Survey on Wireless Information Energy Transfer (WIET) and related applications in 6G Internet of NanoThings (IoNT)

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Abstract
In the Wireless Information and Energy Transfer (WIET) technology, in addition to information, electromagnetic waves carry energy in the energy harvesting mode, and hence, wiring infrastructure to charge the battery is not required. WIET is envisioned to execute a vital role in the deployment and expansion of the sixth generation (6G) Internet of NanoThings (6GIoNT) devices which will operate with limited-battery usage. As the 6G technology will enable the use of wireless information for signaling and energy transfer due to the use of mm-wave/THz frequency for operation, antennas will be required at close proximity. Hence, the Internet of Things/Internet of Everything/IoNT devices will operate in near field region. In effect, the same electromagnetic wave will be able to carry sufficient energy to significantly charge the nano-devices. This article overviews the WIET and related applications for 6G IoNT. Specifically, to explore the following, we: (i) introduce the 6G network along with the implementation challenges, possible techniques, THz communication and related research challenges, (ii) focus on the WIET architecture, and different energy carrying code words for efficient charging through WIET, (iii) discuss IoNT, with techniques proposed for communication of nano-devices, and (iv) conduct a detailed literature review to explore the implicational aspects of WIET in the 6G nano-network. In addition, we also investigate the expected applications of WIET in 6G IoNT based devices and discuss WIET implementation challenges in 6G IoNT for the optimal use of technology. Lastly, we overview the expected design challenges which may occur during the implementation process, and identify the key research challenges which require timely solutions, and which are significant to spur further research in this challenging area. Overall, through this survey, we discuss the possibility to maximize the applications of WIET in 6G IoNT.

Keywords 6G · WIET · SWIPT · IoNT · Rectenna

Introduction
In the near future, the sixth generation (6G) technology is expected to integrate millions of devices with the Internet due to seamless network capabilities. It is expected that new dimensions will be explored for small, medium and large scale industries. Hence, there is an increasing demand to minimize the dependency on wired devices for charging the Internet operated devices. This propels the need of wireless information and energy transfer (WIET) which uses the same electromagnetic wave for communication. The advanced technologies in the field of wireless communication are expected to utilize the potential of Internet-of-Nanothings (IoNT) vision where, many nano-meter wavelength devices are able to communicate and exchange the information wirelessly. The WIET technology allows to power-up or charge the devices without the need of any wiring infrastructure.
The WIET mechanism includes three classes viz., magnetic resonant coupling, inductive coupling or electromagnetic radiation (Bi et al. 2014). The electromagnetic radiation (or radio frequency), enables WIET to cover long distances at low cost, and is able to provide signal to the low power nano-devices. A low power battery operated device can be charged efficiently using the wireless energy without the need of a physical charging unit. The connectivity between the receiver and the transmitter can be divided between the following two modes (Bi et al. 2014):

- **Mode-1** is the energy flow mode in which the wireless energy is harvested from transmitter to receiver. This energy harvesting (EH) is considered as a key component in next-generation IoNT devices since it provides (i) wireless remote charging, which minimizes the maintenance and servicing needs of the internet-operated devices, and (ii) significant enhancement in energy-efficiency.

- **Mode-2** is the information flow mode in which the information contents are transmitted/received through uplink/downlink communication, respectively. The Multiple Input Multiple Output (MIMO) technology can be deployed to speed up the efficiency of mode 1 and mode 2 by the activation of multiple antennas at the transceiver which are used to enhance data rate. The MIMO technology also maximizes system-efficiency, reduces noise, and minimizes power consumption to achieve the overall goal.

Further, the size of devices is becoming smaller day-by-day; however, such devices are able to provision multiple applications. The possibility of energizing the smart nano-devices is possible after the reduction in power requirements of various smart electronic devices (Smith 2013; Hemour and Wu 2014; Clerckx et al. 2019). The concept proposes high frequency radio waves which will carry both, information and energy simultaneously from transmitter to receiver, and will power the low battery nano-devices. At times, the term energy is replaced by power when a sufficient amount of energy is transferred at a high rate to meet the receiver battery requirements. The term, wireless information transfer (WIT) is used for information/data flow between the transmitter and receiver in uplink and downlink mode targeting communication only; whereas, wireless energy transfer (WET) is used for energy flow from the transmitter to receiver targeting energy transfer only. Further, WIET is the design used for transfer of information and energy. WIET attempts to accomplish a trade-off between communication and energy of the devices for the best use of radio frequency. Further, nano-devices, which operate on the WIET technology, are small in size and need low power to remain functional and connected anytime and anywhere. In this case, the wireless network design needs to integrate new changes to work on WIET which introduces new challenges and opportunities (Clerckx et al. 2019).

**Research methodology**

To conduct a thorough survey in this article, we follow the guidelines provided by Carrera-Rivera et al. (2022); Kitch-enham and Charters (2007); Staples and Niazi (2007). Further, following (Petticrew and Roberts 2006), we frame the specific research questions based on the concept of Population, Intervention, Comparison, Outcomes, and Context. These specific review questions steer the systematic review methodology within the article. The main aim of the review is to answer the following research questions:

- Can WIET implementation aspects be further explored in low power devices such as, nano-devices?
- Is there scope of WIET in nano-devices to ensure their functionality for a long time and provide long life?
- Can WIET be designed to operate at higher band frequency?

To conduct a systematic review of studies shedding light into these questions, our search strategy is implemented in three phases: (i) identification of the keywords and defining search strings, (ii) data sources selection, and (iii) search process within the data sources. During the search process, we use web-based resources (e.g., Google Scholar, Scopus, and Web of Science) as the database, and also conduct a manual search for the articles from key authors within the WIET research domain. The keywords used for searching include WIET, Wiet, wiet, wireless IET, and Wireless IET. To conduct a complete search, we use the following six key databases as sources: (i) IEEE (ieee.org), (ii) Springer (springer.com), (iii) Elsevier (science direct. com), (iv) Wiley-Blackwell (onlinelibrary.wiley.com), and (vi) arXiv (arxiv.org). To obtain a broader insight, the chosen studies contain academic literature, and grey publications such as, reports, authentic websites, and working/white papers. The contribution of a specific database to the current article is shown in Fig. 1a.

The initial literature search provided a total of 165 sources, and upon reviewing the titles, abstracts, and keywords, and removing the duplicates, 135 unique sources were obtained for further evaluation. Then, upon implementing the inclusion and exclusion criteria during a full text reading phase, we excluded 15 sources to obtain a total of 120 sources, which comprise of 90 primary studies, 20 reviews, and 10 authentic websites as shown in Fig. 1b. For inclusion, we set the criteria that the source’s research topic must focus on WIET, and related applications/use cases. Also, the sources detailing WIET and
related content, published in key databases, and published between the years 2018 to 2023 are included.

Next, to implement the data extraction and synthesis, the content analysis method is implemented to identify the appearance of specific word(s), topic(s), and/or concept(s) within the text (Krippendorff 2018). Through the data synthesis process, we integrated a diverse range of studies within a conceptual map, and use Mendeley and Microsoft Excel spreadsheets to synthesize the data within four WIET elements viz., architecture (detailed in Sect. "SWIPT method of WIET"), IoNT (detailed in Sect. "Energy carrying code words for WIET"), applications and use-cases (detailed in Sect. "Open Areas Of Research"), and key challenges and future roadmap (detailed in Sect. "Conclusion").

Finally, for accessing the quality of the included sources, every source is weighted on the following specific questions (Paul et al. 2022): (i) does the source include clear research goals, (ii) did the source achieve the aims stated, and (iii) does the source document the research process aptly and reports sufficient findings related to the goals. As a response, the answer could be (i) ‘1’ implying that the source answered all the questions well, (ii) ‘0.5’ implying that the source partially answered all the questions, and (iii) ‘0’ implying that none of the questions were answered by the source. Following this quality assessment of all the selected primary sources, due to low quality, sources could be excluded. Further, the included sources were identified in relation to the research questions which they answered which enabled the extraction of the applications (detailed in Sect. "Open areas of research") and the challenges (detailed in Sect. "Conclusion").

