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Innovation of Digital Infrastructure Outgrowth of Cloud and 5G in Industrial Internet of Things

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ABSTRACT

Cloud computing[1] is the on-demand availability of computer system resources, especially data storage (cloud storage) and computing power, without direct active management by the user.[2] Large clouds often have functions distributed over multiple locations, each of which is a data center. Cloud computing relies on sharing of resources to achieve coherence and typically uses a pay-as-you-go model, which can help in reducing capital expenses but may also lead to unexpected operating expenses for users.[3] In telecommunications, 5G is the fifth-generation technology standard for cellular networks, which cellular phone companies began deploying worldwide in 2019, and is the successor to 4G technology that provides connectivity to most current mobile phones.

KEYWORDS: *5G, cloud, digital, internet, industrial, innovation*

INTRODUCTION

Like its predecessors, 5G networks are cellular networks, in which the service area is divided into small geographical areas called cells. All 5G wireless devices in a cell are connected to the Internet and the telephone network by radio waves through a basestation and antennae in the cell. The new networks have higher download speeds, with a peak speed of 10 gigabits per second (Gbit/s) when there is only one user in the network.[1] 5G has higher bandwidth to deliver faster speeds than 4G and can connect more devices, improving the quality of Internet services in crowded areas.[2] Due to the increased bandwidth, it is expected the 5G networks will increasingly be used as general internet service providers (ISPs), competing with existing ISPs such as cable internet, and also will make possible new applications in internet-of-things (IoT) and machine-to-machine areas. Cellphones with 4G capability alone are not able to use the 5G networks.

Overview

5G networks are cellular networks, in which the service area is divided into small geographical areas called cells. All 5G wireless devices in a cell communicate by radio waves with a cellular base station via fixed antennas, over frequencies assigned by the base station. The base stations, termed nodes, are connected to switching centers in the telephone network and routers for Internet access by high-bandwidth optical fiber or wireless backhaul connections. As in other cellular networks, a mobile device moving from one cell to another is automatically handed off seamlessly.

The industry consortium setting standards for 5G, the 3rd Generation Partnership Project (3GPP), defines "5G" as any system using 5G NR (5G New Radio) software — a definition that came into general use by late 2018.

Several network operators use millimeter waves called FR2 in 5G terminology, for additional capacity and higher throughputs. Millimeter waves have a shorter range than the lower frequency microwaves, therefore the cells are of a smaller size. Millimeter waves also have more trouble passing through building walls and humans. Millimeter-wave antennas are smaller than the large antennas used in previous cellular networks.

The increased data rate is achieved partly by using additional higher-frequency radio waves in addition to the low- and medium-band frequencies used in previous cellular networks. For providing a wide range of services, 5G networks can operate in three frequency bands — low, medium, and high.

5G can be implemented in low-band, mid-band or high-band millimeter-wave. Low-band 5G uses a similar frequency range to 4G cellphones, 600–900 MHz, which can potentially offer higher download speeds than 4G: 5–250 megabits per second (Mbit/s).[3][4] Low-band cell towers have a range and coverage area similar to 4G towers. Mid-band 5G uses microwaves of 1.7–4.7 GHz, allowing speeds of 100–900 Mbit/s, with each cell tower providing service up to several kilometers in radius. This level of service is the most widely deployed, and was deployed in many metropolitan areas in 2020. Some regions are not implementing the low band, making Mid-band the minimum service level. High-band 5G uses frequencies of 24–47 GHz, near the bottom of the millimeter wave band, although higher frequencies may be used in the future. It often achieves download speeds in the gigabit-per-second (Gbit/s) range, comparable to co-axial cable Internet service. However, millimeter waves (mmWave or mmW) have a more limited range, requiring many small cells.[5] They can be impeded or blocked by materials in walls or windows or pedestrians.[6][7] Due to their higher cost, plans are to deploy these cells only in dense urban environments and areas where crowds of people congregate such as sports stadiums and convention centers. The above speeds are those achieved in actual tests in 2020, and speeds are expected to increase during rollout.[3] The spectrum ranging from 24.25 to 29.5 GHz has been the most licensed and deployed 5G mmWave spectrum range in the world.[8]

Rollout of 5G technology has led to debate over its security and relationship with Chinese vendors. It has also been the subject of health concerns and misinformation, including discredited conspiracy theories linking it to the COVID-19 pandemic.

Application areas

The ITU-R has defined three main application areas for the enhanced capabilities of 5G. They are Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency

Communications (URLLC), and Massive Machine Type Communications (mMTC).[9] Only eMBB is deployed in 2020; URLLC and mMTC are several years away in most locations.[10]

Enhanced Mobile Broadband (eMBB) uses 5G as a progression from 4G LTE mobile broadband services, with faster connections, higher throughput, and more capacity. This will benefit areas of higher traffic such as stadiums, cities, and concert venues.[11]

'Ultra-Reliable Low-Latency Communications' (URLLC) refers to using the network for mission-critical applications that require uninterrupted and robust data exchange. Short-packet data transmission is used to meet both reliability and latency requirements of the wireless communication networks.

Massive Machine-Type Communications (mMTC) would be used to connect to a large number of devices. 5G technology will connect some of the 50 billion connected IoT devices.[12] Most will use the less expensive Wi-Fi. Drones, transmitting via 4G or 5G, will aid in disaster recovery efforts, providing real-time data for emergency responders.[12] Most cars will have a 4G or 5G cellular connection for many services. Autonomous cars do not require 5G, as they have to be able to operate where they do not have a network connection.[13] However, most autonomous vehicles also feature tele-operations for mission accomplishment, and these greatly benefit from 5G technology.[14][15]

Performance

Speed

5G is capable of delivering significantly faster data rates than 4G, with peak data rates of up to 20 gigabits per second (Gbps).[16] Furthermore, average 5G download speeds have been recorded at 186.3 Mbit/s in the U.S. by T-Mobile, while South Korea leads globally with average speeds of 432 megabits per second (Mbps).[17][18] 5G networks are also designed to provide significantly more capacity than 4G networks, with a projected 100-fold increase in network capacity and efficiency.[19]

The most widely used form of 5G, sub-6 GHz 5G (mid-band), is capable of delivering data rates ranging from 10 to 1,000 megabits per second (Mbps), with a much greater reach than mmWave bands. C-Band (n77/n78) was deployed by various U.S. operators in 2022 in the sub-6 bands, although its deployment by Verizon and AT&T was delayed until early January 2022 due to safety concerns raised by the Federal Aviation Administration.

Low-band frequencies (such as n5) offer a greater coverage area for a given cell, but their data rates are lower than those of mid and high bands in the range of 5–250 megabits per second (Mbps).[4]

Latency

In 5G, the ideal "air latency" is of the order of 8 to 12 milliseconds i.e., excluding delays due to HARQ retransmissions, handovers, etc. Retransmission latency and backhaul latency to the server must be added to the "air latency" for correct comparisons. Verizon reported the latency on its 5G early deployment is 30 ms Edge Servers close to the towers can probably reduce latency to between 10 and 15 milliseconds

Latency is much higher during handovers; ranging from 50 to 500 milliseconds depending on the type of handover. Reducing handover interruption time is an ongoing area of research and development; options include modifying the handover margin (offset) and the time-to-trigger (TTT).

Error rate

5G uses adaptive modulation and coding scheme (MCS) to keep the block error rate (BLER) extremely low. Whenever the error rate crosses a (very low) threshold the transmitter will switch to a lower MCS, which will be less error-prone. This way speed is sacrificed to ensure an almost zero error rate.

Range

The range of 5G depends on many factors: transmit power, frequency, and interference. For example, mmWave (e.g.:band n258) will have a lower range than mid-band (e.g.: band n78) which will have a lower range than low-band (e.g.: band n5)

Given the marketing hype on what 5G can offer, simulators and drive tests are used by cellular service providers for the precise measurement of 5G performance.

