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Self-Powered Optical Communication: Opportunities, Challenges and Future Prospects

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Modern optical communication systems, from fiber-optic networks to optical wireless communications, are fundamentally constrained by their reliance on external power sources. This perspective highlights explores the transformative potential of self-powered optical communication (SPOTComm), a paradigm-shift technology in which optical communication is achieved without relying on external power supplies. SPOTComm opens new avenues for building sustainable and maintenance-free communication nodes for the Internet of Things (IoT), particularly in power-constrained or remote environments. In light of this, recent major breakthroughs in this interdisciplinary field and identify key challenges that impeding SPOTComm's wider adoption are reviewed. Specifically, three technical routes that establish SPOTComm link: 1) energy harvester-driven optical transmission, 2) direct mechanical-to-optical conversion, and 3) self-powered optical modulation are categorized. To enlighten future development, we offer a forward-looking vision of how materials and device innovations can overcome current limitations, ultimately enabling optical communication systems that are not only high-performance and secure, but also self-sustaining, scalable, and pervasive.

1. Introduction

Optical signal carriers have revolutionized communication technology, spanning from high-capacity fiber-optic telecommunication backbones to short-range visible and infrared links in consumer devices.[1] However, traditional optical communication systems depend on continuous external power sources, such as electrical grids or batteries, to power light sources, modulate signals, and drive photodetectors. This dependency creates a critical vulnerability: any instability in the power supply can easily paralyze communication channels.[2] Although commercial optical networks are engineered with backup power and redundancies, the growing demand for pervasive connectivity for remote sensors, wearables, and smart devices exposes scenarios where reliable power sources are not guaranteed.[3] For instance, powering billions of distributed Internet of Things (IoT) sensors with batteries or wiring is suboptimal from both a maintenance and sustainability standpoint.[4] This challenge motivates a new paradigm of self-powered optical communication (SPOTComm), wherein the optical carrier is generated, modulated, and received using energy harvested from the device's environment rather than from a dedicated electricity source.

SPOTComm refers to any optical link that partially or entirely operates by harvesting ambient environmental energy. On the transmitter side of SPOTComm, the light source and modulation unit are powered by energy collected from the surroundings, such as mechanical motion, human interactions, or weather conditions. On the receiver side, the photodetector achieves optical-to-electrical signal conversion without a bias voltage supplied by an external power source. SPOTComm promises the development of sustainable, autonomous, and ubiquitous communication systems, enabling the deployment of communication nodes without the lifetime limitations and maintenance demands associated with battery depletion. Moreover, SPOTComm link could also enhance reliability in critical emergency services where the electrical grid is unavailable. By eliminating reliance on external power, these systems minimize maintenance needs, reduce electronic waste, and facilitate communication in locations or situations previously deemed infeasible.

Realizing SPOTComm requires interdisciplinary integration of energy harvesting technologies, communication engineering, and optical electronics devices. In the context of SPOTComm, mechanical energy harvesters such as piezoelectric and triboelectric nanogenerators (P/TENGs) convert vibrations, motion, or tactile agitation into electrical energy, which is then utilized to power optical emitters.[5] Moreover, recent advances in optical emitters, particularly perovskite light-emitting diodes (LEDs), have significantly enhanced electrical-to-optical conversion efficiency, providing direct benefits to SPOTComm architectures.[6] Ambient solar energy can also be harnessed for SPOTComm.

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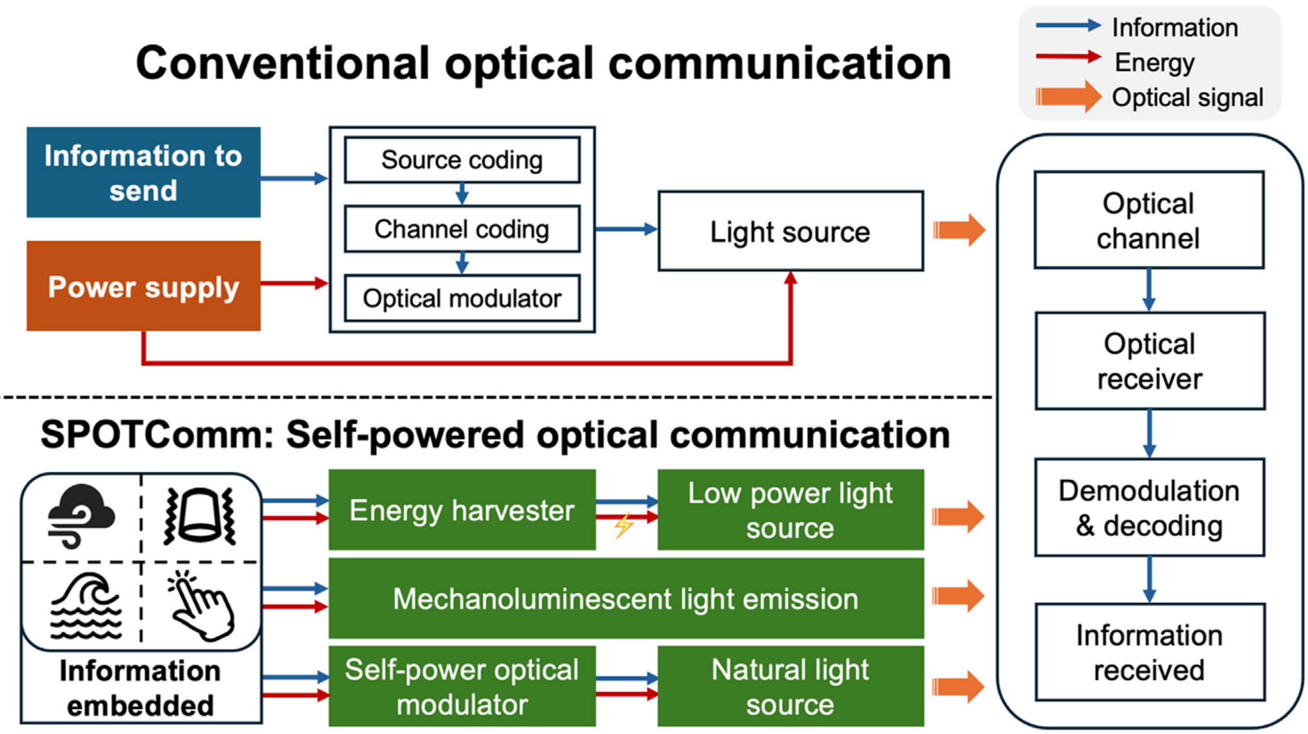