Motivation and contributions

In recent years, WIET has attracted much attention from both, academia and industry (Sangmahamad et al. 2022; Luo et al. 2018). Although initial research has demonstrated that WIET is key to the development of advanced applications, continued progress has been limited by the lack of timely solutions to key issues. These include, issues such as interference mitigation schemes in WIET MIMO receiver, and massive MIMO for WIET are yet to be addressed. Additionally, challenges due to information detection (ID)/EH mode, Interference, and large number of antennas also require timely solutions. This motivates us to explore and highlight new dimensions of nano-devices and feasibility for the deployment of WIET in 6G IoNT. Additionally, we are motivated to address multiple opportunities and challenges for sustainability of research in this state-of-art domain.

The above motivation and the systematic literature review from sub-Sect. "Research Methodology" enabled us to identify key research gaps and aided us in providing the key contributions. Overall, this survey is one of the first to discuss state of the art advances with a center of attention on aspects related to wireless energy transfer over nano-devices. Further, towards the end of the survey, several important current and future research challenges are presented followed by the proposal of the corresponding research directions. The main contributions of this study are as follows:

- Discussion and exploration of the state of art advancements towards obtaining solutions to the power related issues in the nano-devices through the use of WIET
• Detailing the related Applications of WIET in 6G IoNT survey.
• Presenting and discussing multiple research challenges of current and future research and the expected solution of these challenges with an outlook towards enhancing research in regard to finding the technology which better suits the 6G nano-devices communication and implementation on the low power IoNT devices.

The rest of the article is structured as follows. Section "6G Network and implementation challenges" details the 6G network architecture and implementation challenges. In Sect. "WIET architecture", we describe the WIET architecture. Section "IoNT" focuses on IoNT, and the related design directions for operation. In Sect. "Related literature review", we present the related detailed literature review. Section "WIET applications and implementation challenges in 6G IoNT" details the various applications and challenges in WIET technology related to 6G nano-network and IoNT devices. Section "Open areas of research" lists the future directions of research considering the existing challenges. Finally, Section "Conclusion" concludes the article.

6G Network and implementation challenges

The existing technologies are not comparable with the 6G technology. The bandwidth of 3G, 4G and 5G is 25 MHz, 100 MHz and 1000 MHz or 1 GHz, respectively; and data rates are 14.7Mbps, 100 Mbps and 1Gbps, respectively; latency is 100 ms, 50 ms and 5 ms, respectively. However, 6G will unlock the potential of many applications providing more bandwidth, higher data rate and very small latency, as shown in Fig. 2 (Alsabah et al. 2021).

The 6G technology will offer extremely broad coverage and universal connectivity using artificial intelligence (AI). It also opens doors to the possibilities for Space-Air-Ground-Underwater networks which consists of a joint layered tier network. The communication occurs in the THz frequency band; thus, the wavelength (λ) is suitable for the nano-devices. The power requirement will also be low due to very small size of nano-devices. The key parameters supporting 6G must provide services which are to be implemented on ultra-high spectrum bands (0.1 to 10 THz), and which travel shorter distances compared to the lower bands used in the 4G and the 5G technology. The potential 6G technology applications include IoNT, molecular communications, AI, and Big data analytics, visible light communications (VLC), quantum communications and computing, energy and spectrum efficient hardware and resource allocation, holographic beam forming, large intelligent surface, dynamic network slicing, 3D networking, unmanned aerial vehicle (UAV), integration of access backhaul networks, etc., as shown in Fig. 3 (Mao et al. 2020).

The key characteristics of 6G wireless network include (Zhang et al. 2021):
• Peak data rates are of greater than 1 Tb/s (nearby 100 times that offered by 5G)
• User data rates are of 1 Gb/s (nearly 10 times that offered by 5G)
• THz frequency range: 0.1–10 THz

![Fig. 2](image-url)  
Comparison of bandwidth, data rate, and latency for technology spanning between 3 to 5G

![Fig. 3](image-url)  
The 6G communication architecture framework
• Higher Spectrum efficiency that is nearly 5–10 times of 5G
• Boosted Energy efficiency that is nearly 10–100 times of 5G
• Ten times the connectivity density of 5G
• High throughput, network capacity
• Latency rate is 10–100 µs
• Mobility is high
• Enhanced data security
• Ubiquitous connectivity
• AI integrated communication

The Processing techniques work on the concerned technology to ensure that it is suitable for the betterment of society in particular and public in general. The 6G processing occurs at the frequency range of the THz band (Mao et al. 2020; Zhang et al. 2021). Hence, 6G can employ the use of IoNT for connectivity and communication purposes when it deals with nano-devices (Nguyen et al. 2022; Rappaport et al. 2019). Further, 6G is based on orbital angular momentum (OAM) multiplexing through which the transmission capacity can be increased dramatically (Dominici et al. 2021). Another technique is quantum communication and computing which is under investigation (Zhang et al. 2022). The VLC technology can be connected with 6G to provision multiple applications (Abumarshoud et al. 2021). Further, 6G also supports AI and blockchain based spectrum sharing to ensure the authenticity between end user and servers, and allows the maximum use of remote resources (Zuo et al. 2023). The throughput can be increased using non orthogonal multiple access (NOMA) which sends signal at different power levels with the same carrier frequency. When NOMA is combined with mm-wave frequency then, it demonstrates more benefits to reduce interference and to improve the data rate (Bayraktar et al. 2020). Another sub-domain of 6G is the super massive Multiple Input Multiple Output (MIMO) antenna which includes multiple antennas that provide significant improvement in efficiency and offer higher capacity (Squint et al. 2019).

The THz band lies in the 0.1–10 THz frequency range which corresponds to 0.03–3 mm wavelength (Jiang et al. 2023). The immediate target for 6G is low THz band i.e., between 275 GHz to 3THz. The challenges of operating at higher frequencies for communication purpose are (Zhao et al. xxxx):

1. More towers will be needed to offer wide coverage.
2. The omnidirectional antennas will be required to be replaced with highly directional (pencil) antennas which will need to generate narrow beam widths.
3. The spectral efficiencies of the antennas need to be increased for effective communication. It can be achieved using super massive MIMO techniques.
4. Path loss becomes very high at higher frequencies and hence, signal loses intensity over large distances, and can be blocked by buildings.
5. Atmospheric absorption of high frequency waves occurs in addition to natural Friis space loss of electromagnetic waves at sea level with a variation of frequency under different humidity conditions.

At lower frequencies (below 6 GHz), attenuation is primarily caused due to molecular absorption in free space, which is of low amplitude; however, at higher frequencies (above 6 GHz), the wavelength becomes micro/nano meter size. Such low wavelengths are the same as of rain, dust, snow etc., and hence, the effect of Mie scattering is severe. It has been shown that rain attenuation flattens from 100 to 500 GHz which implies that rain will not cause any increase in the attenuation at operating frequency above 100 GHz (Tripathi et al. 2021). The attenuation occurring due to rain at 1THz is 10 dB/km for moderate rainfall of 25 mm/h. This attenuation increases slightly, i.e., 4 dB/km more at 28 GHz frequency (John 2016). The attenuation is controllable if the cell size is high, which is the case in mm-wave frequencies having urban cell sizes of nearly 200 m (Nandi and Maitra 2018). Further, rain attenuation can be minimized drastically by increasing the antenna gain which can be ensured by switching between antenna arrays and adaptive beam steering (Mohammed et al. 2018). Also, scattering, instead of diffraction, causes more notable changes at the nano-wavelength because of its lower size. However, the opportunities available at high frequency THz band is that it removes spectrum dearth and capacity limitation which is the prime challenge in current wireless systems (Elbir et al. 2022).

Fig. 4 The hardware for THz wireless radio transceiver
Figure 4 demonstrates the THz wireless radio transceiver hardware which is designed with a MIMO antenna array to receive the signals of low wavelength, and process these signals using the converters and processors to extract the information. Following aspects to be further investigated at the THz frequency band include:

- Transistor and other active or passive devices with excellent high frequency characteristics
- Robust beam forming and scanning algorithm such as, Hybrid Beamforming Approaches
- Low power consuming hardware
- Noise and Channel modeling
- Wireless charging
- Low complexity
- Energy efficient modulation techniques
- Ultra massive MIMO antenna system
- Powerful and high synchronization schemes
- Low density channel codes

Multiple opportunities arise in 6G communication. The operational frequency lies in the higher end of the frequency band, and hence, the wavelength is in the order of nanometer which allows the use of nano-sensors and other nano-devices with the 6G hardware (Schotten 2023). These nanosensors can be made operational on the Internet generating the IoNT network. The nano-devices face a problem of maintaining their power level because these are tiny devices and hence, it is difficult to power them up through a charger. The WIET technology is able to charge these nano devices (Shen and Li 2013). Information can be easily sent through the radio waves wirelessly; however, to send wireless energy over these waves, the receiver must not be far from the transmitter. Practical implementation of WIET in the 6G IoNT network is possible due to the lesser distance between the transmitting towers. Thus, all the receivers fall under the Fraunhofer distance range, which is also known as the radiating near field. (Hao et al. 2022) The energy can be transferred to IoNT devices or 6G operational devices wirelessly without higher effect of attenuation. WIET is the wireless transferred energy of low amplitude; however, it is sufficient to fulfill the power requirement of low power IoNT devices.