Standards

Initially, the term was associated with the International Telecommunication Union's IMT-2020 standard, which required a theoretical peak download speed of 20 gigabits per second and 10 gigabits per second upload speed, along with other requirements.[16] Then, the industry standards group 3GPP chose the 5G NR (New Radio) standard together with LTE as their proposal for submission to the IMT-2020 standard.[20][21]

5G NR can include lower frequencies (FR1), below 6 GHz, and higher frequencies (FR2), above 24 GHz. However, the speed and latency in early FR1 deployments, using 5G NR software on 4G hardware (non-standalone), are only slightly better than new 4G systems, estimated at 15 to 50% better.[22][23][24]

The standard documents are organized by 3rd Generation Partnership Project (3GPP),[25][26] with its system architecture defined in TS 23.501.[27] The packet protocol for mobility management (establishing connection and moving between base stations) and session management (connecting to networks and network slices) is described in TS 24.501.[28] Specifications of key data structures are found in TS 23.003.[29]

Fronthaul network

IEEE covers several areas of 5G with a core focus in wireline sections between the Remote Radio Head (RRH) and Base Band Unit (BBU). The 1914.1 standards focus on network architecture and dividing the connection between the RRU and BBU into two key sections. Radio Unit (RU) to the Distributor Unit (DU) being the NGFI-I (Next Generation Fronthaul Interface) and the DU to the Central Unit (CU) being the NGFI-II interface allowing a more diverse and cost-effective network. NGFI-I and NGFI-II have defined performance values which should be compiled to ensure different traffic types defined by the ITU are capable of being carried.[page needed] The IEEE 1914.3 standard is creating a new Ethernet frame format capable of carrying IQ data in a much more efficient way depending on the functional split utilized. This is based on the 3GPP definition of functional splits.[page needed]

5G NR
5G NR (New Radio) is the de facto air interface developed for 5G networks.[30] It is the global standard for 3GPP 5G networks.[31]

The study of NR within 3GPP started in 2015, and the first specification was made available by the end of 2017. While the 3GPP standardization process was ongoing, the industry had already begun efforts to implement infrastructure compliant with the draft standard, with the first large-scale commercial launch of 5G NR having occurred in the end of 2018. Since 2019, many operators have deployed 5G NR networks and handset manufacturers have developed 5G NR enabled handsets.[32]

5Gi
5Gi is an alternative 5G variant developed in India. It was developed in a joint collaboration between IIT Madras, IIT Hyderabad, TSDSI, and the Centre of Excellence in Wireless Technology (CEWiT) 5Gi is designed to improve 5G coverage in rural and remote areas over varying geographical terrains. 5Gi uses Low Mobility Large Cell (LMLC) to extend 5G connectivity and the range of a base station.[33]

In April 2022, 5Gi was merged with the global 5G NR standard in the 3GPP Release 17 specifications.[34]

Pre-standard implementations
- 5G TF: American carrier Verizon used a pre-standard variation of 5G known as 5G TF (Verizon 5G Technical Forum) for Fixed Wireless Access in 2018. The 5G service provided to customers in this standard is incompatible with 5G NR. Verizon has since migrated to 5G NR.[35]
- 5G-SIG: KT Corporation had a pre-standard variation of 5G developed called 5G-SIG. This was deployed at the Pyeongchang 2018 Winter Olympics.[36]

Internet of things
In the Internet of things (IoT), 3GPP is going to submit evolution of NB-IoT and eMTC (LTE-M) as 5G technologies for the LPWA (Low Power Wide Area) use case.[37]

Non-Terrestrial Network
Standards are being developed by 3GPP to provide access to end devices via non-terrestrial networks (NTN), i.e. satellite or airborne signal relays to allow for better coverage outside of populated or otherwise hard to reach locations.[38][39]

Several manufacturers have announced and released hardware that integrates 5G with satellite networks:
- Samsung Electronics introduced a standardized 5G NTN modem technology in Korea in February 2023,[40] simulated on their Exynos Modem 5300, facilitating smartphone-satellite communication.
- MediaTek launched the world's first commercially available 5G IoT-NTN chipset, MT6825, capable of automatic satellite message receipt and extensive power efficiency.[41][42]
- Qualcomm, in collaboration with Skylo, announced new satellite IoT solutions on June 22, 2023, including the Qualcomm 212S and 9205S modems, supporting the Qualcomm Aware platform for real-time asset tracking and device management.[43]
- Motorola's Defy Satellite Link hotspot, powered by MediaTek's MT6825, became available in June 2023, providing a portable satellite messaging solution with robust battery life and built-in GPS.[44][45]
- Rakuten Symphony, in collaboration with Supermicro, announced high-performing Open RAN technologies and storage systems for operators of cloud-based mobile services.[46]

Deployment
Beyond mobile operator networks, 5G is also expected to be used for private networks with applications in industrial IoT, enterprise networking, and critical communications, in what being described as NR-U (5G NR in Unlicensed Spectrum)[47] and Non-Public Networks (NPNs) operating in licensed spectrum. By the mid-to-late 2020s, standalone private 5G networks are expected to become the predominant wireless communications medium to support the ongoing Industry 4.0 revolution for the digitization and automation of manufacturing and process industries.[48]

Initial 5G NR launches depended on pairing with existing LTE (4G) infrastructure in non-standalone (NSA) mode (5G NR radio with 4G core), before maturation of the standalone (SA) mode with the 5G core network.[49]

As of April 2019, the Global Mobile Suppliers Association had identified 224 operators in 88 countries that have demonstrated, are testing or trialing, or have been licensed to conduct field trials of 5G technologies, are deploying 5G networks or have announced service launches.[50] The equivalent numbers in November 2018 were 192 operators in 81 countries.[51] The first country to adopt 5G on a large scale was South Korea, in April 2019. Swedish telecoms giant Ericsson predicted that 5G internet will cover up to 65% of the world's population by the end of 2025.[52] Also, it plans to invest 1 billion reals ($238.30 million) in Brazil to add a new assembly line dedicated to fifth-generation technology (5G) for its Latin American operations.[53]

When South Korea launched its 5G network, all carriers used Samsung, Ericsson, and Nokia base stations and equipment, except for LG U Plus, who also used Huawei equipment.[54][55] Samsung was the largest supplier for 5G base stations in South Korea at launch, having shipped 53,000 base stations at the time, out of 86,000 base stations installed across the country at the time.[56]

The first fairly substantial deployments were in April 2019. In South Korea, SK Telecom claimed 38,000 base stations, KT Corporation 30,000 and LG U Plus 18,000; of which 85% are in six major cities.[57] They are using 3.5 GHz (sub-6) spectrum in non-standalone (NSA) mode and tested speeds were from 193 to 430 Mbit/s down.[58] 260,000 signed up in the first month and 4.7 million by the end of 2019.[59] T-Mobile US was the first company in the world to launch a commercially available 5G NR Standalone network.[60]

Nine companies sell 5G radio hardware and 5G systems for carriers: Altiostar, Cisco Systems, Datang Telecom/Fiberhome, Ericsson, Huawei, Nokia, Qualcomm, Samsung, and ZTE.[61][62][63][64][65][66][67] As of 2023, Huawei is the leading 5G equipment manufacturer and has the greatest market share of 5G equipment and has built approximately 70% of worldwide 5G base stations.[68]:182

Spectrum
Large quantities of new radio spectrum (5G NR frequency bands) have been allocated to 5G.[69] For example, in July 2016, the U.S. Federal Communications Commission (FCC) freed up vast amounts of bandwidth in underused high-band spectrum for 5G. The Spectrum Frontiers Proposal (SFP) doubled the amount of millimeter-wave unlicensed spectrum

to 14 GHz and created four times the amount of flexible, mobile-use spectrum the FCC had licensed to date.[70] In March 2018, European Union lawmakers agreed to open up the 3.6 and 26 GHz bands by 2020.[71]

As of March 2019, there are reportedly 52 countries, territories, special administrative regions, disputed territories and dependencies that are formally considering introducing certain spectrum bands for terrestrial 5G services, are holding consultations regarding suitable spectrum allocations for 5G, have reserved spectrum for 5G, have announced plans to auction frequencies or have already allocated spectrum for 5G use.[72]

5G devices

In March 2019, the Global Mobile Suppliers Association released the industry's first database tracking worldwide 5G device launches.[73] In it, the GSA identified 23 vendors who have confirmed the availability of forthcoming 5G devices with 33 different devices including regional variants. There were seven announced 5G device form factors: (telephones (×12 devices), hotspots (×4), indoor and outdoor customer-premises equipment (×8), modules (×5), Snap-on dongles and adapters (×2), and USB terminals (×1)).[74] By October 2019, the number of announced 5G devices had risen to 129, across 15 form factors, from 56 vendors.[75]

In the 5G IoT chipset arena, as of April 2019 there were four commercial 5G modem chipsets and one commercial processor/platform, with more launches expected in the near future.[76]

On March 4, 2019, the first-ever all-5G smartphone Samsung Galaxy S10 5G was released. According to Business Insider, the 5G feature was showcased as more expensive in comparison with the 4G Samsung Galaxy S10e.[77] On March 19, 2020, HMD Global, the current maker of Nokia-branded phones, announced the Nokia 8.3 5G, which it claimed as having a wider range of 5G compatibility than any other phone released to that time. The mid-range model is claimed to support all 5G bands from 600 MHz to 3.8 GHz.[78]

Many phone manufacturers support 5G. Google Pixel devices support 5G, starting with the 4a 5G and Pixel 5.[79] Apple devices also support 5G, starting with iPhone 12 and later models support 5G.[80][81]

Technology

New radio frequencies

The air interface defined by 3GPP for 5G is known as New Radio (NR), and the specification is subdivided into two frequency bands, FR1 (below 6 GHz) and FR2 (24–54 GHz)

Frequency range 1 (< 6 GHz)

Otherwise known as sub-6, the maximum channel bandwidth defined for FR1 is 100 MHz, due to the scarcity of continuous spectrum in this crowded frequency range. The band most widely being used for 5G in this range is 3.3–4.2 GHz. The Korean carriers use the n78 band at 3.5 GHz.

Some parties used the term "mid-band" frequency to refer to higher part of this frequency range that was not used in previous generations of mobile communication.

