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Novel Data Fusion Scheme for Enhanced User Experiences in Terahertz-Enabled IoNT

Amjad Ali
Hamad Bin Khalifa University

Muhammad Aazam
Carnegie Mellon University

Maryam M. Al Dabel
University of Hafr Al Batin

Farman Ali
Sungkyunkwan University

Ali Kashif Bashir
Manchester Metropolitan University and Institute of Engineering and Technology- Chitkara University

Shaker El-Sappagh
Galala University

Ala Al-Fuqaha
Hamad Bin Khalifa University

***Abstract*—The terahertz band, spanning from 100 GHz to 10 THz, has garnered significant attention for its potential to support ultra-high transmissions. Moreover, the Internet of Nano Things (IoNT) offers efficient data collection and analysis mechanisms to optimize nano systems performance for enhance users' experiences and comfort in daily life. In this paper, we explore the integration of IoNT and the terahertz band, envisioning ultra-high-speed transmissions in nano-communication systems for improved users' experiences. We introduce the key components of the IoNT networks based on terahertz band and discuss the challenges with respect to data fusion. Further, we propose an efficient data fusion scheme for the hierarchical IoNT networks and evaluate its performance using simulation under channel capacity, noise, path loss, and power control. We further provide comprehensive use cases in which the proposed method can be beneficial. Additionally, we discuss potential challenges, limitations, and future research directions related to our proposed solution and IoNT operating over terahertz bands.**

THE rapid advancements in nanotechnology have paved the way for the development of nano-devices, sensors fabricated on a scale of up to a hundred nanometers [1] [2]. These nano-devices, equipped with communication units, can interact with each other via short-range communication and connect to traditional

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wireless networks. This connectivity to the Internet has given rise to the Internet of Nano Things (IoNT), enabling remote monitoring and introducing a new networking paradigm. IoNT networks are capable of detecting activities at atomic and molecular levels, opening up applications in diverse fields, such as biomedical systems, environmental research, and the military. However, for nano-devices to connect and transmit data efficiently to the traditional Internet, they need to perform data fusion, forwarding sensed data to micro-sinks with minimal communication costs.

Two main technologies enable communication among nano-devices in IoNT networks: molecular communication and terahertz electromagnetic communication. In molecular communication, transmitters release small particles like molecules or lipid vesicles into a fluidic or gaseous medium, which propagate until they reach a receiver that detects and decodes the information encoded in these particles [3]. On the other hand, in nano-electromagnetic communication, nano-devices transmit and receive data packets at the terahertz band using electromagnetic radiation from components made possible by novel nanomaterials [4]. The terahertz band offers extensive throughput, theoretically capable of supporting large capacities in the order of terabits per second (Tbps), making electromagnetic communication more promising than molecular communication.

This paper explores the convergence of IoNT and terahertz band technologies, focusing on data fusion in IoNT networks operating within the terahertz spectrum. We propose an efficient data fusion scheme for hierarchical IoNT with multiple nano-devices and micro-sinks, formulated as a channel capacity maximization problem. Additionally, we discuss the potential applications of this scheme and provide a future outlook aligned with the transformative potential of cognitive and semantic computing in consumer electronics. The main contributions of our paper are as follows:

- We present a comprehensive perspective for data fusion in the IoNT networks using terahertz band. Specifically, we introduce the key components of the IoNT networks based on terahertz band and discuss the challenges with respect to data fusion.
- By exploiting the channel characteristic of terahertz band, we propose an efficient data fusion scheme for the hierarchical IoNT networks. We further propose an improved Joint Network Clustering and Resource Allocation (JNCRA) scheme to achieve efficient data fusion by combining the Markov approximation method and continuity relaxation theory.
- The effectiveness of the proposed scheme is evaluated in terms of channel capacity and compared with other state-of-the-art schemes using MATLAB.
- We present application use-cases and future outlook of data fusion in IoNT networks using terahertz band.

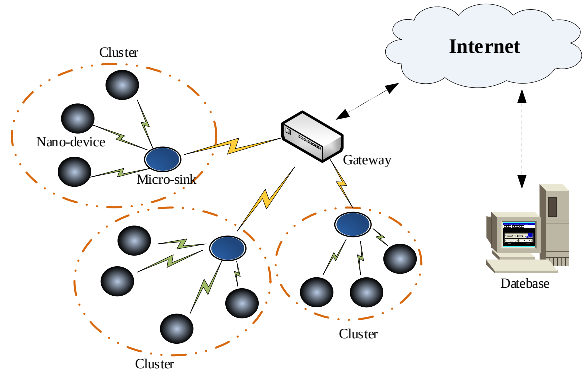

Figure 1: Illustration of terahertz-enabled hierarchical IoNT network.

The rest of the paper is organize as follows. We discuss the IoNT networks using terahertz band and data fusion in the IoNT networks in the Section II. We present the proposed efficient data fusion scheme for the hierarchical IoNT networks along with the optimization formulation in Section III. Performance analysis and simulation results are presented in Section IV. Finally, applications use cases, future research directions, and conclusion are presented in the Section V, and Section VI, respectively.

