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Original article

Wired and Wireless Physical Media Technologies: Comparative Analysis of Throughput, Reliability, Energy Efficiency, and Deployment Constraints

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Abstract
Physical media technologies play a crucial role in modern communication networks, enabling rapid data transmission among interconnected devices and systems. Given how cloud computing, IoT, smart cities, industrial automation, and real-time apps are exploding in popularity, there's a huge need now for top-notch communication infrastructure. As a result, picking the right medium for your needs is super important if you want efficient, dependable, and affordable network ops. In this paper, we dig into a thorough comparison of wired and wireless techs used today in networking. We look at big wired players like Ethernet and Fiber Optic, plus the newest wireline transceivers. At the same time, we also check out the latest in wireless tech - think Wi-Fi 6/7 and Private 5G. We focus on essentials like throughput, latency, and reliability, along with energy efficiency, scalability, costs, and security. constituting essential parameters for infrastructure evaluation when picking what fits your specific needs. Our paper also looks at the pros and cons of each tech in various networking situations and apps. We cover current issues too, like signal interference, bandwidth limits, high infra costs, and energy use. Plus, we review recent research to point out what areas need more study. Lastly, we discuss exciting new trends, such as combining optical and wireless tech, using AI to optimize networks, and going green. The findings will help researchers, network designers, and decision-makers pick the right communication tech for today's complex networking setups.
Keywords. Wired and Wireless, Physical Media Technologies, Energy Efficiency.

Introduction

For years, wired and wireless communication had distinct roles. Wired connections ruled for high-capacity, reliable data needs, whereas wireless media was restricted to mobile applications. However, this distinction has been obscured due to new tech advances. Wi-Fi 7 (IEEE 802.11be) with its Multi-Link Operation and super-fast Private 5G networks are leading this charge. These innovations enable wireless to hit multi-gigabit speeds, rivaling old Ethernet norms directly [1,2]. Technology's always advancing, so now we've got wireless closing in fast on wired's traditional high-speed turf. Technological changes push us to rethink Layer 1 media choices [2]. Network designers can't depend on old assumptions because wireless now matches the speed of physical cables. Wired systems have also advanced, hitting Terabit speeds to stay relevant. This paper does a thorough comparison of these new physical media. We look at real-world data to see if today's wireless options really work as well as wireline ones. Our analysis explores whether the natural limits of open space keep wire-based setups necessary.

Media Classification and Physical Characteristics

Data transmission rules in any communication system come from the physical layer's properties. In computer networking, we split transmission media into two main types. So, the actual limits and abilities depend on those basic characteristics, not some higher-level stuff.: Guided (Wired) Media and Unguided (Wireless) Media.

Guided Media

This category covers twisted-pair copper cabling and silica-based optical fiber. It keeps electromagnetic or optical signals inside a physical path. This containment greatly reduces signal loss and provides strong protection from external interference. It also creates a secure channel that's hard to access [2].

Unguided Media

On the flip side, Wi-Fi and cellular networks broadcast RF signals through the air without any guidance. This means there's no need for physical setup, and devices can move around freely. However, that makes them easier to interrupt. They face issues like environmental damage, signal fading, and overcrowding all the time [8]. As illustrated in (Figure 1), the physical boundaries of guided media inherently provide deterministic performance, whereas unguided media must dynamically navigate atmospheric and spatial contention challenges.

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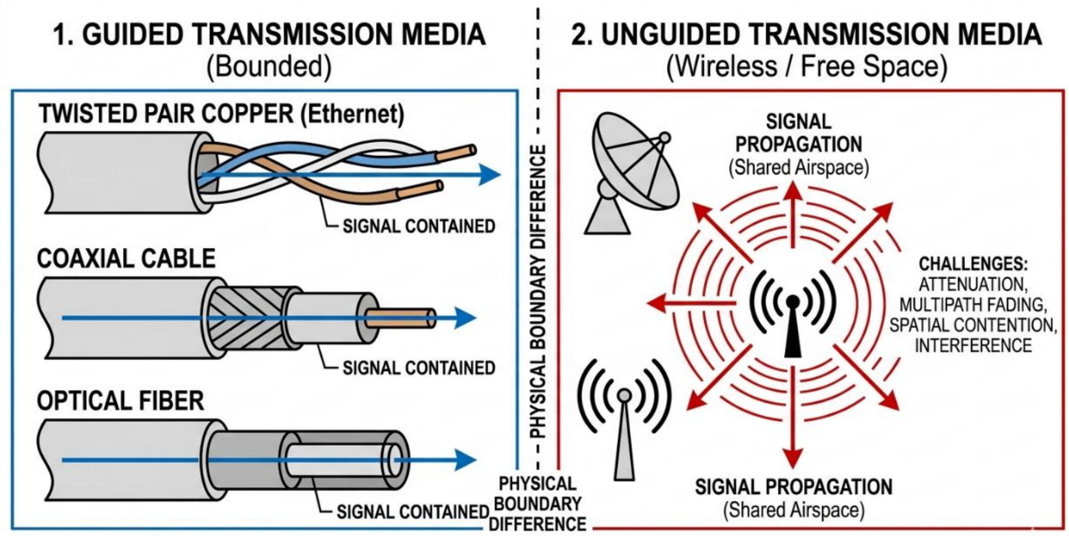

