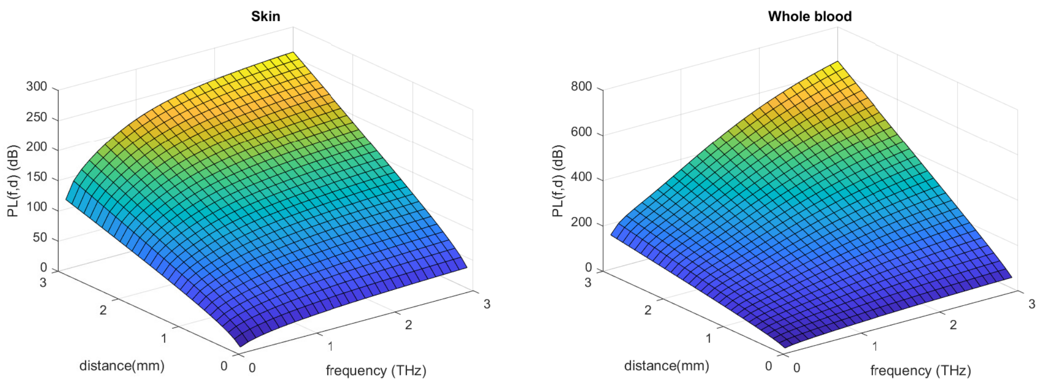
where n_r represents the real part of the refractive index of the medium and $\lambda_0 = c/f$ is the free-space wavelength. The absorption loss in (1) is expressed as

$$\mathrm{PL}_{\mathrm{abs}}(f,d)[dB] = 10\,(\mu_{\mathrm{abs}})\,d\log_{10}(e),$$

where the absorption coefficient μ_{abs} and the refractive index are obtained from measurements.

We can also derive these parameters from the complex dielectric parameters of the human skin, in particular, the complex permittivity, $\epsilon = \epsilon_r - j\epsilon_i$, and the complex refractive index, $n = n_r - jn_i$, where j denotes the complex number ($j^2 = -1$) and the subscripts r and i represent the real and imaginary parts, respectively. Note that the parameters μ_{abs}, ϵ, ϵ_r, and ϵ_i are frequency dependent. The following equations describe the relations between the electromagnetic and optical parameters

$$\mu_{\mathrm{abs}} = \frac{4\pi n_i}{\lambda_0},$$
$$\epsilon = n^2,$$



(a) Skin path loss

(b) Whole blood path loss

Fig. 3: Skin and whole blood path loss as function of distance and frequency.

$$\epsilon_r = n_r^2 - n_i^2,$$
$$\epsilon_i = 2n_r n_i.$$

Another way to compute the absorption coefficient is to model it from individual particles [58]. This procedure is complicated because there are various elements with different concentrations in the human body. A simpler alternative in [58], [61], [64] uses complex permittivity, which is computed using the double Debye relaxation model [185]. The technical report in [186] gives more insight into different models, describing the absorption coefficient and refractive index by performing several experiments.

Since the human body is mainly composed of water and sodium chloride (NaCl) solutions, [100] investigates the path loss model for these components. The analytical and simulation results are found to almost agree, where it is shown that THz communications are possible in water over a millimeter range. Using (1), [100] computes the total path loss for different human tissues. Intuitively, the increase in communication distance or frequency leads to an increase in path loss. Also, the path loss varies for different tissues for a given frequency and distance. For example, the path loss in the blood is higher compared to skin and fat. This is due to the water concentration difference, with the highest percentage of water being in the blood. The work in [61] further investigates the absorption coefficient and refractive index for human blood in the THz band, where experiments are conducted on different blood components: Full blood, plasma, blood cells, and blood clots, showing their different responses alongside pure water. Due to the heavy existence of water molecules, plasma and whole blood encounter prominent path losses. The simulation in Fig. 3 demonstrates that the path loss is higher in blood cells compared to skin tissues for a given distance and frequency. Similarly, [62], [63] study the use of THz spectroscopy on artificial human skin (Dermis) that mainly consists of blood vessels and hair cells, by characterizing the human tissue in terms of absorption coefficients and refractive indices as a function of THz frequencies.

A THz pulsed spectroscopy (TPS) method is proposed in [64] to study the THz refractive index and absorption coefficient of the human skin. The authors investigate the accuracy of the measurements compared to the known data, where agreements are noted with healthy human skin, except for some body parts; in-body THz propagation depends on the structure and thickness of each component of the skin. The analysis in [64] takes into consideration the built-in noise in experimental waves to solve the TPS inverse problem. It also excludes the examination of lower and higher frequencies due to the fluctuation of error at these frequency ranges (because of different scattering on the surface and in the tissue volume). Moreover, [66] examines THz propagation inside the human body by considering a multi-layered human tissue model, where the components of the cascaded multi-layer intrabody model are, from deep to superficial, blood, fat, skin, and air. To better characterize the communication link between the nanodevices inside and outside the body at THz band, [66] proves the need to account for cross-layer reflection.

A recent IBN channel model that also considers the scattering effect of the THz waves alongside the absorption and spreading loss is proposed in [58], where

$$\mathrm{PL}(d,f)[dB] = \mathrm{PL}_{\mathrm{abs}}[dB] + \mathrm{PL}_{\mathrm{spr}}[dB] + \mathrm{PL}_{\mathrm{sca}}[dB]. \quad (2)$$

The scattering loss is caused by small and large particles, and the corresponding loss factor is expressed as

$$\mathrm{PL}_{\mathrm{sca}}[dB] = 10\left(\mu_{\mathrm{sca}}^{\mathrm{small}} + \mu_{\mathrm{sca}}^{\mathrm{large}}\right) d \log_{10}(e),$$

where $\mu_{\mathrm{sca}}^{\mathrm{small}}$ and $\mu_{\mathrm{sca}}^{\mathrm{large}}$ are the absorption coefficients due to small and large particles, respectively. The scattering factor can be ignored in IBNs since it is negligible compared to the absorption coefficient.

Despite that the previous path loss models are the most popularly used models for IBNs, several researchers have proposed simpler models, and we hereby distinguish two main alternatives. The first is an analytical path loss model which is expressed in [57] as

$$\mathrm{PL}(d,f)[dB] = 10\log_{10}(K) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (3)$$

where K and n are the path loss at reference distance d and path loss exponent, respectively, and X_σ represents the shadowing effect caused by particles in the path, which is modeled

TABLE III: THz-band IBN channel models.