Frequency range 2 (24–71 GHz)

The minimum channel bandwidth defined for FR2 is 50 MHz and the maximum is 400 MHz, with two-channel aggregation supported in 3GPP Release 15. Signals in this frequency range with wavelengths between 4 and 12 mm are called millimeter waves. The higher the carrier frequency, the greater the ability to support high data-transfer speeds. This is because a given channel bandwidth takes up a lower fraction of the carrier frequency, so high-bandwidth channels are easier to realize at higher carrier frequencies.

FR2 coverage

5G in the 24 GHz range or above use higher frequencies than 4G, and as a result, some 5G signals are not capable of traveling large distances (over a few hundred meters), unlike 4G or lower frequency 5G signals (sub 6 GHz). This requires placing 5G base stations every few hundred meters in order to use higher frequency bands. Also, these higher frequency 5G signals cannot penetrate solid objects easily, such as cars, trees, walls, and even humans, because of the nature of these higher frequency electromagnetic waves. 5G cells can be deliberately designed to be as inconspicuous as possible, which finds applications in places like restaurants and shopping malls.[82]

Cell types		Deployment environment	Max. number of users	Output power (W)	Max. distance from base station
5G NR FR2	Femtocell	Homes, businesses	Home: 4–8 Businesses: 16–32	indoors: 0.01–0.1 outdoors: 0.2–1	tens of meters
	Pico cell	Public areas like shopping malls, airports, train stations, skyscrapers	64 to 128	indoors: 0.1–0.25 outdoors: 1–5	tens of meters
	Micro cell	Urban areas to fill coverage gaps	128 to 256	outdoors: 5–10	few hundreds of meters
	Macro cell	Urban areas to provide additional capacity	more than 250	outdoors: 10–20	hundreds of meters
Wi-Fi (for comparison)		Homes, businesses	fewer than 50	indoors: 0.02–0.1 outdoors: 0.2–1	few tens of meters

Massive MIMO

MIMO systems use multiple antennas at the transmitter and receiver ends of a wireless communication system. Multiple antennas use the spatial dimension for multiplexing in addition to the time and frequency ones, without changing the bandwidth requirements of the system.

Massive MIMO (multiple-input and multiple-output) antennas increases sector throughput and capacity density using large numbers of antennas. This includes Single User MIMO and Multi-user MIMO (MU-MIMO). Each antenna is individually-controlled and may embed radio transceiver components.

In general, more antennas equal better performance. But more antennas also require bigger arrays that draw more power. Some of the places service providers deploy radio links have very tight constraints, so finding the right solution means weighing tradeoffs. For in-building coverage, the performance gain is often worth it. For outdoor or street-level coverage, maybe not.[83]

Edge computing

Edge computing is delivered by computing servers closer to the ultimate user. It reduces latency, data traffic congestion[84][85] and can improve service availability.[86]

Small cell

Small cells are low-powered cellular radio access nodes that operate in licensed and unlicensed spectrum that have a range of 10 meters to a few kilometers. Small cells are critical to 5G networks, as 5G's radio waves can't travel long distances, because of 5G's higher frequencies.[87][88][89][90]

Beamforming

There are two kinds of beamforming (BF): digital and analog. Digital beamforming involves sending the data across multiple streams (layers), while analog beamforming shaping the radio waves to point in a specific direction. The analog BF technique combines the power from elements of the antenna array in such a way that signals at particular angles experience constructive interference, while other signals pointing to other angles experience destructive interference. This improves signal quality in the specific direction, as well as data transfer speeds. 5G uses both digital and analog beamforming to improve the system capacity.[91][92]

Convergence of Wi-Fi and cellular

One expected benefit of the transition to 5G is the convergence of multiple networking functions to achieve cost, power, and complexity reductions. LTE has targeted convergence with Wi-Fi band/technology via various efforts, such as License Assisted Access (LAA; 5G signal in unlicensed frequency bands that are also used by Wi-Fi) and LTE-WLAN Aggregation (LWA; convergence with Wi-Fi Radio), but the differing capabilities of cellular and Wi-Fi have limited the scope of convergence. However, significant improvement in cellular performance specifications in 5G, combined with migration from Distributed Radio Access Network (D-RAN) to Cloud- or Centralized-RAN (C-RAN) and rollout of cellular small cells can potentially narrow the gap between Wi-Fi and cellular networks in dense and indoor deployments. Radio convergence could result in sharing ranging from the aggregation of cellular and Wi-Fi channels to the use of a single silicon device for multiple radio access technologies.[93]

NOMA (non-orthogonal multiple access)

NOMA (non-orthogonal multiple access) is a proposed multiple-access technique for future cellular systems via allocation of power.[94]

SDN/NFV

Initially, cellular mobile communications technologies were designed in the context of providing voice services and Internet access. Today a new era of innovative tools and technologies is inclined towards developing a new pool of applications. This pool of applications consists of different domains such as the Internet of Things (IoT), web of connected autonomous vehicles, remotely controlled robots, and heterogeneous sensors connected to serve versatile applications.[95] In this context, network slicing has emerged as a key technology to efficiently embrace this new market model.[96]

Service-Based Architecture

The 5G Service-Based architecture replaces the referenced-based architecture of the Evolved Packet Core that is used in 4G. The SBA breaks up the core functionality of the network into interconnected network functions (NFs), which are typically implemented as Cloud-Native Network Functions. These NFs register with the Network Repository Function (NRF) which maintains their state, and communicate with each other using the Service Communication Proxy (SCP). The interfaces between the elements all utilize RESTful APIs.[97] By breaking functionality down this way, mobile operators are able to utilize different infrastructure vendors for different functions, and the flexibility to scale each function independently as needed.[97]

5G Network Functions [98]		
NF Name	NF Acronym	Analogous EPC element
Authentication Server Function	AUSF	MME / HSS (Authentication)
Access and Mobility Management Function	AMF	MME
Unstructured Data Storage Function	UDSF	N/A
Network Exposure Function	NEF	N/A
Network Slice Specific Authentication and Authorization Function	NSSAAF	N/A
Network Slice Selection Function	NSSF	N/A
Policy Control Function	PCF	PCRF
Session Management Function	SMF	MME / PGW-C
Unified Data Management	UDM	HSS (DB Front End)
Unified Data Repository	UDR	HSS (User Database)
User Plane Function	UPF	SGW-U / PGW-U
UE radio Capability Management Function	UCMF	N/A
Application Function	AF	AF (IMS)
Network Data Analytics Function	NWDAF	N/A
CHarging Function	CHF	CSCF

In addition, the standard describes network entities for roaming and inter-network connectivity, including the Security Edge Protection Proxy (SEPP), the Non-3GPP Inter Working Function (N3IWF), the Trusted Non-3GPP Gateway Function (TNGF), the Wireline Access Gateway Function (W-AGF), and the Trusted WLAN Interworking Function (TWIF). These can be deployed by operators as needed depending on their deployment.

Channel coding

The channel coding techniques for 5G NR have changed from Turbo codes in 4G to polar codes for the control channels and LDPC (low-density parity check codes) for the data channels.[99][100]

Operation in unlicensed spectrum

In December 2018, 3GPP began working on unlicensed spectrum specifications known as 5G NR-U, targeting 3GPP Release 16.[101] Qualcomm has made a similar proposal for LTE in unlicensed spectrum.

Future evolution

5G-Advanced

5G-Advanced (also known as 5.5G) is a name for 3GPP release 18, which as of 2021 is under conceptual development.[102][103][104][105][106] 5G-Advanced is expected to appear in commercial products in 2024.[107]

Concerns

Security concerns

A report published by the European Commission and European Agency for Cybersecurity details the security issues surrounding 5G. The report warns against using a single supplier for a carrier's 5G infrastructure, especially those based outside the European Union. (Nokia and Ericsson are the only European manufacturers of 5G equipment.)[108]

On October 18, 2018, a team of researchers from ETH Zurich, the University of Lorraine and the University of Dundee released a paper entitled, "A Formal Analysis of 5G Authentication".[109][110] It alerted that 5G technology could open ground for a new era of security threats. The paper described the technology as "immature and insufficiently tested," and one that "enables the movement and access of vastly higher quantities of data, and thus broadens attack surfaces". Simultaneously, network security companies such as Fortinet,[111] Arbor Networks,[112] A10 Networks,[113] and Voxility[114] advised on personalized and mixed security deployments against massive DDoS attacks foreseen after 5G deployment.