Figure 1. Block diagram of conventional and self-powered optical communication (SPOTComm) systems.

Photovoltaic devices, typically solar cells, can harvest environmental light to power an optical emitter, or even serve dual purposes as both a power source and an optical signal receiver.[7] Beyond generating electricity to power stand-alone light-emitting devices, researchers are also exploring novel integrated self-powered light emitters. Emerging mechanoluminescent[8] and electroluminescent[9] materials offer a more direct pathway to self-powered optical signal emission. These materials can emit photons in response to mechanical deformation or electric fields applied by a nanogenerator.[10] For example, stress-activated mechanoluminescent polymers can produce light flashes under mechanical deformation, and when coupled with a TENG or PENG output, can function as an optical signal source that converts mechanical energy into optical emission without traditional electronics.[11] Additionally, self-powered optical modulators offer an alternative solution for optical signal transmission. A self-powered optical modulator manipulates an existing light source with minimal energy input.[12] For instance, a liquid-crystal optical modulator requires only a small amount of energy to alter the transparency or reflectivity of a material,[13] thus encoding data onto ambient light. Such passive optical signal transmitters significantly reduce the energy demand on active optical emitters by leveraging pre-existing illumination sources.[14]

Looking ahead, SPOTComm stands at an exciting intersection of photonics, materials science, and electronics engineering. This emerging paradigm is crucial for the future, addressing a key challenge of the information age: connecting an ever-growing number of devices and sensors in a sustainable, autonomous manner.[15] SPOTComm could form the backbone of future battery-free sensor networks, enabling real-time data exchange in smart cities, environmental monitoring, and wearable electronics without the labor and environmental cost of battery replacements. It also offers a path to robust, fault-tolerant communication by leveraging locally available environmental energy to sustain information exchange when conventional infrastructure fails. In the following sections of this perspective, we examine recent advancements, identify the remaining challenges, and highlight opportunities for innovation at the nexus of energy and communication. By fostering interdisciplinary collaboration and advancing self-sustaining electronic systems, SPOTComm is poised to play a pivotal role in shaping a more sustainable and interconnected future.

2. SPOTComm Architecture

The defining distinction between SPOTComm and traditional optical communication lies in the relationship between energy and information, as shown in **Figure 1**. In SPOTComm, the energy input is intrinsically linked with information transmission. In conventional architectures, energy supply and information encoding are decoupled processes, where energy supply serves merely as an enabler, powering components that encode separately generated information onto optical carriers. In SPOTComm, the harvested energy either directly constitutes the information carrier or drives the information encoding process, representing a paradigm shift in how communication systems can operate sustainably and autonomously. This convergence of energy harvesting and optical information transmission introduces a new communication paradigm, allowing systems to operate autonomously, sustainably, and resiliently in environments where continuous external power is impractical or unavailable.