TERAHERTZ-BASED IoNT NETWORKS

Nano-communication systems refer to the communication paradigm in which nano-devices at the scale of nanometers (one billionth of a meter) transmit, receive, and process information using various communication environments, such as molecular communication, electromagnetic communication, and acoustic communication. However, IoNT envisions a network where nano-devices interact and communicate with each other to achieve complex tasks. Thus, nano-communication systems are the backbone of IoNT, facilitating connectivity and interoperability. Moreover, terahertz band, ranging from 0.1 to 10 THz, offers a unique advantage for nano-communication systems due to its high-frequency and short-wavelength properties. Thus, recent advancements in nano-technology can enable revolutionary communication paradigm for Hierarchical IoNT networks which mainly consist of nano-devices, micro-sinks, and gateway nodes as illustrated in Figure 1.

- **Nano-devices:** The nano-devices are the basic sensing and computation units, which further can communicate with each other to transmit and compute the sensed data within short range commodities. However, due to their tiny sizes, their memories and computational capacities are very limited. Therefore, they can only deal with simple tasks, such as simple computing, data storing, sensing, and actuation, etc.
- **Micro-sinks:** The micro-sinks are tiny devices which have more transmission and computational abilities than the nano-devices. Therefore, they can handle more complex tasks and also perform hybrid function by communicating using nano-communication as well as conventional communication. Hence, the nano-sink nodes can aggregate the data packets from the nano-devices and then forward to the IoT networks via gateway nodes.
- **Gateways:** The gateways serve as an interface for transmitting data packets to the Internet and can also control the IoNT network remotely over the Internet.

The structured approach of hierarchical IoNT can facilitate efficient communication and management of vast numbers of nano-devices. Hierarchical IoNT comprises multiple layers, where nano-devices communicate with micro-nodes, which then relay aggregated data to macro-gateways before it reaches the central network. Thus, hierarchical IoNT is more suitable for data transmission. Moreover, it significantly reduces communication overhead and energy consumption compared to flat architectures by localizing data processing and minimizing long-range transmissions. Furthermore, hierarchical architecture includes enhanced scalability, as it supports the seamless integration of additional nano-devices without overwhelming the network and it also provides better fault tolerance. The hierarchical model allows for more sophisticated data processing at each fusion point, improving data quality and relevance before it reaches the higher layers. Modular nature of hierarchical IoNT helps to address the potential scalability issues efficiently, in which each layer can be optimized and scaled independently. Thus, it ensures that as the network grows, the architecture can adapt by expanding the number of micro-devices and gateways, accordingly, maintaining overall network efficiency and performance.

Initially, the concept of terahertz is introduced for targeting high-speed communications and it can achieve high data rates over short distances of just a few tens of millimeters in air medium. Therefore, it is being considered as an ideal option for facilitating communications between nano-devices in IoNT networks. The authors in [5] concluded that by using terahertz band in the wireless communication scenarios, the capacity can reach as high as tera-bits per second at the level of millimeter. A geographic routing algorithm for efficient data dissemination is introduced in [6] for wireless nano sensor-based networks. Similarly, a terahertz communication-enabled dynamic multi-hop routing scheme is proposed in [7] for modeling in-body, flow-guided IoNT networks using reinforcement learning and artificial intelligence techniques. A co-operative communication for vivo nano-networks is presented in [8] to enhance the performance of nano-networks operating over terahertz bands. However, the above research works do not consider and analyze the detailed properties of terahertz band for communications of nano-devices in IoNT networks. An in-body nano-network built by nano-machines is presented in [9] to detect and potentially directly treat infectious diseases. Similarly, various ways to integrate molecular communications with terahertz communications for Internet of Every Nano Things (IoENT), human body, and acoustic networks is presented in [10].

Data Fusion Challenges in IoNT Networks

The terahertz band, which covers the frequency range from 0.1-to-10 THz can provide high bandwidth to support data fusion for nano-devices. However, IoNT networks are characterized by nano-devices with limited energy and computing resources owing to their physical dimensions [11]. Therefore, when multiple nano-devices transmit data packets to multiple micro-sinks devices in resource-limited networks, problems with load balancing and low channel capacity may arise. Moreover, due to some other constraints, such as molecular absorption, frequency selective path loss, and noise may create hurdles in the implementation of terahertz band result in fluctuations of channel capacity and further decrease the efficiency of data fusion [12].

Over the past few years, there has been a gradual increase in research focused on optimizing node assignment and capacity for efficient data fusion. A

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power control scheme is proposed in [13] to achieve reliable wirelessly powered data fusion. However, the authors in [13] have only considered the general wireless networks and their adaptability towards the IoNT networks is still an open and unresolved issue. In [14], an on-demand probabilistic polling scheme is presented for low-cost data fusion in electromagnetic-based wireless nano-sensor networks. However, the proposed scheme ignores the terahertz channel properties while channel assignment to nano-devices. Similarly, in [15] the authors proposed a reliable data gathering scheme for terahertz-enabled body area networks to facilitate healthcare applications. Nevertheless, they didn't consider the resource allocation for the data fusion in nano-sensor networks. Further to improve the data fusion efficiency and to perform channel selection in nano-communication networks, an evolutionary algorithm is introduced in [16]. The proposed algorithm brought in typically prohibitive computational complexity to the networks.