Equation	Type	Focus	Ref.
(1)	Analytical	Accounts for molecular absorption and spreading.	[59], [183]
(2)	Analytical	Accounts for molecular absorption, spreading and scattering.	[58]
(3)	Empirical	Log distance path loss model.	[57]
(4)	Empirical	A correlation-based model which takes into account distance, frequency alongside number of ducts.	[60]

as a random variable following the log-normal distribution. The second alternative model is empirical, based on actual measurements for IBNs in the THz band [60]. An artificial layer that mimics the human tissue is used to perform multiple experiments, resulting in the path loss model

$$\mathrm{PL}(d,f)[dB] = A(N) + B(N) r^{0.65} + C(N) f^{4.07}, \qquad (4)$$

where $A(N)$, $B(N)$, and $C(N)$ are the offset coefficient, distance coefficient, and frequency coefficient, respectively. These coefficients are a function of the number of sweat ducts N, which is explained by the fact that they are mainly composed of water, causing higher absorption at THz frequencies; a regression-based technique is used to obtain these coefficients. We summarize the channel models used for THz-band IBNs in Table III.

B. Noise Modeling

Besides the path loss, THz systems encounter a noise factor that originates from different sources. The main noise component comes from molecular noise. According to [84], [86], the molecular noise is composed of two parts: Body radiation noise and molecular absorption noise. During wave propagation inside the human body, a fraction of the energy is absorbed, causing an increase in the temperature. This phenomenon is considered as noise, namely body radiation noise or atmospheric noise, where the medium becomes an effective black body radiator. This background noise can be represented using the sky noise model and is a function of the transmission medium's temperature. The corresponding noise temperature is expressed as

$$T_{\mathrm{mol}} = T_0 \left(1 - e^{-\mu_{\mathrm{abs}} d}\right),$$

where μ_{abs} is the absorption coefficient and T_0 is the reference temperature. This noise model is more suitable for communications in the atmosphere. As highlighted in [84], the use of temperature as a parameter is not reliable for evaluating noise inside the human tissues. Therefore, in line with the work in [82], the work in [84] uses the following expression of background noise (which is given using Plank's law):

$$B(T_0, f) = \frac{2h\pi (nf)^3}{c^2} \left(e^{\frac{hf}{k_B T_0}} - 1\right)^{-1},$$

where $B(T_0, f)$ is the Plank's function, n is the corresponding refractive index of the THz wave in the human tissue, and h and k_B are the Plank's and Boltzmann's constants, respectively. Consequently, the power spectral density of the background noise inside the human body is expressed as

$$N_b(f) = B(T_0, f) \frac{c^2}{4\pi (n_0 f_0)^2}.$$

Alongside the propagation waves' attenuation, the molecules in the medium introduce molecular absorption noise due to internal vibration caused by the incident THz waves. As a result, this would transform into retransmission of EM radiation at the same frequency in random directions [187]. This phenomenon is considered to result in an additional noise factor for intra-body communications. In [28], [59], this noise is represented using the same model in [129]. The corresponding power spectral density (PSD) can be defined as

$$N_m(f,d) = k_B T_0 \left(1 - e^{\frac{4\pi}{c} f\, d\, \kappa}\right),$$

where κ is the extinction coefficient. Based on [82], the work in [84] expresses the PSD as

$$N_m(f,d) = S_{Tx}(f) \left(\frac{c}{4\pi n f d}\right)^2 \left(1 - e^{-\mu_{\mathrm{abs}} d}\right),$$

where $S_{Tx}(f)$ is the PSD of the transmitted signal. Finally, the total noise PSD is given by

$$N(f,d) = N_m(f,d) + N_b(f).$$

There are other noise models for IBNs in the literature. For instance, in [83], the noise temperature for the THz band is modeled as the sum of three different noises: T_{sys}, originating from the electronic system, T_{other}, emerging from other surrounding devices, and a third one coming from molecular absorption T_{mol}, and is expressed as

$$T_{\mathrm{mol}} = T_0 \left(1 - e^{\frac{4\pi}{c} f d \kappa}\right).$$

The total noise can be expressed as a sum of the three components:

$$T_{\mathrm{noise}} = T_{\mathrm{mol}} + T_{\mathrm{sys}} + T_{\mathrm{other}}.$$

Note that in graphene-based systems, the electronic noise temperature is quite low and can be neglected, leaving only the molecular absorption noise temperature as a main contributor to the overall noise [188].

Another approach for IBN noise modeling is presented in [87]; it considers a stochastic noise consisting of three parts: the Johnson–Nyquist noise, the black-body noise, and the Doppler-shift-induced noise. The overall noise PSD is derived after figuring out each component's probability distribution, verified via 2-D particle simulations.

IV. Modulation Schemes

Even though THz-band communications offer an extra piece of spectrum, the design of adequate THz modulation schemes remains critical for efficient utilization of this new spectrum, especially that we encounter multiple unsolved constraints in transceivers' conception. Generally, at high-frequency communications, carrier-modulated signals use low-complexity modulation schemes to mitigate the technical restrictions in the design of THz modulators. According to [6], THz modulators do not follow the capabilities of THz transmission. Despite the considerable progress in THz modulators, their speed does not exceed a few gigabits-per-second (Gbps), which hinders the use of complex modulations for THz communication systems. Such constraints have motivated researchers to think about new optimized modulation techniques for THz applications.

While the achievable data rate may not be of primary concern in IBNs, the communication paradigms should be energy efficient. Nanosensors cannot communicate using classical communication techniques of long duration signals due to the size and energy constraints, especially when implanted inside the human body. Given the availability of large bandwidths, short pulses are considered for intra-body THz communications. The work in [103] introduces the transmission of pulses in an asymmetric On-Off Keying modulation Spread in Time (TS-OOK). The TS-OOK technique uses a hundred femtosecond-long pulse for binary "1", and silence for logical "0". To avoid confusion of silence from no transmission with the transmission of logical "0", the authors propose taking advantage of initialization preambles and constant-length packets. Therefore, the transmitted signal can be expressed as

$$s(t) = \sum_{k=1}^{K} A_k p(t - kT_s),$$

where K is the number of transmitted bits, $A_1, A_2, \ldots A_K$ are the amplitudes of the transmitted symbols where each kth transmitted symbol A_k can take the values 0 and 1, $p(t)$ denotes the Gaussian pulse with duration T_p, and T_s is the time between two consecutive pulses where $T_p << T_s$.