Further, 6G also provides the opportunity to power up the receiver using radio frequency waves. For efficient charging of the device, it should be a low power device with a small size (Gaire et al. 2021). These parameters make 6G communication feasible and easier for nanodevices. The nanodevices are designed with the nanometer wavelength to operate on higher frequencies. Such devices are small in size and consume low power; therefore, a low EH signal is able to charge the battery completely (Esswie 2022). When these nanodevices use Internet for communication purposes, it is known as Internet of nano Things (IoNT). All IoNT devices are smart and are able to communicate which makes them applicable in many fields such as, medical, health monitoring, commercial electronics, industry, etc. (Almazrouei and Shubair 2018).

The THz frequency band is expected to be used for 6G communication; however, it is not an easy task to operate over such a high frequency. Therefore, 6G faces many challenges before the successful operation over the THz frequency band. These challenges must be addressed timely considering both, hardware and communication aspects of 6G. The key challenges (shown in Fig. 5.) include (Zhang et al. 2108):

- Use of high frequency hardware components to reach the desired speed of operation
- Sufficient WET for speed charging of low wavelength and nano sized components
- Channel modeling and estimation for adept operation of high frequency
- Bandwidth enhancement for wide use and enormous capacity
- Use of VLC for minimization of Non-ionized radiation
- Intelligent dynamic spectrum access for virtual reality of spectrum availability to user
- Orthogonal multiple access for enhanced and efficient communication
- Focused directional networking for THz wireless communication

Fig. 5 The key challenges in 6G wireless technology
High frequency operational directional base stations transceivers offer low distance coverage therefore large numbers of transceivers are required for 6G coverage.

**WIET architecture**

In regard to radiation exposure, wireless power transfer may be of radiative type or non-radiative type (see Fig. 6) (Zhang et al. 2018). The microwave and laser powers fall under the radiative power zone; whereas, induction, magnetic, acoustic and capacitive powers fall under non-radiative power zones (Brown 1984). The EH through wireless power can be implemented in direct mode or background mode (Chen et al. 2016). In direct mode the receiver directly receives energy from the transmitter which is actually meant to provide energy to the receiver; whereas, in background mode the energy is retrieved by such device which is not aimed to power the receiver directly, instead, harvesting energy by some other process (Shinohara 2011; Cheah et al. 2019). The radio frequency based WIET can be divided into three categories, as shown in Table 1. Further, it can be visualized through a model for transfer of wireless information and energy as shown in Fig. 7.

**WIET HAP model**

The model in Fig. 7 shows all the three modes of wireless information and energy transfer. Hybrid access point (HAP) is the transmitter used for transmission of information and possibly energy as well (Diaz-Vilor and Ashikhmin 2022). In the figures, energy flow is shown using red line, and information flow is shown by the green line.
The energy transfer from HAP to receivers is known as downlink, and the reverse process is known as uplink. As shown in Fig. 7, $R \times 2$ and $R \times 3$ represents WET mode in which the energy is sent from HAP to the receiver. The SWIPT mode is shown in receiver $R \times 1$, $R \times 4$ and $R \times 7$, and the WPCN mode is shown in $R \times 5$ and $R \times 6$. Multiple antennas at HAP enable energy beamforming (EB), as shown in Fig. 8a, which is a technique used for efficient energy transfer. Multiple sharp beams in different directions are generated to minimize the near-far problem (Han et al. 2023). Therefore, nearby users from HAP harvest more energy while the distant/far users harvest less energy (Mao et al. 2020; Zhang et al. June 2021). The high RF based wireless power transfer easily locates the receiver which is in the radiating near field zone (Dolgov et al. 2010), as shown in Fig. 8b. When the receiver is under the Fraunhofer’s limit then, energy can be easily harvested because the receivers are easily diagnosed. Antenna array, with a large number, is desirable for the purpose of expanding radiation in the near-field region (Hao et al. 2023). Radiating wireless power transfer allows an energy transmitter to charge multiple remote low power receivers or IoNT devices, which are referred to as energy

Fig. 8  a WIET Infrastructure consisting of EH receiver (Huang et al. 2019a), b Increased radiating near field at 100 GHz in comparison to 2.4 GHz

Fig. 9  Non-linear Rectenna model
receivers. The EH receiver is used to receive RF energy in the form of alternating current, and converts it to direct current signals which are used to charge battery of low power receiver. The Energy harvested rectified signal is received at diode output; whereas, energy harvested filtered signal is received at low pass filter output, as shown in Fig. 9.

**Non-linear rectenna model**

The EH receiver receives signal from the nano-antenna known as the receiving antenna or rectenna. This signal is delivered to the diode for rectification and a low pass filter for smoothing the direct current. This direct current signal dc is then purified by a parallel capacitor forming a low pass filter (LPF), as shown in Fig. 9 (Clerckx and Kim 2018).

**SWIPT method of WIET**

WIET provides energy to the nano-receivers and simultaneously transmits the energy with information over the spectrum. To avoid any interference which may occur due to energy transfer, and disruption in the information, a simple method is used which transmits the energy and information in orthogonal frequency channels. This SWIPT method provides a trade-off to balance the EH and information decoding (ID), as shown in Fig. 10 (Hu et al. 2019).

**Energy carrying code words for WIET**

On the basis of different power requirements of battery capacity, the code words can be digitally modulated with a transmitted signal for wireless charging of the battery,
as shown in Fig. 11 (Sarma et al. 2023). The low power receivers can be efficiently charged even at less harvested energy as they are coded with less number of 1’s in data word. The energy is converted in terms of digital code words using amplitude shift keying (On–Off keying) which is then transmitted using an energy transmitter. The codes are received and decoded at the receiver and are used to power the receiver (Hu et al. 2019). The decoded code word must contain sufficient energy which should not be a cause of battery overflow or underflow.

The energy received at the receiver is very low (in order of microwatt) after passing through the atmosphere (Sarma et al. 2023). Harvested energy of mm-wave is in the range of 1–5 μW when the source radiates 1–4 W power (Zhang et al. xxxx). The authors in Abumarshoud et al. (2021) observed that the received power level is not sufficient to charge the wireless devices. The received power is in microwatt; hence, focus is required on low-power devices such as, small relays, nanosensors etc. Hardware development is required for widespread use of SWIPT technology (Lu et al. 2015). In the RF based WIET, various techniques can be adopted at receivers to optimize the results. These techniques include antenna switching, time switching or power splitting (Liang et al. 2019). In antenna switching, receivers consist of separate antennas for information decoding or EH. The time switching mechanism is designed using one receiving antenna which is based on TDM for the operation. In power splitting, the power is divided in between information decoder or battery, as shown in Fig. 12.

IoNT

The Internet of Nano things (IoNT) implies that nanomaterials, nano-implants and nano-biosensors are connected with the IoT networks (Yang et al. 2019). All the components to design the basic IoNT devices may include nano nodes, nano routers, nano micro interface devices and nano gateways. The basic building block of IoNT which is interfaced at the nano-scale is shown in Fig. 13 (Nayyar et al. 2017). Nano nodes are used to sense the data and to process the information for further communication, and the nano routers perform the task of data collection from nodes and can control nodes to operate in the on/off mode. The collected information from the nano-routers is sent to the nano-micro interfaces. Gateways are connected to the nano-devices, which transfer information on the cloud through the Internet, and control the nano-devices remotely. The complete combination is referred to as the IoNT.