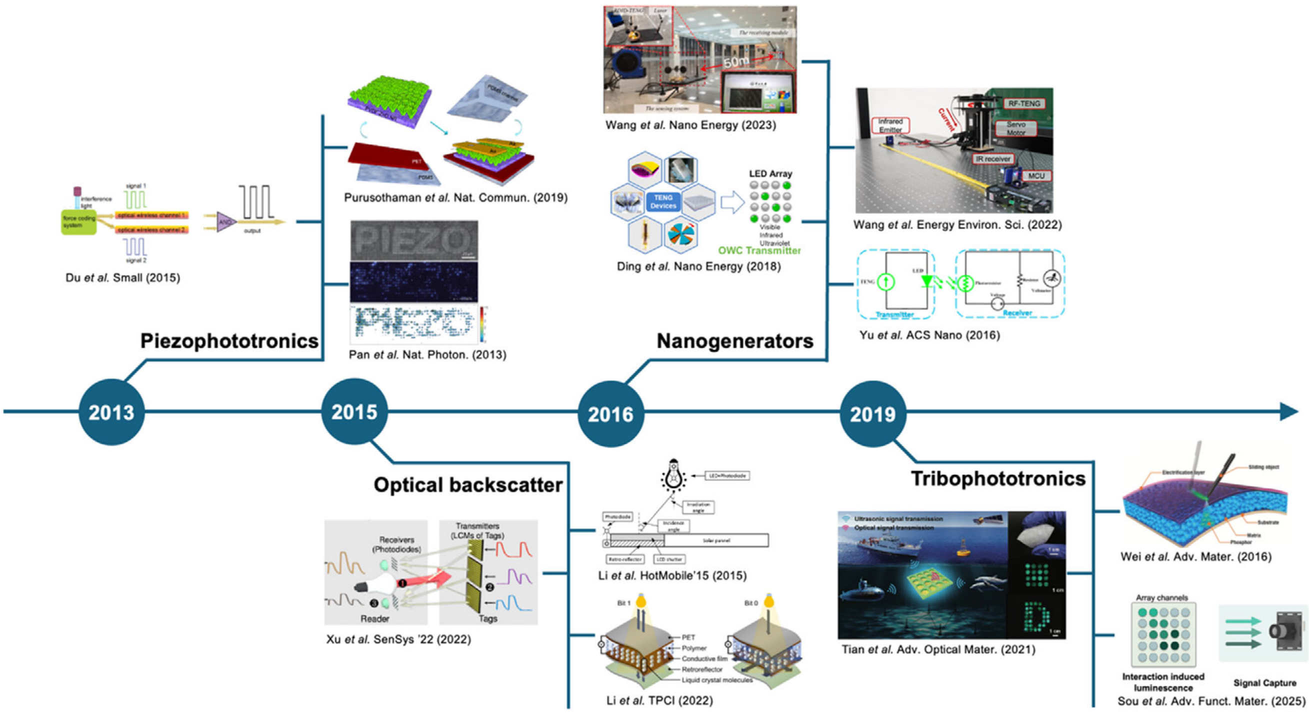

Figure 2. Technology enablers in SPOTComm. Reproduced with permission.[5,9,16] Copyright 2013, Springer Nature; Copyright 2015, John Wiley and Sons; Copyright 2019, Springer Nature; Copyright 2015, Association for Computing Machinery; Copyright 2022, Association for Computing Machinery; Copyright 2022, Springer Nature; Copyright 2016, American Chemical Society; Copyright 2018, Elsevier; Copyright 2022, The Royal Society of Chemistry; Copyright 2023, Elsevier; Copyright 2016, John Wiley and Sons; Copyright 2021, John Wiley and Sons; Copyright 2025, John Wiley and Sons.

In this perspective, we broadly classified SPOTComm systems into three major categories according to their mechanisms of energy harvesting and optical signal generation:

1) Energy harvester-driven,
2) Direct light emission via mechanoluminescence or electroluminescence materials,
3) Self-powered optical modulation.

These categories are supported by various technologies such as nanogenerators, photonic materials, and optical backscatter devices, as shown in **Figure 2**.

Advances in tribophototronics, piezophototronics, and integrated energy-communication platforms have driven diverse SPOTComm designs, each suited to specific energy sources, conversion methods, and application needs. Building on these technologies, **Figure 3** summarizes the core working mechanisms of SPOTComm systems, illustrating energy and information flow in three representative architectures: harvested-energy-driven emitters, direct mechanical-to-light conversion, and ambient light modulation. **Table 1** presents a quantitative comparison across key metrics such as data rate, bandwidth, optical output power, communication distance, and energy-conversion efficiency. This framework unifies the operational diversity of SPOTComm systems.

2.1. Energy Harvester-driven SPOTComm

In energy harvester-driven SPOTComm systems, external energy inputs are first converted into electrical signals through energy harvesting devices, such as TENGs, PENGs, or photovoltaic cells. These harvested electrical signals subsequently drive conventional optical transmitters, including LEDs or semiconduc-

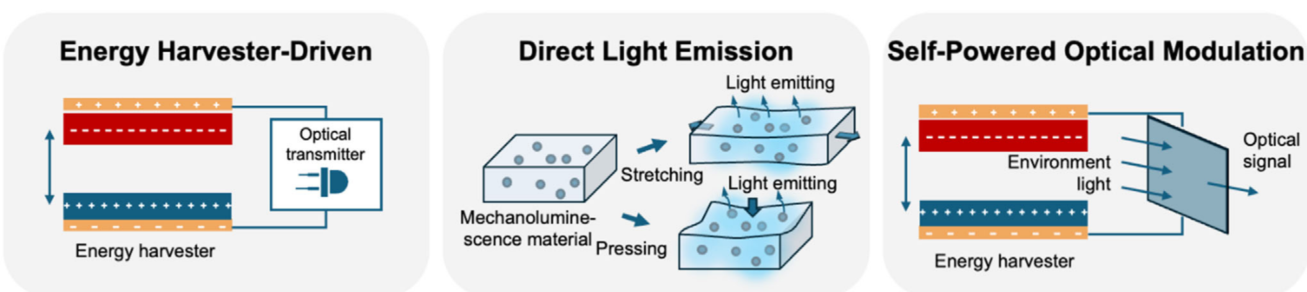

Figure 3. Working mechanisms of SPOTComm schemes.

Table 1. Quantitative comparison of representative SPOTComm systems.

