



The Wireless Ascent: From Breaking the Cord to Weaving Reality

Dr. Ritesh Kumar

Assistant Professor of Physics

Maulana Azad National Urdu University, Polytechnic, Bangalore.

manuuphy2020@gmail.com

Abstract

From 1G analog voice, through 2G digital voice/SMS and basic data, 3G mobile internet, 4G all-IP broadband, to 5G NR (sub-6 + mmWave) with eMBB/URLLC/mMTC and edge, wireless has progressed from cutting the cord to a programmable, spatial fabric that fuses connectivity, sensing, compute, and power—effectively weaving digital and physical reality. We trace the 6G toolkit—THz/sub-THz and mmWave, massive MIMO and reconfigurable intelligent surfaces, non-terrestrial networks, joint communication–sensing–localization, semantic/intent-driven networking with edge AI, and ambient energy/backscatter—enabling seamless XR, cyber-physical control, and ambient intelligence. We pair capability with stewardship: open and interoperable stacks, spectrum sharing, safety and privacy by design, energy/carbon budgets, and resilience to ensure equitable, sustainable deployment.

Keywords: 6G and NTN; JCAS; RIS and massive MIMO; edge AI and semantic communications; spectrum sharing and privacy; energy efficiency and sustainability.

Introduction

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Wireless has climbed a century-long gradient from the audacity of untethered voice to a pervasive medium that coordinates people, machines, and environments. The journey from 1G to 5G tuned radios for human-centric connectivity—steadily improving spectral efficiency, latency, and ubiquity—while virtualizing the core and disaggregating the RAN. The next ascent is qualitatively different. Rather than merely breaking the cord, 6G aims to weave reality: a programmable, spatial fabric in which connectivity, sensing, compute, and even power distribution cohere to perceive and act on the physical world.

Historical arc (1G→5G) anchors this transition:

- 1G: Analog, circuit-switched voice and mobility.
- 2G: Digital GSM/CDMA; SMS and packet data (GPRS/EDGE); stronger security.
- 3G: Mobile internet (UMTS/HSPA, CDMA2000); Mbps data and multimedia.
- 4G: LTE/LTE-A; all-IP broadband, low latency, VoIP/VoLTE; the app economy.

- 5G: NR across sub-6 and mmWave; eMBB/URLLC/mMTC, network slicing, and edge/cloud-native cores—extending broadband to industry-grade reliability.

6G reframes the objective: not just faster pipes, but an orchestrated field that shapes electromagnetic propagation, localizes with cm-scale precision, senses with radar-grade acuity, and closes control loops with intelligent edge compute. We use “weaving reality” to denote three convergent capabilities:

1. Programmable propagation via massive MIMO and reconfigurable intelligent surfaces (RIS) that sculpt the radio environment.
2. Joint communication, sensing, and localization (JCAS) that fuses data and perception for situational awareness.
3. Intent- and semantics-driven networking guided by edge AI, where networks exchange task-relevant meaning rather than raw bits.

This vision draws on a maturing toolkit. Higher bands (mmWave to sub-THz/THz) expand bandwidth but challenge coverage and hardware linearity; hybrid beamforming and cryo/photonic front-ends mitigate losses. RIS and software-defined metasurfaces externalize part of “the channel” into a controllable asset. Non-terrestrial networks (LEO satellites, HAPS, UAVs) extend the fabric skyward for resilience and global reach, stitched to terrestrial cells via cloud-native orchestration. JCAS elevates radios into sensors—reusing waveforms to detect, range, and map—while privacy-preserving fusion across devices enables cooperative awareness. Semantic communications and intent APIs reduce overhead and improve reliability in cyber-physical loops by aligning transmission with task utility. Ambient/backscatter links and RF energy harvesting push the boundary toward battery-optional endpoints, enabling dense, maintainable sensing fabrics.

The economic and societal pull is clear. Immersive XR and “internet of senses” experiences demand Tbps-class aggregate capacity, sub-10 ms glass-to-glass latency, and ultra-precise localization. Industrial autonomy needs bounded jitter, five-nines (or better) reliability, and verifiable safety. City-scale digital twins require continuous, low-power sensing and edge inference to steer energy, mobility, and public safety systems. Global connectivity mandates NTN integration to erase coverage deserts. Crucially, this ascent must be inclusive: open interfaces, interoperable stacks, and affordable deployment models are essential to avoid deepening the digital divide.

These ambitions introduce hard trade-offs. Sensing-rich networks heighten privacy risks unless differential privacy, on-device learning, and federated analytics are standard. Higher frequencies amplify energy consumption; energy-per-bit, energy-per-sensed-event, and embodied carbon must become first-class KPIs alongside throughput and latency. RIS and dense cells add control complexity; zero-touch management must be explainable and auditable. Spectrum scarcity and fragmentation call for more dynamic sharing, cross-border coordination, and coexistence strategies that balance incumbents with new entrants. Security must extend beyond cryptography to supply-chain integrity, over-the-air integrity for reconfigurable elements, and resilient operation under interference or disasters.

This work frames 6G as the transition from communications to a programmable, physics-aware infrastructure, and it advances three contributions:

- A reference architecture for the “spatial fabric” that unifies radio, sensing, compute, and power across terrestrial and non-terrestrial domains, clarifying control loops from PHY to intent.
- A capability-to-stewardship mapping: for each enabling technology (THz, RIS, NTN, JCAS, semantic/edge AI, ambient/backscatter), we specify maturity, bottlenecks, and guardrails (privacy, security, safety, and sustainability).
- A measurement and governance agenda: standardized benchmarks and disclosures (spectral/energy efficiency, sensing resolution and false-alarm rates, localization accuracy, reliability “nines,” carbon

per delivered QoE), plus open and interoperable interfaces to enable multi-vendor, multi-tenant ecosystems.

We also delineate research questions that will determine whether the fabric is robust, trustworthy, and economically viable:

- How do we co-design waveforms, RIS control, and inference to optimize joint task performance under energy and privacy constraints?
- What abstractions expose “intent” safely to the network and bind it to verifiable service-level guarantees across heterogeneous access and compute?
- How can NTN be made scheduler-aligned with terrestrial RANs given Doppler, latency, and intermittency, without sacrificing simplicity for developers?
- Which lifecycle metrics (J/bit, J/task, CO₂e/session) truly reflect sustainability, and how should they shape spectrum policy and deployment incentives?

By articulating both the technical stack and its stewardship, the Wireless Ascent aims to guide the community from isolated breakthroughs to engineered, interoperable systems that are performant and responsible. If 1G–5G gave us connectivity at scale, 6G’s task is to weave that connectivity into the fabric of reality—perceptive, programmable, and principled.

A simple alphanumeric symbol—4G, LTE, 5G—flickers in the top corner of billions of displays as a silent, continual sign of our connection to the globe. We automatically think of this sign as a measure of speed. We love the video stream that never stops, the download that happens right away, and the game that doesn't lag. But if you only look at the speed of wireless technology over time, it's like looking at a beautiful tapestry and seeing only one thread. It's not only a story of getting faster from the analogue crackle of 1G to the theoretical, cyber-physical weave of 6G. It tells the tale of a fundamental change in how we think about being linked that will change society. We went from untethering the human voice to wiring our global infrastructure and, finally, to weaving our digital and physical worlds into one interactive continuum.

1G: The Revolution in Analogue Technology and the Free Voice

Copper cable connected people before the 1980s. The phone was a tool that was tied to a place, such a home, an office, or a booth. 1G, the first generation of wireless technology, did something amazing that is today normal: it cut the physical cord. 1G made voice communication transportable for the first time by using analogue radio transmissions, which are similar to FM radio frequencies. The gadgets themselves were symbols of this new freedom: big, power-hungry "brick phones" that only rich people or people in important jobs could afford. Calls could be listened to, there wasn't enough space, and there was often static during the call. But the technology's flaws were overshadowed by the strength of its main premise. 1G didn't just make a new device; it changed the way people move around. It established the seed of a future where your identification and point of contact were no longer a set address, but the device you carried. It was a one-dimensional revolution: the spoken word was free.

2G: The Digital Dawn and the Power of the Written Word

The change to the 1990s introduced the digital revolution to the radio. Moving to Second Generation (2G) technology was a big change in how things were built. 2G turned voice into digital code, which made it clearer, safer through encryption, and far more efficient, allowing more people to utilise the same piece of spectrum. This efficiency, which was made possible by standards like GSM (Global System for Mobiles) and CDMA (Code Division Multiple Access), was what started the process of democratisation. Phones got smaller, batteries lasted longer, and mobile phones went from being a luxury item to something that everyone needed.

But 2G's biggest legacy wasn't just better phone conversations. The Short Message Service, or SMS, was its most popular feature. This 160-character protocol transformed the way people talked to one other by giving them the power of asynchronicity and privacy. A message could be delivered and received without the need for a live interaction, which changed how people interact with each other. The initial, timid moves into mobile data came with SMS. GPRS and EDGE, which are sometimes called "2.5G," were the first services to show off the mobile internet. They were slow and cumbersome, and you had to use Wireless Application Protocol (WAP) browsers to get to them. It was frustratingly limiting, but it was also predictive. 2G taught people how to text, which set the stage for the data-driven future that would follow. It made voices clearer, but more crucially, it connected us through writing and the first bits of data.

3G: The Internet in Your Hand and the Birth of the Smartphone

If 2G unlocked the door to data, 3G kicked it all the way open. The Third Generation's promise was "mobile broadband," and it came out in the early 2000s. It was built from the bottom up to handle not just voice calls, but also a constant stream of internet data. Technologies like UMTS and EV-DO made mobile web browsing, email, and location services possible by making them much faster and lowering latency.

But the network was only half of the problem. A breakthrough in hardware and software at the same time revealed 3G's entire potential. The release of the Apple iPhone in 2007 and the growth of Android after that turned 3G from a technical standard into a cultural phenomenon. Having a powerful computer in your hand and a good network was a game-changer. This synergy led to the app economy. The cell phone was no longer only a way to talk to people; it became a computer, a GPS, a music player, and a way to access information from around the world. 3G changed "connecting people to people" to "connecting people to information." This was the first time we had the idea of a smartphone, which changed how we use technology forever.

4G/LTE: The App's Dominance and the World of On-Demand Services

The Fourth Generation, which is mostly renowned for its Long-Term Evolution (LTE) standard, was more of a sociological explosion than an evolution. 3G made the mobile internet conceivable, but 4G made it fast, reliable, and everywhere. 4G made a huge difference by switching to an all-IP (Internet Protocol) network design. This improved bandwidth and, most importantly, cut latency, which is the time it takes for a command to be sent and a response to be received. This wasn't just a small improvement; it made the difference between a video buffering forever and streaming in high quality.

This environment, which had minimal latency and great speed, led to a Cambrian explosion of novel behaviours and services. 4G is the foundation of our current digital lives. It made the on-demand economy possible by connecting users, service providers, and location data in real time. This made businesses like Uber, Lyft, and DoorDash conceivable. It helped visual-first social media sites like Instagram, Snapchat, and TikTok grow, as video became the main way to communicate. It freed up entertainment, turning streaming from Netflix and YouTube into a daily need instead of a luxury that only worked on a computer. For hundreds of millions of people around the world, 4G didn't just put the internet in their pocket; it made the mobile internet their main way to get online, and sometimes their only way. It made the smartphone the centre of modern life, like a remote control for our lives.

5G: The Industrial Network and the Revolution in Machine-to-Machine Communication

As we use and implement the Fifth Generation, we are seeing another major change in purpose. Enhanced Mobile Broadband (eMBB), which is the main focus of consumer marketing, is not where 5G's truly revolutionary potential lies. It is the first generation that was made mostly for machines, systems, and infrastructure, not for people.

Two other, more important pillars support its architecture. Ultra-Reliable Low-Latency Communication (URLLC) is the first. It promises near-instantaneous responsiveness for mission-critical tasks. This is the

technology that will let self-driving cars talk to each other and to city infrastructure in milliseconds to prevent crashing into each other. It will make remote surgery possible, where a robotic arm on the other side of the continent can see and hear what the surgeon is doing. The second pillar is Massive Machine-Type Communications (mMTC), which lets billions of low-power devices communicate to each other. These devices can be anything from soil sensors in a farmer's field to electricity meters in a smart grid.