Due to the correlation between communication capabilities and the distribution of the transmitted power in the frequency domain, three types of in-body communications paradigms can be distinguished:

- Flat communication: It assumes that the total transmitted power is uniformly distributed over the entire operative bandwidth.
- Pulse-based communication: It considers pulses that can be modeled as Gaussian waves, especially with the promising use of graphene for THz communications.
- Optimal communication: Given that the channel is frequency selective, the total bandwidth is divided into small, locally flat sub-bands. The power is then allocated as a function of frequency-selective properties of the medium to maximize the overall channel capacity.

These communication types are analyzed in [28], [94] by highlighting the channel capacity and communication ranges of each. It is noted that optimal communication outperforms the flat and pulsed alternatives in both channel capacity and transmission ranges, as it can adapt its power distribution to the attenuation levels experienced at multiple frequencies. The results also show that the transmission range cannot exceed 9 mm, which inspires designing effective networking techniques like multi-hop communications alongside new MAC and routing protocols. However, pulse-based modulations can be argued to be more beneficial in THz IBNs. In addition to their simplicity, pulse-based modulations can mitigate the noise effect. For instance, in the case of graphene-based transceivers, the electronic noise is negligible, and the source of noise is molecular absorption only, which emerges from the re-emissions of the absorbed radiation. Such noise only affects the pulses and not the silences. In [116], TS-OOK is utilized to propose a realistic network architecture and communication scheme for in-vivo THz communications assuming a human hand scenario.

Single-pulse variable duration (SPVD) modulation [104] is another novel modulation scheme that can be tailored for THz-band IBNs. It is a combination of TS–OOK and pulse position modulation (PPM), which aims at ensuring higher energy efficiency rather than achieving high data rates. This novel scheme is based on varying the single-pulse duration, which reduces the energy consumption of nanosensors. In particular, a fixed number of bits are transmitted using a waveform that is composed of a certain number of silences and a very short pulse; the latter is in the order of 100 femtoseconds. The proposed design of SPVD waveforms consists of a variable number of equal time slots with a variable number of silences and one slot for the pulse. Consider $M = 2^k$ to be the modulation order, where k is the number of bits per symbol. Then, each vector of different bitstreams corresponds to a unique transmitted waveform which is expressed as

$$s_n(t) = p(t - nT_{\text{slot}}), \qquad t \leq (n+1)T_{\text{slot}},$$

where $p(t)$ is a 100-femtosecond-long pulse, $n \in \{0, 1, \ldots, M-1\}$ denotes the number of silences in the waveform, and T_{slot} is the time slot duration. SPVD proves to be more efficient than classical TS-OOK, especially that it manages to send more information by using fewer pulses and more silences. Taking into account that the main source of noise is molecular absorption caused by re-radiated waves, this approach reduces the effect of noise and thus increases the overall signal-to-noise ratio. Therefore, compared to TS-OOK, SPVD sends the same information using less energy, but at the expense of longer time durations. As previously mentioned, such a delay may not be of primary concern for BCNs operating at THz frequencies.

V. Networking Topologies

Besides channel modeling and modulation techniques, effective networking in BCNs is crucial because nanoscale devices suffer from many limitations. In the following, we summarize some of these challenges:

- The nanoscale size of BCN devices limits their processing and memory capabilities. One way to overcome the energy constraint is to use energy-harvesting techniques at a nanoscale level, by converting fluidic, vibrational, and EM energies into electrical energy [189]. Moreover, BCNs need to consider the balance between energy consumption and harvesting. Also, the nanoscale components limit the devices' battery size that further limits the amount of stored energy.
- Another major hurdle for nanoscale networking is the use of flooding mechanisms in which each node broadcasts packets blindly, thus leading to severe collisions and redundancy.

- As discussed in the previous sections, the THz band suffers from molecular absorption, spreading, and scattering losses. The substantial path loss limits the overall efficiency of the network.
- The limited memory of nanoscale THz devices is also a challenge for multi-hop transmission, especially in THz networks where the transmitter and receiver use directional communication [190].

To overcome these challenges, BCNs require appropriate network layer protocols that can enable an efficient path for communicating among various nanodevices under various network constraints [191]. The networking protocols mainly aim to maximize the network lifetime, improve coverage and reliability, reduce latency, and minimize energy consumption. In the following, we review various networking protocols for BCNs that can be classified into single- and multi-path routing protocols.

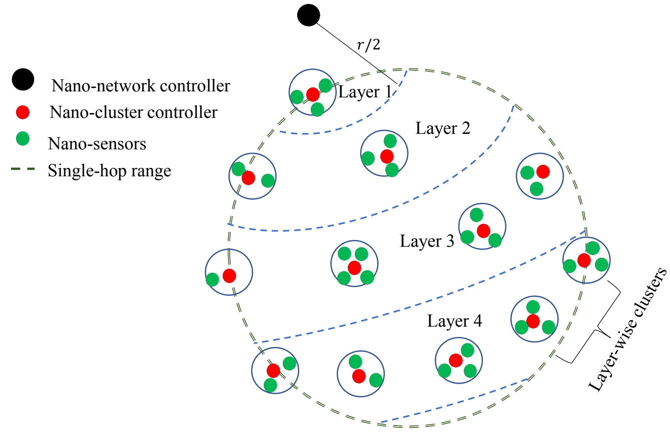


Fig. 4: ESR protocol: The NNC is placed at the center of all layers, whereas the link between the NCC and NS is single-hop.

A. Single-Path Routing (SPR)

The routing protocols which consist of a single path between the transmitter and the receiver consume less energy than multi-path routing protocols. However, SPR can lead to a low packet delivery rate and high latency. Optimal SPR protocols should consume less power, minimize the delay, and improve the packet delivery rate. In the following, we discuss various protentional SPR protocols for BCNs.

1) Energy-saving Routing (ESR): As nanodevices are implanted on the human body in BCNs, a hierarchical architecture is required to maintain an efficient wireless communication link. Accordingly, [192] proposes an energy-saving routing (ESR) protocol for THz-operating BCNs, in which the main components of the BCNs consist of various nanodevices, including nano-sensors (NSs), nano-cluster controllers (NCCs), and a nano-network controller (NNC). In ESR, the network is divided into multiple layers based on the NS's distance from the NNC and their single-hop transmission range (see Fig. 4). Once the layers are defined, the NSs with leftover residual energy are selected as NCCs. Then, the NCCs broadcast an advertisement, and each NS picks its NCC based on the received signal strength indicator (RSSI) (joining the NCC with the highest RSSI value). The information from the NS to the NNC is transmitted through the NCC by using a time division multiple access protocol. This multi-layered clustering and time division approach reduces data collision and the network's overall energy consumption. However, one major issue with the ESR protocol is that it allows only one- or two-hop transmission, thus requiring a dense deployment of NSs and NCCs.