IoT Analytics estimated an increase in the number of IoT devices, enabled by 5G technology, from 7 billion in 2018 to 21.5 billion by 2025.[115] This can raise the attack surface for these devices to a substantial scale, and the capacity for DDoS attacks, cryptojacking, and other cyberattacks could boost proportionally.[110] In addition, the EPS solution for 5G networks has identified a design vulnerability. The vulnerability affects the operation of the device during cellular network switching.[116]

Due to fears of potential espionage of users of Chinese equipment vendors, several countries (including the United States, Australia and the United Kingdom as of early 2019)[117] have taken actions to restrict or eliminate the use of Chinese equipment in their respective 5G networks. A 2012 U.S. House Permanent Select Committee on Intelligence report concluded that using equipment made by Huawei and ZTE, another Chinese telecommunications company, could "undermine core U.S. national security interests".[118] In 2018, six U.S. intelligence chiefs, including the directors of the CIA and FBI, cautioned Americans against using Huawei products, warning that the company could conduct "undetected espionage".[119] Further, a 2017 investigation by the FBI determined that Chinese-made Huawei equipment could disrupt U.S. nuclear arsenal communications.[120] Chinese vendors and the Chinese government have denied claims of espionage, but experts have pointed out that Huawei would have no choice but to hand over network data to the Chinese government if Beijing asked for it because of Chinese National Security Law.[121]

In August, 2020, the U.S. State Department launched "The Clean Network" as a U.S. government-led, bi-partisan effort to address what it described as "the long-term threat to data privacy, security, human rights and principled collaboration posed to the free world from authoritarian malign actors". Promoters of the initiative have stated that it has resulted in an "alliance of democracies and companies", "based on democratic values". On October 7, 2020, the UK Parliament's Defence Committee released a report claiming that there was clear evidence of collusion between Huawei and Chinese state and the Chinese Communist Party. The UK Parliament's Defence Committee said that the government should consider removal of all Huawei equipment from its 5G networks earlier than planned.[122] In December 2020, the United States announced that more than 60 nations, representing more than two thirds of the world's gross domestic product, and 200 telecom companies, had publicly committed to the principles of The Clean Network. This alliance of democracies included 27 of the 30 NATO members; 26 of the 27 EU members, 31 of the 37 OECD nations, 11 of the 12 Three Seas nations as well as Japan, Israel, Australia, Singapore, Taiwan, Canada, Vietnam, and India.

Electromagnetic interference

Weather forecasting

The spectrum used by various 5G proposals, especially the n258 band centered at 26 GHz, will be near that of passive remote sensing such as by weather and Earth observation satellites, particularly for water vapor monitoring at 23.8 GHz.[123] Interference is expected to occur due to such proximity and its effect could be significant without effective controls. An increase in interference already occurred with some other prior proximate band usages.[124][125] Interference to satellite operations impairs numerical weather prediction performance with substantially deleterious economic and public safety impacts in areas such as commercial aviation.[126][127]

The concerns prompted U.S. Secretary of Commerce Wilbur Ross and NASA Administrator Jim Bridenstine in February 2019 to urge the FCC to delay some spectrum auction proposals, which was rejected.[128] The chairs of the House Appropriations

Committee and House Science Committee wrote separate letters to FCC chairman Ajit Pai asking for further review and consultation with NOAA, NASA, and DoD, and warning of harmful impacts to national security.[129] Acting NOAA director Neil Jacobs testified before the House Committee in May 2019 that 5G out-of-band emissions could produce a 30% reduction in weather forecast accuracy and that the resulting degradation in ECMWF model performance would have resulted in failure to predict the track and thus the impact of Superstorm Sandy in 2012. The United States Navy in March 2019 wrote a memorandum warning of deterioration and made technical suggestions to control band bleed-over limits, for testing and fielding, and for coordination of the wireless industry and regulators with weather forecasting organizations.[130]

At the 2019 quadrennial World Radiocommunication Conference (WRC), atmospheric scientists advocated for a strong buffer of −55 dBW, European regulators agreed on a recommendation of −42 dBW, and US regulators (the FCC) recommended a restriction of −20 dBW, which would permit signals 150 times stronger than the European proposal. The ITU decided on an intermediate −33 dBW until September 1, 2027, and after that a standard of −39 dBW.[131] This is closer to the European recommendation but even the delayed higher standard is much weaker than that requested by atmospheric scientists, triggering warnings from the World Meteorological Organization (WMO) that the ITU standard, at 10 times less stringent than its recommendation, brings the "potential to significantly degrade the accuracy of data collected".[132] A representative of the American Meteorological Society (AMS) also warned of interference,[133] and the European Centre for Medium-Range Weather Forecasts (ECMWF), sternly warned, saying that society risks "history repeat[ing] itself" by ignoring atmospheric scientists' warnings (referencing global warming, monitoring of which could be imperiled).[134] In December 2019, a bipartisan request was sent from the US House Science Committee to the Government Accountability Office (GAO) to investigate why there is such a discrepancy between recommendations of US civilian and military science agencies and the regulator, the FCC.[135]

Aviation

The United States FAA has warned that radar altimeters on aircraft, which operate between 4.2 and 4.4 GHz, might be affected by 5G operations between 3.7 and 3.98 GHz. This is particularly an issue with older altimeters using RF filters[136] which lack protection from neighboring bands.[137] This is not as much of an issue in Europe, where 5G uses lower frequencies between 3.4 and 3.8 GHz.[138] Nonetheless, the DGAC in France has also expressed similar worries and recommended 5G phones be turned off or be put in airplane mode during flights.[139]

On December 31, 2021, U.S. Transportation Secretary Pete Buttigieg and Steve Dickinson, administrator of the Federal Aviation Administration asked the chief executives of AT&T and Verizon to delay 5G implementation over aviation concerns. The government officials asked for a two-week delay starting on January 5, 2022, while investigations are conducted on the effects on radar altimeters. The government transportation officials also asked the cellular providers to hold off their new 5G service near 50 priority airports, to minimize disruption to air traffic that would be caused by some planes being disallowed from landing in poor visibility.[140] After coming to an agreement with government officials the day before,[141] Verizon and AT&T activated their 5G networks on January 19, 2022, except for certain towers near 50 airports.[142] AT&T scaled back its deployment even further than its agreement with the FAA required.[143]

The FAA rushed to test and certify radar altimeters for interference so that planes could be allowed to perform instrument landings (e.g. at night and in low visibility) at affected airports. By January 16, it had certified equipment on 45% of the U.S. fleet, and 78% by January 20.[144] Airlines complained about the avoidable impact on their operations, and commentators said the affair called into question the competence of the FAA.[145] Several international airlines substituted different planes so they could avoid problems landing at scheduled airports, and about 2% of flights (320) were cancelled by the evening of January 19.[146]

Satellite

A number of 5G networks deployed on the radio frequency band of 3.3–3.6 GHz are expected to cause interference with C-Band satellite stations, which operate by receiving satellite signals at 3.4–4.2 GHz frequency.[147] This interference can be mitigated with low-noise block downconverters and waveguide filters.[147]

Wi-Fi

In regions like the US and EU, the 6 GHz band is to be opened up for unlicensed applications, which would permit the deployment of 5G-NR Unlicensed, 5G version of LTE in unlicensed spectrum, as well as Wi-Fi 6e. However, interference could occur with the co-existence of different standards in the frequency band.[148]

Overhype

There have been concerns surrounding the promotion of 5G, questioning whether the technology is overhyped. There are questions on whether 5G will truly change the customer experience,[149] ability for 5G's mmWave signal to provide significant coverage,[150][151] overstating what 5G can achieve or misattributing continuous technological improvement to "5G",[152] lack of new use case for carriers to profit from,[153] wrong focus on emphasizing direct benefits on individual consumers instead of for internet of things devices or solving the last mile problem,[154] and overshadowing the possibility that in some aspects there might be other more appropriate technologies.[155] Such sort of concerns have also led to consumers not trusting information provided by cellular providers on the topic.[156]

Misinformation

Health

There is a long history of fear and anxiety surrounding wireless signals that predates 5G technology. The fears about 5G are similar to those that have persisted throughout the 1990s and 2000s. They center on fringe claims that non-ionizing radiation poses dangers to human health.[157] Unlike ionizing radiation, non-ionizing radiation cannot remove electrons from atoms. The US Centers for Disease Control and Prevention (CDC) says "Exposure to intense, direct amounts of non-ionizing radiation may result in damage to tissue due to heat. This is not common and mainly of concern in the workplace for those who work on large sources of non-ionizing radiation devices and instruments."[158] Some advocates of fringe health claim the regulatory standards are too low and influenced by lobbying groups.[157]

Many popular books of dubious merit have been published on the subject including one by Joseph Mercola alleging that wireless technologies caused numerous conditions from ADHD to heart diseases and brain cancer. Mercola has drawn sharp criticism for his anti-vaccinationism during the COVID-19 pandemic and was warned by the Food and Drug Administration to stop selling fake COVID-19 cures through his online alternative medicine business.[157][159]

According to the New York Times, one origin of the 5G health controversy was an erroneous unpublished study that physicist Bill P. Curry did for the Broward County School Board in 2000 which indicated that the absorption of external microwaves by brain tissue increased with frequency.[160] According to experts[citation needed] this was wrong, the millimeter waves used in 5G are safer than lower frequency microwaves because they cannot penetrate the skin and reach internal organs. Curry had confused in vitro and in vivo research. However Curry's study was widely distributed on the internet. Writing in The New York Times in 2019, William Broad reported that RT America began airing programming linking 5G to harmful health effects which "lack scientific support", such as "brain cancer, infertility, autism, heart tumors, and Alzheimer's disease". Broad asserted that the claims had increased. RT America had run seven programs on this theme by mid-April 2019 but only one in the whole of 2018. The network's coverage had spread to hundreds of blogs and websites.[161]