Techniques proposed for IoNT

Two techniques proposed for communication of nanodevices are THz electromagnetic communication and molecular communication (Akhtar and Perwej 2020). The
THz electromagnetic communication transmits and receives the information from nano transceivers through EM waves, whereas molecular communication transmits and receives the information which is encoded in molecules (Pradhan et al. 2210). Molecular communication is radiation-less and feasible at instances where conventional wireless communication may result in health issues due to the use of EM waves (Huang et al. 2019b). Molecular communication uses biochemical signals to transfer the information at nano-scale. In regard to IoNT which is introduced from the concept of IoT with the only difference being in size of things ranging between 1 to 100 nm, the 6G technology needs to deploy nano-antenna to ensure that tiny devices communicate at higher radio frequency. Graphene-based nano-antenna is suggested to be implanted in the IoNT technology because it has the ability to operate at the THz frequency band (Akyildiz et al. 2008). Nano-antenna and other basic nano-components are shown in Fig. 14.

The IoNT infrastructure can use other technologies such as, cloud computing, WSN, big data, etc., for collection, processing and refining of the data (Şentürk et al. 2023). The complete network of nano-devices is able to collect the data and granular information from places which are difficult to access with existing EMS/MEMS devices. Molecules are considered as the basic unit for bio-nano-communication which works as an IoT sensor (Bartunik et al. 2023). Internal parts of cells perform the task of various nano-devices such as, sensor, processor, actuator, etc., and thus behave like an IoNT device (see Fig. 15). Various cells are based on the propagation and reception of the molecules for the exchange of information between the cells (Akhtar and Perwej 2020).

**Empirical exploration of WIET in 6G IoNT**

The nano-devices are able to work in the same fashion as a normal IoT device. These devices have their own transmitter and receiver for data communication, nano-sensors for data collection, nano-processors for data processing and sharing (Miraz et al. 2015). A small power unit is required to make all the building blocks operational. The main challenge is to provide an uninterrupted power supply which can be rectified using WIET (Liu et al. Apr. 2014). The role of 6G is interesting in the implementation of WIET in IoNT devices. This is due to the fact that 6G operates at THz-frequency band with wavelengths in order of nano-meters which can connect with a nano-camera, nano-sensor network, nano-object or nano-phone (Bi et al. Apr. 2015). The connectivity diagram of WIET in 6G IoNT is shown in Fig. 16 along with highlighted parameters or uses.

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**Fig. 14** Basic components of nano devices for THz electromagnetic communication

**Fig. 15** Connect between IoNT and molecular communication
Related literature review

In this section, we review the latest studies which have addressed the key issues in 6G networks, WIET, and IoNT. The authors in Clerckx et al. (2019) addressed the fundamentals of wireless information and power transfer (WIPT) considering the WIET technology. The study explains various energy harvesting models through circuit simulations, experimentation and prototyping, and discusses system design for WIPT. The authors reviewed and discussed network aim for two purposes of information and energy transfer. Lastly, as scope for future research, it is suggested to address new modulation formats for experimental validation, beam forming and modulation efficient networks. In (Alsa-bah et al. 2021), the AI-based joint optimization of QoS and Security for the 6G networks is addressed. The authors focused on link-layer security in harvesting-based 6G IoT networks. The study is centered on the EKF technique which is able to calculate the expected power needed to harvest with better accuracy. Authors suggested to evaluate the performance for network throughput in comparison with commonly utilized service configuration method. It is also suggested to use adaptive security configuration methods which will be able to work on limited energy requirements. This suggested method is able to fulfill the need of energy requirements and capacity-constrained for IoT devices and has very low complexity. For future study, authors directed research towards harvesting power to be predicted with high accuracy using EKF technique thereby, improving throughput rate and time. It is also suggested to minimize the complexity in security configuration.

The authors in Mao et al. (2020) focused on the 6G wireless communications networks depicting a detailed analysis from 1 to 5G technology. The article elaborates a review on such technologies which are needed to increase energy efficiency and network connectivity. There is also focus on Blockchain technology and Quantum communication to increase security and privacy. The authors state that 6G will support massive IoTs, and will provide various advantages over the older technology. This will include advanced intelligence and reliability, advanced security, adaptive data rates, ultra-low latency, etc. Further, 6G will be able to provide seamless coverage without any communication difficulty and will require new advanced modulation schemes, multiple access techniques, energy harvesting solutions, edge computing technique, integration of terrestrial and non-terrestrial communications, cell-free massive MIMO, blockchain and quantum technologies and adoption of AI and ML techniques. In (Zhang et al. June 2021), the authors aimed to address the issue of optimal resource allocation in 6G networks. The overall interference in the THz band is analyzed. Further, finite block length coding is used to analyze channel capacity and dispersion. It is shown that the optimal resource allocation techniques can maximize the
nano-network capacity. In future, research on 6G networks must focus on issues related to massive low-latency communications to develop advanced IoT devices. The authors in Nguyen et al. 2022 focused on IoTs by comparing the 5G and 6G IoTs. Specifically, the study elaborates on network features and enabling technologies which guides towards the new features of 6G. Authors also provided a taxonomy for 6G IoT applications and widens it for HIoT, VIoT, UAV, SIoT, and IoT. Lastly, challenges related to security, privacy, hardware, energy efficiency, etc. for 6G are elaborated including the possible direction of research.

In (Cheah et al. 2019), the limitations of WPT technology for mobile robots is detailed. Authors detailed different types of mobile robots and their environments of operation are identified followed by the listing of power transfer scenarios. The study reviews new applications for mobile robots and WPT technology. Finally, it is shown that the various types of WPT technology makes it possible to operate between mid to far range for communication. The authors in Clercix and Kim (2018) focused on the fading and transmit diversity in WPT. The main focus is to increase the efficiency of RF energy harvesters. For which the fading environment is analyzed. Authors developed a new design utilizing many dumb antennas to increase the RF energy harvesting at transmitter. It is suggested that the role of multiple antennas maybe beneficial in WPT even when there is no channel state information at transmitter. The authors in Dominici et al. (2021) aimed at the design of modulation and coding for SWIPT. The study focused on SWIPT and coding controlled SWIPT, MIMO aided modulation, SWIPT with modulation for single user and multi user. A case study for 4-QAM,16-QAM and 64-QAM modulation design is demonstrated and it is shown that coding of simultaneous power transfer technology for one and more than one users is possible. Finally, three future challenges are highlighted. The authors in Huang et al. 2019a addressed the promising technologies for green 6G network including THz band operation, VLC, molecular communication, quantum communication, and blockchain for decentralized security. It is suggested that molecular communication, which is a new communication paradigm, provides advantages in comparison with radio communication are demonstrated. It is also highlighted that the current 5G architecture is incapable of covering high altitude and deep sea scenarios, and this drawback will be overcome by 6G by providing wireless networks on a global scale through non-terrestrial networks. Lastly, it is pointed that green 6G will explore many new aspects to increase efficiency and quality, and will be capable of providing network anytime and anywhere. In (Liang et al. 2019), the authors focused on SWIPT for 5G mobile networks. The article surveys energy rate tradeoff and radio frequency allocation. Further, SWIPT technology is explored for 5G mobile network and summarizes related recent advances. It is stated that challenges exist for high mobility users, ultra-dense networks, AI, and information security. The authors in Nayyar et al. (2017) focused on IoNTs and suggested a clear picture of components to design basic IoNT devices. The IoNT network may include various sensing nodes, processing units and gateways, and the basic building block interfaced at nanoscale. Further, it is stated that IoNT will advance IoT to a new level which will operate on nanonodes and nano transceivers. It is proposed that transmission and reception aspects of IoNT should be investigated to maximize the efficiency.

In (Akhtar and Perwej 2020), the authors have detailed the future prospects of IoNT. Also, the basics of molecular communication are investigated, and it is suggested that molecules work on chemical reactions for their actions; therefore, electric energy requirement is low. Therefore, molecular communication can be adopted as a good method of communication. The study concentrates on IoNT market trends, various applications, reasons to employ IoNT, challenges and the nano-sensor fabrication techniques. It is concluded that nano-devices’ evolution and IoNTs have sufficient potential to connect every single object on earth with Internet and hence, there is a tremendous future scope for IoNT research. In (Huang et al. 2019b), a survey on green 6G network is presented. The authors performed comparison of THz and VLC communication. It is observed that 100 Gbps data rate could be achieved in THz communication while it is only 10 Gbps in VLC communication. It is concluded that, similar to VLC, Green 6G communication, is emerging through which energy and high speed data can be transmitted sustainably. In (Akyildiz et al. 2008), the authors have addressed the deployment approaches for nano-networks. The similarities between micro robot nodes (nano-network communication blocks) and nano-network nodes (molecular communication blocks) are detailed. Further, graphene is suggested as the future technology as it is capable of detecting extremely low concentration of charge. The study also overviews traditional and nano communication, and highlights that molecular communication scalability could be further investigated for short range and long range communication.

