

# The Current Application Status and Future Prospects of 5G Technology in Remote Surgical Robot Systems

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**Abstract.** The remote surgical robot system is a key technology to solve the uneven spatial and temporal distribution of high-quality medical resources. The high cost, low efficiency, and low flexibility of traditional networks limit their development. 5G relies on three major application scenarios of eMBB, uRLLC, and mMTC, as well as technologies such as network slicing and MEC, to provide millisecond level latency, high network speed, and dedicated network support, breaking through the bottleneck of precise remote surgical control. This article aims to review the current status and prospects of the application of 5G in remote surgery systems. By sorting out the 5G network framework and the composition of the remote surgical robot system, it deeply analyzes the performance enhancement and practical effects of 5G in low latency, large bandwidth, and high reliability. Combined with successful surgical cases at home and abroad, such as inter-provincial remote surgery and high-altitude remote surgery, it demonstrates the enormous value of popularizing high-quality medical resources. Afterward, by pointing out the challenges of current latency stability, network coverage, data security, and ethics, the article looks forward to the direction of AI deep integration and 6G terahertz communication to promote multi-robot collaborative surgery, promote technological integration and medical inclusiveness, and ultimately achieve the optimization of high-quality medical resources and the innovation of surgical service models.

**Keywords:** 5G technology, Remote surgical robot, Low latency, large bandwidth, High reliability.

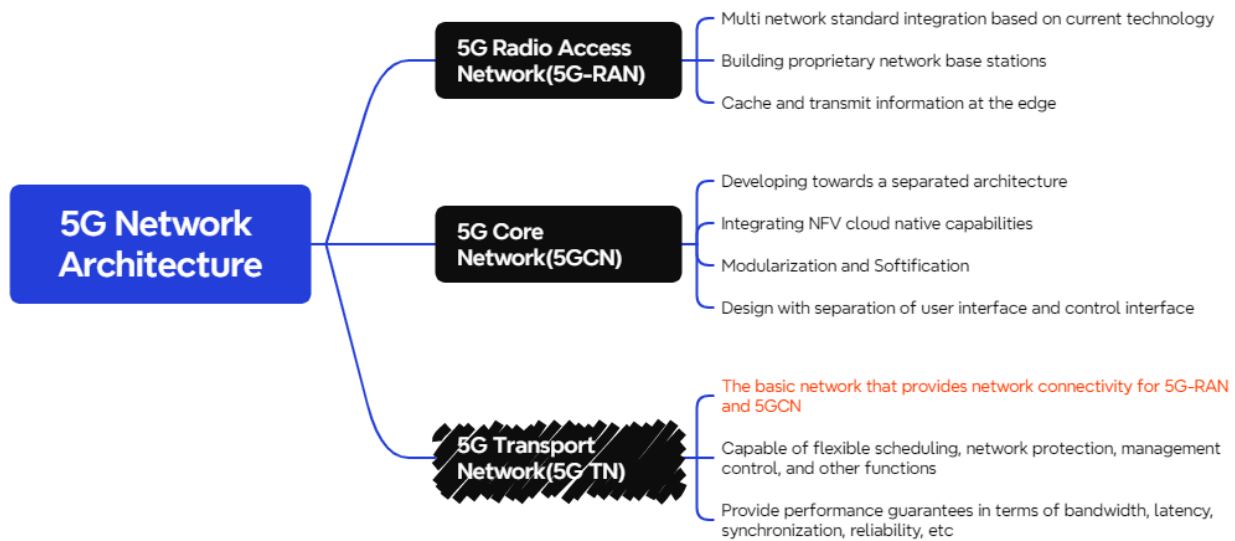
## 1. Introduction

The uneven distribution of medical resources in time and space has long constrained the application of high-quality healthcare. The emergence of the remote surgical robot system has provided an effective means to achieve efficient sharing of medical resources. However, the development of the system has long been limited by the high deployment costs of traditional wired networks and insufficient geographical flexibility. At the same time, there may be fluctuations in data transmission, which seriously affect the accuracy and safety of remote surgical control. The fifth generation mobile communication technology (5G), with its key characteristics such as latency, mobility and three application scenarios, Enhance Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (uRLLC), Massive Machine Type Communication (mMTC) [1, 2], as well as its combination with network slicing and Mobile Edge Computing (MEC) technology, provides end-to-end millisecond latency, large broadband transmission at Mbps rate, and a highly reliable dedicated wireless network for remote surgery, thus solving the challenge of precise manipulation of remote surgery. This article aims to explain how 5G technology can enhance the performance of remote surgical systems in terms of low latency, large bandwidth and high reliability.