In [17], the authors proposed an algorithm to build an optimal spanning tree for reliable and effective data collection in Industrial IoT systems. The proposed algorithm combines artificial bee colony concept, genetic operators, and density correlation degree to generate a suitable tree. In [18], the authors introduced an efficient IoT-edge offloading system using Markov Decision Process (MDP) and Deep Learning (DL) concepts. The proposed system can be used both online and offline. To improve the covert throughput and reduce UAVs' propulsion energy consumption in IoT networks, the authors in [19], have formulated a max–min optimization problem in terms of minimum average energy efficiency and proposed a low-complex algorithm. In the proposed scheme, confidential data is transmitted from Access Point (AP) toward multiple users using terahertz channels. However, to further maximize the number of users served by both the backhaul link and the AP, in [20], L. Wang et al. developed a non-linear integer optimization problem and proposed a rate ratio user association and transmission scheduling algorithm. The conventional terahertz channel allocation algorithms are not applicable in Space-Air-Ground Integrated Networks (SAGIN). Therefore, to solve this problem along with tackling the issue of dynamic topology, and terahertz channel allocation, in [21], X. Yuan et al. proposed simulated annealing algorithm-based optimization algorithm using Binomial Point Process (BPP) model.

To the best of our knowledge, none of the earlier research works jointly considered the nano-device assignment and resource allocation for capacity maximization in hierarchical IoNT networks operating over terahertz band.

PROPOSED EFFICIENT DATA FUSION SCHEME FOR HIERARCHICAL IONT NETWORKS

In this section, we discuss our proposed efficient data fusion scheme for hierarchical IoNT. We first present our system model and problem formation and then present the proposed Improved Joint Network Clustering and Resource Allocation (JNCRA) procedure.

System Model and Problem Formulation

In this subsection, we present the problem formation for this paper. We use a hierarchical IoNT which comprises of M micro-devices and N nano-devices. Each nano-device follows a normal distribution and is equipped with relevant sensor-based processing and storage units along with a communication block and a power block. Moreover, each nano-device can select a micro device from the set of micro-devices M to transmit the sensed data over a single-hop communication. The micro-devices, are capable of performing complex tasks and forwarding the collected packets to the higher layers (e.g., gateway node). We assume that the Nano-devices are operating over the terahertz band that is divided into K equal narrow channels. The transmissions among different pairs of nano and micro devices take place over orthogonal terahertz channels. However, data transmission over the terahertz channels may be significantly affected by the path loss. The total channel capacity of the terahertz band can be expressed as the summation of all individual channel capacities. However, the channel capacity of each individual channel can be calculated with the help of Shannon's model.

In this paper, we assume that each nano-device can choose one micro-device to transmit its data packets by jointly considering the load balance among micro-devices and the network performance. After having decided their connections α to the micro-devices (nano-device assignment), the nano-devices need to perform resource allocation including channel selection x and power control S to improve the total channel capacity. Therefore, the channel capacity maximization problem

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can be formulated as follows:

$$\textbf{P1:} \max_{\alpha,x,S} \quad C_{THz}(\alpha, x, S)$$

Some natural constraints on $\mathbf{P1}$ are as follows:

- C1: The nano-device can connect only to one micro-device in the IoNT network.
- C2: The allocated frequency band for the nano-devices must be non-overlapping.
- C3: The total energy consumption of the system must be less than a preset fixed value.

P1 is a Mixed Integer Nonlinear Programming (MINLP) problem whose computational complexity increases exponentially with the increase in the number of binary variables. Thus, obtaining its optimal solution directly by adopting the conventional convex optimization method is not straightforward. Moreover, finding the optimal nano-device assignment x is a combinatorial optimization problem, which is challenging to solve especially when the network contains a large number of nano-devices. Therefore, it is necessary to explore some other effective methods to find its approximate solution. Thus, we decompose it into two subproblems: 1- Nano-device assignment subproblem for maximizing utility under constraint *C1*, and 2- Resource allocation subproblem for maximizing utility C_{THz}(*x, S*).

Network Clustering and Resource Allocation Subproblem

As mentioned earlier, that the nano-device assignment subproblem is a combinatorial optimization problem, which is hard to solve directly. However, the nano-device assignment results can be regarded as a specific network cluster configuration. Therefore, a new perspective to describe the nano-device assignment is provided, which is to obtain the optimal network cluster configuration from the potential configuration set through which each nano-device achieves the optimal resource allocation. Hence, we convert the nano-device assignment subproblem into the network clustering subproblem denoted as **P2** whose objective is to maximize $C_{THz}(g)$, where g is a specific network cluster configuration that belongs to cluster set **G** given as follows:

$$\mathbf{P2}: \max_{g} \quad C_{THz}(g){=}C_{THz}(g, \mathbf{x}, \mathbf{S})$$

Where $\mathbf{G}$ is an exponentially large set of network cluster configurations and makes the problem **P2** be an NP-hard problem. However, by designing the transition rate of cluster configuration based on the Markov approximation theory, we can solve it. The resource allocation subproblem which is denoted as **P3** given below is performed under a specific cluster configuration g. Therefore, the target of subproblem **P3** is to maximize utility $C_{THz}(g, x, S)$ under constraints *C2* and *C3*. **P3** is an MINLP problem that has a prohibitive computational complexity and is typically difficult to solve. However, with the help of the continuity relaxation theory and the gradient descent method, we can obtain its suboptimal solution.