FIGURE 2.1: Structural Comparison of Signal Propagation in Guided vs. Unguided Media

Figure 1. Adapted and synthesized based on operational boundaries defined in [2] and [8]

Layer Performance Metrics

To rigorously analyze and evaluate the operational efficiency of these contrasting media types, four critical performance vectors must be mathematically and conceptually defined:

Vector 1: Bandwidth vs. Throughput

Bandwidth is the max data-carrying capacity of a physical channel based on its freq allocation, measured in Hertz. Throughput? That’s the actual rate of data delivery over time—after protocol overhead, noise, and layer interference knock speeds down [7].

Vector 2: Latency Dynamics

Latency is the total time delay a data packet undergoes as it travels from its source to its destination. This delay includes the time it takes to travel at the speed of light—or for electrons to move through the material, processing time at each end, and any wait time in queues. For crucial systems, designers look at average latency and the longest likely delays, like what happens at the 99th percentile [2,7].

Vector 3: Packet Loss Rate

This metric measures how many data frames fail to reach their destination. In guided media, packet loss is nearly nonexistent and mostly happens from switch buffer overflows. For unguided media, packet loss changes often because of signal weakening, collisions between multiple users, and environmental noise, though [8].

Vector 4: Energy Efficiency (Joules per Gigabyte)

Evaluating power use for modern sustainability and edge computing is crucial. We focus on the juice network interfaces, hardware, and transceivers gulp while moving data—measured in Joules per GB—to figure out where to cut energy waste [1,6].

Taxonomy and Classification of Physical Media Architectures

To create a solid analysis, we need to sort communication technologies by their structure, how info moves, and where they work [7]. Basically, physical layer comms split into Wired and Wireless. Then each group gets sorted by things like design, coding methods, and scope – what recent studies show.

Guided Media Taxonomy (Wired Interconnects)

Guided media architectures use physical paths to guide electromagnetic or optical signals. Based on high-performance transceiver topologies and smart grid infrastructure data, guided media has three main operational types, as integrated data shows.

Optical Fiber Networks (High-Reach & Core Backbones)

Utilizing Total Internal Reflection (TIR) within silica cores, optical networks are sub-classified into Single-Mode Fiber (SMF) for long-haul inter-data center links, and Multi-Mode Fiber (MMF) for short-reach intra-cabinet interconnects. These architectures leverage advanced wave-division multiplexing to isolate channels and achieve maximum throughput.

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Multi-Gigabit Twisted-Pair Copper (Local Area Interconnects)

Structured Category cabling (e.g., Cat 6a, Cat 7, and Cat 8) is characterized by balanced differential signaling. These systems are taxonomically defined by their shielding mechanisms (e.g., S/FTP) designed to suppress Near-End Crosstalk (NEXT) and sustain high pulse-amplitude modulation profiles (such as PAM-4) over localized distances up to 100 meters [2,7].

Power Line Communication (PLC) & Substation Bus Topologies

Specialized wired architectures utilizing existing power infrastructure for data transmission. Classified into Narrowband PLC (NB-PLC) for low-data-rate Neighborhood Area Networks (NANs) and Broadband PLC (BB-PLC) for Field Area Networks (FANs) within industrial utility automation [3].

Unguided Media Taxonomy (Wireless Infrastructure)

Unguided media architectures utilize free-space radio frequency (RF) propagation, requiring dynamic channel management due to the shared nature of the airspace [9]. Modern wireless architectures are classified into three distinct structural paradigms:

Deterministic Cellular Systems (Private 5G NR)

Architectural deployments operating in licensed or shared localized spectrums (e.g., CBRS bands). These systems are structurally classified by their support for Ultra-Reliable Low-Latency Communications (URLLC), utilizing centralized Orthogonal Frequency Division Multiple Access (OFDMA) scheduling to guarantee deterministic time slots [8].

