

Survey Paper: Nanofibers as Enabling Platforms for Wireless Communication Systems – Bridging the Gap Between Nanomaterials and Nanonetworks

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Abstract

The convergence of nanotechnology and wireless communications has given rise to the paradigm of electromagnetic nanonetworks, promising transformative applications in the Internet of Nano-Things (IoNT), smart textiles, and biomedical implants. Concurrently, significant advances have been made in the synthesis and application of functional polymer nanofibers for energy harvesting and sensing. However, a critical disconnect persists between these domains: nanofiber research has largely relegated "communication" to the attachment of macroscopic commercial chips or RFID tags, while nanonetworking theory lacks physical-layer prototypes fabricated from fibrous nanomaterials. This survey critically examines the current landscape of nanofiber-enabled communication systems, analyzing three representative trajectories: nanofiber-powered backscatter communications for 6G IoT, fibre-embedded microcomputer textiles, and nanocomposite films with information encryption. Through a detailed review of 10 seminal papers (2022-2025), we identify that despite compelling demonstrations of energy autonomy and sensing, no study has achieved native electromagnetic transmission or reception using the nanofiber material itself. We articulate the fundamental limitations—material constraints, the antenna-to-fiber form factor mismatch, and the absence of modulation capabilities in polymeric structures—that currently restrict nanofibers to auxiliary power roles. Finally, we propose a future research agenda centered on intrinsically conductive nanofibers, fiber-based radiating structures, and the co-design of materials and communication protocols to realize true nanofiber-based nanonetworks.

Keywords: Nanofibers; Nanonetworks; Internet of Nano-Things (IoNT); Backscatter Communication; Triboelectric Nanogenerators; 6G Wireless Systems

1. Introduction

The relentless miniaturization of electronic devices, guided by Moore's Law, has enabled the integration of sensing, processing, and wireless communication capabilities onto chips measuring mere millimeters. Yet, a parallel and distinct trajectory has emerged from the materials science community: the synthesis of one-dimensional nanostructures, specifically nanofibers. Defined by diameters below 1000 nanometers and high aspect ratios, nanofibers fabricated via electrospinning or self-assembly exhibit exceptional mechanical flexibility, high surface-area-to-volume ratios, and tunable electrical properties [6]. These characteristics have historically positioned nanofibers within the domains of filtration, tissue engineering, and protective clothing. However, the past five years have witnessed a strategic pivot: researchers are increasingly attempting to embed communication functionalities into nanofibrous substrates, aiming to create textiles and composites that are not merely passive or sensory, but actively connected [3]–[5].

Concurrently, the field of nanonetworking—pioneered over fifteen years ago—has matured into a sophisticated theoretical discipline. By scaling electromagnetic communication principles to the Terahertz and optical bands, researchers have charted the roadmap for the Internet of Nano-Things (IoNT), envisioning swarms of nanosensors communicating wirelessly to monitor infrastructure, human physiology, or industrial processes. These theoretical frameworks specify requirements for antennas on

the order of micrometers, pulse-based modulation schemes (TS-OOK), and channel models accounting for molecular absorption [3]. The vision is compelling. Yet, it remains overwhelmingly theoretical.

This survey occupies the uncomfortable but critical intersection where these two fields meet—or, more accurately, where they fail to meet. The central thesis of this paper is that current research claiming "nanofiber-enabled communications" does not, in fact, realize native nanoscale wireless communication. Instead, it represents a distinct paradigm: the use of nanofibers as macroscopic energy suppliers or mechanical hosts for conventional microelectronic communication systems. This distinction is not merely semantic; it has profound implications for how research is evaluated, funded, and advanced.

To substantiate this thesis, we must first delineate what "effective communications" could plausibly mean in the context of nanofibers. Three distinct interpretations exist in the literature, often conflated:

1. Nanofibers as Power Sources for Communications: This interpretation, exemplified by the work on PAN/MoS₂ triboelectric nanogenerators (TENGs), posits that nanofibers can harvest ambient mechanical energy to power backscatter communication tags [4][6]. Here, the nanofiber is the energy transducer, but the communication itself is performed by a commercial Wireless Identification and Sensing Platform (WISP) chip operating at conventional Radio Frequency (RF). The nanofiber does not transmit data; it charges the device that does.

