White Paper

Ten Cross-domain Innovation Directions Affecting the Future Information and Communication Development

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Preface

Over the past few years, fifth generation (5G) commercialization has accelerated consumption upgrading, production efficiency and social harmony, taking the transformation of digital intellectualization and achieving high-quality development as the main objective. The rapid development of 5G has led to the advancement and integration of big data, cloud computing, artificial intelligence (AI) as well as other cross fields, such as chips and devices. The deep integration of communication technology (CT) , information technology (IT) and data technology (DT) has become an inevitable trend in the future.

Compared with 5G, cross-domain and interdisciplinary IT (i.e., cross-domain technology supporting or influencing the information and communication development) will accelerate integration in sixth generation (6G) development, and play an important catalyst role. It is expected to break through the key challenges of ultra-large bandwidth, deterministic delay, low power consumption, low cost, high security, easy deployment and operation in the development of 6G, which will promote the society to the "digital twin" and "wisdom ubiquitous", and truly realize the "Metaverse" where the virtual and real world are integrated and interacted.

Recently, for the traditional information and communication field, China Mobile has released a series of white papers such as the ones, entitled 2030+ vision and requirement, technology trend, network architecture prospect, etc. The aim of this white paper is to select ten cross-domain innovation directions affecting the development of information and communication in the future according to the blueprints of information and communication technology (ICT) in 2035. The white paper analyzes the related challenges, and calls on the academia and industry for more attention and investment to address these challenges together, in order to ensure the sustainable, healthy and great-leap forward development of the information and communication industry in the future.

The ten cross-domain innovation directions are key areas that might affect the development of information and communication industry in the future from the perspective of China Mobile. They involve terminals, management, cloud, computing, security, low carbon as well as paradigm, which are only for enlightenment,even not comprehensive. It is necessary to keep making calibration and iterative updating during research and exploration with colleagues from academia and industry.

Content

The people's desire for a better life will keep going. By 2035, human being is expected to build a digital intelligence society with "digital twin and wisdom ubiquitous", and live in the meta cosmic world of virtual and real interaction. In the future, the information and communication network will expand to more scenarios and enable more industries, and be more closely integrated with cross fields such as "new perception", "new terminal", "new networking", "new computing power", "new bionics", "new security", "Low-carbon Innovation" and "new materials". The communication infrastructure may be integrated with "new facilities" such as municipal administration, transportation and property management. This will result in more blurred boundary between the future information and communication industry and these cross fields so that cross-border integration will become a "new paradigm" and a new normality. Thus, more disruptive innovations will emerge into the business model and industrial ecology.

1. New Perception -- Sensing the Physical World Comprehensively and Intelligently

With the advancement of internet of things (IoT) technology and applications, the sensing technology in the future will be developed from single-function and low intelligence to multifunction, collaborative, and high intelligence to support emerging application scenarios such as integrated sensing and communication, and human digital twins.

1.1 Sensing Technology

As a bridge that connects between the physical and the digital world, the sensing technology has become the cornerstone of industrial digitalization, and is increasingly important to the development of the whole industry. In the future, the development of sensors will feature the fusion of various technologies, the sensors will integrate with technologies such as communication, energy harvesting, and heterogeneous integration, thus achieve more accurate, reliable, and powerful sensing capabilities.

- **Integrated sensing and communication**

In the future, the sensing technology will no longer be limited to hardware devices, instead, it can realize environmental perception by employing the ubiquitous network signals. When an object moving in radio frequency (RF) field, the position, moving speed, moving direction, and attitude of the object can be identified by analyzing the signal variation of the radio electromagnetic wave, thus a large-scale environment perception can be realized. The integrated sensing and communication technology is the fusion of communication and radar, and therefore, the base station needs to allocate sensing resources in the time-domain and spatial-domain, and needs to support sensing and data processing functions, although the current relevant research is still in the early stage.

- **Passive-sensing technology**

By integrating environmental energy harvesting technology with sensors, the sensors can employ vibration, temperature, light, and communication signals as energy sources, thus the sensors require no power supply, and can greatly expand the application scenarios. The key of passive sensing technology is to improve energy conversion efficiency, which is related to the physics and materials science, and it also involves low-voltage energy storage mechanisms, efficient energy management algorithms and software. Therefore, the biggest challenge of passive sensing is to combine basic science, electronic circuit, and software together, and meanwhile achieve optimal balance among those technologies.

- **Microsystem technology**

With emerging technologies, the performance of integrated circuit (IC) is gradually approaching to the limit of Moore’s law. Therefore, the industry integrating microelectronics with other disciplines to produce a new technology — microsystems, thus to achieve "More than Moore". The microsystem technology is a combination of microelectronics, micro-electro-mechanical system (MEMS) and optoelectronics, featuring miniaturization and systematization. Microsystems are miniaturized by using advanced integration schemes to produce new functions at the system level, which greatly increases the function density of systems. The difficulty of microsystems technology is to ensure high integration density while realizing coupling and coalition between different modules, and the microminiaturization also causes challenges to robustness, reliability, and validation technologies of microsystem technology.