Scheme type	Data rate	Bandwidth	Optical output power	Communication distance	Energy-conversion efficiency
Energy harvester-driven (TENG-LED)[16f,17]	≈10–100 bps	<1 kHz	μW–mW	≈1–50 m	≈1–10%
Direct light emission (TIEL)[18]	≤1 bps	<100 Hz	nW–μW	<1 m	<1%
Self-powered optical modulation[19]	≈10–100 bps	0.1–1 kHz	Subject to light source	≈1–10 m	>10% (modulation only)

tor lasers, to produce optical signals that encode the original information.

Mechanical energy harvesters, particularly TENGs, have demonstrated observable potential in enabling self-powered optical wireless sensing and communication.[20] TENG-driven visible light communication (VLC) established the paradigm of powering an LED using harvested mechanical energy for sensing and communication.[16f] Water droplet-driven TENGs were employed for weight sensing via position modulation, where gravity-induced changes in droplet impact angles altered the optical output.[21] Huang et al. reported a tactile interactive system where simply tapping a surface, thereby activating a TENG, generates coded optical signals through an LED-photodetector pair, allowing wireless control of appliances without any external power supply.[17] Moving forward, researchers developed TENG-LED array capable of encoding complex information through spatial modulation.[5a] Similarly, arrays of optimized nanogenerators have been used to send optical Morse-code messages.[22] More complex information can be encoded by more advanced device designs. For example, a TENG-powered quantum dot LED (QLED) with memory effects was used to modulate both light intensity and emission wavelength, enabling frequency-encoded communication.[23] Additionally, innovations in TENG-driven VLC systems for package counting,[24] humidity sensing,[25] temperature sensing,[26] vibration monitoring[27] have expanded the application scope. Infrared light although invisible, but robust to environment light interference and has been widely used in household applications have its SPOTComm realization via TENG,[28] such as infrared remote controller[5b] and infrared vibration sensing.[29] Beyond LEDs, TENG-driven laser sources demonstrate superior performance.[30] A 50-meter-long-distance wireless optical communication is achieved by TENG-powered 625 nm wavelength laser diodes.[16j]

Besides mechanical energy harvesting, solar energy presents another avenue for SPOTComm systems. Organic photovoltaic devices have been developed that simultaneously harvest solar energy and support high-speed, multiple-input multiple-output (MIMO) OWC links.[31] Additionally, reconfigurable self-powered MIMO optical communication systems based on solar photodetectors were demonstrated, operating without any battery assistance.[32] High-bandwidth InGaN-based self-powered photodetector arrays have further advanced the capabilities of VLC through efficient energy harvesting and optical signal reception.[33] To enhance system integration, optocouplers based on solar cells were proposed, allowing the simultaneous harvesting of light energy and optical signal transmission.[34] In addition, recent progress in optical multiplexing, reconfigurable photonic processing, and integrated optical sensing-communication with LEDs has further demonstrated the potential of optical systems to support both high data throughput and energy-aware designs.[35]

Another related concept that further enhances the synergy between energy harvesting and communication is Simultaneous Lightwave Information and Power Transfer (SLIPT). SLIPT systems utilize a single optical carrier to deliver both energy and information, typically by employing solar cells or photodiodes to simultaneously decode data and harvest power from the incident light.[36] While conventional SLIPT systems often rely on externally powered transmitters, the architectural philosophy aligns well with energy harvester-driven SPOTComm, particularly in cases where photovoltaic receivers serve dual functions.[37] Recent SLIPT studies have demonstrated the feasibility of achieving both high energy harvesting efficiency and data throughput in visible or infrared communication settings.[38] These strategies, including dynamic beamforming, mobility-aware transmission optimization, and coordinated transmitter–receiver control, offer valuable insights for enhancing the co-design of energy and information transfer in SPOTComm applications.

The energy harvester-driven conversion strategy enables the reuse of mature, high-efficiency optical emitters while eliminating the need for continuous power supplies. Such systems are particularly attractive for applications where ambient mechanical or light energy is abundant but stable electrical infrastructure is absent.

2.2. Direct Light Emission SPOTComm

In direct light emission SPOTComm systems, environmental mechanical inputs trigger light emission through mechanoluminescence materials without an intermediate electrical circuit. Emerging mechanoluminescence materials, also known as electroluminescence materials, can instantaneously convert mechanical energy into light signals, bypassing the need for traditional power management circuits and simplifying system architectures.

The fundamental mechanisms underlying triboelectric-induced electroluminescence (TIEL) occur when electron transitions during contact electrification are shown to generate photon emission.[39] Building on this principle, practical implementations of TIEL for optical communication have been demonstrated. For example, dynamic TIEL was used for visual sensing applications,[16g] serving as a platform for mechanically modulated optical signaling. Color modulation based on TIEL represents a particularly promising direction for optical signal encoding. TIEL was incorporated into flexible, self-powered pressure sensors to achieve tunable emission colors, thereby enabling frequency or multi-channel optical

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communication.[18a] Similarly, a stretchable bilayer luminescent composite material was developed, combining mechanical flexibility with triboelectric-induced color-tunable emission, suitable for self-powered variable-color communication systems.[18b] Furthermore, triboelectric-driven color control devices were demonstrated,[40] providing an adaptive means for dynamic optical signal modulation in response to mechanical stimuli.