$$\mathbf{P3}: \max_{\mathbf{x},\mathbf{S}} \quad C_{THz}(g, \mathbf{x}, \mathbf{S})$$

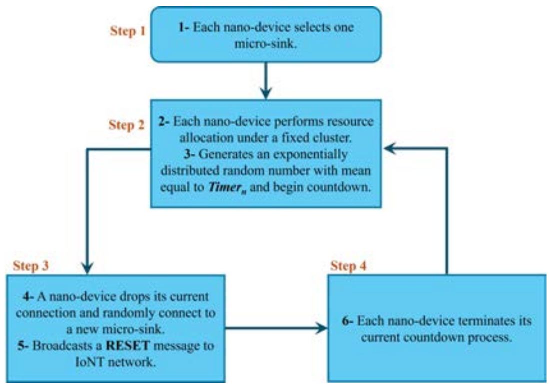

Figure 2: Step-by-step description of the proposed architecture.

Improved Joint Network Clustering and Resource Allocation (JNCRA) Procedure

In this section, we discuss the proposed distributed data fusion scheme that jointly considers network clustering and resource allocation. The working procedure of the proposed improved JNCRA scheme is presented in Figure 2. The proposed hybrid approach implements network clustering and resource allocation subproblems. In the first step of proposed scheme, each nano-device selects a micro-sink device randomly to form the original clustering configurations and then in the second step each nano device performs the frequency and power allocation under fixed clustering settings and performs a countdown on a random number generated exponentially, *Timer*$_n = e^{\varpi C_{THz}^{n_l}(g)}$ and also tracks the record of its local utility $C_{THz}^{m_l}(g)$. Where ϖ is the system parameter. The communication link under specific clustering settings g between the pair of nano-device and micro-device is denoted by n_l. In Step three, nano-device drops its current connection and randomly connects to a new micro-sink node and broadcasts “RESET” message to the IoNT network. Thus, in step 4, based on the measurements under the new configuration g', a nano-device can inform other devices when to stop the current countdown and when to start a new countdown.

PERFORMANCE EVALUATION

We implement and evaluate the performance of the proposed Improved JNCRA algorithm using MATLAB for obtaining the optimal resource allocation solution under a fixed cluster configuration and network clustering for the hierarchical IoNT networks. We performed the simulation for $M = 4$, $N = 6$, and $K = 8$. We set the maximum transmit power of nano-devices to -180 dB. We compare the performance of the proposed scheme with the; 1) traditional Distance-Based nano-device Assignment (DBA), and 2) Random nano-device Assignment (RA) schemes. In the DBA scheme, the nano-devices find the nearest micro-devices for connection and perform the resource allocation. Whereas, in the RA-based scheme the nano-device randomly selects a micro-device for connection and to perform the resource allocation.

Figure 3 shows the performance evaluation of the proposed Improved JNCRA algorithm in terms of channel capacity. Figure 3 depicts the effectiveness under variable cluster settings, and it is clear from this figure that the initial performance of the proposed scheme exhibits some limitations. However, as the network dynamically transitions to alternative clustering configurations, a substantial improvement in performance is observed. This observation suggests that the proposed scheme’s efficiency is contingent on its ability to adapt to varying cluster configurations. The consistent enhancement in performance, illustrated by the recurrent transitions in Figure 3, highlights the adaptive nature of the proposed algorithm. The initial observed drawback is mitigated by the algorithm’s agility to adapt and transition to different cluster configurations. The periodic shifts in the network’s clustering strategy contribute to a consistent upswing in performance, elucidating the algorithm’s adaptability and responsiveness. The average capacity of the proposed scheme surpasses that of other state-of-the-art schemes. The ability of the proposed algorithm to dynamically adjust and optimize its cluster configurations contributes to a consistently higher average capacity. This superiority positions the proposed scheme as a robust solution, showcasing its potential

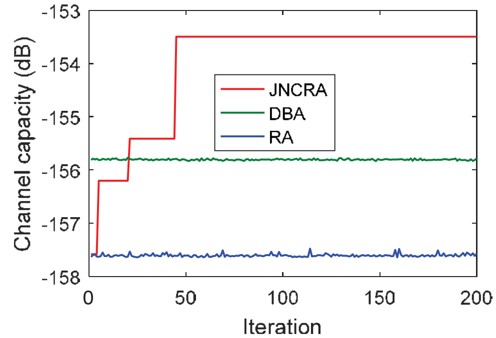

Figure 3: Channel capacity under $\varpi = 0.7$.

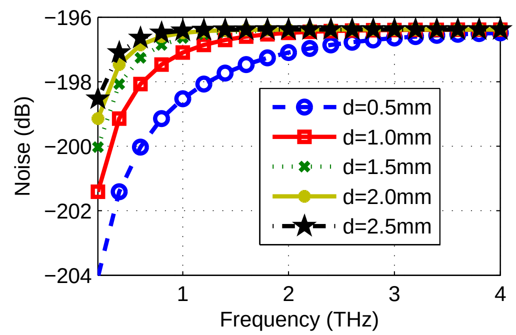

Figure 4: Noise of terahertz band.

for achieving superior channel capacity compared to existing methodologies.