The authors in Miraz et al. (2015) focused on IoT, IoE and IoNT by elaborating the differences between them. The authors detailed the challenges in IoNT that must be countered during the process of channel modeling. The study interfaces nano devices with existing micro devices to utilize existing infrastructure for future technology. The authors in Bi et al. (2015) focused on the wireless powered communication wherein, the methodology includes various aspects of design challenges, WPT technologies on real platforms and opportunities. The design considerations of wireless powered communications are demonstrated through SWIPT and WPCN. It is suggested that the research in the field of wireless power communication can create a new dimension for
wireless power enabled future devices to transmit information and energy simultaneously. In (Liu et al. 2020), wireless powering IoT with UAVs is detailed. Specifically, UAV-enabled wireless powering IoT technologies are identified and analyzed through simulation. The results are found to be effective for UAVs enabling IoT technologies. The authors suggest that the Ue-WP IoT have immense potential in IoT, and can be made functional for 6G to explore enormous applications in the micro and nano field region. The authors in Wagih et al. (2019) detailed the use of mm-wave textile antenna for on-body energy harvesting. Various parameters of omni-directional mm-wave textile antenna are analyzed for energy harvesting purposes by measuring the impedance bandwidth and peak gain. The study presents first antenna on textile for wearable ambient RFEH in the 26 GHz and 28 GHz bands. It is shown that the small antenna size is useful for wireless energy transfer. Further, as a scope, it is mentioned that research on mm-wave can be explored to minimize induced losses, and textile based microstrip rectifiers can be investigated. In (Qadri et al. 2020), emerging technologies of H-IoT are described by elaborating on the role of AI, ML and Big data for various applications and circuitry of healthcare devices. The Author delves into ways in which nanosensors are transforming the health sector. Finally, prominent future research directions are listed.

The authors in Pramanik et al. (2020) detailed aspects related to advancing modern healthcare with nanotechnology, nanobiosensors, and IoNT. The study describes elements and general workflow of bio sensors. Further, the article explores IoNT potential in the medical field, and concentrates on health consequences and clinical risks that may occur during the operation of IoNT. Lastly, the study provides future scope for targeted drug delivery, medical implants, breast implant, dental implant. In (López et al. 2021), massive wireless energy is addressed, and channel state information for simultaneous operation of a large number of devices is explained. The challenges and possible solutions for 6G WET technology are identified and summarized in the article. For sustainable WET, conventional deployment to actively green WET is discussed. It is pointed that WET is a key enabler for the next-generation, and the use of nano devices may be beneficial to achieve this goal. Table 1 presents a summary of the above detailed studies. In (Lyu et al. 2020), the authors provided the fundamental idea of an intelligent reflecting surface to improve uplink and downlink energy and information transfer efficiency. It is pointed out that IRS will work in between the HAP and user. The results shown that as reflecting elements are increased, the intelligent reflecting surface WPC rate also increases. Further, phase shift is highlighted as an important parameter for energy transfer and information transfer which influences the beamforming gain. Lastly, it is pointed that IRS assisted WPCN has high scope to maximize energy from HAP to user and to transfer information from user to HAP. Hence, IRS is beneficial for increasing the energy efficiencies for wireless power transfer in 6G. The authors in Kamga and Aïssa (2019) detailed WPT in mm-wave considering rain attenuation. The study suggests WPT for coverage and exclusion radius in rain attenuation environment, and confirms that harvested energy increases at low coverage radius, and vice versa. Also, it is shown that when WPT needs enhancement then, small cells endowment can be used. Lastly, it is highlighted that rain attenuation affects WPT highly; hence, research is required for mm-wave WPT (Table 2).

WIET applications and implementation challenges in 6G IoNT

The use of sensors in multiple devices has increased tremendously in the current decade which has resulted in diverse micro/nano-sensors. Currently, multiple applications are governed through nano-sensors at present, and it is predicted to increase in the near future (López et al. 2021). As wavelength in 6G communications is in order of nanometers, new components can operate over nano-meter wavelengths. This will enable to reduce the latency rate as well as ensure effectiveness of wireless communication. The nano-sensors based devices, known as Internet of Nanothings (IoNT), are capturing attention of researchers due to their small size and low power requirements (Tomkos et al. 2020). WIET technology is beneficial to sort charged related issues of nano-devices, and to communicate information effectively. IoNT devices are applicable in diverse fields such as, medical, commercial, environmental, industrial, research, etc. (Zhang et al. 2108; Brown 1984; Chen et al. 2016; Shinohara 2011; Cheah et al. 2019; Diaz-Vilor and Ashikhmin xxxx; Han et al. xxxx). Next, we detail the key applications.

1. Health care Application: These applications are used to analyze and examine human health, immune system support, radiation analysis, disease identification, etc. The IoT system designed with the aim to focus on health aspects is popularly known as Healthcare-IoT (H-IoT). Normal fungal diseases to neurological diseases can be examined and identified through nano-sensors. These nano-sensors can operate with IoT nodes properly when they are powered through wireless energy without any disruption (Chen et al. 2005). Currently, personalized healthcare services provide dedicated services and require specific environment. Hence, such services are unable to consider multiple inter-related health conditions which results in inappropriate diagnosis, and adverse effects on sustainability and long-term health life of patients. As the healthcare sector is continuously transforming towards a more personalized and IoT ena-
| References          | Aim                                      | Problem addressed | Methodology                                                                 | Key results                                                                 | Future scope                                                                 |
|---------------------|------------------------------------------|-------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Clerckx et al. (2019) | Fundamentals of WIPT                      | WIET              | Discussion on system design for WIPT                                         | Discussion on network aim for information and energy transfer               | New modulation format                                                      |
| Alsabah et al. (2021)| AI-based joint optimization of QoS and security | 6G                | Focus on link-layer security in harvesting-based 6G IoT networks             | Use of adaptive security configuration methods                             | Predict harvesting power and minimize complexity in security configuration |
| Mao et al. (2020)   | 6G wireless communications networks      | 6G                | Detailed analysis from 1 to 5G technology, blockchain technology and quantum communication | 6G will support massive IoT                                                | 6G requires adoption of AI and ML techniques                                |
| Zhang et al. (2021)  | Optimal Resource Allocation              | 6G                | Analyze THz-band interference, channel capacity and dispersion functions    | Maximize capacity of the nano network via optimal techniques               | Massive low latency communication                                          |
| Nguyen et al. (2022) | 6G IoT                                   | 6G                | Comparison of 5G and and 6G IoT applications                                | Taxonomy for 6G IoT applications                                           | Promising challenges in 6G are elaborated                                    |
| Cheah et al. (2019)  | Limitations of WPT for mobile robots     | WIET              | Different types of mobile robots                                           | Review of applications for mobile robots and WPT technology               | WPT enables mid to far range communication                                  |
| Clerckx and Kim (2018)| Fading and Transmit Diversity in WPT    | WIET              | Increase efficiency of RF energy harvesters                                | Design uses dumb antennas to increase RF energy harvesting                 | Multiple antennas maybe beneficial in WPT in absence of channel state information |
| Hu et al. (2019)     | Modulation and coding design for SWIPT   | WIET              | SWIPT and coding controlled SWIPT, MIMO aided modulation, SWIPT with modulation for single user and multi user | Coding of simultaneous power transfer technology                           | Identified challenges include concatenated code, coded modulation and adaptive modulation |
| Liang et al. (2019)  | SWIPT in 5G mobile networks              | WIET              | Survey on energy rate tradeoff and radio frequency allocation              | SWIPT technology is explored for 5G mobile network                       | Challenges are highlighted and discussed                                  |
| Nayyar et al. (2017) | Design of IoNTs                          | IoNT              | Components required to design basic IoNT devices                           | IoNT basic building block will interface at nanoscale                     | Transmission and reception aspects of IoNT must be investigated             |
| Akhtar and Perwej (2020)| IoNT future Prospects                   | IoNT              | Basics of molecular communication is investigated                          | Paper concentrates on various aspects of IoNT, related challenges and nanosensor fabrication techniques | There is immense future scope for IoNT research                            |
| Huang et al. (2019b)| Survey on Green 6G Network               | 6G & IoNT         | Comparison between THz and VLC communication                               | Transmission power is high in case of THz communication. Paper suggests molecular communication in a new communication paradigm | Green 6G communication is an emerging research area and explore many new aspects to increase efficiency and quality |
| Akyildiz et al. 2008)| Nanonetworks for communication           | IoNT              | Various deployment approaches are explained                                 | Graphene can be used in wearable sensors                                   | Molecular communication scalability requires investigation                  |
| Miraz et al. (2015)  | IoT, IoE and IoNT                        | IoNT              | Difference between IoT, IoE and IoNT is highlighted                        | Challenges in IoNT are detailed                                           | Interfacing future devices with current ones is proposed as future study   |
| References       | Aim                                | Problem addressed                                                                 | Methodology                                                                 | Key results                                                                 | Future scope                                                                 |
|-----------------|------------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Bi et al. (2015) | Wireless powered communication    | WIET                                                                               | Aspects of design challenges, WPT technologies on real platforms and opportunities | Design considerations of wireless powered communications are demonstrated | Research must focus on wireless power communication                        |
| Liu et al. (2020)| Wireless powering IoT with UAVs   | WIET                                                                               | Analysis of UAV-enabled Wireless Powering IoT technologies                  | UAVs are effective to enable IoT technologies                            | Ue-WPIoT have immense potential in IoT                                    |
| Wagih et al. (2019)| mm-wave textile antenna for on-Body energy harvesting | WIET                                                                               | Parameters of omni-directional mm-wave textile antenna are analyzed          | Small antenna size is useful for wireless energy transfer easily          | mm-wave to reduce induced losses, and textile based microstrip rectifiers can investigated |
| Qadr et al. (xxxx)| Emerging technologies of H-IoT    | IoNT                                                                               | Role of AI, ML and Big data is discussed                                    | IoT for health sector is discussed                                       | Tactile Internet and future IoNT must be investigated                     |
| Pramanik et al. (2020)| Advancing Modern Healthcare    | IoNT                                                                               | Nano materials are classified and workflow of bio sensors are described      | IoNT’s potential in the medical field is discussed                        | Future scope is listed as drug delivery, medical, breast implant, and dental implant |
| López et al. (2021)| Massive wireless energy           | 6G                                                                                 | Channel state information for simultaneous operation of multiple devices is detailed | Challenges and possible solutions for 6G WET technology are identified   | Nano devices may be beneficial to achieve WET                              |
| Lyu et al. (2020)| Intelligent Reflecting Surface    | WIET                                                                               | Basic of intelligent reflecting surface are detailed                        | The results shown that WPC rate increases with increase in the elements | IRS assisted WPCN has scope to maximize energy from HAP to user            |
| Kamga and Aïssa (2019) | WPT in mmWave for rain attenuation | WIET                                                                               | WPT is suggested for coverage and exclusion radius in rain attenuation environment | Harvested energy increases at low coverage radius, and vice versa        | Investigation is needed for mm-wave wireless power transmission            |
bled sector, the advanced services are provisioned via control and monitoring applications which are developed using AI. This has led to the evolution of healthcare 5.0 technology that supersedes the previous healthcare technologies. The aim of healthcare 5.0 is to achieve a completely autonomous healthcare service, accounting for the inter-dependent effect of multiple health conditions of a patient. Overall, with the implementation of healthcare 5.0, patient monitoring and alarm systems can be incorporated with the use of AI (Taimoor xxxx).