2) Multi-hop Decision Algorithm (MHDA): Another potential routing protocol for THz-based BCNs is the multi-hop decision algorithm (MHDA) that ensures infinite network lifetime while achieving a sufficient throughput [115]. Similar to ESR, the framework of MHDA is hierarchical, consisting of NSs and NCCs. In general, the NCCs have more resources than the NSs, and therefore act as cluster heads. The MHDA estimates the probability of the amount of average energy consumed in single- and multi-hop transmissions. It suggests that when the power of each NS is optimized, the multi-hop transmission can result in lower energy consumption. The expression for the probability of energy saved for any arbitrary SN i in a multi-hop transmission is given as

$$P_e(i) = \Pr\{E_{bm}(i) \leq E_{bd}(i)\},$$

where $E_{bm}(i)$ and $E_{bd}(i)$ are the average energies required for a single bit in a multi- and single-hop transmissions, respectively. Moreover, $P_e(i)$ depends on the density of NSs and the distance (d_i) between the ith NS and the NNC. Consider that the distance between ith NS and its random neighbor is d_{in}, and the distance between the ith NS and an NNC is d_{ic}, which are both random variables and follow a Poisson point process (see Fig. 5). Then, $P_e(i)$ can be expressed as

$$P_e(i) = 1 - e^{\rho A(d_{ic})}$$

where ρ is the NS density and $A(d_c)$ is the spanning area to

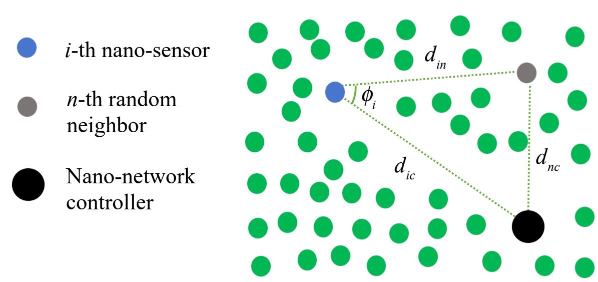


Fig. 5: Illustration of single- and multi-hop transmission in MHDA. The probability of having less energy consumption through multi-hop path (d_{in}-d_{nc}) is higher than using the direct path (d_{ic}).

find the neighboring NS. Moreover, in MHDA, the NS adjusts its transmission power for selecting the next hop based on its residual energy and multi-hop transmission.

3) Energy-efficient Routing (EER): In the energy-efficient routing (EER) protocol, the calculations are mainly performed by the NNC to reduce the computation burden on NSs [193]. One significant difference between MHDA and EER is that in the latter, the NS stores the distance between itself and the NNC, where the single-hop range of the NS is kept fixed, reducing the computational complexity. In the EER protocol, different regions are defined based on the distance between NS and NNC and the single-hop range of the NS, as shown in Fig 6. For instance, the regions A1 and A2 are within the single-hop range of the source NS, whereas region A3 is defined by the radial distance between the source NS and NNC. The EER protocol consists of the following steps:

- The NNCs broadcast hello signals to which the NSs respond and share their location and ID.
- When the ith NS wants to send data, it checks whether the NNC is in its single-hop range or not. If the NNC is in single-hop range, the ith NS can directly send the data to the NNC; however, if the NNC is not in a single-hop range, the ith NS broadcasts query signals to neighbor NSs.
- The NSs in region A2 becomes the candidate set of nodes, where each candidate calculates its link cost and sends it to the source NS. Once the ith source NS receives all the neighbors' responses, it selects the forwarding node based on the smallest link cost. This process continues until the NNC receives the data.

One major advantage of the EER protocol is that it limits the number of forwarding candidates by taking into account the direction towards the NNC. Both the energy consumption and computation complexity of EER is less than MHDA.

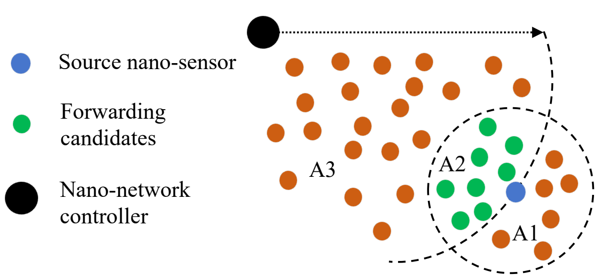


Fig. 6: Illustration of path selection in EER protocol. Candidate forwarding nodes are defined based on single-hop distance from the source and direction towards the nano-network controller.

4) Time-to-live-based Routing (TTLR): Unlike the data tier network in THz-based BCNs that consists of densely populated NSs, the backhaul tier is formed by sparse NNCs. Therefore, the dynamic channel in the THz-band leads to higher vulnerability to the backhaul tier. To compensate for this issue, [194] proposes a low complexity, time-to-live-based routing (TTLR) scheme for NNCs that adapts itself to the dynamic channel state. In the TTLR protocol, NNCs collect data from NSs and forward it to the IoT gateway, where the aim is to select a few NNCs among all in the presence of a dynamic channel. First, the IoT gateway disseminates a beacon signal for polling to extract the data. The packet in the polling signal sets the time-to-live (TTL) for beacons to a maximum value. The forwarding path is then decided based on the total number of neighboring NNCs for each NNC and the number of NNCs accumulated during the transmission. To further elaborate, consider five NNCs as shown in Fig. 7, here "NNC 5" selects "NNC 2" as a forwarding node instead of "NNC 4" because the cumulative number of neighbors for "NNC 2" is less than "NNC 3". One major problem of the TTLR protocol is that it does not take into account the energy of NSs, which is a critical factor for nano-scale devices in BCN.

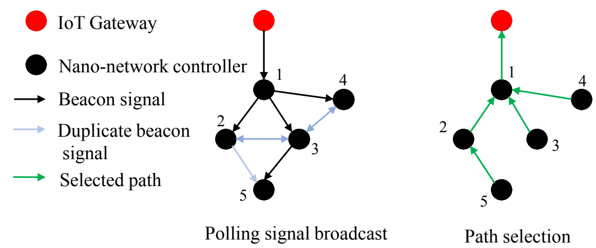


Fig. 7: Illustration of TTLR protocol; on the left side, we have a polling mechanism while the right figure shows the selected path.