The noise and path loss in the terahertz channel model are critical factors influencing the performance and reliability of communication in the terahertz frequency range. The frequency and communication distance play pivotal roles in determining these parameters. Figures 4 and 5 depict the variation in total path loss and noise in the terahertz channel model concerning frequency, considering different communication distances. The figures reveal that the Y-axis values exhibit an upward trend with increasing frequency and communication distance, particularly noticeable for path loss. This observation suggests that both distance and frequency significantly influence the characteristics of the terahertz band in communication. These findings underscore the importance of carefully considering communication distance and frequency selection in terahertz communication systems and these parameters need to optimize to mitigate the challenges posed by path loss and noise, ensuring efficient and reliable communication in the terahertz frequency range. Furthermore, the observations from Figures 4 and 5 provide valuable insights for developing strategies to enhance the performance of terahertz communication technologies. Figure 6 plots the dynamics of power control for the nano-devices. From this figures, we can

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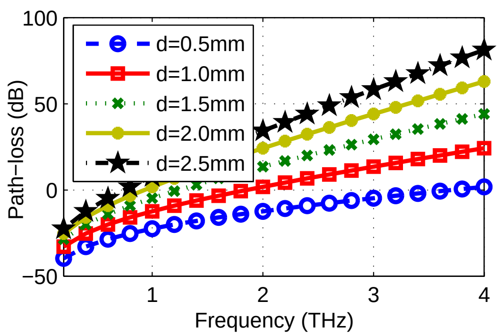

Figure 5: Path loss of terahertz band.

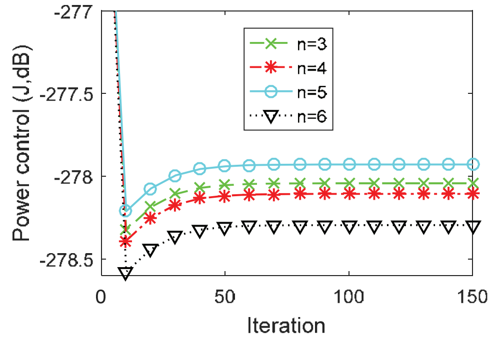

Figure 6: Power control for nano-devices.

observe that the selection possibility of the frequency and the power control will finally approach the constant values, which shows the efficient and improved convergence of the proposed scheme.

APPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

With the development of nanotechnologies, nanomachines, the IoNT will have a great impact on advanced development in almost every field in the near future. The IoNT allow the existing applications to venture into new fields by offering new techniques for the collection of fine-grained information. Our proposed hierarchical IoNT framework can enhance the performance of the conventional IoT architecture greatly from many aspects and meets the challenges of many emerging applications. In this section, we discuss and open a new door towards some emerging applications of IoNT which can improve the nanotechnology benefits in the field of intra-body healthcare systems, precision agriculture, environmental pollution monitoring system, autonomous vehicles assisted driving, and smart cities [22].

Intra-body Cognitive Healthcare Systems

Rapid detection of various viruses, tumors, and chemicals inside the body is highly critical and required as their timely detection can ensure the on-time treatment to save millions of precious lives every year. The IoNT has a great potential to enable medical devices at a nano-scale level that can be easily implanted inside the human body and can connect to the Internet to provide real-time healthcare monitoring, as demonstrated in Figure 5. The intra-body nano-devices can detect the operation state of the tissue periodically and forward the tissue's state information to the doctor's office via micro-sinks and gateway. Then, based on the received data, the doctor can perform disease detection and can better decide about microsurgery on cell or DNA level in time [23]. Moreover, the nano-communications in the IoNT can also be used in the field of microsurgery to repair or replace the damaged tissues in a controlled manner. Furthermore, combining the proposed data fusion technique with virtual reality technology can greatly improve the efficiency of remote micro-surgery.

Precision Agriculture

Traditional agricultural strategies, such as crop planting, irrigation, pest control, etc. are insufficient to meet the needs of modern society. Moreover, using chemical pesticides like DDT have also adverse effects on the environment. To enhance agricultural productivity, the IoNT can enable "precise agriculture" by integrating advanced communications means, remote sensing, and geographic information systems. Our proposed architecture can enable environment learning around the plants and the use of micro-drone to monitor the plants' growing conditions. For example, once a micro-drone finds any information about the pest, it may report the infected plant's information to the farmer by using our proposed data fusion technique and enable farmers to take the appropriate measures on time, such as sending control messages to micro-drones to release the nano-particle carrying a mediated gene for pest control.

Environmental Pollution Monitoring systems

Industrial pollution is a serious global issue that has a significant impact on both human and animal lives, and it is also a major contributor to global warming and climate change [24]. By using the proposed IoNT architecture, the detection accuracy of real-time emerging contaminants in the environment can be enhanced. For example, multiple nano-devices can be

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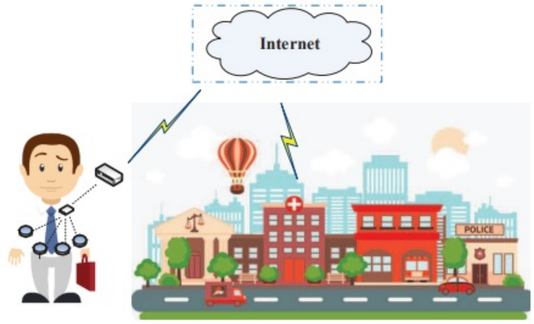

Figure 7: IoNT for intra-body healthcare systems.

used for environmental monitoring and detection, once the target contaminant is detected, the nano-devices can quickly transfer the sensed data to the control center via a proposed IoNT data fusion architecture to take the appropriate measures and actions to control the environmental pollution.