2. Medical Application: Applications of nano-sensors are proposed for drug delivery and bio hybrid implants. Specifically, the self-propelled nano-motors and pumps could be used for the next generation drug delivery systems since, carriers enable self-propulsion towards the target in response to specific bio-markers (Patra et al. 2013). The drugs injected inside the body may be in the form of smart pills, which consists of a complete set of transceivers in a tiny package. The power requirement of the smart pills is fulfilled by an energy device which is a self-powered and computer-controlled medical nanorobot system. It is capable of providing digitally precise transport, timing, and targeted delivery of pharmaceutical agents to specific cellular and intra-cellular destinations within the human body (Freitas 2006). Further, wired charging is not practical on the small size transceivers; however, wireless charging through WIET can provide new dimensions, and can remove the hurdles in medical applications. In regard to the bone defects, bio-hybrid implants will be able to restore such defects. Specifically, the implementation of nano-sensor networks within the human body can benefit the medical field by providing health monitoring to monitor and control the oxygen, cholesterol level, and hormonal disorders, and provide early diagnoses of the health status (Wowk xxxx). However, it will be required to maintain an adequate level of connectivity between the nano-network and the those are able to access the transferred health information.

3. Commercial Application: WIET is useful in the advanced 6G mobile communication. Specifically, the wireless EH will be beneficial in the smart city application as will be able to charge the nodes wirelessly. In this case, the radiating WPT will offer the possibility to charge the charge wireless devices efficiently without requiring a wiring infrastructure. This will enable deployment of limited-battery communicating devices, as part of 6G IoE vision. Currently, radiating WPTs are designed assuming that the devices are located in far-field region of power radiating antenna which results in relatively low energy transfer efficiency. With migration to the 6G systems which will operate over the THz frequencies in combination with the use of large-scale antennas, future WPT devices are envisioned to operate in the radiating near-field (Fresnel) region. This will make it possible to realize beam focusing in the near-field radiating conditions, and will highlight the possible implications for the use of WPTs in future IoE networks. However, there will arise several design challenges including, simultaneous operation with wireless communications, radiating waveform considerations, hardware aspects, and operation with typical antenna architectures, which will require timely solutions. This will also enable the provisioning of applications related to security and surveillance (Zhang, et al. 2108).

4. Military Application: Wireless communication has proven to be a boon in military applications. With the UAVs having the potential to overcome deployment constraint of IoT in remote or rural areas, WIET can address battery limitations of IoT devices by transferring wireless power to the IoT devices. The integration of UAVs and WIET known as, UAV-enabled wireless powering IoT, can extend the IoT applications ranging from cities to the remote or rural areas. Specifically, UAVs will provide aerial mobility in contrast to the ground vehicles as they can be flexibly dispatched to remote, rural or disaster area where ground vehicles can hardly or cannot directly reach. Hence, UAVs will be able to foster remote IoT applications such as, environment monitoring, farm observation, and emergency communications. In such case, all the UAV vehicles will be navigated through wireless communication, and the utility will increase when wireless charging is available (Liu et al. 2020). Specifically, this will be ensured through nano-functionalized equipments wherein, WIET technology will be a viable alternative with respect to EH as it will implement energy recharging in a cordless manner. This will also provide adjustable parameters of flexibility, positioning and mobility, and enablers to energize the electric-driven devices.

5. Environmental Application: Environmental contamination is one of the important issues that the world is confronting today, and it is expanding with each passing year, leading to grave and harmful effect on the planet. Currently, the air contains various pollutants such as, CO, chlorofluorocarbons, volatile organic compounds, hydrocarbons, and nitrogen oxides. Further, water and soil are also contaminated with organic and inorganic compounds. In this regard, the major sources for water and soil contamination are sewage water, industrial effluents, random use of pesticides, fertilizers, and oil spills. Simultaneously, the rapid growth of nano-technology has gained immense interest for various applications as it has the potential to improve systems for monitoring and cleaning-up, including all the three phases of environment. Also, it can develop pollutants sensing and
6. Industrial Applications: With the maturing of wireless energy transfer, it is plausible to foresee the 6G base stations providing basic power transfer for devices, specifically, implants and sensors. The adjunct energy-centric ideas such as, energy harvesting (from RF or renewable sources) and backscatter will also be a component of 6G. Hence, as 6G will be expected to remain present ‘Everywhere’; therefore, the ‘Things’ will be smart to maintain various quality controls in regard to food, water, textile, health industry, etc. (Saad et al. May 2020). As worldwide population grows continuously, guaranteeing food security is recognized as a key challenge. Food production should be maintained despite increasingly challenging environmental and climatic conditions. In recent years, changing climatic conditions, with rise of temperatures, periods of drought or on the contrary, heavy rainfall, can ruin crops in some areas. They can also favor the appearance of diseases or parasites, also endangering the cultivation of local fruit and vegetables, or threatening species such as bees, whose role is crucial for biodiversity. Deployment of solutions enabled by 6G will rely on captors and sensors to capture the status of environmental and climatic indicators within the production areas. Further, Digital Twins will be used to monitor the evolution of the key indicators, identify the threats, and take actions to prevent the impact on production. In the case of livestock, farmers will be supported by augmented reality equipment to guide them towards individual animals which need attention. Overall, the solution will rely mainly on two parts (i) collection of data via wide set of sensors, deployed over wide areas, mainly rural, and sometimes with harsh environmental conditions from one side, and (ii) management of the data collected to visualize the instant status of crops and conditions, to monitor and prevent potential threats harmful for the food production.