In April 2019, the city of Brussels in Belgium blocked a 5G trial because of radiation rules.[162] In Geneva, Switzerland, a planned upgrade to 5G was stopped for the same reason.[163] The Swiss Telecommunications Association (ASUT) has said that studies have been unable to show that 5G frequencies have any health impact.[164]

According to CNET,[165] "Members of Parliament in the Netherlands are also calling on the government to take a closer look at 5G. Several leaders in the United States Congress have written to the Federal Communications Commission expressing concern about potential health risks. In Mill Valley, California, the city council blocked the deployment of new 5G wireless cells."[165][166][167][168][169] Similar concerns were raised in Vermont[170] and New Hampshire.[165] The US FDA is quoted saying that it "continues to believe that the current safety limits for cellphone radiofrequency energy exposure remain acceptable for protecting the public health."[171] After campaigning by activist groups, a series of small localities in the UK, including Totnes, Brighton and Hove, Glastonbury, and Frome, passed resolutions against the implementation of further 5G infrastructure, though these resolutions have no impact on rollout plans.[172][173][174]

Low-level EMF does have some effects on other organisms.[175] Vian et al., 2006 finds an effect of microwave on gene expression in plants.[175] A meta-analysis of 95 in vitro and in vivo studies showed that an average of 80% of the in vivo research showed effects of such radiation, as did 58% of the in vitro research, but that the results were inconclusive as to whether any of these effects pose a health risk.[176]

COVID-19 conspiracy theories and arson attacks

As the introduction of 5G technology coincided with the time of COVID-19 pandemic, several conspiracy theories circulating online posited a link between COVID-19 and 5G.[177] This has led to dozens of arson attacks being made on telecom masts in the Netherlands (Amsterdam, Rotterdam, etc.), Ireland (Cork,[178] etc.), Cyprus, the United Kingdom (Dagenham, Huddersfield, Birmingham, Belfast and Liverpool),[179][180] Belgium (Pelt), Italy (Maddaloni), Croatia (Bibinje)[181] and Sweden.[182] It led to at least 61 suspected arson attacks against telephone masts in the United Kingdom alone[183] and over twenty in The Netherlands.

In the early months of the pandemic, anti-lockdown protesters at protests over responses to the COVID-19 pandemic in Australia were seen with anti-5G signs, an early sign of what became a wider campaign by conspiracy theorists to link the pandemic with 5G technology. There are two versions of the 5G-COVID-19 conspiracy theory:[157]

1. The first version claims that radiation weakens the immune system, making the body more vulnerable to SARS-CoV-2 (the virus that causes COVID-19).
2. The second version claims that 5G causes COVID-19. There are different variations on this. Some claim that the pandemic is coverup of illness caused by 5G radiation or that COVID-19 originated in Wuhan because that city was "the guinea-pig city for 5G".

Marketing of non-5G services

In various parts of the world, carriers have launched numerous differently branded technologies, such as "5G Evolution", which advertise improving existing networks with the use of "5G technology".[184] However, these pre-5G networks are an improvement on specifications of existing LTE networks that are not exclusive to 5G. While the technology promises to deliver higher speeds, and is described by AT&T as a "foundation for our evolution to 5G while the 5G standards are being finalized", it cannot be considered to be true 5G. When AT&T announced 5G Evolution, 4x4 MIMO, the technology that AT&T is using to deliver the higher speeds, had already been put in place by T-Mobile without being branded with the 5G moniker. It is claimed that such branding is a marketing move that will cause confusion with consumers, as it is not made clear that such improvements are not true 5G.[185]

DISCUSSION

The United States National Institute of Standards and Technology's definition of cloud computing identifies "five essential characteristics":

- On-demand self-service. A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.
- Broad network access. Capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous thin or thick client platforms (e.g., mobile phones, tablets, laptops, and workstations).

- Resource pooling. The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand.
- Rapid elasticity. Capabilities can be elastically provisioned and released, in some cases automatically, to scale rapidly outward and inward commensurate with demand. To the consumer, the capabilities available for provisioning often appear unlimited and can be appropriated in any quantity at any time.
- Measured service. Cloud systems automatically control and optimize resource use by leveraging a metering capability at some level of abstraction appropriate to the type of service (e.g., storage, processing, bandwidth, and active user accounts). Resource usage can be monitored, controlled, and reported, providing transparency for both the provider and consumer of the utilized service.[4]

Cloud computing has a rich history that extends back to the 1960s, with the initial concepts of time-sharing becoming popularized via Remote Job Entry (RJE). The "data center" model, where users submitted jobs to operators to run on mainframes, was predominantly used during this era. This was a time of exploration and experimentation with ways to make large-scale computing power available to more users through time-sharing, optimizing the infrastructure, platform, and applications, and increasing efficiency for end users.[5]

The use of the "cloud" metaphor to denote virtualized services traces back to 1994, when it was used by General Magic to describe the universe of "places" that mobile agents in the Telescript environment could go. This metaphor is credited to David Hoffman, a General Magic communications employee, based on its long-standing use in networking and telecom.[6] The expression cloud computing became more widely known in 1996 when the Compaq Computer Corporation drew up a business plan for future computing and the Internet. The company's ambition was to supercharge sales with "cloud computing-enabled applications". The business plan foresaw that online consumer file storage would most likely be commercially successful. As a result, Compaq decided to sell server hardware to internet service providers.[7]

In the 2000s, the application of cloud computing began to take shape with the establishment of Amazon Web Services (AWS) in 2002, which allowed developers to build applications independently. In 2006 the beta version of Google Docs was released, Amazon Simple Storage Service, known as Amazon S3, and the Amazon Elastic Compute Cloud (EC2), in 2008 NASA's development of the first open-source software for deploying private and hybrid clouds.[8][9]

The following decade saw the launch of various cloud services. In 2010, Microsoft launched Microsoft Azure, and Rackspace Hosting and NASA initiated an open-source cloud-software project, OpenStack. IBM introduced the IBM SmartCloud framework in 2011, and Oracle announced the Oracle Cloud in 2012. In December 2019, Amazon launched AWS Outposts, a service that extends AWS infrastructure, services, APIs, and tools to customer data centers, co-location spaces, or on-premises facilities.[10][11]

Since the global pandemic of 2020, cloud technology has surged in popularity due to the level of data security it offers and the flexibility of working options it provides for all employees, notably remote workers.[12]

Value proposition

Advocates of public and hybrid clouds claim that cloud computing allows companies to avoid or minimize up-front IT infrastructure costs. Proponents also claim that cloud computing allows enterprises to get their applications up and running faster, with improved manageability and less maintenance, and that it enables IT teams to more rapidly adjust resources to meet fluctuating and unpredictable demand,[13][14][15] providing burst computing capability: high computing power at certain periods of peak demand.[16]

Additional value propositions of cloud computing include:

Topic	Description
Cost reductions	A public-cloud delivery model converts capital expenditures (e.g., buying servers) to operational expenditure.[17] This purportedly lowers barriers to entry, as infrastructure is typically provided by a third party and need not be purchased for one-time or infrequent intensive computing tasks. Pricing on a utility computing basis is "fine-grained", with usage-based billing options. As well, less in-house IT skills are required for implementation of projects that use cloud computing.[18] The e-FISCAL project's state-of-the-art repository[19] contains several articles looking into cost aspects in more detail, most of them concluding that costs savings depend on the type of activities supported and the type of infrastructure available in-house.
Device independence	Device and location independence[20] enable users to access systems using a web browser regardless of their location or what device they use (e.g., PC, mobile phone). As infrastructure is off-site (typically provided by a third-party) and accessed via the Internet, users can connect to it from anywhere.[18]
Maintenance	Maintenance of cloud environment is easier because the data is hosted on an outside server maintained by a provider without the need to invest in data center hardware. IT maintenance of cloud computing is managed and updated by the cloud provider's IT maintenance team which reduces cloud computing costs compared with on-premises data centers.
Multitenancy	Multitenancy enables sharing of resources and costs across a large pool of users thus allowing for: centralization of infrastructure in locations with lower costs (such as real estate, electricity, etc.) peak-load capacity increases (users need not engineer and pay for the resources and equipment to meet their highest possible load-levels) utilization and efficiency improvements for systems that are often only 10–20% utilized.[21][22]

Performance	Performance is monitored by IT experts from the service provider, and consistent and loosely coupled architectures are constructed using web services as the system interface.[18][23]
Productivity	Productivity may be increased when multiple users can work on the same data simultaneously, rather than waiting for it to be saved and emailed. Time may be saved as information does not need to be re-entered when fields are matched, nor do users need to install application software upgrades to their computer.
Availability	Availability improves with the use of multiple redundant sites, which makes well-designed cloud computing suitable for business continuity and disaster recovery.[24]
Scalability and Elasticity	Scalability and elasticity via dynamic ("on-demand") provisioning of resources on a fine-grained, self-service basis in near real-time[25][26] (Note, the VM startup time varies by VM type, location, OS and cloud providers[25]), without users having to engineer for peak loads.[27][28][29] This gives the ability to scale up when the usage need increases or down if resources are not being used.[30] The time-efficient benefit of cloud scalability also means faster time to market, more business flexibility, and adaptability, as adding new resources does not take as much time as it used to.[31] Emerging approaches for managing elasticity include the use of machine learning techniques to propose efficient elasticity models.[32]
Security	Security can improve due to centralization of data, increased security-focused resources, etc., but concerns can persist about loss of control over certain sensitive data, and the lack of security for stored kernels. Security is often as good as or better than other traditional systems, in part because service providers are able to devote resources to solving security issues that many customers cannot afford to tackle or which they lack the technical skills to address.[33] However, the complexity of security is greatly increased when data is distributed over a wider area or over a greater number of devices, as well as in multi-tenant systems shared by unrelated users. In addition, user access to security audit logs may be difficult or impossible. Private cloud installations are in part motivated by users' desire to retain control over the infrastructure and avoid losing control of information security.

