Ten Trends in the Cellular Industry and an Outlook on 6G

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Abstract

With the completion of Release 15 of the 5G standard in early 2018, 2019 has become the first year for the commercialization of 5G. At this stage, it is too early to speculate what key technologies will mark 6G, since it is not known what the drivers for 6G might even be. However, the next generation system typically does not emerge from a vacuum. By examining the industrial and technological trends from previous generations, directions and trajectories associated with each new generation can be discovered. In this article, we shall provide observations regarding these trends and their potential for later releases of 5G and 6G. The goal of this article is to shed light on possible directions of 6G to help researchers jumpstart projects in this field while searching for new directions and breakthroughs.

Introduction

When the concept of cellular reuse was invented at Bell Labs, its inventors may never have imagined that their concept would give birth to an industry that would produce 5 percent of the world GDP [1]. Within 50 years, the industry has evolved from the first generation (1G) to 5G with the research community now shifting their attention to 6G [2]. Since the cellular industry is entering its maturity in a variety of directions, some experts have begun to question how long this evolution can continue [3]. This type of skepticism is not unfounded and needs to be considered when pursuing 6G.

The founder of information theory, Claude Shannon, decomposed a typical communication system into four basic building blocks [4]: the source coder, the channel coder, the modulator, and the antenna. The last three blocks are the focus of the cellular industry evolution.

For the channel coder, cellular evolutions have come a long way from the analog with no coder in 1G to the convolutional coder with the constraint length of 7 in 2G, followed by the constraint length of 9 in 3G. Beginning with 4G, turbo coders provided an impressive performance that is only a fraction of a dB from the famous Shannon limit [5]. For 5G, only small gains have been achieved by adopting low density parity check (LDPC) and polar coders. At this point, the performance of the channel coders is so close to the theoretical limit that many believe there is not enough room left for noticeable progress in the additive white Gaussian noise (AWGN) environment unless research interests are extended to special circumstances such as in a delay-sensitive situation using short block-length code or in other modes of operations such as broadcast or multihop communication.

Regarding the multiple access technology in the modulation block, 1G utilized frequency-division multiplexing (FDM), and 2G adopted time-division multiple access (TDMA). Code-division multiple access (CDMA) was able to surpass TDMA to dominate 3G, while 4G abandoned the wideband CDMA approach, preferring the narrowband orthogonal frequency-division multiple access (OFDMA). Interestingly, 5G continues to use OFDMA without much change. This has caused speculation that the research in the multiple access direction may have reached the saturation point. Indeed, in the 3G time period the system bandwidth utilization was 74 or 76 percent for the CDMA 2000 or the Universal Mobile Telecommunications System (UMTS) limited by the chip rate. By using OFDMA, the 4G-LTE network was able to achieve a bandwidth utilization of 90 percent based on the number of usable radio blocks. By further improving the filtering and the precoding technology, OFDMA in 5G pushed the system bandwidth utilization to 98 percent based on the number of usable radio blocks. Given that bandwidth utilization is one of the most important metrics for spectral efficiency, further progress in multiple access may indeed need imagination.

Despite the above-mentioned difficulties, much progress has been made in 5G. In this article, we shall review the current status of 5G, examine the prevailing trends of past evolutions, and reveal which directions might have the potential to jumpstart 6G research while searching for new directions in parallel.

5G Progress and Challenges

Since 3G, the cellular industry has been focused on increasing the data rate. This can be observed in major 5G features that can easily be mapped into each quantity of Shannon's data rate formula as follows:

- The ultra-dense network (UDN) is related to increasing the number of cells in the formula.
- The massive multiple-input multiple-output (MIMO) is related to increasing the number of parallel transmission channels, taking advantage of the channel symmetry property of time-division duplex (TDD).

The author provides observations regarding the trends discussed herein and their potential for later releases of 5G and 6G. The goal of this article is to shed light on possible directions of 6G to help researchers jump-start projects in this field while searching for new directions and breakthroughs.

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While the intent of the 5G standard was on the right track, the execution was not as promising. Most operators will be deploying 5G using the TDD spectrum because the required bandwidth of up to 100 MHz cannot be easily found in pairs required by frequency-division duplex (FDD). Furthermore, one key technology of 5G is massive MIMO, which prefers the use of the TDD channel reciprocal principle to reduce the detection feedback overhead.