7. Agriculture Application: 6G WIET has scope in good quality seed identification, crop production, and crop monitoring (Jalil ur Rehman Kazim, Tie Jun Cui, Ahmed Zoha, Lianlin Li, Syed Aziz Shah, Akram Alomainy, Muhammad Ali Imran, Qammer H. Abbasi xxxx). Specifically, smart or precision agriculture will provide an application of modern and accurate information and communications technology to automate and optimize difficult agricultural tasks and/or processes. The IoT will be the core networking technology of smart agriculture in which, through IoT, data will be collected from the sensors which will measure different parameters such as, soil, moisture, and humidity. The, these parameters will be monitored remotely via a developed mobile application to make decisions or to actuate devices. In such cases, soil moisture level can be monitored through WIET, and UAV can be used for seed disbursement (Karar et al. xxxx). As a results, workload of the farmers will be reduced with efficient use of available resources and low-cost appliances. Further, AI techniques will be implemented to analyze the agricultural and environmental data for supporting the specialists and the farmers. This, however, will require continuous screening and monitoring of the crops, automated water irrigation, and plant disease detection. Further, smart agriculture will significantly improve the agro-ecological environment, yield, and quality of agricultural products. It will also be able to minimize usage of pesticides and chemical fertilizers, thereby, alleviating the pollution of farmland, and improving the sustainability of agricultural activities. The key here will be to utilize information and communication technologies to ensure that agricultural cultivation and production is automatic and intelligent. Specifically, the 6G WIET technology will play an active role in the development of smart agriculture to drive it agriculture towards an intelligent stage.

The quality implementation of these applications, ensuring the long life of nano-devices, is possible when these devices implement the WIET technology for communication and charging purposes. In the near future, numerous new sectors will also be able to benefit from the 6G operated IoNT devices after solving the implementation challenges (Chowdhury et al. 2019). Further, the 6G IoNT devices are small size, low power nano-devices which could be charged wirelessly through the 6G network. The key issues which are required to be addressed immediately include:

1. Network architecture: IoNT devices are ultra-low power receiving devices which need WET to fulfill the energy needs. In near future, when the transmission will begin over the THz band frequency in 6G technology, then it will be necessary to realize the potential of WET.
for nano-devices after the IoT deployment (Iyer et al. 2022). To maximize the harvested energy, the antenna must be highly directional thereby allowing efficient energy beamforming. Hence, there is a need to focus on enhanced efficiency, and high gain HAP antenna design. The receiving antenna or the rectenna must operate on the frequency selective bands to widen the spectrum (Divakaran and Krishna 2019; Mathur et al. Jan. 2018; Nguyen, et al. 2018; Merz and Kupris 2016; Hameed and Moez Apr. 2017). Specifically, the challenge will exist in implementing the sensor devices for IoTs in view of the operating power supply. The RF energy harvesting will be a promising solution since the RF power will be suitable for cases where solar harvesting is not feasible. However, this will present multiple challenges including harvesting of ambient RF signals, aggregate conversion efficiency, bandwidth, and form factor. Also, a key challenge for IoT devices is to ensure such a rectenna hardware which can receive maximum power efficiently over a short wavelength (Suh and Chang 2002). Such an antenna can be designed using the large array MIMO technique; however, the interaction of large arrays and high frequency results in several implications during the WET of energy due to the small size and low power handling capabilities of the receiver.

2. Mobility management: The power supply problem of IoT devices constitutes a major challenge in the current IoT development, due to poor battery endurance and troublesome cable deployment. The efficiency of EH systems decreases quickly when distance between the transmitter and the receiver is increased (Zhang et al. Oct. 2019). This occurs due to the losses and attenuation in the path, and presents a challenge to maintain energy efficiency even when the communication occurs at nano-scale. The WPT technology, which is a promising solution, is yet to advance in view of supporting free and mobile charging such as, Wi-Fi communications. Also, the existing WPT technologies are extensively based on inductive coupling, magnetic resonance, and magnetic induction. With the view of safety, currently, these technologies only support charging devices with low power over short distances which results in users not obtaining safe charging of the devices over long distances while in transit. The solution could appear through mobile energy transfer which depends on the resonant beam charging technology which aims to improve the charging efficiency by charging devices in an adaptive manner at the devices’ preferred current and voltage levels.

3. Interference management: Another challenge exists with the transmission of low wavelength signals which can encounter several fading aspects during the process of carrying energy and information. The low wavelength signals may suffer from high scattering which can weaken the signal, and can be responsible for the loss in energy and increased interference (Shen et al. 2014; Shen and et. al.”, 2012). Thus, it is a challenge to achieve high efficiency at the lower mm-wave bands. In recent years, there has been growing research interest on developing interference-aware protocols to support multiple concurrent transmission in the next-generation wireless communication systems. Specifically, the existing techniques do not consider node cooperation while establishing the routes since motivating the nodes to cooperate and modeling that cooperation is a complex process. In addition, information regarding the cooperative behavior of a node is not directly visible to the neighboring nodes. Hence, it will be required to develop advanced techniques in which the nodes’ cooperation information is utilized for improving the performance of the WIET enabled wireless system. Another important advancement is in the form of the space-terrestrial-integrated-network which is a promising paradigm for realizing the world wide wireless connectivity in 6G wireless communication systems. However, excessive interference in such networks degrades the wireless links and results in poor performance. This presents a major hurdle in the commercial deployment of such networks. Therefore, it is crucial to investigate the interference mechanisms in such networks, and provide appropriate candidate solutions for interference management.

4. Resource management: The near-far field problem may occur during the transmission of wireless energy to the nano-devices in a 6G network because of the large Fraunhofer limit in the GHz band (Shafique et al. xxxx). This aspect should be investigated to avoid any charging issue for the wireless sensor networks, RFID tags or small nano-devices. Further, the demand for wireless communications enabled services has increased due to the deployment of wireless networks with various service capabilities. In 6G networks, massive connectivity will be a key component between devices through the cellular network, and equipments. Therefore, effective resource management techniques will be key for achieving the ever increasing demands. Resource management, which dynamically assigns the available resources considering multiple constraints is an efficient technique to efficiently handle high-quality services, new-and-emerging applications such as, virtual reality and augmented reality, holographic technology, remote surgery, and infinite connection for multiple smart devices (Gui et al. Oct. 2020). Further, the aggregate energy consumed by the 6G network will decide the network setup cost for the operators. Hence, it will be essential to manage the network resources at an optimum level simultaneously ensuring the user’s desires QoS. As a solution, renew-
able energy sources for the base stations can be utilized to lower the total power consumption of the network.

5. Security management: The deployment of 6G WIET at nano-scale must counter all the challenges in view of network security which will be a key issue that cannot be compromised (Bariah et al. 2020). The integration of sensor nodes and massive machine type communication devices in the ubiquitous 6G networks will facilitate the design of critical enabling technologies for supporting multiple data-hungry applications. By leveraging sensor nodes in the WIET 6G networks, sensitive user information can be harvested and transmitted to the receivers via the 6G enabled channels, which are often not well secured. Hence, sensitive user information can be intercepted and used unlawfully. The security and confidentiality measures used for data transmission over the WIET 6G enabled channels are limited, and are envisaged to face fiercer security challenges. In the WIET 6G networks, a new set of sensing and precise localization techniques will be implemented which will require that the user information is secured against adversarial attacks, and this needs to be implemented at the design stage. Overall, any unauthorized access of data must be completely ensured to maintain system security, and to minimize the associated risks (You et al. Jan. 2021). As a solution, viable solutions to revamp the traditional security architectures will be required. This will need the addressing of critical security challenges in the commercialized 5G and the envisioned 6G wireless systems. The research community will have to find timely solutions to the critical security and privacy issues which affect the wireless ecosystem, and also provide practical AI-based solutions.