Autonomous Vehicles Assisted Driving

Autonomous vehicles with assisted driving technology use sensors, cameras, and AI altogether to help drivers to drive more safely and efficiently [25]. With the help of the proposed IoNT architecture, nano-devices can help vehicles to sense their surroundings, make decisions, and take appropriate action on behalf of the driver, such as navigating traffic, or parking, changing lanes, and deactivating engine.

Smart Cities

The proposed efficient data fusion scheme for IoNT can be applied to smart cities for traffic monitoring and management, waste management, air quality monitoring, and public safety. For example, the proposed architecture can help to aggregate data from multiple cameras, sensors, and other nano-devices to provide a comprehensive view of public spaces and identify potential safety threats.

Challenges, Limitations, and Future Directions

- Terahertz bands suffer from multi-path propagation, high-frequency selectivity, and scattering from the nano particles in the field which severely affect the signal strength at the receiver. Therefore, there is a great need for investigating the channel modeling of the terahertz band for very short-range applications.
- The IoNT requires the redesign and development of new communication paradigms and networking concepts that will be compatible with nanoscale machines. It is also of great importance to investigate the cross-layer routing protocols for IoNT coupled with the Medium Access Control layer.
- Nanorobots is a promising application of IoNT operating over THz band. Therefore, it's of great interest to explore how data fusion and resource allocation schemes can be optimized for nanorobots. Researchers can explore how edge computing and IoNT networks operating over THz band can be integrated to achieve faster and more efficient data processing. Our work exploits THz channel characteristics to maximize channel capacity. Researchers can focus on further investigating these characteristics and their potential applications in IoNT and other communication systems. It can help in the development of new nano-devices and micro-sinks that are optimized for use in THZ band and IoNT networks.
- THz communications have a limited range, and therefore, hybrid communications techniques need to be explored, such as visible light communication and radio frequency together can be used to extend the range of IoNT. Future research can investigate how to optimize the performance of hybrid communication systems for IoNT.
- Ultra-high-speed transmissions in IoNT may raise significant security and privacy issues (i.e., unauthorized data access, eavesdropping, and data tampering) due to the high volume of sensitive data exchanged. Therefore, ensuring data integrity (e.g., interception and alteration during transmission) involves implementing robust encryption methods. Whereas confidentiality can be achieved via end-to-end encryption which ensures sensitive data is only accessible to authorized users. Thus, authentication measures, such as efficient digital signatures and secure key exchange protocols are highly required to verify the identity of communicating devices and to prevent unauthorized access. Moreover, designing lightweight cryptographic algorithms tailored for resource-constrained nano-devices are highly required to balance the security and performance of IoNT networks.
- Challenges and limitations associated with propagation characteristics, hardware constraints, and regulatory considerations: High path loss, scattering, and limited penetration capabilities. Moreover, challenges in antenna design, high power consumption, and thermal management. Therefore, addressing these challenges requires advances in materials science and manufacturing technologies, efficient

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power management and energy harvesting techniques, designing efficient and compact antennas to fully exploit the potential of THz communication in nano-scale networks. Moreover, there are some significant issues with spectrum allocation, regulatory frameworks, and safety standards. The International Telecommunication Union can play an important role in defining the global standards for terahertz spectrum allocation, ensuring interoperability and minimizing interference between different communication systems. However, it mandatory that these policies should consider key factors (i.e., frequency allocation, power limits, and usage permissions) to balance the needs of scientific research, commercial applications, and public safety. Thus, compliance with these regulations is important to facilitate the safe and efficient usage of the terahertz band and promoting innovation in nano-communication while safeguarding against potential conflicts.

- Economic Feasibility and Commercial Viability of Deploying Terahertz-Based IoNT Networks: The economic feasibility and commercial viability of deploying IoNT networks operating over terahertz bands are greatly influenced by cost-benefit analysis and market trends. However, the primary cost considerations involve the development and deployment of nano-devices, terahertz-based transceivers, and necessary infrastructure required for efficient communication. The initial investment in terahertz technology is significantly important because of advanced materials and manufacturing processes required to gain the potential benefits, such as ultra-high-speed data transmission, enhanced bandwidth, and the ability to support numerous connected nano-devices, which further can bring innovation in healthcare, environmental monitoring, and smart cities. Market trends showing increased interest in terahertz technology, with raising focus on research and development projects. However, as technology matures, and economies of scale are achieved then costs will be reduced which makes the deployment of IoNT networks more viable. Thus, the commercial success of terahertz technology greatly depends on its ability to provide substantial benefits over other existing solutions, regulatory support, and the development of a robust ecosystem of compatible devices and services.
- Environmental Impact and Sustainability Considerations: The deployment and operation of IoNT networks pose significant environmental challenges and sustainability concerns. Energy consumption related to the operation of a large number of nano-devices and transceivers is a major concern which further led to increased carbon footprints. Thus, to resolve this issue energy efficiency measures, such as energy harvesting from ambient sources (e.g., solar, thermal, and vibrational energy) and the use of low-power consumption protocols need to be implemented. Moreover, eco-friendly practices need to be adopted to mitigate the environmental impacts. Furthermore, the miniaturization of devices can also contribute to reducing material usage and wastage. Thus, integrating energy-efficient technologies and eco-friendly practices is highly demanded for the sustainable development of IoNT networks while ensuring its benefits do not come at the cost of environmental pollution.
- Real-world Deployment Challenges: Practical deployment of terahertz communication in IoNT faces significant challenges where device interoperability is a serious concern, as the diverse range of nano-devices must seamlessly communicate. Therefore, standardized protocols and interfaces are significantly required. Moreover, real-world environmental factors (i.e., atmospheric absorption and scattering) can severely impact terahertz signals and reduce signal range and reliability. Additionally, integrating terahertz-based IoNT with existing IoT infrastructures requires substantial modifications to current network architectures and ensuring backward compatibility. Thus, these challenges demand robust solutions in protocol design, environmental adaptation techniques, and comprehensive testing to ensure reliable and efficient operation in diverse real-world scenarios.