Despite the promising developments in TIEL-based direct light emission SPOTComm systems, it is important to note that most reported studies have not provided quantitative measurements of light output in standard photometric units such as lumens or candelas. This is largely due to the diversity in material compositions, device structures, and mechanical input conditions across different works, which makes cross-comparison and normalization difficult. Nevertheless, such quantitative characterization is essential for evaluating the practical feasibility of these systems in real-world optical communication applications—particularly in terms of visible distance, signal-to-noise ratio, and data transmission reliability. Future studies are encouraged to incorporate standardized optical measurement techniques, such as integrating sphere measurements or calibrated photodetectors, to report luminous flux, luminance, and efficiency under defined mechanical stimuli. Establishing such benchmarks will help translate laboratory-scale innovations into deployable, self-powered optical communication technologies.

Further material innovations have expanded the versatility of direct light emission SPOTComm systems. Mechanoluminescent phosphorescent materials embedded in smart wood composites were used to realize multi-stimuli-responsive optical modulation, supporting robust self-powered optical signal generation and transmission.[41] A rotary-driven triboelectric optical sensor system was also developed, enabling instantaneous discharge-triggered optical signals suitable for dynamic sensing and communication.[16j] A super elastic and negative triboelectric polymer matrix has been recently developed for high-performance mechanoluminescent.[42]

Complementary progress in electroluminescent materials powered by mechanical harvesting has further enhanced the field. For example, electroluminescent devices driven by TENGs demonstrated stable optical signaling without external power sources.[11] Handwriting-based human-machine interfaces utilizing triboelectrification-induced light emission were proposed,[43] highlighting opportunities for intuitive user interaction. Additionally, triboelectrically driven dual-color light emission,[44] underwater triboelectric electroluminescence arrays for information transmission,[16h] and fiber-shaped triboelectric light-emitting systems have broadened the design space for flexible, wearable, and underwater optical communication.[45]

Piezophototronic effects have been applied to enhance VLC systems,[16a] offering an integrated approach where mechanical deformation modulates optical emission characteristics. Combining such effects with tribophotonic mechanisms could further optimize the performance of self-powered optical communication architectures.

This direct conversion pathway offers a highly robust and efficient strategy for realizing self-powered communication nodes, particularly in extreme or infrastructure-scarce environments. The simplicity of the mechanism also enhances system durability and miniaturization, making it promising for applications such as wearable electronics, underwater sensing, and environmental monitoring.

2.3. Self-Powered Optical Modulation-enabled SPOTComm

Self-powered optical modulation-enabled SPOTComm systems utilize optical modulators that require minimal energy to function. In this architecture, a pre-existing external light source, such as ambient sunlight or indoor lighting, is dynamically modulated to encode information without the need for independent light generation.[46] The modulation of light in these systems can be achieved using triboelectric and piezoelectric devices, supporting a variety of schemes such as temporal, spatial, and spectral modulation tailored to the available energy and communication demands, as illustrated in **Figure 4**.

For a triboelectric device, Wang et al. proposed TENG-power electrowetting-based optical switches, enabling dynamic modulation of light paths for remote optical signal control.[47] Programmable optical prisms, driven by TENG outputs, were further demonstrated to enhance beam steering and energy efficiency in optical transmission, offering new opportunities for adaptive optical communication.[48] Liquid crystal (LC)-based devices have emerged as an important class of self-powered optical modulators. Triboelectric-driven control of liquid crystal orientation allowed for dynamic optical modulation suitable for information display and encryption communication applications.[19a] In particular, cholesteric liquid crystals were manipulated via triboelectric fields to achieve visual enhancement and secure optical information transmission.[14] Additionally, triboelectrically driven smart windows with tunable transparency were developed, enabling dynamic modulation of transmitted light intensity for VLC systems.[19b] Reflective optical modulators powered by triboelectric effects have also been explored. Intelligent reflectors capable of modulating reflectance under mechanical stimuli were demonstrated,[49] offering an effective approach to enhance the sensitivity and stability of optical communication links.

Researchers have pursued piezoelectric and piezophotonic strategies for dynamic light control in self-powered systems. For instance, piezoelectric inversion-structured OLEDs gated by nanowire arrays were developed, achieving a high current switching ratio through the piezo-phototronic effect, providing a promising route toward low-power optical modulation for self-powered communication.[50] ZnO-based optical resonators have further expanded the potential of self-powered optical modulation. Tuning the whispering gallery modes of ZnO microwires via strain-controlled refractive index modulation allowed for precise dynamic control of laser wavelength, suitable for optical communication and sensing.[51] Moreover, single-mode lasing in ZnO microcavities was dynamically regulated by synergistic piezoresistive and piezoelectric polarization effects, providing new strategies for highly sensitive optical switching.[52] Dynamic meta-surfaces powered by piezoelectric micro-electromechanical system (MEMS) structures have also emerged as powerful platforms for self-powered optical signal processing. Full-range birefringence control with high polarization conversion efficiency and fast response times was achieved,[53] offering low-power solutions for advanced optical signal manipulation. In addition, thin-film Lead Zirconate Titanate (PZT)-based MEMS tunable

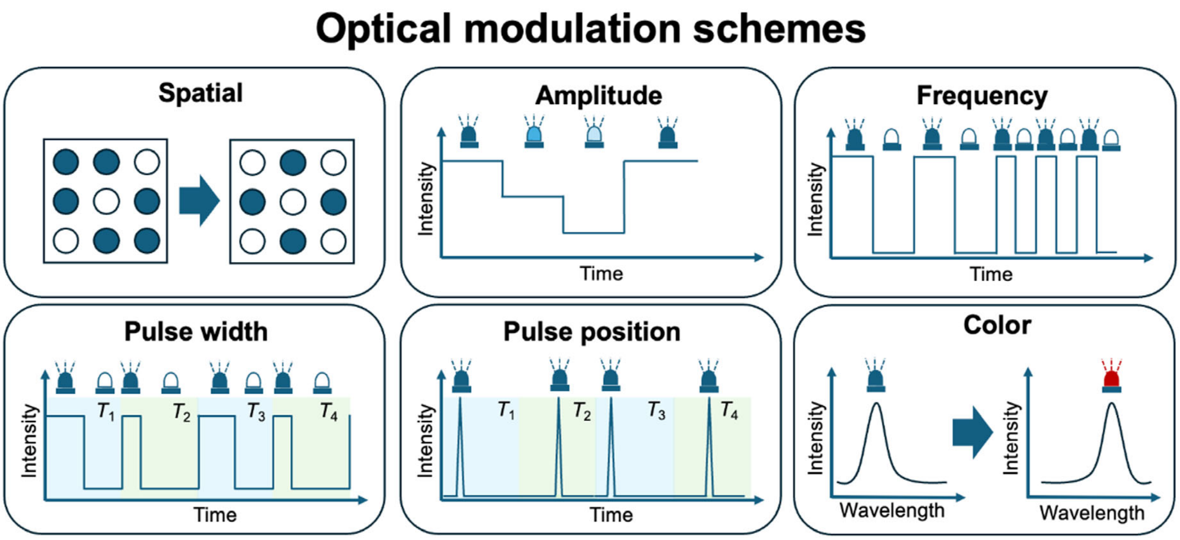

Figure 4. Modulation schemes in a self-powered optical communication system.

dielectric meta-surface lenses were realized, enabling large displacements and focal length adjustments at low voltages, ideal for energy-efficient optical tuning in SPOTComm systems.[54] Finally, transparent piezoelectric meta-surfaces with multiple mechanical deformation modes were developed for adaptive lensing and image stabilization, further broadening the capabilities of self-powered optical communication devices.[55]

By dynamically leveraging minimal ambient energy, SPOTComm systems based on optical modulation mechanisms can achieve sustainable, low-maintenance, and flexible optical communication. This approach dramatically reduces system energy consumption, extending device lifetime and enhancing deployment flexibility, particularly in environments rich in ambient illumination.

3. Challenges and Future Opportunities

Each self-powered optical communication approach inherently involves certain trade-offs in performance and practicality. By combining multiple energy harvesting modalities and employing ultra-low-power optical components, researchers can improve both the reliability and transmission capacity of self-sustaining optical links. Furthermore, incorporating novel energy materials for improved harvesting efficiency and storage, developing next-generation emitters with reduced power thresholds and multi-band capabilities, and optimizing modulation architectures can help overcome present limitations. **Table 2** summarizes the key challenges, emerging opportunities, and long-term visions for advancing self-powered optical communication systems, providing a roadmap from present limitations to future innovations.

3.1. Challenges

Despite notable progress, significant practical challenges persist in SPOTCom systems. A fundamental issue remains the limited optical signal power generated by existing self-powered technologies. Typically, TENGs or PENGs, generate intermittent, pulse-like outputs, which constrain the achievable communication distance, system capacity, and data transmission rate. These limitations directly affect the reliability and robustness of communication systems, especially under unpredictable environmental or operational conditions. Furthermore, ambient energy sources exhibit considerable instability in real-world deployments; for instance, solar energy fluctuates significantly with weather conditions and shading from surrounding infrastructure. Similarly, mechanical harvesting is influenced by variability in human or machine movements. Such an inconsistent energy supply poses critical constraints on continuous and stable data transmission, presenting significant hurdles in maintaining consistent operation.

Another critical challenge is the sensitivity of self-powered optical communication systems to environmental interference. Optical signals inherently suffer from susceptibility to ambient lighting interference, atmospheric conditions, dust, or physical obstructions, potentially resulting in significant data loss or communication interruptions. While various modulation techniques have been developed to mitigate interference effects, the problem becomes more pronounced in self-powered systems where the energy available for sophisticated signal processing or adaptive filtering is limited. Consequently, robust strategies that provide reliable optical communication under diverse and harsh environmental conditions without substantial additional energy consumption are urgently required. As summarized in **Figure 5**, current SPOTComm systems typically exhibit limited transmission range, low data rate, single functionality, and reliance on single energy sources or modulation strategies, highlighting the urgent need for comprehensive advancements.

3.2. Next Stage Opportunities

Effectively addressing these challenges calls for significant multidisciplinary innovations, especially in materials development and system-level engineering. Advancements in

Table 2. Scaling challenges, opportunities, and future visions.