- The system carrier bandwidth has expanded from 20 MHz in 4G to 100 MHz in 5G. Wider bandwidth could be further accommodated using carrier aggregation (CA).
- Interference cancellation is used to reduce the interference effects, both in bits detection and in non-orthogonal multiple access (NOMA).
- The LDPC and polar codes are adopted to minimize the effect of the noise.
- The beam forming techniques are used to maximize the signal energy S in the direction of the transmission.

As a result of the techniques listed above, the spectral efficiency of 5G has more than tripled. The data and the peak rate for 5G have increased more than 10-fold while the radio delay has decreased considerably. Despite the above progress under the discussed difficulties, these improvements have not boosted the financial value of the cellular system, as measured by the average revenue per user (ARPU) for major telecom operators worldwide. To understand why, one must look more closely at the drivers from each evolution.

When moving from 2G to 3G, the main application was voice. The need for a high data rate was not urgent when Qualcomm promoted CDMA technology. To compete with the CDMA2000 standard from the Third Generation Partnership Project 2 (3GPP2) organization, 3GPP introduced UMTS. When evolving from 3G to 4G, the WiMAX technology promoted by Intel became a threat to the status quo when most of the world operators were still satisfied with the performance of UMTS. As a defensive measure, 3GPP proposed the LTE standard that resulted in 4G commercialization. Obviously, the evolution of these two generations were competition (3GPP2 vs 3GPP) or technology (CDMA and FDMA) driven, not market driven. The willingness to pay from the markets remained unchanged. This could be one of the main reasons for the lack of ARPU improvement.

Implemented as a change, the 5G standard process was accelerated by the establishment of the 5G Open Trial Specification Alliance (OTSA) in 2015. The intention of OTSA was to use 5G for fixed wireless applications as a less expensive alternative to fiber to the home to support TV and Internet services in suburban and rural homes using radio frequencies beyond 6 GHz. This was a market-driven effort that had the potential to improve the operator's income. Unfortunately, the need for the fixed wireless application may be limited and cannot sustain the gigantic ecosystem needed to keep terminals at low cost. To solve this problem, 3GPP issued 5G standards that would support both sub-6 GHz for traditional mobility and beyond 6 GHz for fixed wireless operations. While the fixed wireless application at 28 GHz can generate new revenues, for operators evolving to 5G in the traditional mobility markets using sub-6 GHz frequencies, the same ARPU problem remains since there is still no market driver for this evolution to date.

To counter the lack of market drivers for 5G under the mobility environment, 5G for the first time made a clear effort [6] not only to enhance the enhanced mobile broadband mode (eMBB) but also other modes such as massive machine type communication (mMTC) and ultra-reliable low-latency communication (uRLLC).

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Currently, engineering choices from major operators have indicated that this TDD delay alone will exceed the 1 ms target for the uRLLC application set by the International Telecommunication Union (ITU) for the purpose of achieving the desired time utilization efficiency. As a result, the TDD systems of 5G in the real world will not be able to support the uRLLC application because of the system efficiency choices even though the standard itself can. To support the uRLLC application in the real world, China Telecom has now proposed the adoption of the FDD system, which does not have the downlink and uplink switch delay problem.

As for the mMTC application, no new candidate technologies have been identified in 5G that could surpass the existing 4G narrowband LTE to meet the key requirements for better coverage, cost sensitivity, and battery longevity. As a result, 3GPP has opted to improve the narrowband LTE system as a solution to delivering the mMTC application in 5G.

Consequently, the much touted three application pillars of 5G, delivered by one 5G standard, actually require that three separate hardware systems be supported: the TDD system for eMBB, the FDD system for uRLLC, and the improved NB-LTE system for mMTC. Given the leveling trend of the ARPU in the mobility industry, this three-system solution for 5G can be a financial challenge for many operators.

If this is not enough of a setback for operators, a one-two-three punch could make life even tougher. The capital expenditure (CAPEX) of the 5G equipment per cell site is expected to increase considerably due to the use of massive MIMO, which significantly increases the amount of needed hardware to support the channel increase from 2 to 64. To counter this significant increase, there are two schools of thought regarding potential deployment strategies: non-standalone (NSA) and standalone (SA). The NSA approach is to use 4G-LTE as the anchor coverage base and to use 5G cells for hotspots only. The SA choice is to deploy 5G ubiquitously, which would evidently result in a significant CAPEX increase. To reduce the CAPEX pressure, the operators adopting SA hope to improve their financial situations through possible revenues from vertical applications, which may in turn require the deployment of multiple hardware systems, as discussed previously.

In addition to a possible CAPEX increase, the third punch is the operational expenditure (OPEX) of 5G, which may be increased significantly due

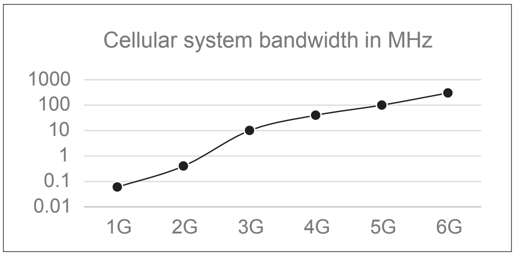

Figure 1. Bandwidth evolution of cellular systems from 1G to 6G.

to the higher consumption of electricity. The main cause is that more electricity is needed for wider bandwidth to maintain the target signal-to-noise ratio (SNR). Consider the electric consumption of RRU for 4G-LTE. A typical two-antenna 4G-LTE sector of 20 MHz uses two 30 W power amplifiers. To maintain the power density, a 5G sector of 100 MHz with 64 channels is typically equipped with a 200 W power amplifier. The transmit power of 5G is more than three times that of 4G because of the wider bandwidth. It is known that the total power amplifier efficiency of 5G is reduced further since the chipset power consumption of the 64 antenna array unit (AAU) is much more than that of 4G-LTE. Consequently, the total electric bill for 5G is estimated to be about three times that of 4G-LTE. Because of this, it is estimated that the electric bill in the OPEX over 10 years could approach the initial CAPEX of the 5G equipment for the first time in history for the ubiquitous deployment strategy using SA.

Evidently, the deployment of 5G is full of challenges. We hope that the above discussions will stimulate consideration into research of 6G so that solutions can be discovered to overcome these problems in the future.

An Outlook on 6G

While the challenges faced by 5G are being resolved, research on 6G has already started. Currently, we know very little about 6G and its possible drivers given that the 6G performance requirements are not even available yet. For the purpose of this article, the major performance requirements of 5G [6] will be extrapolated as a place holder for 6G. One set of possible minimum requirements include 3 times the spectral efficiency, 10 times the data rate, 1/10 of the one-way delay, and 10 times the power efficiency.

With these 6G objectives in mind, we shall now summarize the current industrial and technological trends and provide potential research directions consistent with these trends and requirements.

Trend 1: 6G Will Continue to Move to Higher Frequencies with Wider System Bandwidth

For each generation, the data rate has increased more than 10 times. This increase usually cannot be accomplished by improving spectral efficiency alone. The system bandwidth must also be increased to achieve this objective. Given that the spectrum at lower frequencies has almost been depleted, the current trend is to obtain wider bandwidth at higher frequencies. In addition, the 6G standard will also need to be defined in both TDD and FDD since paired frequencies are harder to find, although in certain situations they are preferred.

Starting from 5G, bandwidth is defined in both low (below 6 GHz) and high (beyond 24 GHz) bands. The low band is typically used as the primary or anchor band, while the high band is secondary or for non-mobile applications such as fixed wireless.

When the primary system bandwidth for mobile application is examined, it can be observed that the system bandwidth is 2 × 200 kHz for 2G-GSM, 2 × 5 MHz for 3G-UMTS, 2 × 20 MHz for 4G-LTE, and 100 MHz for 5G, as shown in Fig. 1. Obviously, the speed of the bandwidth expansion is strikingly consistent because not only does it depend on the required data rate improvement, it is also limited by the required power increase because of the coverage consideration and the possible advances of the chipset density, which are discussed later. From Fig. 1, it seems that the projected possible system bandwidth for the 6G primary band under the ubiquitous environment could be over 300 MHz. When more bandwidths are available, multiple bands are typically combined using the CA technique to limit the system complexity. Note that the above analysis does not apply to the bandwidth evolution for the secondary band, which is 400 MHz in 5G.

Currently, much speculation has been on the terahertz band as a candidate for 6G. Due to its limited coverage, the band will at most be considered as the secondary band, if adopted. Furthermore, its adoption will depend heavily on whether the set of technologies in this band can be made cost effective and if operators can find applications in addition to mobility to justify the expenditure.

Trend 2: Massive MIMO Will Remain as a Key Technology for 6G

Massive MIMO [7, 8] has been the defining technology for 5G that has enabled the antenna number to increase from 2 to 64. Based on a recent field test in the suburbs of Beijing, 10.3 Gb/s were achieved with a bandwidth of 100 MHz operating at the 3.5 GHz band using a 64T4R configuration in the downlink, as shown in Fig. 2. The number of parallel users for vendors 1, 2, 3, and 4 are 16, 12, 4, and 4 respectively.