Contention-Based Local Systems (Wi-Fi 6 / Wi-Fi 7)

Wi-Fi 7, also known as IEEE 802.11be, operates in 2.4 GHz, 5 GHz, and 6 GHz bands. Unlike older versions that stuck to stochastic CSMA/CA, it brings in Multi-Link Operation [5]. This lets it do cool stuff like multi-band stream aggregation and steering traffic dynamically.

Hierarchical Sensor Networks (WSNs & Low-Power Node Topologies)

Decentralized wireless structures for collecting ambient data use energy-constrained routing protocols. For example, there's PEGASIS, which is a power-efficient chain-based hierarchical architecture. With PEGASIS, nodes just talk to nearby neighbors to reduce energy expenditure [2].

Comparative Structural Classification Matrix

The following table presents a systematic classification of physical communication technologies based on modulation schemes, throughput capabilities, latency characteristics, and architectural constraints.

Table 1. Compiled by the authors from empirical research and engineering data in [1], [2], [3], [5], [7], and [8].

Media Paradigm	Technology Standard	Core Modulation Scheme	Theoretical Max Data Rate	Structural Latency Profile	Primary Architectural Constraint
Guided (Optical)	Single-Mode Fiber (SMF)	NRZ / QAM-16 / PAM-4	Up to 800 Gbps (per lane)	Deterministic (Sub-millisecond)	High Initial Installation Capital (CapEx)
Guided (Copper)	Category 8 Ethernet	PAM-4 / DSQ128	40 Gbps Base-T	Deterministic (< 1 ms)	Strict Distance Limitations (30 meters)
Guided (Utility)	Broadband PLC (BB-PLC)	OFDM	Up to 200 Mbps	Variable / Load-Dependent	High Impulsive Noise & Attenuation
Unguided (Cellular)	Private 5G (URLLC)	QAM-256	Up to 10 Gbps	Semi-Deterministic (1-5 ms)	Complex Core Infrastructure Overhead
Unguided (Local)	Wi-Fi 7 (802.11be)	QAM-4096 (4K-QAM)	Up to 46 Gbps	Stochastic / Jitter-Prone	Co-channel Contention & Interference
Unguided (Sensor)	WSN (PEGASIS Node)	BPSK / QPSK	Low-rate (< 250 Kbps)	High Accumulative Jitter	Severe On-Node Battery Lifecycle Bounds

According to (Table 1), communication technologies using physical media exhibit great disparities in performance capabilities, modes of signal transmission, and deployment capabilities. Communication media employing guided technology, such as Single-Mode Fiber (SMF) and Category 8 Ethernet, exhibit high data transfer rates, low latency, and guaranteed performance capabilities, thus making them ideal for use in backbone networks and mission-critical environments. On the other hand, these communication technologies entail heavy infrastructure costs. On the other hand, the use of communication technology

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that is not guided, like Wi-Fi 7 and Private 5G, offers better mobility and scalability features as well as easier deployment. Nonetheless, the performance of these technologies can be compromised due to factors like interference, congestion, the environment, and user density. WSNs focus on energy saving and long battery life, although they support limited data rates and have high latency. This table also indicates the effect of modulation techniques in terms of effectiveness in communication and the capacity to transmit data. Techniques like PAM-4, QAM-256, and QAM-4096 help in faster transmission but need sophisticated equipment. In general, it can be said that none of the communication technologies discussed here is the best choice for any purpose because each has its own advantages and disadvantages.

Performance Analysis and Comparative Evaluation

When evaluating networks for mission-critical edge processing—such as automated pipelines and smart grid infrastructure—the real benchmark isn't the typical average execution time, but rather how well the system resists sudden spikes in tail latency jitter."

Throughput and Spectrum Efficiency

Throughput capabilities are deeply governed by the maximum modulation order, channel bandwidth configurations, and environmental attenuation parameters characteristic of each medium's physical layer.

Guided Wireline Superiority

According to the contemporary wireline transceiver architecture, dedicated channels guarantee unmatched determinism in achieving throughput. Optical fiber technology ensures a consistently high bit rate ranging between 100 Gbps and 800 Gbps for each infrastructure by using multi-lane serial architectures and advanced baseband modulation schemes like PAM-4 [1]. At the same time, locally deployed Ethernet twisted pair networks like Cat6a/Cat8 are capable of transmitting at up to 10 Gbps to 40 Gbps without interference [2,3].

Unguided Overheads and Contention Bottlenecks

In terms of the wireless spectrum, some of the current technologies, such as Wi-Fi 7 (IEEE 802.11be), provide an upper limit data transfer rate of up to 46 Gbps using ultra-wideband 320 MHz channel aggregation and 4096-QAM [5]. Nevertheless, the actual measurement results from the edge show considerable disparity between theory and practice in the implementation of these technologies. As opposed to the controlled environment provided by optical fiber technology, unguided signals experience a substantial exponential degradation in their throughput rates due to environmental factors like atmospheric absorption, multi-path fading, and co-channel interference [8]. Under heavy network load conditions, contention CSMA/CA protocol causes packet collision and leads to a dramatic decrease in throughput rate [2,5].

Latency Profiles: Mean vs. Tail Jitter

Assessment of such networks in terms of workload requirements for their use to support edge applications like automated industrial pipeline systems and smart grid infrastructures must center on tail latency/jitter and not just average execution latencies.

Deterministic Guided Links

Multi-gigabit Ethernet systems are known to be deterministic with their sub-millisecond latency, which is resistant to any sudden increases in traffic load [2]. Absolute determinism is an important characteristic because even small differences in timing lead to a complete breakdown of the system in applications such as power substations and smart grids [3].

Cellular Scheduled Links

Airspace collision issues can be addressed through the deployment of private 5G NR that uses central gNodeB hardware scheduling, as opposed to stochastic contention. By configuring the network with URLLC configurations, Private 5G ensures a deterministic latency envelope that strictly lies within the limits of 1ms to 5ms [2,7].

Contention-Based Wireless Jitter

On the other hand, guided wireless architectures have deterministic low-latency characteristics during congested conditions. Even though Wi-Fi 7 uses multi-link operations (MLO) to shift traffic between the 5 and 6 GHz frequency bands to enhance efficiency, excessive network data loads cause tail-latency surges at the 99th percentile level [2,5]. The inability to guarantee latency performance levels limits the usability of guided wireless media in closed-loop industrial control scenarios.

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Energy Consumption and Sustainability Metrics

Energy sustainability imposes strict operational boundaries on both high-capacity computing environments and remote, battery-dependent sensor architectures.

High-Speed Transceiver Links

In core wireline link transceivers, power efficiency can only be assessed using the ratio of power to data. Current high-rate serial links achieve optimized power dissipation of just a few picojoules per bit (pJ/bit) or Joules per Gigabyte through advanced analog signal equalizers that mitigate the effects of channel insertion losses without requiring heavy power-consuming digital feedback loops [1].

Enterprise Access Points

Regarding the energy efficiency characteristics in the wireless enterprise infrastructure environment, based on practical experience, it becomes evident that newer versions, such as Wi-Fi 7, cannot offer intrinsic optimization with regard to energy efficiency metrics on a per-megabit basis. The issue with regard to power usage in this instance is mainly attributed to hardware design, including the amount of RF chains used in MIMO architecture, along with constant handling of the 320 MHz spectrum [6].

Resource-Constrained Sensors

In a decentralized architecture of WSNs, the concept of energy efficiency becomes important for ensuring the lifetime of the entire network. One approach is using hierarchical routing systems like the PEGASIS protocol, which reduces radio propagation energy consumption through the formation of localized chain-like communication among nodes [8]. In this way, nodes can communicate only with their physically nearest neighbors, thereby reducing far-field radio power consumption much more than base station broadcasting [2].

Research Gaps and Open Challenges

Based on the comprehensive review of contemporary literature, this section outlines the four primary engineering challenges and research gaps in guided and unguided media integration:

The Mobility-Determinism Paradox

High-speed communications networks call for absolute stability and less than a millisecond latency, which at present can be accomplished only by means of a stationary guided medium such as Gigabit Ethernet or Fiber Optics. But this would preclude device mobility. On the other hand, the use of unguided mediums such as Wi-Fi offers freedom of mobility at the cost of very significant throughput variability and latency introduced by channel interference and random contention among neighbors.

Idle-State Power Consumption Deficit

The new protocols for wireless communications, like Wi-Fi 7, provide an incredibly fast data rate due to their ability to incorporate multi-RF antenna chains and super-wideband channels (320MHz). Nevertheless, according to empirical studies, the power consumed by these routers is extremely large in cases where they are inactive and do not transfer any information. The key problem for the future development of this technology is designing zero-latency sleep modes for these devices [6].

Structural Vulnerabilities in Sensor Chains

In energy-limited WSNs, 7 such hierarchical approaches, including PEGASIS, are used to create an unbroken communication chain among the nodes so that radio propagation power is reduced. The major problem with this topology is that even when one node within the chain loses power or experiences severe fading, the chain gets broken. Existing network topologies fail to provide automatic physical-link self-healing solutions, resulting in an enormous amount of overhead [2,8].

High Economic Cost of Infrastructure Upgrades

Fast Internet access to these distant areas entails upgrading from outdated infrastructures using copper, for instance, to optical fiber infrastructures that provide much faster services. It is a very costly process, necessitating high levels of Capital Expenditure (CAPEX). The issue here is the need to devise a technology that would increase the speed of current outdated systems without necessarily undergoing complete physical replacement [3,4].

Future Research Directions

To address the technical challenges identified in the previous section and enhance heterogeneous network integration, future research should focus on the following deployment paradigms:

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AI-Driven Intelligent Medium Selection

Future research should aim at creating intelligent machine learning systems that can be implemented on light-weight devices in order to mitigate the issue of determinacy arising out of mobility [2]. Such intelligent systems are able to predict when a channel would deteriorate or drop packets, which allows for seamless switching between wired and wireless connections.

Low-Power Wake-Up Radios and Dynamic Hardware Management

For addressing the issue of high power consumption while the access point remains in idle mode, the solution lies in developing sophisticated hardware-level techniques to ensure wake-up of the transceiver [6]. Future transceivers would automatically switch off their multiple RF chains while sleeping and then wake up immediately whenever needed.

Self-Healing Link Protocols for Sensor Networks

In terms of sensor networks that work using chain-based routing protocols such as PEGASIS, there is a need to incorporate self-healing capabilities for future developments. In the event of failure of a particular node, other surrounding nodes should be able to compute distances between them immediately and reconfigure themselves [2,8].

Hybrid Interconnect Convergence Over Legacy Infrastructure

In order to overcome the large CAPEX involved in fiber-optic deployment, future investigations may consider more sophisticated hybrid strategies. This would include the creation of high-throughput modulation schemes for integrating the use of optical backhaul into PLC or even old copper-based infrastructure [3,4].

Conclusion and Future Outlook

This study has made an appropriate comparison between the guided and unguided physical media technology. Based on their practical performance, the following are the primary conclusions that one may draw from this study:

Speed and Reliability

Wired connections such as SMF and Cat 8 Ethernet are still preferred for fast speeds because they provide constant and guaranteed transfer speeds without any interference from outside sources [1,2]. On the other hand, wireless connections like Wi-Fi 7 and 5G offer amazing flexibility but have much lower speeds because of signal interference in the environment [5].

Latency and Jitter

Critical applications that require flawless synchronization will always benefit from using a wired connection, due to its predictable low latency, which is less than one millisecond [2,3]. Private 5G networks provide a viable alternative to wired connectivity, albeit not perfectly stable [7]. WiFi 7 can experience unpredictable delay (jitter) in case the network is overloaded [5].

Energy and Sustainability

Fiber optics and advanced cables are very energy efficient when covering large distances [1]. On the other hand, wireless access points tend to use up more energy since they maintain many antennas active at once. With small wireless sensor networks, employing intelligent routing techniques (for example, PEGASIS) becomes crucial for energy conservation [8].

Future Outlook

In the future, network engineers will not choose between wired and wireless; instead, they will work together. The next big steps include:

AI-driven Networks

Merging Digital Signal Processing (DSP) technologies with Artificial Intelligence (AI) to provide smarter and more stable wireless links, and enable automatic repair of signal anomalies [1,2].

Optical Wireless Hybridization

Using fiber-optics speed in wireless transmitters (e.g., 6G and new Wi-Fi) to provide latency-free transmission of multi-gigabit data to end-users [4,5].

Eco-Friendly Networking

Implementing efficient hardware sleep states and power-saving protocols for the future multi-antenna network infrastructure due to excessive energy consumption [6].

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Conclusion

This study presented a comparative evaluation of wired and wireless physical media technologies with respect to throughput, reliability, latency, energy efficiency, and deployment constraints. The analysis demonstrated that wired technologies continue to provide superior performance in terms of stability, deterministic communication, and high-speed data transmission, whereas wireless technologies offer greater flexibility, mobility, and deployment scalability. The findings further indicate that the selection of a communication medium should be based on application-specific requirements rather than a single performance metric. Consequently, future network infrastructures are expected to adopt integrated wired-wireless architectures to achieve optimal performance, reliability, and operational efficiency.

Conflict of interest. Nil

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