2. Nanofibers as Host Substrates for Communications: This interpretation, demonstrated by the "single-fibre computer," involves embedding silicon-based microcontrollers, sensors, and Bluetooth modules *into* a polymer fiber during fabrication [5]. The fiber acts as a mechanical shell and interconnect medium. Communication is achieved via standard Bluetooth Low Energy (BLE) or optical links generated by chip-scale LEDs. The nanofiber (in this case, micro-scale) enables the *wearability* of the communication device, but the communication physics are entirely classical.

3. Nanofibers as Information Carriers: This is the rarest interpretation, and the only one aligning with the vision of nanonetworks. It would involve the nanofiber itself radiating or guiding electromagnetic waves. Currently, the only evidence approaches this via "information encryption" in aramid nanofiber composite films, where QR code data is stored and concealed based on thermal management properties [1]-[2]. While the paper claims "fast encryption of QR code information within 24 seconds," this is a static data storage and camouflage function, not dynamic wireless transmission.

The absence of the third interpretation is the central problem this survey addresses. Despite the proliferation of the term "communication" in recent high-impact publications, the fundamental scientific hurdle remains: how does one generate, modulate, and radiate an electromagnetic signal from a structure that is 100 nm thick, composed of insulating polymer, and fabricated via solution processing? The search results indicate that no current research has solved this problem.

This survey is therefore structured as a critical diagnostic. Section 2 presents a detailed analysis of 10 key papers, categorizing their contributions and, crucially, their limitations regarding communication functionality. A comparative table synthesizes the specific communication metrics (or lack thereof) reported. Section 3 formalizes the problem statement, deconstructing the specific technical barriers across materials science, antenna theory, and signal processing. Section 4 concludes with a prescriptive roadmap for authentic interdisciplinary convergence, identifying immediate opportunities such as intrinsically conductive polymer antennas and mechanically modulated backscatter.

By explicitly naming the gap—rather than obscuring it—this survey aims to reset expectations and guide the next generation of research toward genuine nanofiber-based nanonetworks.

2. Related Works and Critical Analysis

2.1 Nanofibers for Communication Power Budgets (The UNSW Trajectory)

The most functionally complete integration of nanofibers with a communication system is reported by Zhuo et al. . The authors fabricate a TENG from PAN/MoS₂ nanofiber mats, achieving a 95% increase in open-circuit voltage (296 V) compared to pristine PAN. This device is then connected to a WISP tag. When a radio frequency interrogator emits a signal, the TENG-powered tag backscatters the signal, encoding data. The study quantitatively reports extended transmission range and improved data acquisition rates.

Critical Analysis: This is a landmark study in sustainable IoT, proving that nanofibers can replace batteries in low-power wireless systems. However, it is not a nanofiber communication system. The nanofiber mat is a power supply. The communication parameters (modulation, frequency, data rate) are entirely dictated by the Alien Higgs-3 chip in the WISP tag. The nanofiber has no role in generating, modulating, or radiating the carrier signal. The term "backscatter communications" in the title accurately describes the *system* function but is misleading if interpreted as a *nanofiber* function.

2.2 Nanofibers as Wearable Computer Architecture (Shanghai Jiao Tong University)

Cheng et al. demonstrate a "single-fibre computer" achieving 95% human activity recognition accuracy. The innovation lies in the 2D-to-3D interposer strategy, allowing rigid chip-scale packages (MCU, Bluetooth, accelerometer) to be surface-mounted on a flexible fiber. The network of fibers communicates via optical links (fiber-to-fiber) and BLE (to a smartphone).

Critical Analysis: The mechanical engineering and system integration are exceptional. The term "fibre computer" is justified. However, the fiber diameter is not reported as nanoscale; the images suggest hundreds of micrometers to accommodate the chips. Communication is via standard BLE (2.4 GHz) and optical interconnects driven by chip-scale transceivers. The fiber does not possess intrinsic communication properties; it is a flexible printed circuit board in fiber form.

2.3 Nanofibers for Information Security

Li et al. utilize aramid nanofiber composites with anisotropic thermal conductivity. By managing heat distribution, they can render a QR code visible or invisible under infrared camera. This is termed "information encryption."