Challenges	Next stage opportunities	Future visions
Signal and transmission limitations	Material and device innovations	Advanced communication capabilities
• Small optical signal power • Short transmission distance • Low data rate • Small communication capacity	• High-performance energy harvesters • Low-power optical emitters (VCSELs, low-threshold LEDs) • Efficient optical signal conversion strategies	• High-bandwidth, long-distance communication • Multi-spectrum optical communication (UV, visible, IR) • Chip-level integration for compact systems
Energy and stability constraints	Hybrid energy systems and power management	Reliable and sustainable deployments
• Unstable energy harvesting (mechanical, solar, environmental fluctuations) • Limited energy storage capacity • Intermittent operation and power supply instability	• Integration of multiple ambient energy sources (e.g., hybrid solar–TENG systems) • Development of high-efficiency power management circuits • Advanced energy storage systems (supercapacitors, batteries)	• Large-scale applications in smart cities and remote sensing • Stable, maintenance-free operation under harsh environments
Functional and standardization gaps	System integration and standard development	Autonomous intelligent networks
• Single-function communication nodes • Sensitivity to environmental interference (dust, occlusion, lighting) • Lack of standardized protocols and interoperability	• Multi-functional nodes combining sensing, energy harvesting, and communication • Self-adaptable encoding and modulation strategies • Establishment of IEEE standards for self-powered communication	• Optical-RF hybrid self-powered networks • Self-adaptable communication systems • Standardized ecosystem supporting commercialization

high-performance energy harvesting devices designed for superior ambient energy extraction and conversion efficiency are fundamental. Recent advancements in perovskite photovoltaics, flexible organic solar cells, and advanced TENGs promise substantial improvements in energy conversion efficiency, power density, and operational stability. Moreover, the innovation of low-power optical emitters such as vertical-cavity surface-emitting lasers (VCSELs) and low-threshold LEDs represents a crucial pathway to reduce the power threshold for optical signal generation. Additionally, novel optical signal conversion strategies that integrate photovoltaic detection with direct optical-to-electrical modulation can further optimize energy usage, thereby enhancing the operational capacity and transmission reliability of SPOTComm systems.

Hybrid energy systems refer to architectures that combine multiple ambient energy sources to mitigate the intermittency of individual harvesters. A typical example is the integration of TENGs, which harvest sporadic mechanical energy, with photovoltaic cells that offer relatively stable output under sunlight. By coupling these complementary sources, hybrid solar–TENG systems provide more continuous power for stable optical communication. Beyond this, other hybrid schemes—such as PENG–TENG combinations for motion situations, solar–thermoelectric pairs for temperature-varying environments, and RF–optical energy fusion—have shown promise in broadening deployment scenarios. These designs improve energy accessibility and functional adaptability in dynamic or heterogeneous conditions. Besides, power management circuits with higher efficiency and ultra-low power consumption capabilities can significantly improve the reliability and stability of harvested energy storage and utilization. Techniques such as maximum power point tracking (MPPT)[56] and ultra-efficient rectification circuits[57] can help optimize the harvesting process.

In parallel, strategic innovations in communication engineering are essential. The investigation of more efficient and adaptive information encoding and modulation techniques tailored specifically for low-power conditions could markedly improve the achievable data rates and communication quality. Methods such as pulse position modulation,[58] differential encoding,[59] and intelligent dynamic modulation[60] strategies capable of adapting in real-time to changing energy availability could significantly enhance energy efficiency. Moreover, establishing comprehensive theoretical models that explicitly define and predict the relationship between harvested energy, channel capacity, and data rates can enable better optimization of system resources and performance. Such theoretical frameworks are indispensable for guiding the practical engineering and deployment of future SPOTComm technologies.

Advancing SPOTCom will greatly benefit from real-world, small-scale deployments in favorable initial scenarios. Real-world deployments, including short-range industrial IoT systems, smart home environments, and wearable healthcare devices, offer optimal initial testing grounds. These scenarios typically demand relatively low-data-rate communication such as alarm signals, periodic status updates, or simple control signals, making them ideal candidates for self-powered solutions. Such early-stage deployments not only demonstrate feasibility and operational reliability but also provide valuable insights and datasets to refine energy harvesting, communication protocols, and system integration, thereby laying a strong foundation for subsequent expansion into broader applications.

3.3. Future Impacts

Looking ahead, considerable opportunities exist for scaling self-powered optical communication into large-scale, interconnected network infrastructures. An envisioned future includes large-scale deployments where individual SPOTComm nodes collaborate to form integrated communication infrastructures. In such

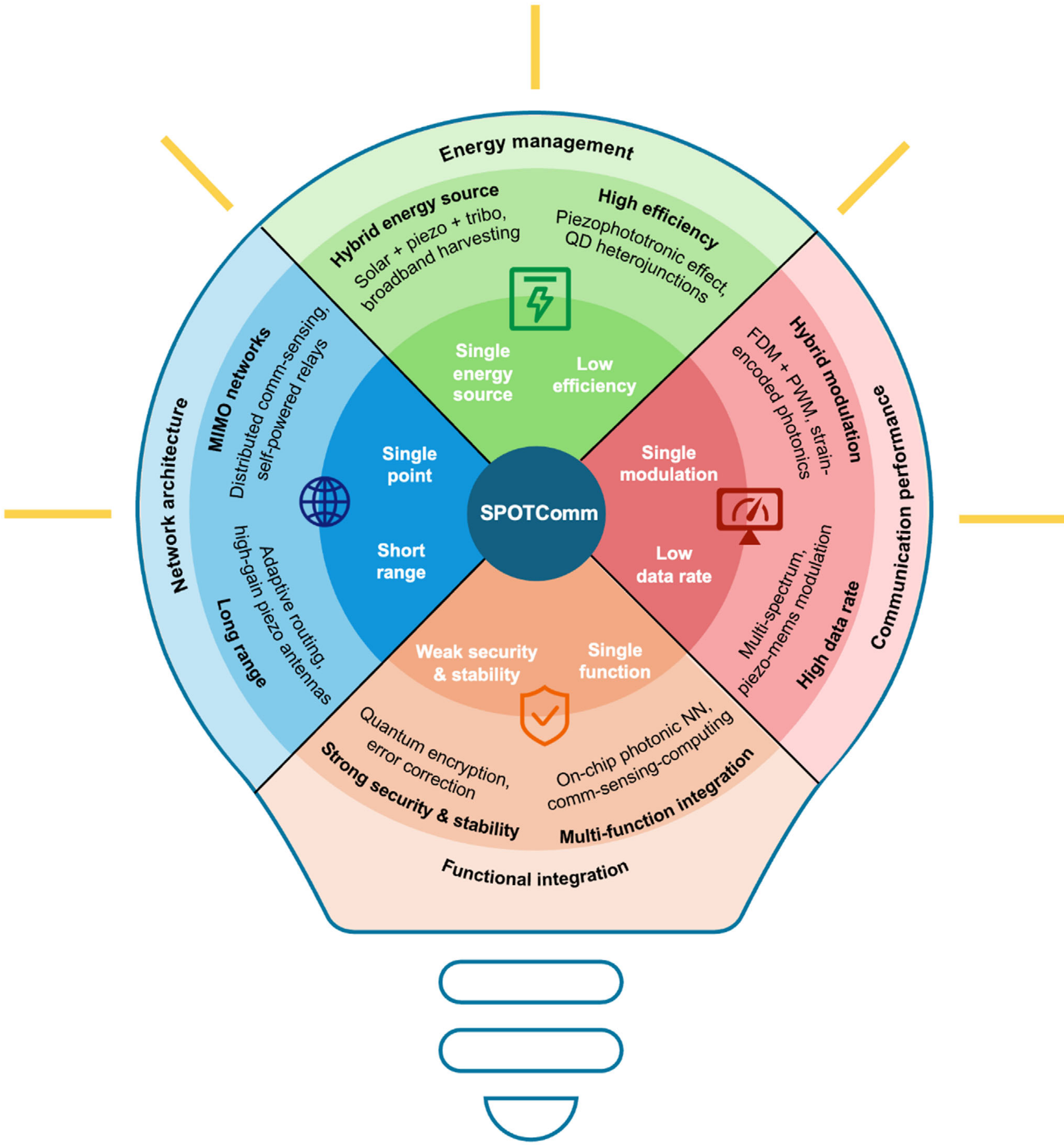

Figure 5. Evolution pathways of SPOTComm functions.

scenarios, hybrid networking integrating SPOTComm nodes with conventional wireless systems such as Wi-Fi, and future 6G or 7G networks would enhance connectivity, provide multi-hop routing capabilities, and significantly broaden coverage areas. Applications in smart city infrastructure as well as distributed environmental monitoring networks in remote or rural regions exemplify the significant societal benefits of such large-scale SPOTComm implementations.[61] Eventually, these integrated networks may deliver high-bandwidth data transmissions, effectively supporting emerging IoT demands while reducing environmental and maintenance burdens.

The successful maturation of SPOTCom technologies will further require robust standards and cohesive ecosystem development. Establishing formal IEEE standards addressing communication protocols, power management interfaces, energy harvesting specifications, and security regulations will be essential for ensuring interoperability, reliability, and security across diverse devices and networks. Industry engagement, through proactive investment and partnerships, will further promote the production of highly reliable and consistent devices, accelerating commercial adoption and fostering broader societal acceptance. Such coordinated standardization and industry efforts will significantly streamline integration, reduce costs, and enhance the overall robustness of SPOTComm systems, encouraging widespread adoption.

Finally, continuous advancements in novel device technologies promise to dramatically extend the capabilities of self-powered optical communication. Innovations such as chip-level integration of harvesting and optical communication functionalities will significantly reduce device size, energy consumption, and deployment complexity. Advances towards multi-spectrum communication, including ultraviolet, visible, and infrared regions, will further expand application domains and operational capabilities. Moreover, the development of self-adaptable encoding and modulation strategies that dynamically optimize performance based on environmental conditions will significantly enhance communication robustness and reliability. Ultimately, these technological advances promise a future wherein SPOTComm forms an integral and ubiquitous component of global communication infrastructures, facilitating sustainable, autonomous, and resilient information networks that seamlessly integrate into everyday environments.

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Conflict of interest

The authors declare no conflict of interest.

Keywords

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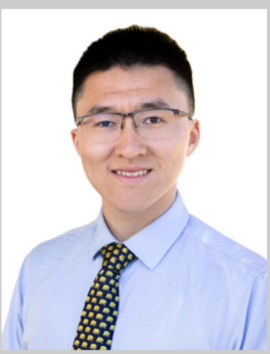

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