CONCLUSION

In this paper, we discussed the key concepts in the IoNT networks that operate over terahertz band and analyzed the challenge of data fusion in such networks. We propose an efficient data fusion scheme for hierarchical IoNT networks with multiple nano-devices and micro-sink nodes for enhanced user experience. To achieve efficient data fusion, we build a channel model for the terahertz band and propose a joint nano-device and channel resource allocation procedure based on Markov approximation theory and continuity relaxation theory. We also explored several potential applications of data fusion for improved user experience in hierarchical IoNT networks operating over terahertz band, such as intra-body healthcare, precise agriculture, environmental pollution monitoring systems, autonomous vehicles assisted driving, and smart cities. Finally, we provide a comprehensive discussion on challenges, limitations, and future research directions related to our proposed solution and IoNT operating over terahertz bands.

REFERENCES

1. O. Gulec and E. Sahin, “Red deer algorithm based nano-sensor node clustering for iont,” *Journal of Network and Computer Applications*, vol. 213, p. 103591, 2023.
2. C. Cortés, P. Pérez, and N. García, “Understanding latency and qoe in social xr,” *IEEE Consumer Electronics Magazine*, vol. 13, no. 3, pp. 61–72, 2023.
3. L. Chouhan and M.-S. Alouini, “Interfacing of molecular communication system with various communication systems over internet of every nano things,” *IEEE Internet of Things Journal*, vol. 10, no. 16, pp. 14 552–14 568, 2023.
4. D. Jing, L. Lin, and A. W. Eckford, “Energy allocation for multi-user cooperative molecular communication systems in the internet of bio-nano things,” *IEEE Internet of Things Journal*, vol. 11, no. 9, pp. 16 303–16 313, 2024.
5. H.-J. Song and N. Lee, “Terahertz communications: Challenges in the next decade,” *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 2, pp. 105–117, 2021.
6. H. Ferjani and H. Touati, “Efficient data dissemination in electromagnetic wireless nano-sensor networks,” in *Proc. of International Wireless Communications & Mobile Computing Conference (IWCMC), Tangier, Morocco*, 2019, pp. 531–536.
7. A.-J. Garcia-Sanchez, R. Asorey-Cacheda, J. Garcia-Haro, and J.-L. Gomez-Tornero, “Dynamic multi-hop routing in terahertz flow-guided nanosensor networks: A reinforcement learning approach,” *IEEE Sensors Journal*, vol. 23, no. 4, pp. 3408–3422, 2023.
8. Q. H. Abbasi, A. A. Nasir, K. Yang, K. A. Qaraqe, and A. Alomainy, “Cooperative in-vivo nano-network communication at terahertz frequencies,” *IEEE Access*, vol. 5, pp. 8642–8647, 2017.
9. M. Stelzner, F.-L. Lau, K. Freundt, F. Büther, M. L. Nguyen, C. Stamme, and S. Ebers, “Precise detection and treatment of human diseases based on nano networking,” in *Pro. of the 11th EAI International Conference on Body Area Networks, Turin, Italy*, 2016, pp. 58–64.
10. L. Chouhan and M.-S. Alouini, “Interfacing of molecular communication system with various communication systems over internet of every nano things,” *IEEE Internet of Things Journal*, vol. 10, no. 16, pp. 14 552–14 568, 2023.
11. W. Xu, Z. Yang, D. W. K. Ng, M. Levorato, Y. C. Eldar, and M. Debbah, “Edge learning for b5g networks with distributed signal processing: Semantic communication, edge computing, and wireless sensing,” *IEEE journal of selected topics in signal processing*, vol. 17, no. 1, pp. 9–39, 2023.
12. L. Feng, A. Ali, M. Iqbal, F. Ali, I. Raza, M. H. Siddiqi, M. Shafiq, and S. A. Hussain, “Dynamic wireless information and power transfer scheme for nano-empowered vehicular networks,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 7, pp. 4088–4099, 2020.
13. X. Li, G. Zhu, Y. Gong, and K. Huang, “Wirelessly powered data aggregation for iot via over-the-air function computation: Beamforming and power control,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 7, pp. 3437–3452, 2019.
14. H. Yu, B. Ng, and W. K. Seah, “On-demand probabilistic polling for nanonetworks under dynamic iot backhaul network conditions,” *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 2217–2227, 2017.
15. F. Afsana, N. Jahan, and M. Kaiser, “An energy efficient cluster based forwarding scheme for body area network using nano-scale electromagnetic communication,” in *Proc. of IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE), Dhaka, Bangladesh*, 2015, pp. 491–494.
16. A. Afsharinejad, A. Davy, B. Jennings, and S. Balasubramaniam, “Ga-based frequency selection strategies for graphene-based nano-communication networks,” in *Proc. of IEEE International Conference on Communications (ICC), Sydney, Australia*, 2014, pp. 3642–3647.
17. A. Heidari, H. Shishehlou, M. Darbandi, N. J. Navimipour, and S. Yalcin, “A reliable method for data aggregation on the industrial internet of things using a hybrid optimization algorithm and density correlation degree,” *Cluster Computing*, pp. 1–19, 2024, doi: 10.1007/s10586-024-04351-4.
18. A. Heidari, N. J. Navimipour, M. A. J. Jamali, and S. Akbarpour, “A green, secure, and deep intelligent method for dynamic iot-edge-cloud offloading