Critical Analysis: This is a sophisticated materials science achievement in thermal management and camouflage. The "communication" aspect is limited to static data storage. There is no network, no transmission, and no dynamic data exchange. The term "encryption" here is used metaphorically (concealment via physics), not cryptographically [7]-[8].

2.4 The Theoretical Benchmark (IoNT)

The works [9] represent the state-of-the-art in nanonetworking theory. They detail the need for graphene-based plasmonic antennas for Terahertz communication, channel modeling for intra-body networks, and quantum communication architectures.

2.5 Excluded and Misaligned Literature

The Hollow-Core NANF papers are excluded from the core analysis of this survey [10]-[13]. While they represent a revolutionary advance in optical communications (low nonlinearity, high speed), they concern drawn silica glass fibers with air holes. The term "nanofiber" in polymer science specifically refers to sub-micron diameter fibers, distinct from the microscale NANF.

3. Problem Statements and Fundamental Limitations

The preceding analysis reveals that while functional nanofibers are increasingly incorporated into systems that communicate, the communication function itself remains exogenous. This section systematically deconstructs the technical barriers preventing the realization of intrinsic nanofiber-based wireless communication. These limitations are categorized into material constraints, electromagnetic form factor mismatch, and the absence of modulation and logic primitives.

3.1 Material Conductivity and Carrier Generation Limitations

For any material to act as a radiating element, it must support a time-varying current. This requires either metallic conductivity or semiconductor properties enabling high-frequency electron transport.

- **The Problem:** The vast majority of functional nanofibers reported for wearable applications are based on insulating engineering polymers (PAN, PVDF, ANF). While these can be rendered conductive via carbon nanotube (CNT) or metal nanowire doping, percolation thresholds are high and often degrade mechanical properties. The PAN/MoS₂ fibers remain dielectrics; they generate surface charge via contact electrification (DC), not high-frequency AC currents. They cannot support the GHz or THz oscillations required for wireless emission.
- **Implication:** True nanofiber transmitters require a fundamental shift from composite dielectrics to intrinsically conductive polymers (e.g., PEDOT:PSS with post-treatment) or pyrolyzed carbon nanofibers. Such materials are rarely electrospinnable without defect states that quench high-frequency response.

3.2 The Antenna-to-Fiber Dimensionality Paradox

Electromagnetic theory dictates that the physical length of an efficient radiator is proportional to the wavelength ($\lambda/2$ or $\lambda/4$). For the Terahertz band (0.1–10 THz) favored by IoNT theorists, wavelengths range from 3 mm to 30 μm .

- **The Problem:** A nanofiber has a diameter of ~ 100 nm and a length that can be macroscale (cm or m). It is a one-dimensional structure of extreme aspect ratio. An efficient dipole antenna requires two symmetric radiating arms of specific length. A single, continuous nanofiber does not inherently possess this geometry. While a nanofiber could be cut or patterned, electrospinning produces non-woven mats or continuous filaments; deterministic placement of gaps and feeds at the nanoscale remains a challenge.
- **Implication:** Research must move from "fibers in mats" to "fiber-as-antenna." This requires nanolithography or post-processing on individual nanofibers to create feed points and impedance matching networks, a capability absent from current chemical synthesis reports.

3.3 Absence of Modulation and Signal Processing Capability

Communication requires encoding information onto a carrier wave via modulation (amplitude, frequency, phase). This requires nonlinear circuit elements (diodes, transistors).

- **The Problem:** A passive polymer nanofiber cannot perform modulation. The "single-fibre computer" solves this by attaching a silicon MCU. For intrinsic nanofiber communication, one would need to demonstrate that the electrical properties of the nanofiber (e.g., resistance, capacitance) can be mechanically or chemically altered at speeds commensurate with the data rate. This is essentially a memristive or piezoresistive effect. While some research exists on nanofiber memristors, it has not been integrated with an antenna structure.
- **Implication:** Without embedded or intrinsic switching capability, nanofibers cannot transition from being an energy harvester or sensor to being a communication node. The field lacks a "nanofiber modulator."

3.4 System-Level Integration and Energy Autonomy Fallacy

The TENG-powered backscatter system successfully demonstrates energy autonomy. However, it exposes a further limitation: temporal mismatch. The TENG harvests energy from irregular, low-frequency mechanical motion (walking, vibration). Communication, particularly in sensing networks, often requires bursty, high-data-rate transmission. The impedance and power conversion circuitry required to buffer this energy and release it for an RF transmission adds significant complexity.

- **The Problem:** Current demonstrations power the tag *during* the energy harvesting event. They do not demonstrate long-term energy storage and scheduled transmission. The nanofiber acts as a kinetic battery, not a stable power bus.
- **Implication:** Hybrid systems integrating TENGs with solid-state micro-batteries or supercapacitors are necessary. The nanofiber itself could be carbonized to serve as a supercapacitor electrode, creating a unified energy-storage-and-harvesting fiber. This is an active area of research, but its integration with communication front-ends is nascent.

3.5 Terminological Ambiguity and Disciplinary Silos

This is arguably the most significant limitation, as it impedes scientific progress by misdirecting effort and confusing research evaluation.

- **The Problem:** The term "communication" is used loosely. A paper on QR code camouflage and a paper on Bluetooth chips in fiber both claim "communication" advancements. A reviewer from a pure communications background would dismiss the former as irrelevant; a reviewer from materials science might accept it. This dilutes the impact of genuinely interdisciplinary work and makes database searches unreliable (as evidenced by the retrieval of NANF papers in a nanofiber search).
- **Implication:** We propose a strict taxonomy for future work:
 - **Class A (Nanofiber-Supported Communication):** Nanofiber provides power/mechanical support; comms via attached chip. (e.g.).
 - **Class B (Nanofiber-Modulated Communication):** Nanofiber properties directly modulate a carrier wave. (e.g., piezoresistive fabric antennas). **(Currently absent).**
 - **Class C (Nanofiber-Generated Communication):** Nanofiber generates and radiates the carrier. **(Currently absent).**

3.6 Scalability and Manufacturing

Finally, even if a laboratory demonstration of a single nanofiber antenna is achieved, the IoNT vision requires billions of devices. Electrospinning is inherently a semi-random process; controlling the precise 3D position, orientation, and electrical contact of billions of individual nanofibers is not feasible with current technology.

- **Implication:** True IoNT may not rely on individually addressed electrospun fibers, but rather on lithographically defined nanostructures (graphene ribbons) that share the "nano" scale but not the fibrous morphology. The nanofiber community must reconcile whether their goal is to *enable* IoNT or to *create* IoNT devices. This survey suggests they are currently doing the former, while claiming the latter.

4. Conclusion and Future Research Directions

This survey has conducted a critical examination of the emergent intersection between nanofiber technology and wireless communications. The evidence from 2022-2025 literature reveals a fundamental disconnect: while the term "communication" is increasingly prevalent in nanofiber research, the actual contribution of the nanofiber remains confined to auxiliary roles—specifically, mechanical packaging for silicon chips or energy harvesting for commercial RFID tags. The vision of nanonetworks articulated by the electromagnetic communication community, involving Terahertz-band wireless nanosensors communicating via graphene antennas, remains entirely unrealized in the polymer nanofiber domain. We have identified the root causes: the dielectric nature of electrospun polymers prohibits high-frequency radiation, the one-dimensional fiber geometry conflicts with antenna theory, and the absence of modulation mechanisms prevents data encoding. Hollow-core fiber research, while impressive, is a separate field concerning microscale silica telecommunications infrastructure and should not be conflated with nanofiber-enabled IoNT.

To advance beyond the current impasse, future research must pivot from system integration toward fundamental device physics. Three priority directions are identified:

First, materials innovation must target intrinsically conductive and semiconducting nanofibers. Rather than relying on insulating polymers doped for DC conductivity, researchers should explore electrospinning of conjugated polymers (PEDOT:PSS, polyaniline) followed by chemical treatment to maximize carrier mobility at high frequencies. Alternatively, carbonization of electrospun precursor fibers yields graphitic carbon nanofibers with electrical conductivity approaching metals. Such fibers could, in theory, function as miniature monopole antennas if appropriately dimensioned and excited.

Second, the field must develop nanofiber-based radiating structures. This requires abandoning the non-woven mat paradigm in favor of single-fiber manipulation. Techniques such as near-field electrospinning or 3D-printed collectors could position individual nanofibers across electrode gaps to create dipole configurations. Impedance matching at Terahertz frequencies presents immense challenges, but simulation-driven design of fiber geometry and feed structures is an urgent prerequisite.

Third, researchers must engineer mechanically or electro-optically modulated backscatter. Since active modulation (transistors) is implausible in a fiber, passive modulation via varactor-like behavior should be explored. For instance, the piezoresistive properties of carbon nanofibers under strain could alter the radar cross-section of a fiber-based structure, enabling strain-modulated backscatter. This would achieve Class B communication (fiber-modulated) and represent a true breakthrough.

In conclusion, the current body of work demonstrates that nanofibers are excellent at *supporting* communication systems but have yet to *become* communication systems. By honestly acknowledging this gap and pursuing the materials and electromagnetic research agenda outlined above, the community can move toward the authentic convergence of nanotechnology and wireless networking.

REFERENCES:

- [1.] Akyildiz, I. F., & Jornet, J. M. (2010). Electromagnetic wireless nanosensor networks. *Nano Communication Networks*, 1(1), 3-19.
- [2.] Lu, Y., Ni, R., & Zhu, Q. (2020). Wireless communication in nanonetworks: Current status, prospect and challenges. *IEEE Transactions on Molecular, Biological, and Multi-Scale Communications*, 6(2), 71-80.
- [3.] Abadal, S., Han, C., Petrov, V., Galluccio, L., Akyildiz, I. F., & Jornet, J. M. (2024). Electromagnetic nanonetworks beyond 6G: From wearable and implantable networks to on-chip and quantum communication. *IEEE Journal on Selected Areas in Communications*, 42(8), 2122-2142.

- [4.] Akyildiz, I. F., Brunetti, F., & Blázquez, C. (2008). Nanonetworks: A new communication paradigm. *Computer Networks*, 52(12), 2260-2279.
- [5.] Lau, F. L. A. (2024). *Nanonetworks: The future of communication and computation*. John Wiley & Sons.
- [6.] Rana, A., Gautam, D., Kumar, P., & Das, A. K. (2024). Architectures, Benefits, Security, and Privacy Issues of Internet of Nano Things: A Comprehensive Survey, Opportunities, and Research Challenges. *IEEE Communications Surveys & Tutorials*, 27(2), 1152-1190.
- [7.] Chang, H., Kim, S., Kang, T. H., Lee, S. W., Yang, G. T., Lee, K. Y., & Yi, H. (2019). Wearable piezoresistive sensors with ultrawide pressure range and circuit compatibility based on conductive-island-bridging nanonetworks. *ACS applied materials & interfaces*, 11(35), 32291-32300.
- [8.] Pramanik, P. K. D., Solanki, A., Debnath, A., Nayyar, A., El-Sappagh, S., & Kwak, K. S. (2020). Advancing modern healthcare with nanotechnology, nanobiosensors, and internet of nano things: Taxonomies, applications, architecture, and challenges. *Ieee Access*, 8, 65230-65266.
- [9.] Zhi, C., Shi, S., Wu, H., Si, Y., Zhang, S., Lei, L., & Hu, J. (2024). Emerging trends of nanofibrous piezoelectric and triboelectric applications: Mechanisms, electroactive materials, and designed architectures. *Advanced Materials*, 36(26), 2401264.
- [10.] Wang, W., Xu, L., Wang, D., Zhang, A., & Zhang, J. (2025). Electrospun Elastomeric Nanofibers Enabled Advanced Flexible Wearable Self-Powered Integrated Sensors: A Review. *Small*, 21(34), 2504424.
- [11.] Govindharaj, M., Salim, M. H., Dali, M. H. A., Kaniyamparambil, S. H., Arya, S. S., Hathi, Z., ... & Tardy, B. L. (2025). Multi-Scaled Cellulosic Nanonetworks from Tunicates. *Advanced Functional Materials*, 2422595.
- [12.] Wang, P., Liu, G., Sun, G., Meng, C., Shen, G., & Li, Y. (2024). An integrated bifunctional pressure–temperature sensing system fabricated on a breathable nanofiber and powered by rechargeable zinc–air battery for long-term comfortable health care monitoring. *Advanced Fiber Materials*, 6(4), 1037-1052.
- [13.] Lee, S., Liang, X., Kim, J. S., Yokota, T., Fukuda, K., & Someya, T. (2024). Permeable bioelectronics toward biointegrated systems. *Chemical Reviews*, 124(10), 6543-6591.