6. Radiation management: The rapid increase in the diffusion of wireless systems has caused an increased concern regarding the potential effects on the human health due to the exposure to the electromagnetic fields which are emitted by antennas and base stations. Many studies have been conducted on the topic of electromagnetic field effects over the human body (Sharma et al. December 2013; Chen et al. 2020; Hu et al. 2017). Similar studies will also have to be conducted for the WIET 6G systems since the increase in frequency of operation will be a cause for deep radiation inside the human body. This also depend on the body conductivity, permittivity, permeability and specific absorption rate, will need to be evaluated. Also, the specific absorption rate (SAR) will have to be evaluated since an increased value of SAR raises the body temperature which finally creates hot spots and causes an increased risk to human body (Guidelines for limiting exposure to time varying electric, magnetic and electromagnetic fields 1998). As a solution, THz enabled meta-devices can be designed to control the radiation direction and coverage area of the THz beams. By rotating the metasurface, the device could promptly direct the 6G signal only to a designated recipient, thereby reducing the power leakage and enhancing privacy. This could provide a highly adjustable, directional and secure means for WIET 6G wireless communications systems.

Open areas of research

In this section, we present the identified challenges and open research problems which direct towards the exploration of future research on WIET. The WIET technology begins device charging through EH from the transmitting station to the mobile. Hence, the main challenge is to investigate the effect on transmitter charging when the receiving device discharges approximately to 98–99%. Next, with migration to 6G technology, it must be verified whether the 2G-4G operational devices will be applicable to adopt wireless charging through few changes in hardware, or an additional unit will be required (Iyer 2022; Ali, et al. 2020, 2020; Dang et al. 2020). The research community is still studying the manner in which the upgrade in technology and change in operating frequency will impact the EH process and the WIET technology. Also, the optimal quality of rectenna must be identified to efficiently charge the receiver, and whether the energy transmitter will charge idle devices, or can power other devices at finite time intervals or on-demand requires in-depth investigation. Lastly, the transmit waveform design utilizing energy harvesting and focusing on energy beam-forming for radiative near-field wireless power transfer systems needs to be addressed.

In view of research on WIET in the distant future, we envision that research will be required to widen the design considerations of low power transceivers to encounter fading and interference effects. The 6G technology research must be directed to investigate radiation hazards (considering both, ionizing and non-ionizing radiation) before implementation, and attenuation occurring at THz frequencies must be considered to effectively implement WIET in the 6G network. Lastly, considering the IoNT technology, multiple challenges will be encountered during the implementation. These will include (i) privacy and security in nanodevices, (ii) use and access of data in IoNT environment, (iii) storage of the data, and (iv) cyber-security related issues (Balghusoon and Mahfoudh 2020; Chettri and Bera Jan. 2020; Yadav and Dobre Aug. 2018; Zhang et al. Sep. 2019). Overall, the IoNT developers must consider these issues before the mass production and utilization of IoNT devices.

For the above detailed open areas of research in WIET, we propose the possible directions. Firstly, it will be key to establish a set of commands to charge the battery after a
specific threshold limit. For e.g., charging of mobile could begin only after the mobile discharges up to 30%. Further, few additional hardware units could be designed to update the 3G–4G mobiles which can support the frequency transition to operate under the 6G technology. Also, there must be the option of upgrade if the frequency is changed further. It is known that size of the antenna depends on frequency, and in general, it should be quarter wavelength of the frequency used. Hence, the rectenna must be designed such that it has narrow beamwidth and MIMO arrangement. In the near future, it will be desired to monitor battery status continuously by the transmitter. This can be implemented by transmitting an extra pilot pulse which will carry the battery status requirement. Additionally, different nanoantennas and their radiation patterns need to be investigated to gather information on waveform design and efficient patterns (Guo et al. 2021; Chengkang and zhengzhimin et al. 2020).

Further, all the indoor and outdoor models of wireless communication need to be investigated considering nanoantennas and high frequency operability simultaneously ensuring rural/urban coverage. An advantage of 6G technology is that it can communicate over low power enabled transceivers. The metric, Specific absorption rate (SAR) is used to analyze the induced radiation inside the body. The SAR is given as, SAR = \( \frac{\sigma E_i^2}{\rho} \), where \( \sigma \) is electrical conductivity, \( \rho \) the tissue density of the body material, and \( E_i \) is the electric field inside that tissue. The equation shows that low powers will impact deeper radiation to lesser extent inside human body despite operating at high operating frequency. Also, it is evident that the induced electric field increases with increase in frequency, whereas, it decreases as the incident EMF decreases. This aspect requires further investigation. It will be required to investigate the indoor and outdoor models considering THz frequency and attenuation problems. Currently, the research community is focusing immensely on connecting the wireless technology with AI to provision numerous applications, which needs further research. Lastly, the IoT infrastructure required in-depth study in view of providing accurate transmission and receiving of low power data (Zhao et al. 1905). Lastly, in Table 3, we summarize the various challenges, and also suggest possible directions which could aid in obtaining timely solutions.

### Conclusion

This article presents a detailed overview of 6G communication and the implementation aspects of the low power IoT devices. Our review suggests that 6G will operate in the THz band which however has numerous limitations. The possible 6G communication architecture is defined and various key possibilities, processing techniques, THz communication and research challenges in the 6G implementation are discussed in detail. This detailing reveals that 6G communication is suited for transfer of energy in addition to

| S. no | Various existing challenges in research of WIET | Proposed directions |
|-------|-----------------------------------------------|---------------------|
| 1     | Charging of transmitter when the receiver starts to discharge (Ramsaroop and Olugbara 2021) | Charge the battery after a specific threshold limit |
| 2     | Change required in hardware for 6G technology or 2G–4G operated devices will be applicable for wireless charging (Zhang 2021) | Update the hardware in 3G–4G mobiles |
| 3     | Effect on energy harvesting mode or WIET due to frequency translation (Huang et al. xxxx) | Support change in frequency within existing units |
| 4     | Investigate quality of rectenna to efficiently charge the receiver (Kar and Islam 2023) | Design rectenna with narrow beamwidth and MIMO arrangement |
| 5     | Investigate if transmitter will charge idle devices at finite time intervals or on-demand (“Sizing Considerations for EV Dynamic Wireless Charging Systems with Integrated Energy Storage” 2022) | Transmit a pilot pulse with battery status requirement |
| 6     | Transmit waveform design for energy beamforming (Mulders et al. 2022) | Investigate nano antennas’ radiation pattern |
| 7     | Design of low power transceivers to encounter fading and interference effects (Liu et al. 2021) | Investigate indoor and outdoor models of wireless communication considering nano antennas |
| 8     | Radiation hazards of 6G technology (Zhao et al. 1905) | Use low power enabled transceivers |
| 8.0   | The attenuation occurring at THz frequencies is of due consideration for the success of WIET in the 6G network (Kapferman and Arnon 2022 Aug 20) | As suggested in Point 7, again all the indoor and outdoor models need to be examined against THz frequency and attenuation problems |
| 8.1   | Consideration of privacy and security in IoNT technology (Aqeel et al. 2022) | Investigate IoT infrastructure enabled via AI |
transfer of wireless information due to operation in the radiative near-field region. We envision that tiny devices will be self-charged without being connected with any hardware for charging, and will only require 6G connection for charging. As the radio frequency is in THz band for 6G communication, more focus should be on health issues to minimize the radiation aspect in humans. Hence, in the article, we also suggest future areas which require research activities for successful implementation of WIET in 6G IoNT as there will be interference effects, fading, rectenna designing, orthogonal modulation etc.

In the article, existing literature has been rigorously surveyed to explore WIET implementation aspects in low power devices such as, nanodevices which require very low power for operation. This can be ensured through the transceiver providing due consideration to new modulation technologies such as, MIMO and OAM etc. The nanosensors based IoT devices have a wide application in the research field, commercial field and bio-medical field. The article also reveals huge scope of WIET in nanodevices to ensure functionality for longer period so that all such devices operating on limited battery energize wirelessly. We gather that currently, WIET is designed for the MHz band which is not sufficient to charge heavy battery devices; hence, the need is to increase band frequency for decreasing the wavelength, increasing the radiative near field region, and to reduce battery size. This will ensure that WIET is suitable for charging low power devices. The ASK or other On–Off keying methods could be utilized for transfer of energy in terms of code length, and SWIPT model WIET could be used to find the hardware needed during simultaneous transfer of energy with information.

Lastly, through this survey, the authors hope to inspire the use of wireless information energy transfer for successful implementation of 6G IoNT devices which will become a milestone for the future wireless communication.

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