- **Smart sensing**

The advancement of IoT, big data and AI technologies facilitates the digital and intelligent transformation of society, enabling all devices to be connected and integrated to achieve data-driven and augmented Intelligence. The future sensing technology will have new features: first, the intelligence, including strong sensing ability and advanced understanding ability; second, the autonomy, when operating in an unattended environments, the sensors have strong environmental adaptability and self-organization ability; Third, the collaboration, devices shall dynamically share resources (data, knowledge, computing, communication and power resources) with each other, and provide complex services through cooperation. However, to achieve those features, smart sensing needs to focus on the following challenges: First, the intelligence level of IoT services needs to be improved. The system requires the ability to learn from small sample data, which can be used to build an IoT knowledge graph, realize resource virtualization, collaborative computing environment sharing, and thus to achieve high intelligence level. Second, the learning ability of IoT service needs to be improved. Through the data interaction between wearable devices, environments, and personnel, the IoT devices should recognize and predict human behavior and emotions, and provide services on demand to meet individual needs. Third, the context linkage ability of IoT service needs to be enhanced, for instance, the many-to-many mapping between user demand and data requires complex computing, and the behavior of sensors and actuators needs to be designed with corresponding coordination models.

1.2 Human Digital Twin

Digital twins is one of the typical use cases of the new perception, which is based on emerging sensing technologies and intelligent perception capabilities, that can perform somatosensory perception, emotional perception, and consciousness perception of the human body, and understand the neuroplasticity of the human brain by learning human somatosensory data and data of the devices and environments used by human beings, so that the human body and the virtual twin can be mapped to each other. The digital twin also involves acquisition and transmission technologies in the human domain such as brain-computer interface and molecular communication, as well as information processing such as computation and presentation.

The realization of digital twins faces many technical and ethical challenges. The first is how to effectively fuse data from different sources and use AI and other algorithms to achieve accurate diagnosis and prediction for the somatic twin; the second is how to read and quantify human emotions and five sensory sensations for the empathic twin. In vivo information transfer requires a complex human channel environment, and related technologies such as multi-dimensional heterogeneous transmission system based on molecular communication still need to be improved and systematically validated. Third, brain science is still in its infancy, and there is need for breakthroughs in brain-computer interface technologies for consciousness perception. Fourth, many new ethical and privacy security risks willemerge, and corresponding policies and regulations need to be formulated.

2. New Terminal -- A New Form of Human-computer Interaction

The new human-computer interaction will shorten the distance between man and machine. In the future, new terminals should be comfortable, convenient, bio friendly, low power consuming and ubiquitous. Flexible electronic devices will be closer to the human body and even integrated into the body; holographic display can generate more immersive and interactive imaging effects, and bring richer sensory experience to users. The new terminal may be "invisible", enabling users to obtain a richer and non-perceptual experience, by ubiquitous sensing equipment, cloud computing power, friendly human-computer interaction technology and ubiquitous communication ability.

2.1 Flexible Electronics

Flexible electronics can be summarized as an emerging electronic technology that makes organic / inorganic electronic devices on flexible plastic and thin metal substrates. It can be used for flexible electronic display, organic light emitting diode organic light-emitting diode (OLED), printing radio frequency identification (RFID), thin film solar panel, with unique flexibility and ductility, as well as efficient and low-cost manufacturing process.

Like traditional IC technology, manufacturing technology and equipment are the main driving force for the development of flexible electronic technology. Flexible thin film transistor technology is one of the important technologies. Compared with rigid silicon-based ICs, flexible non silicon-based chips are realized by making thin-film transistors on plastic or metal foil substrates. It is not only cheaper to manufacture, but also thinner and more flexible. The key of flexible electronic manufacturing is how to manufacture smaller flexible electronic devices on a larger substrate at a lower cost. Its technical level can be measured by the characteristic size of the chip and the area of the substrate. Only when the transistor contained in the chip reaches a certain density, the performance of flexible chip can be compared with that of traditional silicon-based chip.

Flexible electronic technology will break through the intrinsic limitations of classical silicon-based electronics and provide important opportunities for future industrial development such as device design integration, energy revolution and medical technology reform in the post molar era. Currently, there are two main challenges. The first is mechanical problems. Flexible electronic components will continue to bear alternating stress when they are folded and bent repeatedly, which is easy to crack after a long time. It is mainly overcome by structural design. The second challenge is the problem of electronic packaging, that is, how to package the components integrated on the flexible substrate tightly and achieve the expected function.

2.2 Holographic Display

Holographic communication will combine AI, big data and other technologies to build a multi-agent, realize the integration and interaction between the physical world and the digital world, and provide a new life experience of blending virtual and real. Holographic communication will integrate AI and a variety of interaction modes, and use new holographic display terminals and equipment to provide users with a two-way circular coupling experience from multiple dimensions such as vision, hearing and touch.

The key technologies of holographic communication include holographic display, sensing interaction and data communication.

Holographic display may carry a variety of new intelligent terminals, involving dynamic computing, three-dimensional display, optical encryption and compression coding and other technologies; Sensing interaction needs to support multi-channel virtual reality fusion interaction ability (such as gesture, posture, eye movement, voice, smell and touch). The multi-dimensional information is very easy to be distorted by noise, jitter, packet loss and other factors, which is a great challenge to maintain the naturalness, realism, immersion and synchronization of interaction. A large number of complex data generated by the interaction between holographic display and sensing have high requirements for communication. These data may come from video, audio, touch, or people, physical objects and background environment. The required network transmission bandwidth is very large. Efficient encoding / decoding technology must be used for compression processing. At the same time, it needs technical support such as ultra-large bandwidth, ultra-low delay, cloud edge integration computing power, high synchronization and strong security.

3. New Computing Power -- Enabling High-Efficient and Massive Secure Data Processing

As ICT pushes the world into the digital economy society, the massive data has become as an increasing important factor of production. As a new production tool, computing has penetrated into many aspects of economy and society. In other words, computing power is productivity. The demand for computing power is growing rapidly, leading to a big change in global computing technology and industries. And its system presents a trend of diversification and coexistence of multiple evolutions. The non-classical computing, such as quantum computing, optical computing, lightweight computing, and privacy computing, is gradually moving from theory to practice.

3.1 Quantum Computing

Quantum computing is a new computing mode that follows quantum mechanics to control quantum information units for computation. It uses quantum bits as the basic unit, and realizes data storage and calculation through the controllable evolution of quantum states. It has the advantage of strong parallel computing capability and can provide exponential speedup on some specific problems.

Quantum computing can be used for quantum simulations, quantum optimization algorithms, quantum cloud computing, and quantum-enhanced AI, where the quantum optimization is an effective approach to solve many optimization problems including the direction of information processing. The high computing power and high parallel computing requirements of AI make it possible to combine quantum computing with AI. The model of "quantum computing + AI" has been used in data clustering and other fields.

However, the application of quantum computing in information communication still faces some great challenges. First of all, the combination of AI and quantum computing is still in the stage of theoretical exploration, which is far from practical application, and the improvement of quantum computing on machine learning is not clear. Secondly, since quantum computing can only solve specific optimization problems, it is necessary to explore the feasibility of quantum computing on general optimization problems. Thirdly, there are some bottlenecks in the miniaturization and stability of quantum computer. No matter what type of quantum computer is (superconductivity-based, optical-based, ion trap-based or nuclear magnetic resonance-based), there are limitations in maintaining quantum coherence time and in producing coherent quantum, both of which require extremely high material technology.

3.2 Optical Computing

Due to the resistance, capacitance and induction, significant amount of heat would be generated when electric charges move frequently inside the devices. As the circuit integration level keeps growing for communications and computing devices, the energy consumption associated with the moving of charges increase explosively and becomes unsustainable. Hence, it is quite necessary to explore a computing system that is more energy efficient.

Optical computer is a potential candidate with the aim to achieve full-optical computing which includes: optical processors, transmitter/receiver of optical data, optical memory, etc. Among them, optical processors are able to fulfill the functions such as controlled amplification and optical logic-gates, based on the nonlinear diffractions of optical material/devices. Optical data transmission can be through optical fibers or spatial light modulators (similar to optical lenses). Optical memory can be made of phase-change or thermal-change based optical disks. The biggest advantage of optical computing is the low energy consumption. Apart from the optical-to-electro and electro-to-optical conversions at the input and output ports, there is no electric charges moving inside the devices. Another big advantage of optical computing is that it can achieve massive inter-connection very efficiently, for instance, a spatial light modulator is essentially an analog antenna with very large aperture which can distribute optical signals from multiple branches to different receivers.

Currently, the main challenge of optical computing is the maturity of optical devices which involves optical processing, optical data transmission and optical memory. Significant breakthrough is needed in the field of optics and material science.

3.3 Lightweight Computing

It has been envisioned that there will be trillions of AI-enabled IoT devices globally. Computing on resource-constrained IoT devices must be energy-efficient to minimize the energy needs. Different approaches are needed given the diversity of IoT applications.

Using energy harvesting with low power chips in the IoT devices is such an approach. For example, low-power microcontrollers (MCUs) may consume only a few milliwatts to microwatts. Energy may be harvested from many sources, e.g., radio waves, temperatures, vibrations, or sunlight. Thus, the research on technologies of energy harvesting is required.

While the IoT devices may harvest energy, the energy-gain function may be challenged to keep up with the computing applications. This is especially hard for sophisticated applications that need much energy. It may result in software problems if the device energy runs out during the application processes. In order to maintain computing correctness on such devices, additional measures are needed to deal with the outages and more researches on efficient computing in IoT devices are needed.

Further, IoT devices are usually subject to resource constraints, e.g., data, knowledge, energy, computing and communication resources. This requires IoT systems to be resource-aware, which can simultaneously take into account of status of sensor battery, the status of actuator power source, and the possible energy requirement of the applications. Researches on resource-aware, energy-efficient computing technologies are requiredto realize low-cost, small and efficient future IoT systems.

3.4 Privacy Computing

As the realization of cross-domain data fusion and data value mining in a secure and compliant manner has become an urgent demand in the era of big data, privacy computing technologies around multi-party secure computing and federated learning are attracting widespread attention. Privacy computing utilizes cutting-edge cryptography technologies such as secret sharing, oblivious transfer, garbled circuit, homomorphic encryption computing, and zero-knowledge proof to make data available and invisible. However, privacy computing needs further research and breakthroughs in distributed computing systems, the improvement of trusted and secure computing efficiency, the guarantee of model accuracy, the standardization of data elements, and the compliance of business development.

4. New Security -- A Built-in Security System for the Future Network

With the openness of the network and the emerging of new technologies, the traditional security system based on patching and plug-in ideologies can no longer meet the needs of the increasingly complex network environment, which demands built-in security capabilities with network trust, secure data sharing and proactive immunity support, and ultimately realizes the transformation from network security to secured network.

4.1 Secure Quantum Communication

The development of quantum computers has been accelerating and tech giants including Google, IBM, Microsoft, and Intel have invested heavily into the research and development (R&D) of quantum computing, which can solve mathematical problems fundamentally challenging for current computers, for example, Quantum computing may greatly reduce the time of cracking commonly used asymmetric encryption algorithms such as the RSA algorithm. Asymmetric encryption relies on the difficulty of factoring large numbers into primes, but the prime factorization algorithm based on quantum computing (e.g, Shor) can find prime factors of large numbers in a much shorter period of time, which shakes the foundation of asymmetric cryptography systems based on the complex mathematical problems.

Moreover, quantum entanglement is crucial for long-distance quantum communication and scalable quantum computing, but the storage of quantum entanglement, especially high-dimensional quantum entanglement is currently a challenge and must be solved in order to build a quantum communication network capable of high volume and long-distance transmission.

As a result, it is needed to carry out researches on quantum-based security technologies in the context of mobile communication, including:

- Quantum attack resistant cryptographic algorithms;
- The last "one-kilometer" transmission problem of quantum crypto key;
- Mathematically proven secure crypto key by using the time-varying, reciprocal and spatially irrelevant properties of wireless channels;
- The storage of quantum for long-distance and secure quantum communication etc.

4.2 Dynamic Data Coloring Technology

As data gradually become critical assets in business operations and carry great values, the risks of unauthorized data access will increase exponentially when data flow within or outside organizations. Traditional data security technologies are insufficient in solving data pollution, data privacy violation, and data leakage intractability problems exacerbated by increasing data fluidity. In the future, data security capabilities need to adapt to the data fluidity to ensure dynamic security protection for flowing data.

Therefore, it is necessary to study the data security technologies with data fluidity awareness, built-in support of data asset labeling, data flow path management and risk detection, which will provide the capabilities of data pollution control, data value assessment, and data tracing required for data protection in future dynamic network environment.

4.3. Trusted Built-in Security System

The traditional security systems are no longer able to effectively defend against security risk uncertainty and potential attacks because of their plug-in and patching based mechanisms. There are two fundamental challenges:

- Transform network from risk uncertainty to certainty of security trust with the support of trust relationship establishment, transmission and evaluation;

- Evolve from passive protection of network to active self-immunity security to meet the requirements of predictable network behavior, strict management, and extreme end-to-end differentiation for different services.

Zero trust is a security concept based on "continuous verification, never trust", which will play an important role in the future mobile networks and break the traditional practice of providing security mostly at the network border. Facing the future open network environment, it’s of great importance to study the security architecture with deep integration of zero trust and communication networks, to build a trusted endogenous security system, and to plant security into the network's genes to provide ultimate security features such as self-immunity and self-evolution.

4.4 Unified Identity Authentication based on Biometric and Device Characteristics

The development of the digital economy and mobile communications has brought a growing number of economic activities with high security requirements on mobile networks, such as comprehensive government administration, financial payment, medical care, etc. In these scenarios there are demanding requirements for user's identity authentication; however, currently mobile phone numbers are the single commonly used real name identifiers for users, which can’t meet the needs of consistency of authentication between business users and mobile device owners.

In recent years various biometric authentication technologies have emerged following the development of sensor and feature recognition technologies, such as fingerprints, palm prints, face, iris, voiceprint, etc. The biometric based authentication has the advantage of convenience without setting and memorizing passwords, and is rapidly being used in various applications. On the other hand, the device authentication based on RF fingerprints can perform individual identification of wireless devices at the physical layer, which has also become a future research direction.

A trusted digital identity authentication system should be built for mobile networks with unified identity authentication which should combine biometrics, device "fingerprint" and traditional authentication techniques. For this goal more research on cutting-edge intelligent authentication mechanisms incorporating multiple biometric features, multiple authentication factors, continuous assessment and verification are needed.

5. Low-Carbon Innovation -- Help to Accomplish Carbon Peaking and Carbon Neutrality Goals

In September 2020, China announced at United Nations General Assembly (UNGA) that it will strive to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, which is an arduous task. Complex and large scale communication systems are seen as high energy consumption (EC) infrastructures, therefore need to decrease carbon emissions by focusing on two possible solutions: reducing expenditure and broadening sources of income, i.e. to curb energy consumption and switch to green energy.

In terms of reducing expenditure, due to the huge cost pressure on network operators given by the high EC of network devices, ‘Zero Watts@Zero Bits’ is necessary to be realized both in EC and communication volumes simultaneously for future networks. Omni-directional improvement of energy efficiency and EC reduction relies on the following technologies of high efficiency radio signaling transmission, high efficiency hardware implementation, deep sleep technology, integration of communication technology and other applications, etc.

5.1 High Efficiency Radio Signaling Transmission

Future network will adopt minimal signaling structure, reducing energy radiation from multi-dimension including source domain, time domain, frequency domain and spatial domain. For example, new encoding method can be used in source domain to transmit more information with fewer bits; innovation waveform is being developed in time domain to increase sleep time duration of devices; more technologies in spatial domain such as very large scale active meta-material phased antenna and laser communication can help to form more precisely directed beams, and lower energy waste of radio radiation.

5.2 High Efficiency Hardware Implementation

First, we must improve the efficiency of RF devices. RF devices are the main EC components of traditional base station system, among which RF power amplifier (PA) has the highest proportion of power consumption. In terms of material and process, the fourth generation semiconductor will be applied in PA; and new circuit and algorithm design can be used to further simplify the architecture, for instance, direct RF sampling technology and fewer interfaces between modules will increase RF efficiency to 80%, 90% or even

100%.

Second, we must reduce digital processing EC. Future network will use passive optical devices instead of active chip. Thanks to refraction, scattering and other optical properties, series of complex logical operations in digital computing can be completed with almost zero EC. Furthermore, improving chip process will be of benefit to gradually approach the power density limit, and technologies like chiplet encapsulation are also expected to break Moore's Law to further lower the EC of digital signal processing.

Third, we must promote heat dissipation. Let the heat out of the running system through liquid cooling at the plate level and material of fast thermal conductivity, to increase the power density limit of the chip. The main challenges here are high price of new materials, increase of deployment and maintenance cost, difficulty of production process, and low degree of supply chain autonomy, etc.

5.3 Deep Sleep Technology

Traffic-aware based modularization hardware and minimalist protocol design are introduced to switch on/off functionalities according to traffic load conditions. When network is out-of-service, most hardware modules transit into deep sleep mode with almost no power consumption. As soon as a terminal detects traffic arriving, dormant hardware will resume rapidly to provide almost zero-latency loading, and ensure high quality of network service. The main challenge in this case is to completely redesign the hardware and software of the chip.

5.4 Integrating with Other Applications

Communication integrating with other applications is a kind of efficient way to save energy, which can achieve doubled achievement with halved effort. For example, visible light communication combines semiconductor lighting technology with optical communication technology. Combined, the light-emitting diodes (LEDs) light intensity is used for information modulation. It needs to overcome the problems of limited LED bandwidth, limited coverage, and susceptibility to interference. In addition, the scale of network nodes will grow sharply in the future. Free electromagnetic energy and friction power generation can also be employed as energy sources to achieve coordinated transmission of information and energy and recycling energy saving.

In terms of finding more resources, green new energy should be vigorously promoted. However, the new energy consumption rate is low, due to the problems of curtailment. In order to improve the utilization rate, it is necessary to build energy storage facilities. Many base stations in mobile communications are located in top of mountains and rural areas where new energy resources are relatively abundant. Other than running base station directly by the nearby green energy, excess electricity can also be stored in backup batteries in the base station. The intelligent endogenous communication network can be integrated with the intelligent network to maximize the utilization rate of green new energy.

Compared with wind and solar energy, nuclear fusion is stable and environmentally friendly. It is considered to be the ultimate energy source that can solve human energy problems. The difficulty of achieving nuclear fusion lies in controllability. Controllable nuclear fusion methods include magnetic constraints, inertial constraints, gravitational constraints, etc. Magnetic constraints are close to success under laboratory conditions, which is also the mainstream research direction. But there is still a long way to go in terms of commercialization, and there should be more continuous exploration and breakthroughs.

6. New Materials -- the Basis for the Development of Future Information Networks

The development of information and communication networks with higher frequency bands and lower EC has put forward transformative demands for new materials. New antenna materials, new chip materials and new optical fiber materials have become three directions worthy of attention.

6.1 Nanoprinted Antenna

Nanoprinting is an emerging technology for the preparation of flexible electronic devices by printing new materials on different flexible substrates. On a flexible fabric substrate, flexible wearable fabric antennas can be prepared by printing nano-conductive particles or coating conductive polymers according to the antenna structure. This makes flexible wearable communication systems possible. Currently, printing electronic ink to prepare flexible electronic devices has become a new direction, but the printing ink market is less mature and requires huge amounts of polymeric nanocomposites to assist development.

6.2 Carbon Nanotube

Carbon Nanotube (CNT) is an alternative to silicon transistors potential technology for the product. At the same level of integration, carbon nanotube chips are smaller than silicon-based devices.

Carbon nanotubes have extremely high toughness, stronger electrical conductivity, shorter electrical signal transmission delay, high thermal conductivity, and low EC. In theory, compared with silicon transistors with the same characteristics, the energy utilization rate of carbon nanotube chips can be increased by 60% to 70%, the operating speed can be increased by 5 to 10 times, and the power consumption can be reduced by 10 times. However, large-scale production of high-purity and uniform carbon nanotubes and fixing them on the substrate to make field effect transistors according to the design requirements still face huge challenges.

6.3 Anti-resonant Hollow Fiber

With the explosive growth of information traffic, the inherent defects of quartz as a fiber material gradually appear, such as nonlinearity, inherent time delay, limited bandwidth, maximum capacity of single-mode fiber (bandwidth distance product), photo-induced damage, etc. barriers to technological development. New optical fibers such as hollow photonic crystal fibers, hollow anti-resonant fibers, few-mode fibers, and multi-core fibers have become active frontier research fields. Among them, the anti-resonant hollow fiber has achieved breakthrough development in recent years due to its low loss and large bandwidth. In the future, it is anticipated that hollow fiber can reduce the optical communication delay by 1/3, and its ultra-low nonlinearity, large transmission bandwidth window and other characteristics are expected to greatly increase the optical amplification distance and optical system capacity.

At present, the basic theories such as the light-guiding mechanism, bandwidth limit and loss limit of anti-resonator hollow fibers have not yet been thoughtfully studied. The research of end-to-end anti-resonator hollow fiber communication system has just started. The subversive new high-speed long-distance optical communication system based on hollow fiber needs to be explored from scratch, and the industry chain needs to promote the research of hollow fiber and its ultra-high-speed long-distance optical communication system.

7. New Bionics -- Combining Biology Technology and Information Technology

The development of brain science and material science paves the way for fast progress of bionics in the field of information & communications and spawns two new directions: brain-inspired computing and DNA-based storage.

7.1 Brain-inspired Computing

Artificial neural networks (ANN) was proposed in 1940s. The input to each neuron in an ANN is a static electric signal. Its nonlinear responses to excitations can be modeled by various nonlinear mappings. However, this is quite different from the transmission and processing of neural signals inside human brains which are in the form of signal pulses. Compared to the cognitive process of human brains, ANN merely utilizes some topology structures of neurons, which is essentially the pile-up of digital logic gates. Many key mechanisms of human brains are still unknown.

By further inspired by the bionics, models for neurons and synapses that are most closely resemble their biological counterparts have been proposed, the so called the third-generation neural network technology or brain-inspired computing. Its potential is huge: accurate modeling of space-time characteristics of biological signals where neural signal pulses are transmitted and processed. This would drastically reduce the activity of neurons and ensure low-energy consumption with high efficiency.

By passing and distributing neural pulses across neurons and synapses, brain-inspired computing can learn faster than deep learning when it is used for characterization and signal processing. Hence, it is more suitable for high-efficient space-time signal processing and data mining. Brain-inspired computing has gradually shown its benefits in the fields of intelligent decision-making, robot-control and computational neurology. It is anticipated that the architecture and chips for brain-inspired computing will be one of the key areas of computer architectures in post-Moore Era.

Still there are several challenges for brain-inspired computing. First of all, the study is lack of basic support. Brain-inspired computing requires chips of special purposes, as well as a series of hardware and software support that is based on neural science. Such chip architecture is based on new programable architecture that follows the principles of neural science and has bio-neuron like analog circuits to achieve fuzzy logic. This is totally different from the

Von-Neumann architecture which is based on general-purpose processors and heterogeneous accelerators. In Von-Neumann architecture, memory and processors are separated, and the entire system operates with instruction flows. The study on brain-inspired chips is still in its early stage, hampered by the lack of core devices/materials and implementation complexities. While the general processor-based simulator for brain-inspired computing can mitigate the deficiency of chips, the study and development of basic modules is still in exploration stage and quite incomplete.

Second, the human brains are not adequately understood and simulated. Right now we can only achieve quite coarse simulation of neural signal transmissions. There is still a long way to go in exploring how the information is transmitted, exchanged and integrated via intricate coordination among hundred billions of neurons inside a brain. In addition, the study on brain-inspired computing requires deep knowledge and expertise. Yet, such talents are quite rare, not enough to hold up a big industry.

7.2 DNA-based Storage

Efficient data storage is an indispensable part of information technology. Benefiting from the fast development in semi-conductor storage and magnetic storage, the data recording density has kept growing at a pace similarly to Moore’s law. However, as semi-conductor technology is approaching the quantum limit, it is necessary to look for alternative media to store information, to meet the demands by the development of information technology. The idea of DNA-based storage was proposed in 1960s, not long after DNA was found. After about 30 years of a quiet period, the study on DNA-based storage has become active, triggered by the projects of gene sequence decoding.

DNA-based storage is a way of information storage based on the base sequences on the chromosomes of nucleus inside cells. The reading and recording of base sequences on DNA segments are via the chain reaction of polymerase. As the size of each DNA is at molecular level, the information unit has two bits (A, G, T and C), and the structure of DNA is double helix and compressible, extremely high storage density can be achieved within a very small space.

Compared to the traditional solid-state memory devices and magnetic disks/tapes, DNA-based storage has the advantage of low pollution, light weight and organically degradable. Nevertheless, currently the data rate for the reading and recording of DNA-based storage is very slow, much lower than that of solid-state devices or magnetic based storage. Also it is quite expensive to prepare DNA samples suitable for data storage and the cost of read/write is very high. These challenges require breakthroughs in the fields of biology, chemistry, etc. to solve.

8. New Networking -- A "Connection + Computing + Capability" Network with Open, Flexible and Building-block-like Architecture

For the long-term business needs in 2035, the communication network will support the access from space, sky, earth and sea. The scope of business access will greatly expand. The business data will have a huge growth and the business types will be extremely enriched. The current networking mode which include centralized deployment and centralized management and control is difficult to match these above-mentioned needs of future business changes.

Therefore, the future communication will evolve towards an open, flexible, building -block-like "connection + computing + capability" network. In the future, the integration of network abilities including computing ability, perception, intelligence and other capabilities will be significantly improved. Eventually, the network, computing and intelligence will be omnipresent. In the future, communication networking needs to perform flexible and real-time integrated control of multi-standard access, resource sharing and network structure expansion according to the needs of various types of users so as to achieve the optimal management of spectrum, connection, computing and capability. The future networking also can support the ways of network services leap-forward improvement from connection to computing and finally to capacity and support the flexible expansion and on-demand deployment of network service content for user-centric.

Plug-and-play connection: Enabled network has flexible architectures and provides basic architecture support for leapfrogging network services from connection to computing. Design a minimalist end-to-end protocol functions can enable fast, robust, and ubiquitous connections between networks, users and networks, and between different functions. The minimalist end-to-end protocol functions also can achieve resource sharing between multi-standard and multi-function, fusion of the individual domains, local domain and wide domain, space-air-earth-sea integration, and integrated ubiquitous connection and ubiquitous coverage of the fusion multi-dimensional network which supported by all services. When the terminal accesses the network, only the key identity authentication and security authentication are needed to realize basic communication. When other access points, including access points from space, air, earth or sea, access the anchor point to expand the network coverage, the security authentication is performed between other access points and the anchor point to achieve wireless coverage.

Building-block-like service-oriented network function: Enabled network has flexibility functions and realizes user-centric network services. A network functional component is created with "service" unit for user needs. Enabled network can activate the corresponding "service" component according to user needs, and realize the building block like network combining, arranging, configuring and deploying "service" components base on demand.

Each "service" software functional component realizes the universality of "service" components by standardizing its related functions, input and output, and realizes end-to-end consistency through signaling control, the last but not the least, realizes end-to-end compatibility through unified orchestration on the network side.

Crowdfunding network with open capabilities: Based on flexible network architecture, network functions build an open system of distributed intelligent cloud network, and build a capable open crowdfunding network that integrates protocols, perception, intelligence, third-party applications and other multi-dimensional computing networks to achieve network service capabilities for all types of users. We build an end-to-end digital twin autonomical system, realize multi-level autonomical network with collaboration of "centralization + distribution" and "offline + online", and provide network capability services for network management and integration of intelligence and power for third-party applications. Through the cloud, edge, terminal, industry integration can be made with distributed and centralized cooperation. On the one hand, more network functions will be extended to the network edge to realize the regional autonomy of edge network; On the other hand, the global-oriented orchestration and scheduling functions will be centralized to support complex cross-domain services.

Although the industry has reached an agreement on the above-mentioned technology evolution direction, the implementation paths and methods of specific technologies have not been unified yet. It is necessary to continue to gather consensus of industrial, jointly carry out innovation by multi-field integration, build a brand new technology system, and achieve technological breakthroughs. In addition, the industry has formed an independent ecosystem around their respective fields with the closed-form nature. It needs to rely on standardization, open source organizations, and industry alliances to reshape the industrial pattern.

9. New Infrastructure -- Integration of Communications and Public Infrastructure

The coordinated construction and integrated development of information infrastructure, fusion infrastructure and innovation infrastructure have become a new trend. In the future, municipal public infrastructure, building infrastructure, and wide-area infrastructure can adopt various integration solutions with communication systems, which lay the foundation for a new infrastructure with "Connection + Computing + Capability".

9.1 Integration of Communication and Municipal Public Infrastructure

Communication technology is an important means to support the transformation and upgrading of traditional infrastructure, which helps to form a new type of integrated infrastructure and improve the intelligence, efficiency and convenience of traditional infrastructure. The integration of new information infrastructure, for example, communication capabilities with municipal light poles and so on to achieve simultaneous construction of lighting and coverage systems. The transparent antennas are integrated with the bus billboard. The intelligent transformation of the manhole cover can realize blind and heat supplementation or coverage enhancement at the site and along the line. A wide range of IoT applications may be integrated, such as combining sensor technology with water, electricity, and gas pipeline networks to achieve intelligent collection and reporting of IoT information, disaster warning, etc.; A communication management platform may be built for "smart cities" with smart city operation capabilities; "vehicle-road-cloud" communication interactive network integration infrastructure can be constructed for special scenarios such as smart transportation, etc.

9.2 The Combination between Communication and Buildings Infrastructure

We may design and construct buildings together with communication network, by introducing new material, new process and new technology. For example, LED lights are utilized in buildings to modulate information, to develop visible light communication. Reconfigurable Intelligent Surface (RIS) may be embedded on the surface of buildings with beamforming to adjust the electromagnetic wave beam intelligently, promoting the optimization of signal coverage. Antenna technology and metal grid printing & etching technology may be combined based on transparent dielectric substrate to realize the integrated design of transparent antenna and building glass, which update the appearance of communication equipment and construction facilities. It dramatically increases the installability and concealment. Ubiquitous wireless technology helps to complete intelligent buildings, fully utilizing the information transmission capacity of indoor communication equipment. The integration of communication network, location network and IoT could provide new application for buildings.

9.3 Integration of Communication and Wide-area Infrastructure

An space-air-ground-sea wide-area information network may be built to create a multi-level, three-dimensional, all-round, all-weather information space, including space-air-ground-sea wide-area ubiquitous communication system architecture, meeting the requirements of communication immediacy, stability, security, and compatibility; satellite communication system and satellite

Internet at various orbital altitudes of high, medium and low; floating communication platforms such as balloons and airships; broadband wireless access system for high-speed rail, aircraft and other civil transportation vehicles; maritime and underwater communication technology and networks; targeted and customized wide area information network application for various vertical industries (such as agriculture, forestry, fishery and animal husbandry industry).

In order to promote the healthy development of new information and communication infrastructure in the future and realize the ubiquitous deployment of new infrastructures that integrate and synergize, it is necessary to build a broad consensus and address difficulties and challenges: The design of communication network architecture for new infrastructure requires comprehensive innovation. The deep integration of infrastructure needs to be promoted through cross-industry cooperation. The relevant supporting policies need in-depth research, bold formulation, and active implementation. business scenarios towards consumers and businesses and related industrial chains need to be actively supported and cultivated.

10. New Paradigm -- Innovative Industrial and Business Models

Mobile communication will involve more cross-border fields and disciplines. The data, information, and communication technologies (DICT) will cultivate a new open source ecosystem and create new industrial and business models. With the continuous maturity of technology, the increasingly rich scenes and data will help the real world map to the digital world more accurately, and realize the interaction between the virtual and real world through digital identity, digital twinning and digital reconstruction, forming a new rule paradigm.

10.1 Fostering New Industrial Models via DICT Convergence

Future Information Technologies are rapidly evolving and converging along with emerging technologies such as big data, cloud computing, and AI. The deep convergence of DICT has become an inevitable trend in the mobile communications industry. The standardization process in the traditional CT industry demonstrate itself as a long cycle with slow pace of evolution, and it sets a high bar for vendors to participate. For example, the 3GPP often takes 2 to 3 years for a given version of standard to complete from its origination to finalization. It is hence extremely hard for small and medium enterprises to afford and follow through such a long R&D cycle, except for a handful large operators, global equipment vendors, and chip manufacturers. Broad innovation is therefore hindered, preventing the growth and prosperity of the eco-system.

In contrast, the modern IT industry leverages open source communities to promote the creation and growth of eco-systems. Typically, open source projects evolves rapidly, and become the de facto standard after productization, which in turn pushes the standard forward. Furthermore, widely used agile development methods in R&D in recent years, along with various deployment automation, testing frameworks and tools, closed-loop data utilization, life cycle management of AI/ML algorithms and models, they together spawned a wild variety of "software-defined" models and eco-system. The adoption of the microservice architecture and the momentum of cloudification have effectively helped the software and hardware decoupling and the software segmentation. Combined with flexible APIs and SDKs provided by the community, it sets a low bar so that start-ups, even individual developers can participate and contribute in open source community, resulting significant growth of the eco-systems. Enterprises participating in open source and innovation can also benefit from faster go-to-market pace, forming positive feedback to build up a healthy structure of the eco-system.

The deep convergence of DICT also brings new challenges to the future information and communication industry and standardization process. The synergy of the three is not only reflected in the technical perspective, but will also extend to others such as eco-system, security, standardization, open source community and etc.. It remains a challenge to the information and communication industry to foster new industrial models when it sorts out to learn from past lessons, leverage on each other's strengths, and manage organic growth among the three.

10.2 New business models are born from distributed technology

With the popularization of IoT technology and the wide application of related equipment, massive data will greatly promote the development of distributed technology, and it will be improved accordingly for the subsequent industrial application, division for social responsibility and economic mechanism.

The traditional centralized data center can no longer meet the new challenges brought by the changes as above. Instead, it is realized by point-to-point, agile and flexible, data privacy, low-cost and efficient distributed solutions. With the whole life cycle including data generation, collection, storage, circulation, collaboration, analysis, intelligence, etc., it’s needed by technical support and sustainable development, such as blockchain, edge computing, privacy computing, federal learning and other emerging technologies in this field. Distributed technology allows to recognize each other's identities, share data and establish collaboration, generates new business and operation modes among individuals, and organizations. With the new multi-party trust and coordination mechanism, the digitalized and AI-oriented world can greatly improve flexibility and response efficiency. Enterprises can explore new markets with new methods, while the government and relevant organizations should make new policies and industrial eco-system standards.

In addition to the digitalization and intellectualization for industrial economics, the "meta universe" should also have strong characteristics such as division and coordination on social responsibility, and reorganization on social relationship, so as to form a new safe, stable and orderly economic system for production and operation. In this process, the establishment of industrial standards and regulatory order is accompanied. It needs to strengthen the overall planning of distributed coordination, guide scientific and technological giants and industrial leaders to carry out standardization cooperation, and support the entity economy to formulate various standards such as distributed technology, infrastructures, services and contents. In terms of laws and regulations, from monopoly to coordination, from supervision to autonomy, from risk to security, all kinds of new problems and challenges have also emerged accordingly. The formulation of laws and regulations to promote the development and application of distributed technology should start with basic elements such as algorithms, data and transactions.

Conclusion

Focusing on the vision of information and communication in 2035, this white paper selected ten cross-domain innovation directions that affect the development of information and communication technology in the future from the perspective of China Mobile. It is expected to attract more attention and motivate to work together on these directions, and calibrate and iterate the views constantly with the colleagues of academia and industry. It is believed that, with the joint efforts of global innovation chain and industrial chain, the breakthrough of these ten cross-domain innovation directions will have a profound impact on the sustainable, healthy and great-leap forward development of information and communication industry in the future, which will help the bright vision of "digital twin and wisdom ubiquitous" to be a reality!

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