5) Probability-based Routing (PBR): A low-energy consumption probability-based routing (PBR) protocol for BCNs is proposed in [195]. The PBR protocol assumes that the NSs can only communicate with the NCC due to their limited capabilities, thus forming a hierarchical architecture. The path selection in PBR depends on the probability of NCC existence, which further depends on the density of NCCs. The PBR protocol consists of four steps: Topology detection, probability distribution, decision, and data forwarding. An external entity mainly maintains the topology detection, whereas the probability distribution is calculated based on density and area of the clusters and cells. The routing path is then selected based on the probability distribution of the cells rather than the shortest route. As PBR's routing metric is based on the probability of having NCCs in a specific cell, it has better end-to-end reliability than the shortest path.

B. Multi-Path Routing (MPR)

Unlike SPR, multi-path routing is based on a flooding mechanism that allows all the NSs to forward data, leading to a higher number of transmissions and collisions and increasing the total energy consumption. There are mainly two techniques used in MPR: Area-based limiting-flooding (ALF) and infrastructure-based dynamic-flooding (IDF). Only limited NSs are selected as candidate nodes in ALF protocols to forward the packets from the source to the destination. On the contrary, based on the received packet quality, the NSs are classified as "infrastructure" or "users" in IDF protocol, where the NSs are defined as infrastructure forward the data. In the following, we discuss various potential MPR protocols for BCNs.

1) RADAR Routing: A simple flooding-based routing protocol (RADAR) for THz nano-networks is introduced in [196], in which the NSs are distributed equally in a circular region with an NNC at the center. The NSs, which are in the transmission beam of the NNC, are in on-state while the rest of the NSs are in off-state, reducing the total energy consumption. Also, the packets are only transmitted in a sector-based approach leading to controlled flooding. Nevertheless, in RADAR, a routed packet may be lost as the receiving NS may be in an off-state. In RADAR, the probability of the receiving NSs to be in on-state is correlated with the beamwidth rotation of the transmission signal. For example, a flexible beamwidth rotation can lead to a large number of on-state NSs, increasing the overall energy consumption and coverage with a higher number of packet collisions. On the contrary, limited beamwidth rotation leads to a higher packet delivery ratio and reduced energy consumption. Therefore, it is crucial to optimize the beamwidth for the RADAR routing protocol. Due to the RADAR protocol's simplicity, it can be a potential candidate for routing in BCNs.

2) CORONA Routing: Another popular energy-efficient network layer protocol for THz-based wireless nano-networks is coordinated-and-routing (CORONA) [197]. In CORONA, the NSs are uniformly deployed in a rectangular region where four beacon NSs are positioned at the corner of the area (see Fig. 8). Each beacon node transmits a signal based on which all the NSs compute their hop counts to each beacon and define their coordinates. Once the NS coordinates are defined, flooding is performed by the NSs which are located between the source NS and the destination NS. For example, if "NS A" (near to beacon A) wants to transmit a packet to "NS B" (near to beacon B), then the NSs in the blue region can only re-transmit the packets until it arrives at "NS B". The NS coordinates are defined based on the hop-counts from the beacons where flooding is limited to a specific region. CORONA has proved to be an energy-efficient point-to-point routing protocol for nano-networks, which makes it well-suited for BCNs.

3) Stateless Linear Routing (SLR): The stateless linear routing (SLR) protocol is an extension of CORONA for three-dimensional wireless nano-networks in which the information is routed through a linear path [198]. In SLR, the NSs are placed in a cubic setup with eight beacons at each corner of the cube. Similar to the CORONA protocol, in SLR, the beacons transmit a signal based on which the NSs calculate their multi-hop distances to each beacon. In the path selection phase, the SLR protocol selects a forwarding NS if it is positioned on a straight line between the source and the destination. To elaborate, consider that the locations of the source and destination are x_s, y_s, z_s and x_d, y_d, z_d, respectively. Assuming that the NS (at point $P = \{x, y, z\}$) is on the straight line from source to destination, then

$$\frac{x - x_s}{x_d - x_s} = \frac{y - y_s}{y_d - y_s} = \frac{z - z_s}{z_d - z_s}. \tag{5}$$

Since the location of SNs are based on hop counts which are integer values, (5) can be re-written as

$$\triangle_x = (x - x_s)(y_d - y_s) - (y - y_s)(x_d - x_s) = 0,$$
$$\triangle_y = (x - x_s)(z_d - z_s) - (z - z_s)(x_d - x_s) = 0.$$

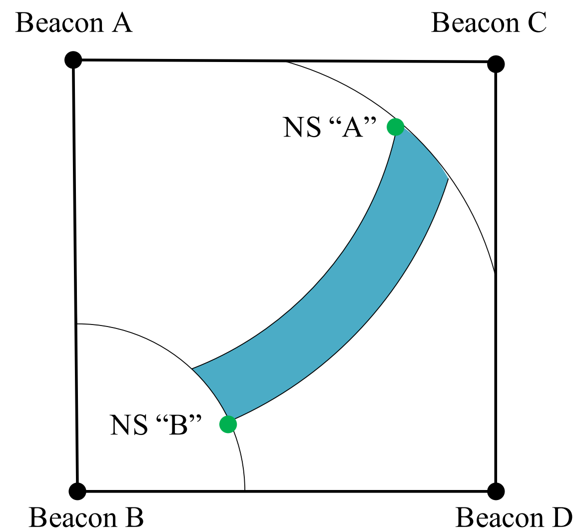


Fig. 8: Illustration of CORONA protocol by using beacons "A" and "B" for path selection. The blue area represents the possible location of forwarding nodes adopting limited flooding.

In case the NS at P is not on the straight line between the source and destination, then compensation for deviation is added to the above expressions. In general, a set of distances to three-beacon nodes can identify a specific zone, which is also referred to as a viewpoint that can be optimized to select the best viewport for a specific NS [199]. One major drawback of the SLR protocol is that each NS needs to store all eight beacons' information, which is quite large for resource-limited NSs.