These features make 5G the brain of the Internet of Things (IoT). Its goal is to go beyond connecting people to integrating the whole fabric of our society—our factories, cities, logistics, and energy grids—into a smart, automated, and responsive network. It is the industrial-grade infrastructure that will support the next wave of automation and data-driven improvement.

6G: The Cyber-Physical Horizon and the Blurring of Realities

The concept for 6G, which is still being worked on in research labs, is the last logical step in this rise: the full merging of the digital, physical, and even biological worlds. 6G is about making a smooth, engaging connection between machines and people, while 5G is about linking machines. This future network plans to use terahertz frequencies, which will provide it much more bandwidth and almost no latency. But its real breakthrough will probably come from putting AI and machine learning right into the network fabric. This will let it manage resources on the fly, predict demands, and even cure itself.

6G's possible uses sound like something out of a science fiction movie, yet they are the subject of a lot of research around the world. They incorporate real holographic communication for immersive telepresence, which lets you meet and talk to others as if you were in the same room. For example, they may make "digital twins" in real time, which are perfect virtual copies of real things like a jet engine, a bridge, or even a human heart. These can be used for simulation, prediction, and control. The "Internet of Senses" or the Tactile Internet is a very interesting idea. It would let the network send not just sight and sound, but also touch, taste, and smell using sophisticated haptic and sensory interfaces. 6G wants to make it so that there is no difference between being in the digital world and being in the real world.

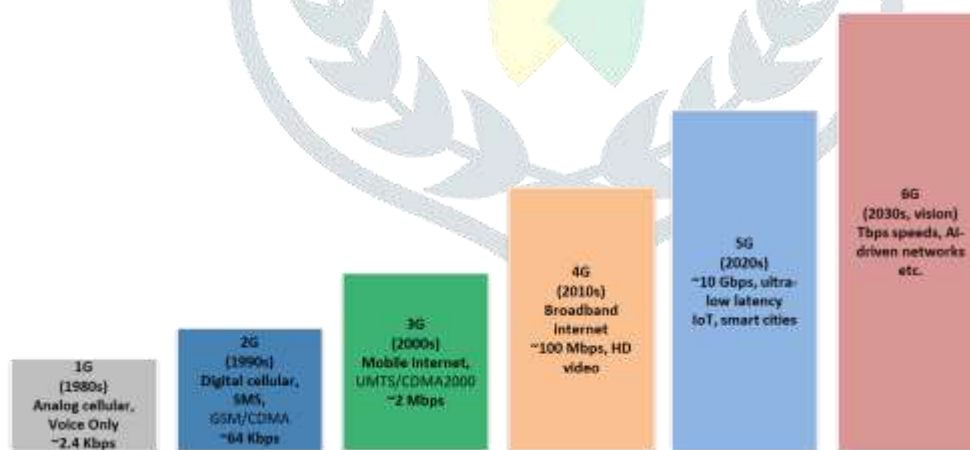


Figure 1. Evolution of Wireless Generations (from 1G to 6G)

Conclusion: The Responsibility of Weaving Worlds

The path from 1G to 6G is simple and amazing: it starts with untethering the voice, then goes to connecting through text, getting information, streaming media, networking our infrastructure, and finally merging with reality itself. Each generation has added to the last, making our environment smaller and our talents bigger, changing our economy, communities, and even how we feel being human.

As this integration gets deeper, the obligation gets bigger and bigger. The problems that will come with this hyper-connected future are huge. They include protecting privacy in a world where everything is always being sensed, protecting important infrastructure, reducing the huge energy needs of these networks, and

closing a digital divide that might become a gap between worlds. The little icon in the corner of our screen is no longer only a way to show speed. It is the quiet planner of our shared future. As we get ready to weave universes, our most important job is to make sure that the fabric we make is fair, safe, and, in the end, serves all of humanity.

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