Challenges and limitations

One of the main challenges of cloud computing, in comparison to more traditional on-premises computing, is data security and privacy. Cloud users entrust their sensitive data to third-party providers, who may not have adequate measures to protect it from unauthorized access, breaches, or leaks. Cloud users also face compliance risks if they have to adhere to certain regulations or standards regarding data protection, such as GDPR or HIPAA.[34]

Another challenge of cloud computing is reduced visibility and control. Cloud users may not have full insight into how their cloud resources are managed, configured, or optimized by their providers. They may also have limited ability to customize or modify their cloud services according to their specific needs or preferences.[34] Complete understanding of all technology may be impossible, especially given the scale, complexity, and deliberate opacity of contemporary systems; however, there is a need for understanding complex technologies and their interconnections to have power and agency within them.[35] The metaphor of the cloud can be seen as problematic as cloud computing retains the aura of something noumenal and numinous; it is something experienced without precisely understanding what it is or how it works.[36]

In addition, cloud migration is a significant issue. Cloud migration is the process of moving data, applications, or workloads from one cloud environment to another or from on-premises to the cloud. Cloud migration can be complex, time-consuming, and costly, especially if there are incompatibility issues between different cloud platforms or architectures. Cloud migration can also cause downtime, performance degradation, or data loss if not planned and executed properly.[37]

Service models

The service-oriented architecture (SOA) promotes the idea of "Everything as a Service" (EaaS or XaaS, or simply aAsS).[38] This concept is operationalized in cloud computing through several service models as defined by the National Institute of Standards and Technology (NIST). The three standard service models are Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).[4] They are commonly depicted as layers in a stack, providing different levels of abstraction. However, these layers are not necessarily interdependent. For instance, SaaS can be delivered on bare metal, bypassing PaaS and IaaS, and a program can run directly on IaaS without being packaged as SaaS.

Infrastructure as a service (IaaS)

"Infrastructure as a service" (IaaS) refers to online services that provide high-level APIs used to abstract various low-level details of underlying network infrastructure like physical computing resources, location, data partitioning, scaling, security, backup, etc. A hypervisor runs the virtual machines as guests. Pools of hypervisors within the cloud operational system can support large numbers of virtual machines and the ability to scale services up and down according to customers' varying requirements. Linux containers run in isolated partitions of a single Linux kernel running directly on the physical hardware. Linux cgroups and namespaces are the underlying Linux kernel technologies used to isolate, secure and manage the containers. The use of containers offers higher performance than virtualization because there is no hypervisor overhead. IaaS clouds often offer additional resources such as a virtual-machine disk-image library, raw block storage, file or object storage, firewalls, load balancers, IP addresses, virtual local area networks (VLANs), and software bundles.[39]

The NIST's definition of cloud computing describes IaaS as "where the consumer is able to deploy and run arbitrary software, which can include operating systems and applications. The consumer does not manage or control the underlying cloud infrastructure but has control over operating systems, storage, and deployed applications; and possibly limited control of select networking components (e.g., host firewalls)."[4]

IaaS-cloud providers supply these resources on-demand from their large pools of equipment installed in data centers. For wide-area connectivity, customers can use either the Internet or carrier clouds (dedicated virtual private networks). To deploy their applications, cloud users install operating-system images and their application software on the cloud infrastructure. In this model, the cloud user patches and maintains the operating systems and the application software. Cloud providers typically bill IaaS services on a utility computing basis: cost reflects the number of resources allocated and consumed.[40]

Platform as a service (PaaS)
The NIST's definition of cloud computing defines Platform as a Service as:[4]

The capability provided to the consumer is to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages, libraries, services, and tools supported by the provider. The consumer does not manage or control the underlying cloud infrastructure including network, servers, operating systems, or storage, but has control over the deployed applications and possibly configuration settings for the application-hosting environment.

PaaS vendors offer a development environment to application developers. The provider typically develops toolkit and standards for development and channels for distribution and payment. In the PaaS models, cloud providers deliver a computing platform, typically including an operating system, programming-language execution environment, database, and the web server. Application developers develop and run their software on a cloud platform instead of directly buying and managing the underlying hardware and software layers. With some PaaS, the underlying computer and storage resources scale automatically to match application demand so that the cloud user does not have to allocate resources manually.[41]

Some integration and data management providers also use specialized applications of PaaS as delivery models for data. Examples include iPaaS (Integration Platform as a Service) and dPaaS (Data Platform as a Service). iPaaS enables customers to develop, execute and govern integration flows.[42] Under the iPaaS integration model, customers drive the development and deployment of integrations without installing or managing any hardware or middleware.[43] dPaaS delivers integration—and data-management—products as a fully managed service.[44] Under the dPaaS model, the PaaS provider, not the customer, manages the development and execution of programs by building data applications for the customer. dPaaS users access data through data-visualization tools.[45]

Software as a service (SaaS)
The NIST's definition of cloud computing defines Software as a Service as:[4]

The capability provided to the consumer is to use the provider's applications running on a cloud infrastructure. The applications are accessible from various client devices through either a thin client interface, such as a web browser (e.g., web-based email), or a program interface. The consumer does not manage or control the underlying cloud infrastructure including network, servers, operating systems, storage, or even individual application capabilities, with the possible exception of limited user-specific application configuration settings.

In the software as a service (SaaS) model, users gain access to application software and databases. Cloud providers manage the infrastructure and platforms that run the applications. SaaS is sometimes referred to as "on-demand software" and is usually priced on a pay-per-use basis or using a subscription fee.[46] In the SaaS model, cloud providers install and operate application software in the cloud and cloud users access the software from cloud clients. Cloud users do not manage the cloud infrastructure and platform where the application runs. This eliminates the need to install and run the application on the cloud user's own computers, which simplifies maintenance and support. Cloud applications differ from other applications in their scalability—which can be achieved by cloning tasks onto multiple virtual machines at run-time to meet changing work demand.[47] Load balancers distribute the work over the set of virtual machines. This process is transparent to the cloud user, who sees only a single access-point. To accommodate a large number of cloud users, cloud applications can be multitenant, meaning that any machine may serve more than one cloud-user organization.

The pricing model for SaaS applications is typically a monthly or yearly flat fee per user,[48] so prices become scalable and adjustable if users are added or removed at any point. It may also be free.[49] Proponents claim that SaaS gives a business the potential to reduce IT operational costs by outsourcing hardware and software maintenance and support to the cloud provider. This enables the business to reallocate IT operations costs away from hardware/software spending and from personnel expenses, towards meeting other goals. In addition, with applications hosted centrally, updates can be released without the need for users to install new software. One drawback of SaaS comes with storing the users' data on the cloud provider's server. As a result, there could be unauthorized access to the data.[50] Examples of applications offered as SaaS are games and productivity software like Google Docs and Office Online. SaaS applications may be integrated with cloud storage or File hosting services, which is the case with Google Docs being integrated with Google Drive, and Office Online being integrated with OneDrive.[51]

Mobile "backend" as a service (MBaaS)
In the mobile "backend" as a service (m) model, also known as "backend as a service" (BaaS), web app and mobile app developers are provided with a way to link their applications to cloud storage and cloud computing services with application programming interfaces (APIs) exposed to their applications and custom software development kits (SDKs). Services include user management, push notifications, integration with social networking services[52] and more. This is a relatively recent model in cloud computing,[53] with most BaaS startups dating from 2011 or later[54][55][56] but trends indicate that these services are gaining significant mainstream traction with enterprise consumers.[57]

Serverless computing or Function-as-a-Service (FaaS)
Serverless computing is a cloud computing code execution model in which the cloud provider fully manages starting and stopping virtual machines as necessary to serve requests. Requests are billed by an abstract measure of the resources required to satisfy the request, rather than per

virtual machine per hour.[58] Despite the name, serverless computing does not actually involve running code without servers.[58] The business or person using the system does not have to purchase, rent or provide servers or virtual machines for the back-end code to run on.

Function as a service (FaaS) is a service-hosted remote procedure call that utilizes serverless computing to enable deploying individual functions in the cloud to run in response to events.[59] Some consider FaaS to fall under the umbrella of serverless computing, while others use the terms interchangeably.[60]

Deployment models

Private

Private cloud is cloud infrastructure operated solely for a single organization, whether managed internally or by a third party, and hosted either internally or externally.[4] Undertaking a private cloud project requires significant engagement to virtualize the business environment, and requires the organization to reevaluate decisions about existing resources. It can improve business, but every step in the project raises security issues that must be addressed to prevent serious vulnerabilities. Self-run data centers[61] are generally capital intensive. They have a significant physical footprint, requiring allocations of space, hardware, and environmental controls. These assets have to be refreshed periodically, resulting in additional capital expenditures. They have attracted criticism because users "still have to buy, build, and manage them" and thus do not benefit from less hands-on management,[62] essentially "[lacking] the economic model that makes cloud computing such an intriguing concept".[63][64]

Public

Cloud services are considered "public" when they are delivered over the public Internet, and they may be offered as a paid subscription, or free of charge.[65] Architecturally, there are few differences between public- and private-cloud services, but security concerns increase substantially when services (applications, storage, and other resources) are shared by multiple customers. Most public-cloud providers offer direct-connection services that allow customers to securely link their legacy data centers to their cloud-resident applications.[18][66]

Several factors like the functionality of the solutions, cost, integrational and organizational aspects as well as safety & security are influencing the decision of enterprises and organizations to choose a public cloud or on-premises solution.[67]

Hybrid

Hybrid cloud is a composition of a public cloud and a private environment, such as a private cloud or on-premises resources,[68][69] that remain distinct entities but are bound together, offering the benefits of multiple deployment models. Hybrid cloud can also mean the ability to connect collocation, managed and/or dedicated services with cloud resources.[4] Gartner defines a hybrid cloud service as a cloud computing service that is composed of some combination of private, public and community cloud services, from different service providers.[70] A hybrid cloud service crosses isolation and provider boundaries so that it cannot be simply put in one category of private, public, or community cloud service. It allows one to extend either the capacity or the capability of a cloud service, by aggregation, integration or customization with another cloud service.

Varied use cases for hybrid cloud composition exist. For example, an organization may store sensitive client data in house on a private cloud application, but interconnect that application to a business intelligence application provided on a public cloud as a software service.[71] This example of hybrid cloud extends the capabilities of the enterprise to deliver a specific business service through the addition of externally available public cloud services. Hybrid cloud adoption depends on a number of factors such as data security and compliance requirements, level of control needed over data, and the applications an organization uses.[72]

Another example of hybrid cloud is one where IT organizations use public cloud computing resources to meet temporary capacity needs that can not be met by the private cloud.[73] This capability enables hybrid clouds to employ cloud bursting for scaling across clouds.[4] Cloud bursting is an application deployment model in which an application runs in a private cloud or data center and "bursts" to a public cloud when the demand for computing capacity increases. A primary advantage of cloud bursting and a hybrid cloud model is that an organization pays for extra compute resources only when they are needed.[74] Cloud bursting enables data centers to create an in-house IT infrastructure that supports average workloads, and use cloud resources from public or private clouds, during spikes in processing demands.[75]

RESULTS

In April 2008, NASA partnered with Geoff Brown and Machine-to-Machine Intelligence (M2Mi) Corp to develop a fifth generation communications technology approach, though largely concerned with working with nanosats.[186] That same year, the South Korean IT R&D program of "5G mobile communication systems based on beam-division multiple access and relays with group cooperation" was formed.[187]

In August 2012, New York University founded NYU Wireless, a multi-disciplinary academic research centre that has conducted pioneering work in 5G wireless communications.[188] On October 8, 2012, the UK's University of Surrey secured £35M for a new 5G research centre, jointly funded by the British government's UK Research Partnership Investment Fund (UKRPIF) and a consortium of key international mobile operators and infrastructure providers, including Huawei, Samsung, Telefónica Europe, Fujitsu Laboratories Europe, Rohde & Schwarz, and Aircom International. It will offer testing facilities to mobile operators keen to develop a mobile standard that uses less energy and less radio spectrum, while delivering speeds higher than current 4G with aspirations for the new technology to be ready within a decade.[189][190][191][192] On November 1, 2012, the EU project "Mobile and wireless communications Enablers for the Twenty-twenty Information Society" (METIS) starts its activity toward the definition of 5G. METIS achieved an early global consensus on these systems. In this sense, METIS played an important role of building consensus among other external major stakeholders prior to global standardization activities. This was done by initiating and addressing work in relevant global fora (e.g. ITU-R), as well as in national and regional regulatory bodies.[193] That same month, the iJOIN EU project was launched, focusing on "small cell" technology, which is of key importance for taking advantage of limited and strategic resources, such as the radio wave spectrum. According to

Günther Oettinger, the European Commissioner for Digital Economy and Society (2014–2019), "an innovative utilization of spectrum" is one of the key factors at the heart of 5G success. Oettinger further described it as "the essential resource for the wireless connectivity of which 5G will be the main driver".[194] iJOIN was selected by the European Commission as one of the pioneering 5G research projects to showcase early results on this technology at the Mobile World Congress 2015 (Barcelona, Spain).

In February 2013, ITU-R Working Party 5D (WP 5D) started two study items: (1) Study on IMT Vision for 2020 and beyond, and; (2) Study on future technology trends for terrestrial IMT systems. Both aiming at having a better understanding of future technical aspects of mobile communications toward the definition of the next generation mobile.[195] On May 12, 2013, Samsung Electronics stated that they had developed a "5G" system. The core technology has a maximum speed of tens of Gbit/s (gigabits per second). In testing, the transfer speeds for the "5G" network sent data at 1.056 Gbit/s to a distance of up to 2 kilometers with the use of an 8*8 MIMO.[196][197] In July 2013, India and Israel agreed to work jointly on development of fifth generation (5G) telecom technologies.[198] On October 1, 2013, NTT (Nippon Telegraph and Telephone), the same company to launch world's first 5G network in Japan, wins Minister of Internal Affairs and Communications Award at CEATEC for 5G R&D efforts.[199] On November 6, 2013, Huawei announced plans to invest a minimum of $600 million into R&D for next generation 5G networks capable of speeds 100 times higher than modern LTE networks.[200]

On April 3, 2019, South Korea became the first country to adopt 5G.[201] Just hours later, Verizon launched its 5G services in the United States, and disputed South Korea's claim of becoming the world's first country with a 5G network, because allegedly, South Korea's 5G service was launched initially for just six South Korean celebrities so that South Korea could claim the title of having the world's first 5G network.[202] In fact, the three main South Korean telecommunication companies (SK Telecom, KT, and LG Uplus) added more than 40,000 users to their 5G network on the launch day.[203] In June 2019, the Philippines became the first country in Southeast Asia to roll out a 5G broadband network after Globe Telecom commercially launched its 5G data plans to customers.[204] AT&T brings 5G service to consumers and businesses in December 2019 ahead of plans to offer 5G throughout the United States in the first half of 2020.[205][206][207]

In 2020, AIS and TrueMove H launched 5G services in Thailand, making it the first country in Southeast Asia to have commercial 5G.[208][209] A functional mockup of a Russian 5G base station, developed by domestic specialists as part of Rostec's digital division Rostec.digital, was presented in Nizhny Novgorod at the annual conference "Digital Industry of Industrial Russia".[210][211]

Other applications

Automobiles

5G Automotive Association have been promoting the C-V2X communication technology that will first be deployed in 4G. It provides for communication between vehicles and infrastructures.[212]

Digital twins

A real time digital twin of the real object such as a turbine engine, aircraft, wind turbines, offshore platform and pipelines. 5G networks helps in building it due to the latency and throughput to capture near real-time IoT data and support digital twins.[213]

Public safety

Mission-critical push-to-talk (MCPTT) and mission-critical video and data are expected to be furthered in 5G.[214]

Fixed wireless

Fixed wireless connections will offer an alternative to fixed line broadband (ADSL, VDSL, Fiber optic, and DOCSIS connections) in some locations.[215][216][

Wireless video transmission for broadcast applications

Sony has tested the possibility of using local 5G networks to replace the SDI cables currently used in broadcast camcorders.[217]

The 5G Broadcast tests started around 2020 (Orkneys, Bavaria, Austria, Central Bohemia) based on FeMBMS (Further evolved multimedia broadcast multicast service).[218] The aim is to serve unlimited number of mobile or fixed devices with video (TV) and audio (radio) streams without these consuming any data flow or even being authenticated in a network. On September 13, 2023, WWOO-LD successfully tested a proof of concept for 5G Broadcasts powered by XGen Network, the first of its kind in the United States. The low power station demoed a programming stream and tests of emergency alerts using a Rohde & Schwarz transmitter.[219]

CONCLUSION

Community

Community cloud shares infrastructure between several organizations from a specific community with common concerns (security, compliance, jurisdiction, etc.), whether managed internally or by a third-party, and either hosted internally or externally. The costs are spread over fewer users than a public cloud (but more than a private cloud), so only some of the cost savings potential of cloud computing are realized.[4]

Distributed

A cloud computing platform can be assembled from a distributed set of machines in different locations, connected to a single network or hub service. It is possible to distinguish between two types of distributed clouds: public-resource computing and volunteer cloud.