4) Light-weight Self-tuning Routing (LSR): Light-weight self-tuning routing (LSR) is also a scalable and straightforward flooding-based routing protocol for wireless nano-networks [200]. The LSR protocol considers a source NS placed at the center of a square region that broadcasts the sensed data. At the packet level, there can be three possible events for an incoming packet: "PARITY_CHECK_ERROR", where the receiver collects the packet but fails the parity check, "DUPLICATION_CHECK_ERROR", where the packet is well-received but discarded because it was already received before, and "SUCCESS", where the packet is correctly collected for the first time. The sequence of these packet events is processed using the Misra-Gries algorithm [201], where the forwarding node's status is evaluated by determining the most common occurrence in the sequence, resulting in the classification of the nodes as "retransmitters' or "auditors" (see Fig. 9). After categorization, only retransmitters blindly forward packets, while the auditors listen but do not take part in the transmission. This classification leads to the selection of straight paths from the central source NS to the external entity, reducing the latency and energy consumption. However, the LSR protocol follows a flooding-based approach, which leads to an increase in the network overhead.

TABLE IV: Comparison of potential routing protocols for BCN.

Protocol	Type	Location awareness	Architecture	Complexity	Scalability	Energy-efficient	Ref.
ESR	Single-path	No	Hierarchical	Medium	Good	Yes	[192]
MHDA	Single-path	Distance to NCC	Hierarchical	High	Good	Yes	[115]
EER	Single-path	Distance to NCC	Hierarchical	High	Good	Yes	[193]
TTLR	Single-path	No	Hierarchical	Medium	Good	No	[194]
PBR	Single-path	No	Hierarchical	Medium	Good	Yes	[195]
RADAR	Multi-path	No	Flat	Low	Limited	No	[196]
CORONA	Multi-path	Number of hops to beacons	Flat	Low	Limited	No	[197]
SLR	Multi-path	Number of hops to beacons	Flat	Medium	Limited	No	[198]
LSR	Multi-path	No	Flat	Low	Good	No	[200]
DR	Multi-path	Hop counts to a central entity	Flat	Low	Good	No	[202]

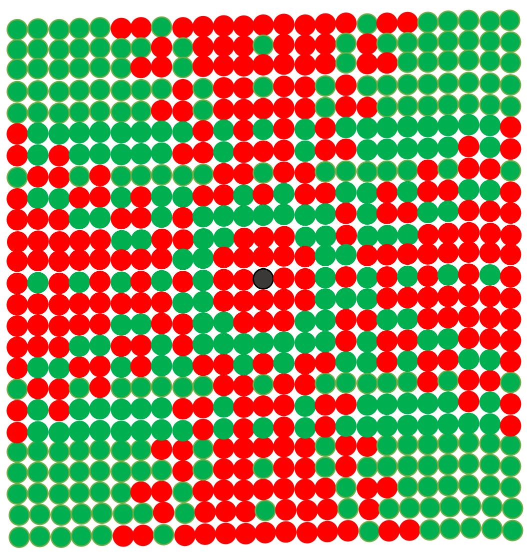


Fig. 9: Illustration of LSR protocol with a source NS, retransmitters, and passive auditors. The central NS performs sensing and transmits data to an external entity using retransmitters.

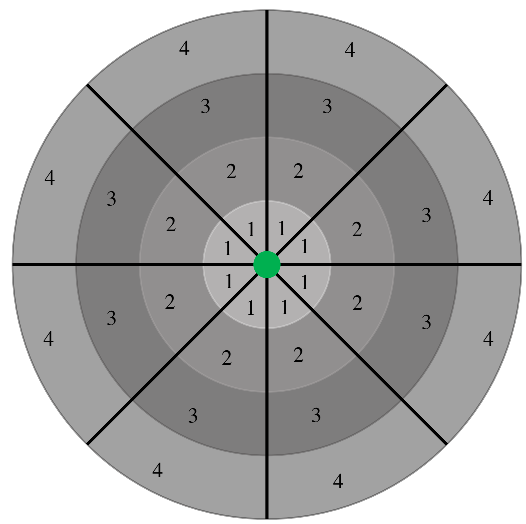


Fig. 10: Data in DR protocol is routed by using the rings of various radii and sectors.

5) Deployable Routing (DR): Another well-known MPR for software-defined metamaterial-based wireless nanonetworks is deployable routing (DR) [202]. In the DR system, NSs are spread over a circular area with a beacon at the center that periodically transmits set-up signals, based on which all other NSs define their hop counts (see Fig. 10). As in LSR, each NS computes its packet reception quality and hop count from the beacon, and then decides whether it can become a "user" or an "infrastructure". In DR routing, an NS can forward the data in two modes: (a) standard power having a large radius and (b) low-power with a small radius. After the deployment phase, the source NS "S" sends packets to the receiving NS "R" where the NS whose radius is between the source and the destination radially forwards the packets. When the radius of a forwarding node is equal to "S" or "R", it radially re-transmit the packets.

Comparison: This section covers various potential single- and multi-path network layer protocols for THz BCNs. The single-path routing protocols are energy-efficient at the cost of low reliability since they depend on a single path between the source and the destination. Furthermore, the SPR protocols follow a hierarchical architecture with NSs, NCCs, and a NNC, whereas the MPRs are based on the concept of flooding and therefore are flat in nature. Besides, some routing protocols can be more complex compared to others based on position awareness or the distance measurement to the NCCs. For instance, RADAR routing does not require any position information of the NCC, and therefore, it has low complexity, while in MHDA the NSs need to estimate the distance to the NCC, which makes it more complex. We summarize all of the above routing protocols in Table IV, where we categorize them based on their type, architecture, and performance.

VI. THz Sensing and Imaging: A COVID-19 Use Case

So far, we have discussed several aspects of THz BCNs, such as signal sources, channel/noise modeling, modulation schemes, and networking aspects. Nevertheless, sensing and imaging are among the popular uses of THz-communications that enable various invaluable biomedical applications. This section highlights the importance of sensing and imaging in the healthcare sector and further relates it to the current COVID-19 pandemic.

THz-band frequencies are currently used for various sensing and imaging applications without damaging the living tissues and bio-molecules because of their non-ionizing feature. Furthermore, research shows that many bio-molecules uniquely vibrate at THz frequencies, which makes this band an invaluable piece for the detection of various diseases. In general, meta-materials are used for THz-based bio-sensing; for example, [203] uses a nano-gap meta-material to detect the PRD1 and MS2 types of viruses. Moreover, THz-time domain spectroscopy (TTDS) is utilized in [204] for the detection of three Avian Influenza viruses (H1N1, H5N2, and H9N2). Their proposed THz nanoreflecter not only detects various types of viruses but can also be used to diagnose cancers. Generally, TTDS can operate in three modes: Transmission, reception, and reflection. The reflection-based techniques are more suited for bodies with water content, where the amount of reflected and scattered light from the material is used to sense the object [205]. The THz-band is thus a prolific frequency-range for the use of spectroscopy as its vibration stimulates bio-molecules. In this context, THz-band technologies have attracted researchers to develop devices that can detect viruses, antibodies, and proteins.

Given the current COVID-19 situation, it is very timely to discuss THz-band's prospect roles in fighting this pandemic. COVID-19 is notoriously impacting humans and the overall worldwide economy. In the presence of such a zoonotic disease, it is crucial to curb the virus's spread. Various tools are introduced to slow down the spread, such as social distancing, contact tracing, and early detection. Towards this end, a fast and easy way of detecting COVID-19 is a vital and challenging task. For instance, recently, a child died in Saudi Arabia due to the break of a Coronavirus swab in his nasal cavity [206]. At the moment, the detection of COVID-19 is primarily done via polymerase chain reaction (PCR) tests. However, researchers are looking for advantageous alternative solutions. Besides the detection of COVID-19, there is also a focus on carrying out the antibody tests that can help determine a previously infected person, resulting in a better understanding of the virus spread. Researchers are looking for out-of-the-box approaches, and THz-based spectroscopy is one of the potential solutions for detecting COVID-19.

The THz frequencies can penetrate various materials, which can enable multiple COVID-19-related imaging-based applications. A research team at Northern Hill University suggested that THz-imaging can have a significant positive impact in low-income countries where existing thermal imaging systems may fail to detect the asymptomatic carriers at necessary places, including airports and rail stations [207]. Unlike X-rays, THz-imaging offers broader screening in populated places without obvious harmful effects on human health. THz-imaging can be used to scan the upper respiratory part of the subjects to determine the difference between an infected and healthy person based on the water content in the cells, indicating the edema. One other use of THz-imaging in COVID-19 detection is ex-vivo testing. For instance, researchers at the University of Negev developed a breath test that offers quick testing without disturbing the patients [208]. A patient breath sample is collected on a chip and analyzed, where THz resonance detects the virus particles. Although this solution is still in the clinical trial stage, it can have a broader impact on COVID-19 detection. In short, the detection of COVID-19 by using THz-imaging may become an essential application in the healthcare industry.

Besides using the THz band in imaging for detecting viruses, THz technology can also assist patients' remote operations during a pandemic. For example, THz-based wearable sensors or implants on the patient's body can collect health data at high rates and forward it to the healthcare support staff, where actions can be taken remotely to assist patients. This way, the crucial hospital staff will have a lower risk of contracting the virus and save the commute time.

VII. Effects of Terahertz Radiation on Health

The deployment of any new technology always raises a mixture of positive and negative feelings. Nowadays, the major focus is on 5G technology, and there is a strong belief among a considerable number of people that 5G negatively affects human health [209]. Such allegations got to a point where non-scientific communities are linking the electromagnetic fields generated by 5G base stations to COVID-19 [210]. These concerns triggered the work on analyzing the health risks of 5G technology. Recent papers cover the following aspects: Health effects from 5G exposure [211]–[214], health risks of 5G features [212], [215], 5G exposure metrics, regulations, and compliance assessment [214]–[217] and the mitigation of 5G risks [214], [217].

The work in [218] analyzes all the above aspects in a comprehensive and in-depth manner. Regarding the effects of electromagnetic waves, two classes of radiations can be distinguished:

- Ionizing radiation: These radiations have enough energy to ionize atoms of living cells (X-rays and gamma-rays are examples of this type), posing a high risk to health because exposed cells can die or become cancerous.
- Non-ionizing radiation: These radiations do not ionize living cells and thus can not result in cell death and cancer. Nevertheless, such radiation's energy can still be high enough for molecules to vibrate, raising other health concerns.

While the first class is well studied in the literature [219], the second class is further classified depending on the radiation effects as thermal and non-thermal. Authorities and organizations around the world seek to define the exposure limits to avoid the heating effect on the human body. However, when it comes to non-ionizing non-thermal radiation, there is no clear evidence of a correlation between 5G standardized radiations and the emergence of biological effects [220]–[223].

The prospect utilization of body-centric THz devices means that higher exposure of the human body to electromagnetic waves at much higher frequencies is expected, raising concerns about THz technology's safety. Therefore, it is necessary to understand THz radiation's effects on living objects and set the corresponding safety limits [224]. The THz spectrum is still within the range of non-ionizing radiations. In fact, THz radiation's low transmission energy is highly unlikely to break the chemical bonds of living cells. Similar to the above classification, we find two popular mechanisms in the literature of how THz waves interact with biological objects:

- Thermal effect: The strong absorption of mainly continuous THz waves by water leads to heating in the human body, and consequently, biological effects [225]–[227].
- Non-thermal effect: THz waves can generate resonance effects in DNA, which in some cases may change the molecular dynamics and damage the local hydrogen bonds between DNA strands, causing the modification of gene expression [228], [229].

Relevant papers in the literature that address the effects of THz radiation on biological cells treat the effect of conformation of bio-polymers (proteins and DNA) [225], [230]–[235] and discuss the organism-level responses [225], [233], [234]. Furthermore, the work in [236] investigates the effects of THz radiation on the cell level.

Several experiments are conducted to understand the effects of the exposure of blood, skin, and nerve cells to THz radiation. Different parameters are varied to explore multiple scenarios [236], including the modulation type (pulsed-based vs. continuous waves), the frequency range, the intensity of radiation, and the exposure time. Some of these demonstrations prove the effect of THz radiation on blood cells [237]–[241], skin cells [242]–[246], and nerve cells [247]–[249]. However, others studies did not report a negative impact on blood cells [238], [250], [251], skin cells [252], [253], and nerve cells [254]. [236] summarizes the data concerning the effects of THz radiation on cells; the conclusion is that THz radiation can indeed affect biological cells through modifications to the membranes, proliferation, and pore formation. Therefore, more in-depth studies are required to set clear rules and establish safe use limits for THz body-centric applications.

VIII. Future Research Directions

Recent advances in body-centric THz networks show the invaluable applications of this research area in the healthcare sector. However, its successful implementation is quite challenging due to many constraints, such as the tiny size of the sensors, limited energy, extreme channel conditions (human body), and complicated deployment. The research on body-centric THz networks is still in the early phase, with numerous open research challenges. Therefore, in this section, we point out some of these future research directions that require further investigation.

A. Development of Novel Signal Sources

One of the major hurdles in the development of THz body-centric networks (BCN) is the availability of efficient THz sources. The invention of new materials (in addition to the techniques discussed in Sec. II) that can support nanoscale communications can be a massive step towards the practical implementation of THz BCNs. For example, a recent study shows that it is possible to use Perovskite to design THz antennas for nanoscale networks [255]. Indeed, the current research trend in the field of biomaterials will soon result in the realization of THz-based nanoscale BCNs. Since such materials could result in new types of signal sources, novel signal processing techniques are required.

B. Novel Channel Models

As discussed in Sec. III, the channel model for THz in-body communications is mainly affected by absorption, spreading, and scattering. Nevertheless, the health conditions vary from person to person, due to different blood compositions, skin types, and fat concentrations that can result in distinct channel characteristics. Therefore, novel and robust channel models need to be investigated to capture these variations based on a person's health condition.

C. Hybrid Systems

Undoubtedly, both molecular and THz-band in-body communication paradigms can enable IBN links. However, research on molecular communication is more mature compared to the THz-based approach. Therefore, developing a hybrid molecular/THz solution can further open new opportunities. For instance, molecular communication can be used within the human body due to its noninvasive and bio-compatible nature, whereas a THz implanted transceiver can collect the data and transmit it to a gateway [256]. The THz transceiver should be able to convert the molecular signal into electrical signals and transmit it over the wireless channel to the gateway. Since there are some recent research works on optical transplants, it is also possible to use an optical transceiver to connect the in-body and on-body networks. The research on hybrid systems is still in its infancy and needs further studies.

D. Light-weight Modulation and Coding Schemes

As previously mentioned, the lifetime of nanodevices in IBNs is a critical system design parameter. Therefore, novel modulation and coding schemes need to be developed to account for different types of channel and noise effects. In particular, the challenge of achieving ultra-low power consumption, ultra-reliability, and low complexity needs to be addressed; the performance in terms of capacity, communication ranges, and bit error rate also needs to be studied. Generally, THz modulation and coding schemes are designed to maximize the channel capacity, typically in conjunction with the use of large antenna arrays to extend the communication distance [257]–[259]. However, in the case of IBNs, the priority is to reduce the overall power consumption [260]. In addition, based on the limited power budget, simple coding schemes can be employed to reduce coding and decoding times. This issue can be addressed by analyzing the error sources, such as the type of noise and the channel behavior, that can help examine the trade-off between decoding complexity and transmission power, leading to the design of power-efficient and low-weight channel coding schemes. In this context, researchers need to investigate low-power consumption and low-complexity modulation and coding schemes for IBNs.

E. Energy Harvesting

The devices used in THz BCNs are nanoscale with a limited amount of energy. Therefore, it is crucial to develop energy-efficient communication paradigms and energy harvesting mechanisms for THz BCNs to improve the network lifetime and reduce the outage probability. However, the deployment environment of BCNs is quite complicated compared to terrestrial networks. Therefore, conventional energy harvesting techniques that can collect ambient RF energy or solar power cannot be directly applied to THz BCNs due to technological limitations [261]. Hence, researchers need to look for novel energy harvesting techniques, such as piezoelectric nanogenerators and fluidic energy harvesters for THz BCNs. Based on the harvested energy, it is also crucial to optimize the duty cycle of nanodevices to minimize the network's overall energy consumption.

F. Localization

In many applications, it is crucial to get geo-tagged sensing data from nanodevices, which is quite hard when the devices are placed in a challenging environment, such as inside the human body. In such constrained environments, conventional outdoor or indoor localization systems fail; therefore, novel solutions are required. Also, unlike the case of terrestrial networks, the size of the devices used in BCNs is in the nanoscale, which requires very accurate localization algorithms. Also, the THz communications range is limited, resulting in a multi-hop setup where the probability of localization error propagation is high. Nevertheless, multi-hop network localization techniques such as multidimensional scaling [262] can be investigated to estimate the location of nanodevices in BCNs.

G. Big Data Analytics

Modern smart healthcare systems use a predictive, personalized, and preventive approach that cannot be guaranteed without big data analytics. Therefore, integrating big data analytics and machine learning for THz-based nanoscale BCNs can enable various new applications, such as early detection of disease and patient-centric treatment [138]. Once BCNs are implemented, they generate a massive amount of data that requires the researchers to investigate various big data analytics tools. Moreover, the crucial health-related data coming from BCNs needs real-time analysis to take timely actions.

H. Security

Terahertz BCNs are envisioned to revolutionize the healthcare sector. However, due to the broadcasting nature of data traffic, they are vulnerable to security breaches. Recent advancements in quantum computing further increase the risk of cyber-security in BCNs. Therefore, it is crucial to secure the patient's sensitive data in THz-based BCNs from passive and active cyber attacks. For instance, recently, the authors in [263] proposed a physical layer authentication mechanism for THz BCNs, where the path loss is used as a footprint for authentication. For evaluation purposes, they used an in-air THz system setup; however, implementing such physical layer protocols for the nano-networks in the human body is still an open research problem.

IX. Conclusions

In this paper, we study the prospects of using the THz band for in-body and on-body communications, as an alternative to molecular, acoustic, optical, and radio-frequency solutions. We examine the literature on THz signal sources, channel and noise modeling, modulation, networking, sensing and imaging, and health and safety concerns. First, we discuss numerous THz signal sources for body-centric networks (BCNs), including electronic, photonic, plasmonic, and hybrid solutions. We then present the literature on channel modeling for in-body THz communications, where the main impediments are absorption, spreading, and scattering. Moreover, we review various types of noise sources for THz in-body communications. We study modulation schemes for THz BCNs, where the main idea is to design energy-efficient and lightweight techniques to reduce the overall energy consumption of the nanoscale devices. We further explain various networking protocols, including single path and multipath routing, showing that single path routing is energy efficient but unreliable, whereas multipath routing is reliable but at the cost of more power consumption. Furthermore, we highlight THz sensing and imaging prospects in the healthcare industry, especially in the detection of zoonotic diseases, such as Coronavirus disease. Finally, we outline several future research directions that highlight the importance of this promising research area. In a nutshell, this tutorial can be a good starting point for researchers working on THz BCNs, which still have a long way to go.

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