## 2. 5G Network Framework and the Composition of the Remote Surgical Robot System

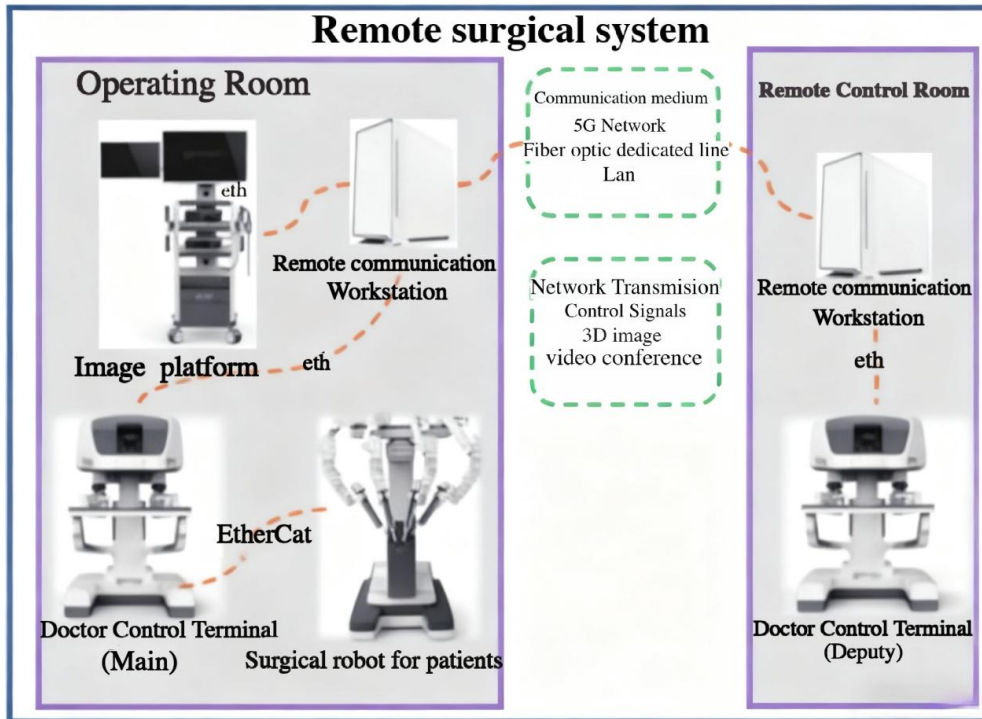
The deep coupling between the 5G network and the remote surgical system has built an intelligent infrastructure to support future healthcare. Wang et al. stated that the 5G network framework consists of two core parts [3]. 5G Radio Access Network (5G-RAN) and 5G Core Network (5GCN). 5G-RAN covers multi network standard fusion, proprietary base station construction, and edge caching transmission mechanism. With a single wireless controller as the core, efficient allocation of virtual

resources is achieved through multi network fusion and base station deployment. The flexible operation of edge caching supports real-time information transmission, and the design is open to third-party service providers enabling them to optimize the network as needed, ensuring user service quality. 5GCN adopts a control plane and user plane separation framework, integrates NFV cloud native technology, and achieves network function decoupling based on modular and software design. The separated framework breaks the limitation of resource calling, while cloud native and software design enhance the flexibility and adaptability of core network deployment. In addition to 5G-RAN and 5GCN, 5G Transport Network (5G TN) is also an indispensable part. 5G TN is the basic network that provides network connections for 5G-RAN and 5GCN. In addition to network protection, and management control functions for network connections, 5G TN also needs to provide performance guarantees in terms of bandwidth, latency, synchronization, and reliability [4]. The above statement is shown in Figure 1.



**Figure 1.** Schematic diagram of 5G network framework (Picture credit: Original)

The remote surgical robot system mainly consists of the doctor's control end and the patient's surgical end located in two different places. The domestically produced Toumai® four arm laparoscopic surgical robot is shown in Figure 2, and stable and reliable remote connection and real-time interaction are achieved through a high-performance network communication system. The doctor's control end is equipped with a remote communication workstation and control terminal for real-time operation and observation of the surgical process by the operator. The patient's surgical end deploys surgical robots, control terminal, image platform, remote communication workstation and related auxiliary equipment to execute remote commands and complete precise surgical actions. The combination of multiple technologies such as 5G network, fiber optic dedicated line or local area network (LAN) between the two ends is used to build a low latency, high reliability, encrypted and secure communication link, thereby achieving real-time synchronous transmission of control signals, 3D images and video conference, ensuring the smooth implementation of remote surgery [5, 6].



**Figure 2.** Schematic diagram of the main equipment modes of the domestically produced Toumai® four arm laparoscopic surgical robot [5]

### 3. Enhancement and Implementation of 5G Communication Technology for Low Latency in the Remote Surgical Robot System

In the remote surgical robot system, end-to-end latency is the core element that determines system safety. Excessive latency can lead to asynchronous operation instructions and visual feedback, resulting in operational errors. So first, it is necessary to clarify what parts end-to-end latency includes. Lu et al. mentioned that the total latency  $T_{E2E}$  refers to the one-way transmission of data between the user equipment (UE) and the application (APP), which is mainly composed of two parts. The first is the wireless latency  $T_{RAN}$ , which is the latency caused by signal processing between UE and RAN. The wireless latency can be controlled within 0.5ms in 5G networks, far less than about 5ms in 4G networks; the second is the wired transmission latency  $T_{Transmission}+T_{CN}+T_{Internet}$ , including the cumulative latency caused by optical fiber transmission, routing and forwarding, virtualization network element processing and other links in the return network, core network and Internet, which is significantly affected by the transmission distance and the number of intermediate nodes [7]. The formula is characterized as follows:

$$T_{E2E}=T_{RAN}+T_{Transmission}+T_{CN}+T_{Internet} \quad (1)$$

The implementation of low latency in 5G is a systematic project. Firstly, considering the implementation of low latency from a wireless perspective, 5G optimizes 5G New Radio (5G NR) design through uRLLC technology that follows the 5G network framework defined by 3GPP, significantly reducing the processing latency of signal transmission between terminals and base stations [8]. Chen et al. proposed that in the 5G uRLLC scenario, the end-to-end latency of the Modbus protocol can be effectively controlled compared to the traditional 5G SA framework [9]. As Adoga mentioned that network slicing technology can effectively manage and allocate network resources, the introduction of network slicing mapping technology has further optimized latency performance [10]. In addition, Zhang mentioned that network slicing technology achieves a low latency guarantee for 5G by providing dedicated computing allocation for 5G [11]. From the perspective of the network framework, low latency implementation is considered. Network

cloudification based on Network Function Virtualization (NFV)/Software Defined Networking (SDN) enables flexible deployment of core network functions, especially by using MEC technology to sink business platforms to the network edge, allowing data to be processed nearby and fundamentally shortening end-to-end transmission paths [12]. These technologies work together to control the end-to-end latency of 5G within milliseconds, meeting the needs of extreme applications such as remote real-time control.

The above content clarifies the synergy between wireless access optimization and network framework innovation in 5G networks, providing a technical framework for end-to-end latency control of remote surgical systems, and clarifying the latency optimization mechanism of each technical link from the perspective of latency composition. Fan et al. mentioned five cases of ultra remote surgery. Under the application of the 5G network, the measured data showed that the median latency of the five surgeries was 73ms. All surgeries were successfully completed, which verified the application value of low latency [13]. Sun et al. mentioned an example of a domestically produced robot remote gynecological surgery application relying on 5G network. The Shanghai surgical end was connected to the Zhoushan patient end with the help of telecommunications 5G telecommunications wireless network and 5G CPE equipment. The actual real-time monitoring latency data was 105-111 ms, with an average latency of 108 ms. Only when the operation amplitude was too large did the operator feel a slight latency, which did not affect the overall surgical process [14]. These cases fully reflect the key role of 5G network in ensuring low latency for remote surgery under ultra remote conditions.

#### **4. Enhancement and Implementation of 5G Technology in Large Bandwidth for the Remote Surgical Robot System**

The principle of ensuring large bandwidth lossless transmission with 5G technology is to comprehensively utilize technologies such as mmWave Communication and massive MIMO, and to achieve synergy from both the spectrum and spatial dimensions. The 5G network brings huge spectrum resources through mmWave Communication, providing continuous bandwidth far beyond 4G networks, and can easily carry uncompressed or lossless 4K/8K video streams. The mmWave Communication provides a huge basic bandwidth like a super highway by exploring high-frequency resources from 30 to 300 GHz, laying the physical foundation for high-speed data transmission [15]; At the same time, massive MIMO technology uses spatial multiplexing, which means deploying dozens to hundreds of antennas to establish multiple parallel data streams on the same spectrum to greatly increase capacity, ensuring that high priority surgical video streams can stably obtain the required bandwidth in complex hospital environments. By using beamforming to transmit to users, this technology not only effectively overcomes the weaknesses of short transmission distance and easy attenuation of mmWave Communication, but also significantly reduces signal interference and improves link reliability, thereby jointly ensuring high-speed, large capacity, and high-quality lossless data transmission [16, 17].

5G expands high-frequency spectrum resources through mmWave Communication, and the collaborative mechanism of massive MIMO technology relying on spatial multiplexing and beamforming to optimize transmission efficiency provides core technical support for high-speed lossless transmission of high-definition surgical video streams in remote surgery. The examples can further prove the role of 5G's large bandwidth transmission capability in ensuring surgical safety. Sun et al. mentioned a case where a robot assisted resection was performed on a patient through a 5G network. Actual transmission data showed that the downstream bandwidth of the Shanghai end network reached 330 Mbps and the upstream bandwidth was 80 Mbps, while the downstream bandwidth of the Zhoushan end network was 280 Mbps and the upstream bandwidth was 75 Mbps. There were no transmission interruptions or signal lags caused by insufficient bandwidth throughout the entire process [14]. Yuan et al. mentioned an example of a micro-surgical remote consultation platform application. The actual transmission data showed that the local surgical video bit-rate in

Chengdu was 62.9Mbps. After being compressed and transmitted to the remote end in Beijing through 5G encoding, the bitrate was 20.4Mbps. The video quality changed slightly after transmission, and it stably carried the synchronous transmission of high-definition surgical video streams and robot control signals [18].

## **5. Enhancement and Implementation of 5G Technology for High Reliability of the Remote Surgical Robot System**

In a remote surgical robot system, the reliability of the network is directly related to the safety of patients' lives. 5G technology constructs an ultra-high reliability that meets medical grade requirements through multipath transmission technology and end-to-end security framework.

The multipath transmission technology copies the original data stream into multiple member streams and sends them in parallel through independent transmission paths. The receiving end performs duplicate detection and elimination based on the sequence number embedded in the data frame, thereby achieving highly reliable data reception and reconstruction, significantly improving the fault tolerance and transmission reliability of the communication system [19].

The end-to-end transmission security framework is deeply integrated with MEC and network slicing, utilizing slicing technology to achieve logical isolation and exclusive resource protection, effectively curbing the spread of security risks. At the same time, MEC has enabled the protection of critical capabilities by sinking user interface functions and computing power, thereby significantly reducing the exposure of sensitive data. Network slicing provides MEC with a secure, isolated, and quality of service guaranteed transmission channel, while MEC serves as the security anchor for slicing. The two work together to form a security protection system that meets the stringent requirements of low latency, high reliability, and data security [20,21].

Through the coordination of multipath transmission technology and security framework, the 5G network has built a reliable and secure environment for remote surgery. Dai et al. analyzed clinical data of 160 patients with pelvic fractures. The Foshan orthopedic team, in collaboration with orthopedic experts from Beijing Jishuitan Hospital, performed 80 remote assisted nail implantation surgeries using 5G networks and orthopedic surgical robots. At the same time, 80 patients in the control group underwent local robot surgeries. The accuracy rate of screw implantation in the 5G group was 98.3% (177/180 pieces), and the accuracy rate of fracture reduction was 98.8% (79/80 cases), fully verifying the high reliability of the 5G network [22]. Wang et al. mentioned the use of a minimally invasive endoscopic surgical robot system to complete surgeries, with an actual transmission packet loss rate of 0.01% to 0.1%, and no network interruptions, fully demonstrating the high reliability of 5G networks [23].

## **6. Main Challenges and Future Development Trends**

### **6.1. Major Challenges Faced by the Remote Surgical Robot System**

5G has already surpassed 4G in terms of latency and transmission quality, but latency and stability remain the top challenges for remote surgery [24]. Nguan et al. mentioned that a latency of 510ms is no longer sufficient to successfully complete the surgery [25]. Xu et al. mentioned that surgery still needs to stabilize latency below 200ms under ideal conditions [26]. The network coverage and anti-interference capability of 5G in remote surgery still need to be broken through, and at the same time, there is a problem of insufficient coverage of public 5G, which makes it difficult to meet the continuous and stable connection needs of surgery.

The security of 5G remote surgery still needs to be further improved, although the dual link network framework and encrypted communication proposed in Japan's "Remote Surgery Operation Guidelines" have made fundamental contributions to security [27]. However, the encryption and privacy protection technologies for surgical data still need to be upgraded, and the emergency response mechanism for network congestion and sudden packet loss is not fully mature, making it

difficult to ensure uninterrupted and highly reliable transmission throughout the surgery. The surgeon responsible for performing remote surgery is also an important factor, as they need to have good hand-eye coordination skills, be familiar with all the functions of the surgical robot, and possess emergency response measures and a good mentality. Secondly, remote surgical robots face multiple ethical challenges, including the ambiguity and shifting of responsibility caused by multiple parties such as doctors, manufacturers, and network service providers. Patient privacy is easily leaked due to internal and external operations and network attacks. The uneven distribution of medical resources between different countries, regions, and individuals is exacerbated, as well as communication barriers and lack of humanistic care caused by technological intervention between doctors and patients [28].

## 6.2. Future Development Trends

AI technology is evolving from assisting decision-making to autonomous execution. Professor Tao's team collaborated with a domestically produced AI surgical robot system and Kashgar to complete the world's first AI remote head and neck minimally invasive surgery. During the surgery, they relied on China Telecom's broadband dedicated line to achieve millisecond-level low-latency communication. AI used a large model to accurately locate the blood vessels and nerves in the throat, intelligent algorithms to achieve sub millimeter level instrument control, and combined multi-modal digital twin technology to track the surgical field in real time and construct a three-dimensional model to complete the surgery [29]. In this surgery, AI not only broke through the bottleneck of surgical accuracy and reduced risks by accurately identifying anatomical structures and optimizing operation trajectories, but also compensated for the spatial perception difference of remote operations through multi-modal data integration, and reduced dependence on dedicated ultra-high-speed networks through data transmission priority optimization, expanding the application scenarios of the technology.

6G relies on the ultra large bandwidth and sub millisecond low latency of terahertz communication, combined with the integration of air, space, and ground networks to break through the coverage limitations of remote and post disaster scenarios, solving the core bottlenecks of remote surgical data transmission, real-time operation, and scene adaptation, and becoming a key support for its future development trend. Terahertz communication is a key technology for 6G, with a frequency range of 0.1 to 10THz and a continuous bandwidth of over 20GHz and transmission rates ranging from Gbit/s to Tbit/s. It is the foundation of 6G communication system design and can support multi-modal data transmission and precise operation in remote surgery through ultra large bandwidth, low latency, and high reliability [30,31]. In the future, 6G will also optimize the transmission dynamic adaptation capability through the integration of AI prediction channel modeling, support multi-robot collaborative surgery, further enhance the accuracy and universality of remote surgery, promote the popularization of high-quality medical resources, and consolidate its development trend position.

## 7. Conclusion

The review indicates that 5G, through three major application scenarios of eMBB, uRLLC, and mMTC, combined with resource isolation guarantee of network slicing and edge data processing of MEC, jointly builds a network foundation adapted to remote surgical systems. 5G has achieved significant results in low latency, large bandwidth, and high reliability for the remote surgical robot system. Clinical practice has also proven that remote surgery can overcome geographical limitations and achieve medical resource sharing through 5G. There are still shortcomings in the current 5G remote surgery, and the stability of latency needs to be further improved. The encryption of surgical data and the protection of patient privacy need to be strengthened, and the ethical responsibilities of multiple parties are not clear. In the future, targeted optimization technology is needed, while deepening the integration of AI and surgical robots, promoting the application of 6G terahertz communication and an integrated network of air, space, and earth, helping remote surgical systems

move from pilot to large-scale clinical applications, and promoting the popularization of high-quality medical resources and the development of smart healthcare.

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