For vendor 1, an impressive field measurement of over 100 b/s/Hz for the peak efficiency of a sector was achieved with 16 parallel users, each of whom was distributed at a carefully selected location. While this peak efficiency is not expected to be achievable in a real-world operation; the test result, nonetheless, points to the potential of achieving tremendous capacity gains through MIMO. Based on the system-level simulations, it is noted that the achievable average spectral efficiency is slightly less than 10 b/s/Hz in 5G.

As previously discussed, given the performance saturation in areas of the channel coder and modulator, the hope of achieving triple the spectral efficiency for 6G will remain in the multiple antenna area. This trend is consistent with that of trend 1, where the number of antenna elements can continue to increase with the operating frequencies. Therefore, research should continue to focus on the optimization of the algorithms for the massive MIMO so that the average perfor-

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More focus may continue to be on the spectral efficiency direction to provide even higher possible peak rates to compete with the progress of Wi-Fi. However, new methods and algorithms will also be needed to improve power efficiency for coverage and battery life of mMTC applications.

mance can approach its already observed peak performance potential.

Trend 3: The Data Rate and Spectral Efficiency Will Continue to Be the 6G Focus

Historically, there have been two separate schools of thought in wireless system design. For the Wi-Fi and Bluetooth industries, the basic underlining assumption is the line of sight (LoS) for the channel. Due to this, the focus of the design is to achieve the highest possible data rate or spectral efficiency. With this assumption, the keep it simple (KIS) principle is used to make the system cost-effective. This is also known as the short distance design philosophy.

In contrast, in the cellular industry there is no such luxury for the LoS channel assumption. The cellular system needs to operate through long distance with the hostile Rayleigh fading. Under this assumption, the handset power has been the main constraint, and the system design aims to achieve the highest possible power efficiency.

From the Shannon formula, the power efficiency and spectral efficiency are at two opposite sides of the curve and cannot be optimized at the same time, as shown in Figure 3.

To mitigate this dilemma, efforts were made in past cellular systems to expand the operating region covering both the power efficiency and spectral efficiency regions but with recent emphasis on higher spectral efficiency by improving modulation constellations. In addition to this, adaptation was used for the system to determine which point on the curve should be operated based on the channel condition.

In 6G design, the system operating region will need to continue to expand in both the power and spectral efficiency regions using new algorithms and techniques. More focus may continue to be in the spectral efficiency direction to provide even higher possible peak rates to compete with the progress of Wi-Fi. However, new methods and algorithms will also be needed to improve power efficiency for coverage and battery life of mMTC applications.

Trend 4: 6G Will Continue to Demand Progress in the Chipset Density

As indicated in trend 3, the best strategy to achieve the highest power and spectral efficiency is to expand the region of the system operation in both efficiency directions and to let the adaptation determine the exact operating point based on the channel condition. This strategy of being able to cope with any environment clearly results in a complex integrated transmission architecture that demands a certain level of chipset density in order to reduce the processing delay and chip heat consumption.

It is known that the commercialization utilized 65 nm technology for the 3G chipset, 28 nm for 4G, and 7 nm for 5G. Based on this trend, the system complexity of 6G will require 3 nm technology or better. Thus, the challenge is set for the semiconductor industry to continue to increase the chip density for 6G. With this expected chip set complexity, obviously the next generation devices will be more dependent on a global ecosystem in order to make the chipset and devices viable and cost effective.

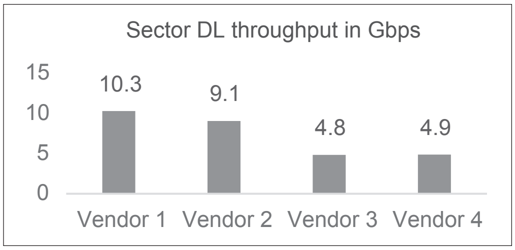

Figure 2. System throughput of a sector of a 5G base station measured in a field trial in suburban Beijing.

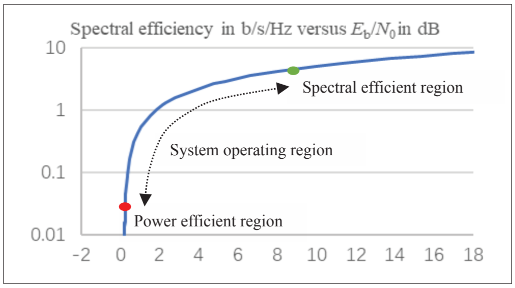

Figure 3. Data rate normalized by the system bandwidth from the famous Shannon formula. The curve indicates that the spectral and power efficiencies cannot be achieved at the same time.

Trend 5: 6G Will Take the Cloud Service to the Next Level

It is well known that the smartphone dominated the handset market in the 4G era. This phenomenon may continue due to the market momentum in the 5G era. However, with the ever-faster data pipe, short delay, and low transmission cost, the trend has already started to move much of the computational and storage functionality from the smartphone to the cloud. The reason for this shift is simple. Today's hard drive speed is around 800 Mb/s. This speed can be matched by the 5G system, not to mention 6G. Therefore, saving data into the cellular system could have a comparable impression as saving data to a hard drive. This seemingly small change in people's impression may have a significant impact on future cellular services and may provide substantial opportunities for the future of cloud-based services.

With many of the computational and storage functions moved to the cloud, most of the computational power of the smartphone can focus on presentation rendering, making virtual reality (VR), augmented reality (AR), or XR more impressive and affordable. Many artificial intelligence (AI) services that are intrinsically cloud-based may prevail more easily and broadly. In addition to smartphones, less expensive functional terminals may once again flourish, providing growth opportunities in more areas of applications, especially in cost-sensitive verticals. Rapid growth in cloud services will also promote big data analytics and stimulate network security.

Trend 6: 6G Will Continue to Integrate More Modes

Starting from 4G, 3GPP has incorporated Wi-Fi operations into cellular operation by using the LTE-WLAN radio-level interworking technique. Other modes of standardized operations in 4G systems include multihop, device-to-device, and unlicensed band operations. In the handset, the combination of cellular, Wi-Fi, and Bluetooth technologies has been standard. Integrating more modes of operation from multiple frequencies is the trend for next generation systems. Although today's cellular systems and handsets both operate at multiple frequencies, the cornerstone for this has primarily been the CA technique where one anchor frequency is chosen and the remaining frequencies are designated as the secondaries. Given the lessons learned from 5G, where three independent hardware systems would be needed for eMBB, mMTC, and uRLLC applications, research and new approaches will be needed for better and more cohesive integration of multiple frequencies than CA in 6G operations.

Satellite is another promising mode to add to 6G; according to an UN survey, about 45 percent of the world population live in suburban or rural areas today. The integration of satellite capability into a handset would greatly enhance the coverage that is one of the core competences of the cellular industry.

In past generations, satellite was never integrated into cellular handsets due to a series of complications. Technically, the satellite link budget has been a road block, while satellite costs have also plagued the fate of past attempts. Recently however, progress has been made on both fronts. Low Earth orbit satellites are the most promising in reducing the satellite link budget over other types of satellites.

However, even if both the link budget and the satellite cost are resolved, the success of the integration of satellites with the cellular system will also depend on the removal of another road block that is more political than technical. One key difference between the cellular system and the satellite system is that the integration of the two systems also requires the full cooperation of authorities all over the globe. This often neglected reality is due to the fact that the air space through which satellite signals must go belongs to different countries. Therefore, a lengthy negotiation needs to be undertaken in each country for this dream to become a reality. This monumental task has prevented the success of many satellite operations in the past. While satellite technology and its cost structure may be ready for 6G, the incorporation of satellite communication into 6G handsets will depend on future cooperation among many of the world's major countries in addition to the technical challenges.

Trend 7: Grant-Free Transmissions Could Be More Prominent in 6G

For past generations, transmissions in the cellular system were primarily based on a grant-oriented design with strong centralized system control for a variety of reasons:

- Almost all cellular transmissions need to be power controlled individually by base stations to minimize the adjacent channel interference.
- The scheduling of transmissions from different users need to be coordinated by the system to maximize channel resources.
- Centralized control is preferred to reduce handset costs.

Although it was an afterthought at the time, some of the 3G control signal, along with small user data, used a grant-free transmission utilizing data on signaling (DOS). This resulted in limited capacity because, historically, signaling was not designed to carry heavy payload.

In 5G, more types of grant-free transmissions are being designed for uRLLC and mMTC but the capacity is still limited [9]. If these two applications become popular, even more grant-free capabilities will be designed for 6G. To accommodate this shift, more advanced grant-free protocols and approaches will be needed. Furthermore, it is possible that NOMA technology [10] may have another opportunity to prevail due to its short delay performance even though it failed to take off during the 5G time period, which is the case because its current observed benefit lay in the gains of the data rate performance, which was limited at the time.

Trend 8: The Trend Is to Move from Unified Service to Personalized Service

Beginning with 3G, the focus of the system designers has been on cost reduction. This objective has been achieved by grouping more bits into a packet and by providing unified service for different bits regardless of importance and urgency. Only limited exceptions are made for special applications such as voice and control signals. This focus on cost is a direct consequence of the system complexity concern in trend 4 discussed earlier and may have led to the commoditization of the industry, which could be the main technical reason why the ARPU stayed the same for so many generations.

Since 5G, special needs from vertical industries were considered, and the 5G core network has introduced the concept of network slicing [11]. Unfortunately, there is a disconnection between the core network and the radio access network (RAN). This is because the concept of slicing in 5G has been limited only to the core network and does not have a well-designed implementation in the RAN. More specifically, special application needs in the RAN are still being treated by using quality of service (QoS) indices that have remained largely unchanged since 3G. The inflexibility of QoS mapping based on applications has significantly hindered the power of core network slicing and has remained the bottleneck for the end-to-end quality guarantee. To meet the vast range of needs for the growing number of application categories, the concept of network slicing in 6G may need to extend to the RAN to provide the end-to-end performance which will offer not only special capabilities to vertical applications but also personalized services to consumers as well.

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Trend 9: mMTC is More Likely to Take Shape in the Older Generation Before It Can Succeed in the Next Generation

mMTC has been one of the major directions for the next generation system design since the market growth of communications between people has saturated. High expectations have been put on 5G's mMTC to deliver significant growth for the cellular industry. Until now, however, this expectation has been mismatched with the reality on the ground.

One of the possible trademarks of 6G could be the harmonious operations of transmission, computing, AI, ML, and big data analytics in unison such that the 6G system is expected to detect the customer's transmission intent autonomously, and automatically provide optimized configurations with the desired quality of experience and price package.

When further analyzing the three factors important for mMTC's success, clearly it is difficult for the next generation network to excel on coverage, cost, and battery life simultaneously. As discussed in trend 1, the next generation system is expected to be at a higher band. The increased path attenuation in a higher band goes counter to the coverage requirement. Furthermore, based on general electronic market trends, new technology equipment tends to be more expensive initially. With the age of the technology, the price will go down with a fast decay. This trend has been very consistent from 2G to 5G.

It is expected that the next generation system will typically be more complex in order to deliver better data rates and efficiency. This makes the goal of increasing the battery life harder to achieve. Therefore, the current trend appears to indicate that mMTC would be more likely to prevail by utilizing older technology that operates in the lower band at lower cost. Only after the mMTC market grows to a certain size with a set of well-defined characteristics identified will it be possible for the next generation system to create shortcuts or breakthroughs by designing the system to take advantage of that set of characteristics.

Trend 10: 6G Will Transform a Transmission Network into a Computing Network

The cellular network has functioned as a fast pipe that transmitted bits from one place to another. Most computational power is located at the data center to provide services. During the 5G deployment period, the core network has been made more flexible by virtue of software defined networking (SDN) and network functions virtualization (NFV). Interest has also been generated on the topic of mobile edge computing (MEC) in which part of the computational power is moved from the data center to the edge of the network in order to reduce delay, relieve backhaul load, and improve application performance. Customers can choose types of network slicing with MEC to meet their diverse transmission needs. In trend 5, it was determined that memory and computing power would also transition from terminals to the system.

In 6G, this trend will likely continue. More computing power will not only be placed at the edge, but at each hop along the pipe and inside the pipe when needed to form an intelligent computing network. With the advance of AI and machine learning (ML) [12], further research is needed to extract information automatically at each hop of the pipe and provide on-time analysis for better personalized services, as discussed in trend 8.

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Conclusions

For the future 6G network, the primary system bandwidth is likely to be over 300 MHz using higher frequencies. The data rate will increase more than 10 times by continuing to perfect the massive MIMO technology. The chipset density is expected to demand 3 nm or better technology. More communication modes, possibly including satellite, could be integrated into the cellular operation for ubiquitous coverage and services. By distributing the storage and computing power more evenly along each hop of the wireless system including handset, base station, edge, core, and data center, the traditional transmission network is likely to transform into a computing network using AI and big data analytics, providing personalized services based on a user's intent and desire.

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