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scenarios," *Sustainable Computing: Informatics and Systems*, vol. 38, p. 100859, 2023.

19. M. T. Mamaghani and Y. Hong, "Aerial intelligent reflecting surface-enabled terahertz covert communications in beyond-5g internet of things," *IEEE Internet of Things Journal*, vol. 9, no. 19, pp. 19 012–19 033, 2022.
20. L. Wang, B. Ai, Y. Niu, H. Jiang, S. Mao, Z. Zhong, and N. Wang, "Joint user association and transmission scheduling in integrated mmwave access and terahertz backhaul networks," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 12, pp. 15 930–15 940, 2023.
21. X. Yuan, F. Tang, M. Zhao, and N. Kato, "Joint rate and coverage optimization for the thz/rf multi-band communications of space-air-ground integrated network in 6g," *IEEE Transactions on Wireless Communications*, vol. 23, no. 6, pp. 6669–6682, 2023.
22. M. Letafati and S. Otoum, "Digital healthcare in the metaverse: Insights into privacy and security," *IEEE Consumer Electronics Magazine*, vol. 13, no. 3, pp. 80–89, 2023.
23. S. P. Ramu, G. Srivastava, R. Chengoden, N. Victor, P. K. R. Maddikunta, and T. R. Gadekallu, "The metaverse for cognitive health: A paradigm shift," *IEEE Consumer Electronics Magazine*, vol. 13, no. 3, pp. 73–79, 2023.
24. S. Zhou, A. Ali, A. Al-Fuqaha, M. Omar, and L. Feng, "Robust risk-sensitive task offloading for edge-enabled industrial internet of things," *IEEE Transactions on Consumer Electronics*, vol. 70, no. 1, pp. 1403–1413, 2023.
25. W. Ejaz, M. Naeem, S. K. Sharma, A. M. Khattak, M. R. Ramzan, A. Ali, and A. Anpalagan, "Iov-based deployment and scheduling of charging infrastructure in intelligent transportation systems," *IEEE Sensors Journal*, vol. 21, no. 14, pp. 15 504–15 514, 2020.

Amjad Ali received his Ph.D. from Electronics and Radio Engineering Department at Kyung Hee University, South Korea in 2015 and served as Assistant Professor at the Department of Computer Science, COMSATS University Islamabad, Lahore Campus, Pakistan for seven years. Currently he is working as Postdoctoral Researcher at College of Science and Engineering (CSE), HBKU, Qatar Foundation, Doha, Qatar.

Muhammad Aazam received his Ph.D. from Computer Engineering Department at Kyung Hee University, South Korea in 2015 and currently serving as Assistant Professor at the Department of Information System, Carnegie Mellon University, USA.

Maryam M. Al Dabel earned her Ph.D. degrees from the university of Sheffield, UK. She is currently an assistant professor of Artificial Intelligence and Machine Learning at the College of Computer Science and Engineering, University of Hafr Al Batin (UHB), She is also serving as vice dean of Computer Science and Engineering College at the UHB.

Farman Ali earned PhD degree in information and communication engineering from Inha university, south korea and currently working as an assistant professor in the Department of Applied AI, School of Convergence, College of Computing and Informatics, Sungkyunkwan University, South Korea.

Ali Kashif Bashir is a Professor at the Department of Computing and Mathematics, Manchester Metropolitan University, UK. He leads Secure and Intelligent Systems Research Group, Future Networks Lab, and IoT/Cybersecurity Testbed. Ali has given over 50 international keynote lectures and written over 300 scholarly articles.

Shaker El-Sappagh Ph.D. degree in computer science from the Information Systems Department, Faculty of Computers and Information, Mansura University, Egypt, in 2015. Currently she is working with Faculty of Computer Science and Engineering, Galala University, Egypt.

Ala Al-Fuqaha received Ph.D. degree in Computer Engineering and Networking from the University of Missouri-Kansas USA. He is currently a Full Professor and Associate Provost at the Information and Computing Technology division, college of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar.