Review

From fixed-line to mobile internet: A review of telephone system evolution and its implications for future telecommunication engineering

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Abstract: The telephone has undergone a remarkable transformation from its origins as a fixed-line analogue device to today's mobile and internet-based systems that form the backbone of global communication. This review traces the historical progression of telephony, beginning with the invention and expansion of circuit-switched fixed-line networks, through the generational evolution of mobile systems from 1G to the emerging vision of 6G, and culminating in the rise of internet-based platforms such as Voice over Internet Protocol (VoIP) and Unified Communications (UC). Each stage reflects not only technical innovation but also broader socioeconomic shifts, with implications for infrastructure, spectrum management, security, sustainability, and user behaviour. The analysis highlights how engineering responses to challenges such as noise, capacity, and scalability have shaped telephony's evolution, while identifying future directions in satellite telephony, artificial intelligence, quantum communication, and immersive extended reality (XR). By synthesising historical, technical, and forward-looking perspectives, this review underscores telephony's continued role as a driver of technological advancement and its enduring relevance to telecommunication engineering in the twenty-first century.

Keywords: telephony evolution; mobile generations (1G–6G); Voice over Internet Protocol (VoIP); Unified Communications (UC); security and sustainability; future telecommunication ecosystems

1. Introduction

The telephone has historically been viewed as one of the most significant inventions in modern civilization. Since its commercial introduction in the late nineteenth century, it has not only served as a tool for interpersonal communication but has also fundamentally shaped social, economic, and technological progress worldwide. In many respects, the telephone symbolizes humanity's transition into a connected age, linking individuals, businesses, and governments through real-time voice interaction [1,2]. From Alexander Graham Bell's first experimental voice transmissions to today's extensive smartphone ecosystems and internet-based communication platforms, the evolution of telephony is a profound narrative of transformation, encompassing not just hardware but also the networks, protocols, standards, and engineering practices that uphold them [3].

The earliest fixed-line systems relied on circuit switching, connecting two endpoints for the duration of a conversation. This revolutionary technology enabled voice transmission over copper wires, gradually expanding from urban centres to rural areas, thus reshaping information exchange in commerce and governance [4]. The significance of telephony in modern economies cannot be overstated; it facilitates essential services such as banking, emergency response, and the

coordination of global supply chains [1]. However, the limitations of fixed infrastructure, particularly in extending copper lines to remote areas, presented ongoing challenges that spurred innovations in wireless communication [5].

The introduction of mobile telephony marked a significant disruption to the dominance of fixed-line systems. First-generation (1G) analogue cellular networks, developed in the 1980s, enabled mobile voice communication, liberating users from the constraints of physical cables. Despite their limited capacity and high costs, these networks proved the viability of large-scale wireless voice communication [6]. Advances into second-generation (2G) systems in the 1990s, which implemented digital technologies like GSM and CDMA, enhanced call quality and user experience, showcasing the necessity for new approaches in spectrum allocation and network management [5]. The ongoing evolution to third-generation (3G) and fourth-generation (4G LTE) networks has further integrated voice, data, and multimedia services [7].

Concurrently evolving alongside mobile telephony has been the rise of internet-based communication, particularly Voice over Internet Protocol (VoIP). Beginning in the late 1990s, VoIP services like Skype, and more recently platforms such as WhatsApp and Zoom, have challenged traditional telephony by utilizing packet-switched data networks as opposed to circuit-switched infrastructures. These VoIP technologies democratize access to global communication, allowing for cost-effective international calls and multimedia interactions while simultaneously introducing engineering challenges related to latency, packet loss, and cybersecurity [8]. The transition from the Public Switched Telephone Network (PSTN) to all-IP architectures encapsulates the extent of this transformation within the telecommunications landscape [9].

Understanding the trajectory of telephone system evolution is crucial for contemporary telecommunications engineering. Each developmental phase has presented unique challenges and solutions that continue to inform current engineering practices. For instance, the shift from analogue to digital systems required advancements in error correction technologies and coding techniques, which remain central to telecommunications engineering today [10]. Indeed, the explosive growth in mobile data usage necessitates ongoing innovations in spectrum efficiency, antenna design, and network virtualization, transitioning not merely seen as incremental improvements but as representations of larger shifts in engineering paradigms from hardware-centric to software-defined approaches. Furthermore, the integration of artificial intelligence, cloud computing, and edge processing into telecommunications systems suggests that future telephony will be characterized by heterogeneous, low-latency, scalable communication environments [11].

In conclusion, the evolution of the telephone reflects not just technical advancements but also broader socio-technical dynamics. The spread of fixed-line telephony coincided with significant industrialization and urbanization trajectories, while mobile networks have evolved parallel to globalization, highlighting their role in today's information and digital age. Addressing these multifaceted concerns necessitates those engineers engage not only with technological optimisation but also with policy frameworks and ethical dimensions. By synthesizing historical, technical,

and anticipatory perspectives, one can appreciate how the evolution of telephony continues to shape communication systems in an increasingly interconnected world.

2. Historical overview of telephony

The development of the telephone represents a story not only of technological innovation but also of the social and engineering systems that enabled its adoption and diffusion. Long before mobile and internet-based platforms reshaped global communication, fixed-line telephony constituted the backbone of human connectivity [12]. To understand the present and anticipate future trends, it is crucial to revisit the historical phases that defined the telephone's trajectory: the invention era, the expansion of fixed-line networks, and the gradual transition to digital switching systems.

2.1. The invention era (bell and early fixed-line systems)

The modern history of telephony begins in 1876 when Alexander Graham Bell was awarded the first US patent for the invention of the telephone. Although other inventors, such as Elisha Gray and Antonio Meucci, made significant contributions to early prototypes of voice transmission, Bell's system of converting acoustic sound waves into electrical signals marked a turning point in communication history [13]. The original apparatus comprised a liquid transmitter and an electromagnetic receiver, allowing voice to travel over copper wire. In Bell's famous demonstration, the phrase "Mr. Watson, come here, I want to see you" was successfully transmitted, symbolizing the dawn of a new era.

The first practical telephone exchanges appeared in the late 1870s, with the Boston Telephone Dispatch Company providing switchboard services to local subscribers. These exchanges relied on manual operators, typically women, who physically connected calls using patch cords. This system, while labour-intensive, enabled rapid scaling of telephony in urban centres. Within a decade of Bell's invention, telephone lines had spread across the United States and into Europe, creating the first commercial communication networks [12].

Despite their novelty, early telephone systems faced limitations. Sound quality was often poor, transmission distances were limited by copper resistance, and crosstalk plagued crowded lines. Moreover, telephony was initially considered a luxury service accessible only to businesses and wealthy households. Still, its impact was profound: by enabling instantaneous voice communication, the telephone surpassed the telegraph's reliance on coded signals and redefined the possibilities of interpersonal and organisational interaction [14].

2.2. Expansion of fixed-line networks

The early twentieth century witnessed the consolidation and expansion of telephone networks into national and eventually global infrastructures. The creation of long-distance lines, made possible by innovations in loading coils and vacuum-tube amplifiers, extended the reach of fixed-line telephony beyond local exchanges. The first transcontinental telephone call in the United States, placed in 1915 from New York to San Francisco, demonstrated the technical feasibility of long-distance

communication [15]. International connections followed, with the establishment of undersea cables linking continents in the 1920s and 1930s [12].

Telephone penetration also shifted from elite to mass adoption during this period. Governments and private corporations invested heavily in public switched telephone networks (PSTN), recognizing their strategic value for commerce, governance, and military communication [12]. By the 1950s, many developed nations had achieved significant household penetration rates, with telephony becoming a standard utility akin to electricity or running water. The expansion of networks, however, was uneven. Rural and remote areas often lagged behind due to the prohibitive costs of laying copper lines across difficult terrain, resulting in a rural–urban divide that would remain a recurring theme in the history of telecommunication infrastructure [16].

The role of operators gradually diminished with the introduction of automatic switching systems. Almon Strowger, a Kansas City undertaker, famously invented the first automatic exchange in 1891 to bypass operator bias in call routing. The adoption of Strowger switches and later electromechanical exchanges in the early twentieth century allowed subscribers to dial numbers directly. This marked a significant step toward network scalability, efficiency, and user autonomy, setting the stage for further technological sophistication [17].

Economically and socially, fixed-line networks facilitated new patterns of interaction. Businesses benefited from faster transaction times and wider customer reach. Families separated by migration or war could maintain contact across vast distances. Telephony also played a central role in emergency response, allowing rapid mobilization of resources in crises [18]. In short, by mid-century, the telephone had evolved from a novelty to an indispensable infrastructure underpinning modern life.

2.3. Transition to digital switching

By the mid-twentieth century, the limitations of electromechanical switching and analogue transmission became increasingly apparent. Analogue systems were susceptible to noise, interference, and limited capacity. As subscriber numbers soared, telecommunication engineers sought more efficient and reliable solutions. The transition to digital switching and transmission technologies in the 1960s and 1970s represented a watershed moment in the history of telephony [19].

Digital switching was pioneered by the use of pulse code modulation (PCM), a technique that converted analogue voice signals into digital data streams. This innovation drastically improved sound quality, reduced susceptibility to noise, and facilitated more efficient use of transmission lines [20]. The introduction of electronic switching systems (ESS), first implemented by Bell Labs in 1965, further enhanced call handling capacity, enabling sophisticated features such as call waiting, voicemail, and conference calling [3].

The adoption of digital technologies also had profound implications for network architecture. The move away from circuit-switched infrastructures laid the groundwork for integrated services digital networks (ISDN) in the 1980s, allowing the simultaneous transmission of voice, video, and data over the same lines. This

integration represented the first step toward the convergence of telephony with broader information and communication technologies (ICT) [21]. Engineers now faced challenges not only of maintaining voice quality but also of managing increasingly heterogeneous traffic types, foreshadowing the all-IP networks of the twenty-first century.

Importantly, the transition to digital switching also transformed the economics of telecommunication. Automated, programmable systems reduced operational costs associated with manual or electromechanical exchanges [22]. They also allowed carriers to scale networks more rapidly to meet surging demand. For users, digital telephony meant greater reliability and an expanding suite of services. For engineers, it marked a paradigm shift from analogue craft to digital science, demanding new expertise in computing, coding, and system integration [23].

2.4. Summary

The historical trajectory of telephony from Bell's first experiments to the digital era underscores the interplay of invention, infrastructure, and engineering adaptation. The invention era established the technical feasibility of transmitting voice across distance. The expansion of fixed-line networks scaled this capability to national and international levels, embedding the telephone into daily life. The transition to digital switching, meanwhile, represented not just an upgrade but a transformation, reconfiguring both the technical architecture and the socioeconomic role of telephony [17].

These historical stages are not merely of antiquarian interest. They form the foundation for understanding subsequent revolutions in mobile telephony, internet-based communication, and next-generation systems. Each historical phase introduced engineering challenges such as signal quality, scalability, and integration that continue to reverberate in contemporary telecommunication practice. Thus, to comprehend the implications of today's mobile internet and the emergent vision of 5G and 6G telephony, it is essential first to appreciate the lessons of the telephone's historical evolution.

3. Mobile telephony evolution

The rise of mobile telephony represents one of the most significant technological revolutions of the twentieth and twenty-first centuries. Unlike fixed-line networks, which required costly infrastructure and constrained mobility, mobile telephony enabled users to communicate wirelessly, liberating voice communication from geographical constraints. The development of mobile systems unfolded in generational stages, each marked by specific technological breakthroughs, engineering challenges, and social transformations. From the analogue foundations of the first generation (1G) to the highly sophisticated visions of sixth-generation (6G) systems, mobile telephony exemplifies the dynamic interplay between user demand, spectrum management, and engineering innovation [24].

3.1. First Generation (1G)—Analogue cellular networks

The first generation of mobile telephony, emerging in the late 1970s and early 1980s, was characterized by analogue cellular systems. Pioneering networks such as the Advanced Mobile Phone System (AMPS) in the United States and Nordic Mobile Telephony (NMT) in Scandinavia marked the beginning of large-scale commercial mobile communication [25].

These systems used frequency modulation (FM) to transmit voice signals over radio waves. The cellular concept, in which geographic areas were divided into smaller cells served by base stations, allowed frequency reuse and more efficient spectrum utilization than earlier car-phone systems. However, 1G networks were limited by several engineering drawbacks: call quality was inconsistent, handover between cells was often unreliable, and capacity was constrained by spectrum availability. Security issues also plagued these systems, as analogue signals were easily intercepted, leading to widespread eavesdropping and cloning [26].

Despite these limitations, 1G demonstrated the feasibility of wireless mass communication, laying the foundation for the digital revolution that would follow. Its success reflected both technical ingenuity and the growing societal appetite for mobility [27].

3.2. Second Generation (2G)—Digital transformation

The 1990s marked the dawn of second-generation mobile systems, defined by the transition from analogue to digital technologies. Standards such as the Global System for Mobile Communications (GSM) in Europe and IS-95 CDMA in the United States exemplified the global shift toward digital cellular telephony [28].

Digitization offered multiple advantages. Digital signals were more resistant to noise and interference, improving call quality. Network capacity increased through techniques such as time division multiple access (TDMA) and code division multiple access (CDMA), which enabled more users to share the same spectrum efficiently. Most importantly, 2G systems introduced Short Message Service (SMS), a feature that revolutionized interpersonal communication by providing a low-cost, asynchronous alternative to voice calls [29].

For telecommunication engineers, the digital shift required new expertise in coding, modulation schemes, and encryption. It also introduced challenges in interoperability and roaming, as different countries adopted varying standards. Nevertheless, 2G succeeded in globalizing mobile telephony, with billions of subscribers worldwide by the early 2000s [30].

3.3. Third Generation (3G)—Mobile data revolution

As the new millennium approached, user demand shifted from voice and text toward data. The third generation (3G) of mobile systems, launched in the early 2000s, responded by offering higher data rates and multimedia capabilities. Standards such as Universal Mobile Telecommunications System (UMTS) and CDMA2000 enabled services such as video calls, mobile internet browsing, and multimedia messaging [31].

From an engineering perspective, 3G was significant for its use of wideband code division multiple access (W-CDMA), which provided higher spectral efficiency and supported data-intensive applications. It also introduced the concept of Quality of Service (QoS), allowing networks to prioritize different types of traffic, essential for balancing voice reliability with emerging data demands [32].

However, 3G networks were expensive to deploy, requiring substantial investment in spectrum licenses and infrastructure upgrades. Adoption was uneven, with advanced economies leading and many developing regions lagging behind. Nevertheless, 3G represented a turning point in mobile telephony, shifting the industry's focus from communication to connectivity [24].

3.4. Fourth Generation (4G LTE)—Broadband mobility

The fourth generation (4G), particularly in the form of Long-Term Evolution (LTE), marked the full convergence of mobile telephony and internet services. Deployed widely from 2010 onward, 4G delivered data rates comparable to fixed broadband, enabling seamless streaming, video conferencing, and mobile applications that became integral to daily life [33].

Technologically, 4G was characterized by the adoption of orthogonal frequency-division multiple access (OFDMA), improving spectral efficiency and robustness. The migration to all-IP networks meant that even voice calls were transmitted as data packets through Voice over LTE (VoLTE). For engineers, this convergence required careful attention to latency, packet prioritization, and interoperability across heterogeneous networks [34].

The impact of 4G was transformative. Smartphones became central hubs for work, entertainment, and social interaction. Entire industries, such as ride-hailing, mobile banking, and social media, emerged and thrived due to 4G connectivity. However, 4G also amplified challenges such as spectrum scarcity, energy consumption, and cybersecurity vulnerabilities, pushing engineers and policymakers to rethink long-term sustainability [35].

3.5. Fifth Generation (5G)—Ultra-connectivity

The fifth generation of mobile systems, first rolled out in the late 2010s, is designed not merely as an upgrade but as a paradigm shift. 5G promises ultra-low latency, gigabit data rates, and massive device connectivity, enabling applications such as autonomous vehicles, smart cities, industrial automation, and the Internet of Things (IoT) [36].

From an engineering standpoint, 5G introduces several innovations. Massive multiple-input multiple-output (MIMO) and beamforming enhance spectral efficiency. Millimetre-wave (mmWave) frequencies provide unprecedented bandwidth but come at the cost of reduced range and penetration. Network slicing enables virtualized networks tailored to specific applications, whether ultra-reliable low-latency communication (URLLC) for medical devices or massive machine-type communication (mMTC) for IoT sensors [37].

The challenges of 5G are equally significant. Deployment requires dense small-cell infrastructure, raising issues of cost, urban planning, and environmental impact.

The reliance on software-defined networks (SDN) and network function virtualization (NFV) heightens concerns about security, resilience, and governance. Still, 5G represents a critical step toward integrating telephony into a broader digital ecosystem [38].

3.6. Sixth Generation (6G)—Vision for the future

While still in its early research stages, sixth-generation (6G) telephony is envisioned as a leap beyond 5G. Expected to be deployed around 2030, 6G aspires to deliver terabit-per-second data rates, sub-millisecond latency, and seamless integration of terrestrial, aerial, and satellite networks [39].

Emerging research highlights several potential pillars of 6G: the use of terahertz (THz) frequencies, integration of artificial intelligence into network management, and the fusion of communication with sensing and localization services. 6G aims not only to connect people and devices but to enable immersive experiences such as holographic communication, extended reality (XR), and fully autonomous systems [40].

For telecommunication engineers, 6G presents unprecedented opportunities and challenges. Designing energy-efficient systems at THz frequencies, ensuring global coverage through satellite integration, and embedding trust and security into AI-driven networks will define the next decade of research and practice. Although speculative, 6G demonstrates how telephony continues to evolve beyond its original scope of voice transmission, positioning itself at the heart of future digital societies [41].

3.7. Summary

The evolution of mobile telephony from 1G to the emerging vision of 6G encapsulates a broader narrative of technological progress, social adaptation, and engineering ingenuity. Each generation has introduced breakthroughs in modulation, spectrum efficiency, and service delivery, while simultaneously creating new challenges in cost, capacity, and security.

From the crackling analogue calls of 1G to the promise of holographic telepresence in 6G, mobile telephony illustrates the relentless pursuit of connectivity. It is a story of shrinking distances, accelerating interactions, and redefining what it means to communicate. Importantly, the engineering lessons of each generation whether the need for secure encryption in 2G, QoS management in 3G, or virtualisation in 5G continue to inform contemporary telecommunication practice.

The chronological progression of these developments is illustrated in **Figure 1**, which summarises the technological milestones of each generation from the 1980s to the anticipated 2030s. This visualisation reinforces the cumulative nature of telephony evolution and sets the stage for the next chapter, which explores the rise of internet-based telephony and its transformative role in redefining communication systems.
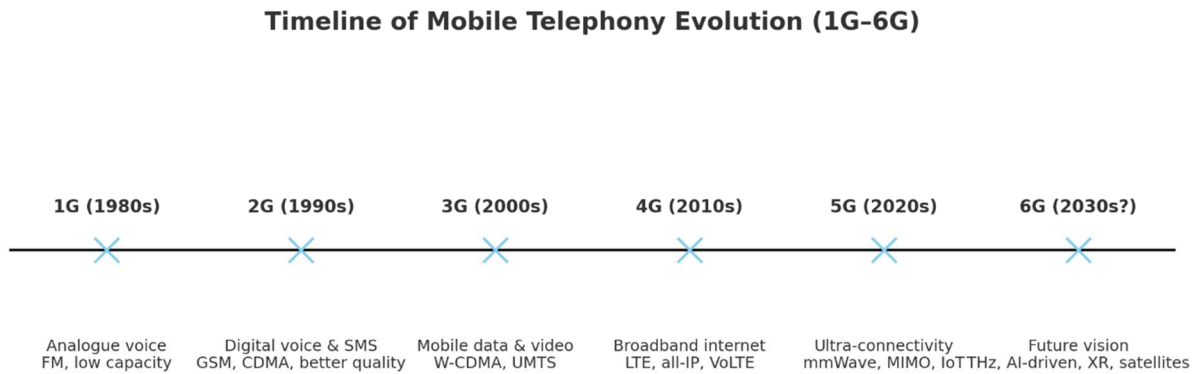
Timeline of Mobile Telephony Evolution (1G–6G)

1G (1980s)	2G (1990s)	3G (2000s)	4G (2010s)	5G (2020s)	6G (2030s?)
Analogue voice FM, low capacity	Digital voice & SMS GSM, CDMA, better quality	Mobile data & video W-CDMA, UMTS	Broadband internet LTE, all-IP, VoLTE	Ultra-connectivity mmWave, MIMO, IoT	Future vision THz, AI-driven, XR, satellites

Figure 1. Timeline of mobile telephony evolution from first generation (1G) analogue systems in the 1980s to the anticipated sixth generation (6G) in the 2030s.

4. Internet-based telephony

The rise of internet-based telephony represents a significant development in the history of communication. Whereas earlier mobile systems expanded the traditional voice-centric paradigm of telephony, the introduction of packet-switched data networks fundamentally altered the underlying architecture. Internet-based telephony, particularly through Voice over Internet Protocol (VoIP), has redefined both the economics and the engineering of communication. Traditional circuit-switched networks, once the backbone of global connectivity, are now being phased out in favour of all-IP systems that integrate voice, video, and data into unified communication frameworks. This chapter examines the emergence, development, and implications of internet-based telephony, highlighting its transformative impact on engineering practices and the telecommunication industry as a whole.

4.1. Voice over Internet Protocol (VoIP)

The concept of transmitting voice as data packets over internet networks began to gain traction in the mid-1990s. Early experiments were conducted by small software companies and research groups, with pioneering applications such as VocalTec's Internet Phone in 1995 demonstrating the potential of bypassing traditional telephony systems [42]. However, widespread commercial viability of VoIP emerged with the availability of broadband connections in the early 2000s [43].

VoIP technology converts analogue voice signals into digital data packets, which are then transmitted across IP networks using standardized protocols such as the Session Initiation Protocol (SIP) and Real-Time Transport Protocol (RTP) [44]. Unlike circuit-switched telephony, which requires a dedicated channel for each call, VoIP leverages packet-switching, enabling more efficient bandwidth utilization and lower costs.

Applications such as Skype, launched in 2003, popularized VoIP by offering free or low-cost international calls, video chat, and instant messaging. The success of Skype, followed by integrated communication tools such as WhatsApp, Viber, and Zoom, shifted user expectations towards integrated, multimedia-rich communication [45]. For engineers, the deployment of VoIP systems introduced new challenges,

including the need to manage packet loss, jitter, latency, and quality-of-service (QoS) guarantees [46].

Security became a major engineering concern. Traditional telephony was relatively secure due to the closed nature of PSTN infrastructures, whereas VoIP systems operating over public IP networks were exposed to risks such as eavesdropping, denial-of-service (DoS) attacks, and call hijacking [47]. To address these, protocols such as Secure Real-time Transport Protocol (SRTP) and Transport Layer Security (TLS) were developed, although implementation remains uneven across platforms [48].

4.2. Unified communications and convergence

One of the most significant outcomes of internet-based telephony is the phenomenon of convergence, whereby voice, video, and data services are integrated into unified platforms. This has transformed telephony from a single-purpose technology into a multi-modal communication system [49].

Unified Communications (UC) platforms, such as Microsoft Teams, Cisco Webex, and Google Meet, exemplify this trend by combining VoIP, video conferencing, instant messaging, and collaborative tools within a single interface [50]. For organisations, UC systems offer efficiency, scalability, and cost savings by replacing disparate communication infrastructures with integrated IP-based networks.

For telecommunication engineers, convergence has necessitated a rethinking of network architecture. Quality-of-service requirements now extend beyond voice clarity to include video resolution, synchronization of audio and video streams, and seamless transitions between devices and networks [51]. The challenge is heightened by the variability of global internet infrastructure, which ranges from high-speed fibre-optic backbones in advanced economies to bandwidth-constrained networks in developing regions.

Another dimension of convergence is the integration of telephony with cloud computing and artificial intelligence. Cloud-based communication platforms enable dynamic scaling, global accessibility, and centralized management, while AI-driven analytics provide features such as real-time transcription, sentiment analysis, and intelligent routing. These developments indicate that internet-based telephony has evolved from being merely a substitute for traditional calling to a critical enabler of digital collaboration [52].

4.3. The decline of the Public Switched Telephone Network (PSTN)

The global decline of the Public Switched Telephone Network (PSTN) serves as a clear indicator of the impact of internet-based telephony. Once the backbone of voice communication, PSTN is progressively being decommissioned as countries migrate towards all-IP infrastructures.

Several major economies, including the United Kingdom, Germany, and Japan, have announced plans to shut down legacy PSTN systems within the coming decade, replacing them with IP-based alternatives [53]. For example, British Telecom (BT) has set a target to switch off the UK's PSTN by 2025, mandating a nationwide transition to digital voice services. The rationale is twofold: maintaining PSTN

infrastructure is increasingly costly and inefficient; IP networks offer greater flexibility, scalability, and compatibility with modern applications [54].

From an engineering standpoint, retiring PSTN poses challenges and opportunities. Legacy systems must be migrated without disrupting critical services like emergency calls, alarm systems, and healthcare devices that still rely on analogue lines. Engineers must also ensure that new IP-based systems provide reliability and resilience comparable to PSTN, which has long been regarded as the gold standard of availability. This requires investment in redundancy, robust security protocols, and universal service provisions to prevent digital exclusion [55].

The decline of PSTN also reflects a cultural shift. For younger generations, the concept of a fixed "landline" phone is increasingly obsolete, as mobile and internet-based communication dominate. Nevertheless, for telecommunication professionals, the PSTN era offers valuable lessons in engineering reliability and regulatory oversight that remain relevant in today's rapidly evolving digital environment [48].

Table 1 shows a comparative feature of PSTN, VoIP, and Unified Communications (UC). While PSTN provided unmatched reliability, it was limited in services and scalability. VoIP democratised communication by leveraging packet-switched networks but introduced new vulnerabilities in quality and security. UC represents the most advanced stage, integrating voice, video, and collaboration into cloud-based platforms, highlighting the convergence of telephony and digital services.

Table 1. Comparison of Public Switched Telephone Network (PSTN), Voice over Internet Protocol (VoIP), and Unified Communications (UC).

Feature	PSTN (Circuit-Switched)	VoIP (Packet-Switched)	Unified Communications (Cloud/IP)
Infrastructure	Copper lines; dedicated circuits	Internet/IP backbone; routers and gateways	Cloud-based platforms integrating voice, video, and collaboration
Cost Model	Distance-based call charges; costly international use	Low-cost or free calls; data-based charging	Subscription or licensing; bundled enterprise services
Services	Voice only	Voice, video, messaging	Voice, video, chat, collaboration, file-sharing, AI-powered add-ons
Quality	High reliability; low flexibility	Variable; depends on bandwidth, latency, and QoS controls	Generally stable with broadband; scalable with redundancy
Security	Closed network; limited cyber risk	Vulnerable to cyber threats (eavesdropping, DoS); needs encryption	Strong encryption, cloud security protocols, multi-layer defences
Scalability	Limited; expensive to expand	Highly scalable with internet access	Global scalability; multi-device and cross-platform integration

4.4. Implications of internet-based telephony

The rise of internet-based telephony carries profound implications for telecommunication engineering. First, it has transformed network design from hardware-intensive infrastructures to software-defined systems, requiring expertise in coding, protocol design, and cloud architecture [43]. Second, it has disrupted business models by shifting revenue streams from call charges to subscription services, advertising, and data monetization. Third, it has accelerated global connectivity, reducing barriers to entry for users in developing regions while concurrently creating new divides based on internet access quality [49].

The integration of internet-based telephony into everyday life has expanded the scope of telecommunication beyond simple voice communication. Platforms now function as hubs for education, healthcare, commerce, and entertainment. This was particularly prominent during the COVID-19 pandemic, when tools like Zoom and Microsoft Teams became essential for remote work and learning [54]. This highlights both the resilience and vulnerabilities of IP-based systems, underscoring the importance of robust engineering, regulatory oversight, and cybersecurity frameworks.

4.5. Summary

Internet-based telephony represents a paradigm shift in communication, moving from dedicated circuit-switched channels to flexible, packet-switched infrastructures. VoIP technologies have democratized global communication, unified communication platforms have redefined collaboration, and the decline of PSTN signifies the end of traditional telephony.

For telecommunication engineers, this transition underscores new priorities: managing latency and quality of service in heterogeneous networks, securing communications against cyber threats, and ensuring equitable access to digital services. More broadly, the rise of internet-based telephony exemplifies how telecommunication has evolved from a standalone utility into a central component of the digital economy.

As the following chapter will explore, these changes carry significant implications for the future of telecommunication engineering, raising questions about sustainability, security, and the integration of emerging technologies such as artificial intelligence and quantum communication into next-generation networks.

5. Implications for telecommunication engineering

The evolution of telephony from fixed-line systems to mobile and internet-based platforms has fundamentally reshaped the field of telecommunication engineering. Each generational shift has demanded new design paradigms, operational models, and regulatory frameworks. For engineers, the implications extend across infrastructure development, spectrum management, security and privacy, energy efficiency, and user-centric service design. Understanding these implications is essential for addressing contemporary challenges and preparing for future communication ecosystems.

5.1. Infrastructure transformation

The first and most visible implication of telephony's evolution is the transformation of infrastructure. Traditional fixed-line systems relied on extensive copper networks, local exchanges, and electromechanical switches. These systems were resource-intensive to build and maintain, especially in rural areas where the cost of laying physical lines was prohibitive. The transition to mobile networks shifted the emphasis toward base stations, cellular towers, and increasingly sophisticated core networks [56]. Today, 5G and beyond require dense small-cell deployments, fibre backhaul, and software-defined cores.

The shift to internet-based telephony further altered the engineering landscape. Infrastructure is now heavily dependent on IP networks, cloud platforms, and distributed data centres. Virtualization technologies, including Network Function Virtualization (NFV) and Software-Defined Networking (SDN), allow operators to replace dedicated hardware with programmable software modules, reducing costs and improving flexibility [57]. However, these changes demand new skill sets: engineers must now possess expertise in both networking and cloud computing, blurring the traditional boundaries between telecommunications and information technology.

Moreover, legacy systems remain part of the challenge. Engineers are tasked with ensuring interoperability between PSTN systems, mobile networks, and IP-based platforms during transition periods. This hybrid environment often complicates operations but also provides an opportunity to build resilience through redundancy [58].

5.2. Spectrum and network management

Spectrum has always been the lifeblood of wireless communication, and the evolution of telephony underscores its critical importance. Early mobile systems used relatively low-frequency bands, but as demand surged, operators had to explore new portions of the electromagnetic spectrum. Techniques such as frequency reuse, time-division multiple access (TDMA), and code-division multiple access (CDMA) were engineering responses to scarcity [59].

The arrival of 4G and 5G intensified the spectrum challenge. High data rates and low-latency applications require wide channels, often only available at higher frequencies such as millimetre-wave (mmWave) bands. While these frequencies offer immense capacity, they also present engineering hurdles such as limited range and poor penetration through buildings [60]. Engineers have responded by designing dense networks of small cells and implementing advanced antenna systems, including massive multiple-input multiple-output (MIMO) and beamforming technologies.

Spectrum management has also become more dynamic. Regulatory bodies now explore spectrum sharing, cognitive radio systems, and dynamic spectrum access to maximize efficiency. Telecommunication engineers must, therefore, design systems that not only exploit assigned spectrum efficiently but also adapt in real time to changing conditions, marking a departure from the more static spectrum environments of earlier eras [61].

5.3. Security and privacy in telephony

Each stage of telephony's evolution has introduced new security and privacy challenges. Analog mobile systems were notoriously insecure, with calls easily intercepted. The shift to digital 2G improved security through encryption, though flaws in early algorithms left vulnerabilities. Internet-based telephony introduced an entirely new threat landscape, as calls now traverse public networks and are subject to cyberattacks [62].

For engineers, securing telephony requires a layered approach. At the network level, encryption standards such as Secure Real-time Transport Protocol (SRTP) and Transport Layer Security (TLS) are critical. At the system level, intrusion detection, authentication protocols, and denial-of-service protection are required. At the user level, end-to-end encryption, as implemented by applications like WhatsApp, provides an additional layer of defence [63].

Privacy has emerged as a parallel concern. Telephony platforms increasingly integrate with digital ecosystems that collect and process vast amounts of user data. Engineers must balance performance optimisation with privacy preservation, developing solutions that meet both regulatory requirements, such as the EU's General Data Protection Regulation, and ethical expectations for data stewardship [64].

5.4. Energy efficiency and sustainability

The growth of telecommunication infrastructure carries significant environmental implications. Fixed-line systems required vast quantities of copper, while mobile networks depend on energy-intensive base stations. As 5G and future 6G networks demand denser deployments and more powerful processing, energy consumption is expected to rise dramatically [65].

Engineers face the challenge of designing energy-efficient solutions. Innovations include dynamic power management of base stations, energy-harvesting techniques, and the use of renewable energy sources in telecom infrastructure. Advances in hardware, such as low-power processors and efficient cooling systems for data centres, further contribute to sustainability goals [57].

The sustainability question extends beyond energy. Electronic waste, arising from rapid device turnover, poses a growing environmental challenge. Telecommunication engineers, in collaboration with policymakers and manufacturers, must explore strategies such as modular design, extended device lifecycles, and circular economy models. The integration of sustainability into telecommunication engineering reflects a broader societal recognition of the need to align technological progress with environmental stewardship [66].

5.5. User behaviour and service innovation

The evolution of telephony has also reshaped user behaviour, creating new demands and expectations that engineers must address. In the fixed-line era, voice calls were the primary mode of communication, with limited features. The introduction of SMS in the 2G era redefined personal communication, while the rise of mobile internet and applications in the 3G and 4G eras transformed telephony into a platform for social networking, e-commerce, and entertainment [67].

Today, users expect seamless, integrated communication experiences across multiple devices and platforms. Unified Communications platforms embody this shift, providing not only voice but also video, messaging, and collaboration tools in a single interface. Engineers must ensure that networks can support these multifaceted demands with low latency, high reliability, and consistent quality [68].

Service innovation has also become a competitive necessity. Features such as AI-driven voice assistants, real-time transcription, and personalized call routing demonstrate how telephony has expanded into broader digital ecosystems [69]. Engineers are now tasked with integrating emerging technologies artificial intelligence, machine learning, and blockchain into telecommunication systems in ways that enhance user experience while maintaining security and performance.

5.6. Regulatory and governance implications

Telecommunication engineering does not exist in a vacuum; it is shaped by regulatory frameworks and governance structures. The transition from PSTN to IP-based systems requires careful management to ensure universal service obligations are met, particularly in rural and underserved regions. Spectrum allocation remains a highly contested regulatory issue, with governments balancing the needs of commercial operators, public services, and national security [70].

Engineers must engage with policy as well as technology. For example, ensuring that emergency services remain accessible during the migration to VoIP requires collaboration between engineers, regulators, and service providers. Similarly, addressing concerns about surveillance, lawful interception, and data sovereignty requires a multidisciplinary approach that combines technical safeguards with legal oversight [32].

The governance of future networks, particularly 6G, is likely to raise even more complex issues, including global coordination of standards, the ethical use of AI in network management, and equitable access across socioeconomic divides [67].

5.7. Summary

The implications of telephony's evolution for telecommunication engineering are far-reaching. Infrastructure has shifted from copper lines to cloud platforms; spectrum management has become dynamic and complex; security and privacy demand multi-layered solutions; sustainability has emerged as a central engineering concern; and user behaviour continues to drive innovation in services and features.

For telecommunication engineers, these implications highlight the need for adaptability. The discipline is no longer defined solely by hardware or network design but by an ability to integrate diverse technologies, respond to societal expectations, and anticipate emerging challenges. In essence, the evolution of telephony is not merely a story of communication systems but a living case study in how engineering must continually evolve to meet the demands of a connected world.

6. Future directions

The trajectory of telephony, from fixed-line systems to mobile networks and internet-based platforms, has been one of continuous transformation driven by technological innovation, societal needs, and engineering adaptation. As the world enters an era defined by ubiquitous connectivity, artificial intelligence, and immersive digital experiences, the future of telephony promises to expand far beyond traditional notions of voice communication. This chapter explores potential future directions, focusing on satellite telephony, artificial intelligence integration,

quantum communication, and immersive services such as extended reality (XR). Together, these developments illustrate how telephony is poised to remain at the centre of human communication in the coming decades.

6.1. Satellite telephony and global connectivity

Despite significant progress made by mobile and internet-based systems, connectivity gaps remain a persistent challenge. Rural, remote, and underserved areas often lack the infrastructure required for broadband access or advanced mobile networks. Satellite telephony offers a promising solution to these disparities by providing coverage in regions where terrestrial networks are economically or technically unfeasible.

Recent advances in low Earth orbit (LEO) constellations, exemplified by projects such as Starlink and OneWeb, have redefined the potential of satellite communication. Unlike traditional geostationary satellites, which suffer from high latency, LEO systems orbit closer to the Earth, enabling faster transmission times and lower latency. For telecommunication engineers, this shift presents opportunities to integrate satellite networks seamlessly with terrestrial mobile systems, creating hybrid infrastructures that can deliver ubiquitous global connectivity [71].

Challenges remain, including spectrum allocation, the cost of deployment, and resilience against space weather and orbital debris. Nonetheless, satellite telephony is expected to play a critical role in achieving universal service goals, bridging the digital divide, and supporting emerging applications such as disaster response, maritime communications, and aviation connectivity [72].

6.2. Artificial intelligence and intelligent networks

Artificial intelligence (AI) is increasingly being integrated into telecommunication systems, offering new possibilities for efficiency, adaptability, and user experience. In the context of telephony, AI is expected to play multiple roles:

- **Network optimisation**: AI algorithms can dynamically allocate resources, predict traffic patterns, and optimize handovers between cells, ensuring efficient use of spectrum and minimizing congestion [73].
- **Quality of Service (QoS)**: Machine learning models can monitor latency, jitter, and packet loss in real-time, enabling proactive adjustments to maintain high call and video quality [74].
- **Security**: AI-driven intrusion detection and anomaly recognition enhance protection against cyber threats targeting VoIP and 5G infrastructures [75].
- **User services**: Virtual assistants, real-time transcription, and intelligent call routing enhance personal and enterprise communication experiences.

Engineers must, however, address challenges associated with AI integration, including transparency, accountability, and energy consumption. The risk of automation bias, where users over-trust AI-driven systems, must also be managed carefully. Nevertheless, AI-driven intelligent networks represent a natural evolution of telephony, aligning with broader trends toward software-defined and self-organizing systems [76].

6.3. Quantum communication and ultra-secure telephony

The rise of quantum technologies introduces a new paradigm for communication security. Quantum key distribution (QKD), based on the principles of quantum mechanics, offers theoretically unbreakable encryption, as any attempt at interception alters the quantum state and becomes detectable [77].

In telephony, quantum communication could address longstanding concerns about eavesdropping and surveillance in both government and commercial contexts. Several pilot projects, including China's Quantum Experiments at Space Scale (QUESS) satellite and the European Quantum Communication Infrastructure initiative, are exploring how QKD can be integrated with existing telecommunication infrastructures [78].

For engineers, the integration of quantum technologies poses significant challenges: specialized hardware, high costs, and the need for global standardization. Yet, as digital threats grow in sophistication, quantum telephony may become an essential layer of secure communication, complementing classical encryption methods. Its development will likely run parallel to 6G research, with convergence points expected in the 2030s [79].

6.4. Immersive communication and Extended Reality (XR)

The future of telephony is not confined to voice, video, or text but extends to immersive communication experiences. Extended Reality (XR) encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR) is increasingly viewed as the next frontier of human interaction. Telephony, in this context, becomes a platform for holographic meetings, virtual classrooms, and immersive entertainment [80].

Emerging visions of 6G networks explicitly incorporate XR as a central application, requiring ultra-low latency (below 1 ms) and extremely high bandwidth. Engineers are thus tasked with designing infrastructures capable of supporting real-time rendering, synchronization of multiple data streams, and seamless integration of sensory inputs beyond sight and sound, such as haptics [81].

While immersive telephony promises transformative experiences, it also raises questions about inclusivity, accessibility, and social impact. Ensuring that XR communication does not exacerbate digital divides will be a critical concern, alongside addressing issues of digital fatigue and privacy in virtual environments. Nevertheless, XR demonstrates how telephony may evolve from connecting voices to connecting experiences [82].

6.5. Toward a holistic communication ecosystem

The convergence of satellite networks, AI-driven optimisation, quantum security, and immersive services points toward the creation of a holistic communication ecosystem. Unlike earlier eras, where telephony was defined by discrete technologies fixed lines, mobile cells, or VoIP the future envisions seamless interoperability across terrestrial, aerial, and orbital systems, unified by intelligent management and underpinned by sustainable design.

For telecommunication engineers, this ecosystem approach demands cross-disciplinary expertise, integrating knowledge from electronics, computing, physics, and social sciences. It also requires close collaboration with policymakers, industry stakeholders, and end-users to ensure that future telephony is not only technologically advanced but also socially responsible and globally inclusive [83].

6.6. Summary

The future directions of telephony underscore the field's enduring capacity for reinvention. Satellite telephony promises universal access, AI offers intelligent network optimisation, quantum communication heralds unprecedented security, and XR redefines the very nature of human interaction. Together, these trends suggest that telephony will remain at the forefront of technological and social transformation.

For engineers, the implications are profound: they must design systems that are secure, efficient, inclusive, and sustainable while navigating uncertainties about cost, regulation, and adoption. The future of telephony is not merely about faster connections or higher capacity but about creating a communication ecosystem that supports human flourishing in an increasingly interconnected world.

7. Conclusion

The evolution of telephony, from fixed-line systems to mobile and internet-based platforms, illustrates how communication technologies adapt to engineering innovation and societal need. Each era has introduced breakthroughs while also posing new challenges, leaving a legacy of lessons for contemporary telecommunication engineering.

Fixed-line telephony demonstrated the transformative power of real-time voice communication, embedding itself as a global utility despite its infrastructural limitations. Mobile telephony freed communication from geographic constraints, with successive generations from 1G to 5G redefining capacity, speed, and services. Looking ahead, 6G is expected to extend this trajectory towards terabit data rates, AI-driven optimisation, and immersive applications.

The rise of internet-based telephony, through VoIP and Unified Communications, has further reshaped the field. By leveraging packet-switched networks, these systems democratised communication, introduced integrated multimedia services, and accelerated the decline of the traditional PSTN. Engineers now face pressing tasks of ensuring quality of service, enhancing cybersecurity, and managing hybrid infrastructures during transition periods.

These transformations carry clear implications. Infrastructure has shifted from copper to cloud, spectrum use has become more dynamic, and security and privacy have emerged as critical design priorities. Energy efficiency and sustainability now frame engineering practice, while user behaviour continues to drive service innovation.

Future directions highlight telephony's continued relevance. Satellite systems promise universal connectivity, AI will enable adaptive networks, quantum communication offers ultra-secure channels, and extended reality (XR) could transform communication into immersive experiences. Together, these developments

point toward a holistic telecommunication ecosystem that is global, intelligent, secure, and inclusive.

In summary, telephony's journey is not simply a record of technological change but a living case study of engineering adaptation. The task for telecommunication engineers is to build systems that balance innovation with resilience, efficiency with inclusivity, and progress with sustainability. In doing so, the next era of telephony can continue its historic role: connecting people, empowering societies, and shaping the future of communication.

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