- Public-resource computing – This type of distributed cloud results from an expansive definition of cloud computing, because they are more akin to distributed computing than cloud computing. Nonetheless, it is considered a sub-class of cloud computing.
- Volunteer cloud – Volunteer cloud computing is characterized as the intersection of public-resource computing and cloud computing, where a cloud computing infrastructure is built using volunteered resources. Many challenges arise from this type of infrastructure, because of the volatility of the resources used to build it and the dynamic environment it operates in. It can also be called peer-to-peer clouds, or ad-hoc clouds. An interesting effort in such direction is Cloud@Home, it aims to implement a cloud computing infrastructure using volunteered resources providing a business-model to incentivize contributions through financial restitution.[76]

Multi

Multicloud is the use of multiple cloud computing services in a single heterogeneous architecture to reduce reliance on single vendors, increase flexibility through choice, mitigate against disasters, etc. It differs from hybrid cloud in that it refers to multiple cloud services, rather than multiple deployment modes (public, private, legacy).[77][78][79]

Poly

Poly cloud refers to the use of multiple public clouds for the purpose of leveraging specific services that each provider offers. It differs from Multi cloud in that it is not designed to increase flexibility or mitigate against failures but is rather used to allow an organization to achieve more that could be done with a single provider.[80]

Big data

The issues of transferring large amounts of data to the cloud as well as data security once the data is in the cloud initially hampered adoption of cloud for big data, but now that much data originates in the cloud and with the advent of bare-metal servers, the cloud has become[81] a solution for use cases including business analytics and geospatial analysis.[82]

HPC

HPC cloud refers to the use of cloud computing services and infrastructure to execute high-performance computing (HPC) applications.[83] These applications consume a considerable amount of computing power and memory and are traditionally executed on clusters of computers. In 2016 a handful of companies, including R-HPC, Amazon Web Services, Univa, Silicon Graphics International, Sabalcore, Gomput, and Penguin Computing offered a high-performance computing cloud. The Penguin On Demand (POD) cloud was one of the first non-virtualized remote HPC services offered on a pay-as-you-go basis.[84][85] Penguin Computing launched its HPC cloud in 2016 as an alternative to Amazon's EC2 Elastic Compute Cloud, which uses virtualized computing nodes.[86][87]

Architecture

Cloud architecture,[88] the systems architecture of the software systems involved in the delivery of cloud computing, typically involves multiple cloud components communicating with each other over a loose coupling mechanism such as a messaging queue. Elastic provision implies intelligence in the use of tight or loose coupling as applied to mechanisms such as these and others.

Cloud engineering

Cloud engineering is the application of engineering disciplines of cloud computing. It brings a systematic approach to the high-level concerns of commercialization, standardization and governance in conceiving, developing, operating and maintaining cloud computing systems. It is a multidisciplinary method encompassing contributions from diverse areas such as systems, software, web, performance, information technology engineering, security, platform, risk, and quality engineering.

Security and privacy

Cloud computing poses privacy concerns because the service provider can access the data that is in the cloud at any time. It could accidentally or deliberately alter or delete information.[89] Many cloud providers can share information with third parties if necessary for purposes of law and order without a warrant. That is permitted in their privacy policies, which users must agree to before they start using cloud services. Solutions to privacy include policy and legislation as well as end-users' choices for how data is stored.[89] Users can encrypt data that is processed or stored within the cloud to prevent unauthorized access.[89] Identity management systems can also provide practical solutions to privacy concerns in cloud computing. These systems distinguish between authorized and unauthorized users and determine the amount of data that is accessible to each entity.[90] The systems work by creating and describing identities, recording activities, and getting rid of unused identities.

According to the Cloud Security Alliance, the top three threats in the cloud are Insecure Interfaces and APIs, Data Loss & Leakage, and Hardware Failure—which accounted for 29%, 25% and 10% of all cloud security outages respectively. Together, these form shared technology vulnerabilities. In a cloud provider platform being shared by different users, there may be a possibility that information belonging to different customers resides on the same data server. Additionally, Eugene Schultz, chief technology officer at Emagined Security, said that hackers are spending substantial time and effort looking for ways to penetrate the cloud. "There are some real Achilles' heels in the cloud infrastructure that are making big holes for the bad guys to get into". Because data from hundreds or thousands of companies can be stored on large cloud servers, hackers can theoretically gain control of huge stores of information through a single attack—a process he called "hyperjacking". Some examples of this include the Dropbox security breach, and iCloud 2014 leak.[91] Dropbox had been breached in October 2014, having over 7 million of its users passwords stolen by hackers in an effort to get monetary value from it by Bitcoins (BTC). By having these passwords, they are able to read private data as well as have this data be indexed by search engines (making the information public).[91]

There is the problem of legal ownership of the data (If a user stores some data in the cloud, can the cloud provider profit from it?). Many Terms of Service agreements are silent on the question of ownership.[92] Physical control of the computer equipment (private cloud) is more secure than having the equipment off-site and under someone else's control (public cloud). This delivers great incentive to public cloud computing service providers to prioritize building and maintaining strong management of secure services.[93] Some small businesses that do not have expertise in IT security could find that it is more secure for them to use a public cloud. There is the risk that end users do not understand the issues involved when signing on to a cloud service (persons sometimes do not read the many pages of the terms of service agreement, and just click "Accept" without reading). This is important now that cloud computing is common and required for some services to work, for example for an intelligent personal assistant (Apple's Siri or Google Assistant). Fundamentally, private cloud is seen as more secure with higher levels of control for the owner, however public cloud is seen to be more flexible and requires less time and money investment from the user.[94]

The attacks that can be made on cloud computing systems include man-in-the middle attacks, phishing attacks, authentication attacks, and malware attacks. One of the largest threats is considered to be malware attacks, such as Trojan horses. Recent research conducted in 2022 has revealed that the Trojan horse injection method is a serious problem with harmful impacts on cloud computing systems.[95]

Market

According to International Data Corporation (IDC), global spending on cloud computing services has reached $706 billion and expected to reach $1.3 trillion by 2025.[96] While Gartner estimated that global public cloud services end-user spending would reach $600 billion by 2023.[97] As per a McKinsey & Company report, cloud cost-optimization levers and value-oriented business use cases foresee more than $1 trillion in run-rate EBITDA across Fortune 500 companies as up for grabs in 2030.[98] In 2022, more than $1.3 trillion in enterprise IT spending was at stake from the shift to the cloud, growing to almost $1.8 trillion in 2025, according to Gartner.[99]

List of clouds

- Amazon Web Services
- Google Cloud
- Microsoft Azure
- OpenStack
- IBM Cloud
- Oracle Cloud
- Adobe Creative Cloud

Similar concepts

The goal of cloud computing is to allow users to take benefit from all of these technologies, without the need for deep knowledge about or expertise with each one of them. The cloud aims to cut costs and helps the users focus on their core business instead of being impeded by IT obstacles.[100] The main enabling technology for cloud computing is virtualization. Virtualization software separates a physical computing device into one or more "virtual" devices, each of which can be easily used and managed to perform computing tasks. With operating system–level virtualization essentially creating a scalable system of multiple independent computing devices, idle computing resources can be allocated and used more efficiently. Virtualization provides the agility required to speed up IT operations and reduces cost by increasing infrastructure utilization. Autonomic computing automates the process through which the user can provision resources on-demand. By minimizing user involvement, automation speeds up the process, reduces labor costs and reduces the possibility of human errors.[100]

Cloud computing uses concepts from utility computing to provide metrics for the services used. Cloud computing attempts to address QoS (quality of service) and reliability problems of other grid computing models.[100]

Cloud computing shares characteristics with:

- Client–server model – Client–server computing refers broadly to any distributed application that distinguishes between service providers (servers) and service requestors (clients).[101]
- Computer bureau – A service bureau providing computer services, particularly from the 1960s to 1980s.
- Grid computing – A form of distributed and parallel computing, whereby a 'super and virtual computer' is composed of a cluster of networked, loosely coupled computers acting in concert to perform very large tasks.
- Fog computing – Distributed computing paradigm that provides data, compute, storage and application services closer to the client or near-user edge devices, such as network routers. Furthermore, fog computing handles data at the network level, on smart devices and on the end-user client-side (e.g. mobile devices), instead of sending data to a remote location for processing.
- Utility computing – The "packaging of computing resources, such as computation and storage, as a metered service similar to a traditional public utility, such as electricity."[102][103]
- Peer-to-peer – A distributed architecture without the need for central coordination. Participants are both suppliers and consumers of resources (in contrast to the traditional client-server model).
- Cloud sandbox – A live, isolated computer environment in which a program, code or file can run without affecting the application in which it runs.

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