

6G NETWORKS: ENABLING TECHNOLOGIES USING MATLAB

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ABSTRACT:

The sixth generation (6G) wireless network is expected to provide ultra-high data rates, ultra-low latency, massive connectivity, intelligent resource management, and ubiquitous coverage. This paper presents an AI-enabled 6G framework that integrates Machine Learning (ML), Deep Learning (DL), Federated Learning (FL), Deep Reinforcement Learning (DRL), Explainable AI (XAI), and Generative AI (GenAI) with key 6G technologies such as THz communication, ultra-massive MIMO, RIS, edge computing, and intelligent connectivity. MATLAB-based simulations are used to evaluate the performance of the proposed AI techniques. The results show a traffic prediction RMSE of 8.95 Mbps, channel estimation RMSE of 0.0496, and DL classification accuracy of 92.57%. Federated Learning achieves a traffic prediction RMSE of 8.89 Mbps while maintaining local data privacy. DRL provides adaptive bandwidth allocation based on network load, while XAI identifies the most influential traffic features. GenAI further demonstrates automated 6G network configuration and service orchestration. The results indicate that AI integration can improve network intelligence, resource optimization, security, adaptability, and operational efficiency, providing a promising foundation for future 6G applications including smart cities, autonomous transportation, industrial automation, healthcare, IoT, immersive XR, and digital twins.

KEYWORDS: 6G Networks, Terahertz (THz) Communication, Artificial Intelligence (AI), Ultra-Massive MIMO, Reconfigurable Intelligent Surfaces (RIS), Edge Computing, Non-Terrestrial Networks (NTN), Internet of Things (IoT), Intelligent Connectivity, Network Security, Digital Twins

INTRODUCTION

Wireless communication has evolved rapidly over the past several decades, progressing from the first generation (1G) of analog cellular systems to the highly capable fifth-generation (5G) networks. Each generation has introduced significant improvements in data rate, coverage, capacity, mobility, and latency. The rapid growth of mobile data traffic, connected devices, and machine-to-machine communication has created an increasing demand for wireless networks with higher capacity, reliability, intelligence, and efficiency [1], [2]. The emergence of 5G has enabled several important applications, including the Internet of Things (IoT), smart cities, autonomous transportation, industrial automation, and healthcare services [3], [4]. However, emerging applications such as holographic communication, immersive extended reality (XR), digital twins, autonomous systems, and highly interactive services are expected to impose requirements beyond the capabilities of current 5G networks [5], [6].

The sixth generation (6G) of wireless communication is therefore being investigated as the next major evolution of mobile networks. Unlike previous generations, 6G is envisioned not merely as an improvement in transmission speed but as an intelligent, highly connected, and adaptive communication platform integrating communication, computing, sensing, and artificial intelligence (AI). The vision of 6G includes extremely high data rates, ultra-low latency, massive connectivity, improved reliability, enhanced energy efficiency, and ubiquitous coverage [7], [8]. Research on 6G has identified several important performance requirements, including higher spectral efficiency, increased network capacity, lower latency, improved mobility support, and significantly greater device density compared with 5G [9].

One of the most important technological directions for 6G is the utilization of higher-frequency spectrum, particularly the terahertz (THz) band. THz communication provides access to extremely large bandwidths and therefore has the potential to support ultra-high data rates required by future applications [10]. However, THz communication also introduces challenges such as severe propagation loss, molecular absorption, limited transmission distance, and beam-alignment requirements. Consequently, advanced antenna technologies and intelligent propagation-control mechanisms are required to make THz communication practical for future 6G networks [10], [11].

Massive MIMO and ultra-massive MIMO are also expected to play a major role in 6G. Increasing the number of antenna elements can provide higher spatial multiplexing, improved spectral efficiency, enhanced beamforming capability, and greater system capacity [12], [13]. In addition, reconfigurable intelligent surfaces (RIS) and holographic MIMO surfaces have emerged as promising technologies for controlling the wireless propagation environment. RIS can manipulate the

phase and direction of electromagnetic waves and can therefore improve coverage, signal quality, energy efficiency, and communication reliability, particularly in challenging propagation environments [14], [15].

Another fundamental characteristic of 6G is the integration of artificial intelligence and machine learning into the network architecture. AI can be applied to channel estimation, beamforming, resource allocation, traffic prediction, network slicing, mobility management, fault detection, and autonomous network optimization [16], [17]. AI-enabled network management can allow future 6G systems to dynamically adapt network resources according to traffic conditions, user requirements, application characteristics, and environmental changes. This transition toward AI-native networking is expected to transform conventional networks from manually configured systems into intelligent and self-optimizing infrastructures [17], [18].

Edge and distributed computing are similarly important for achieving the responsiveness required by 6G applications. By moving computation and AI inference closer to end users and data sources, edge computing can reduce communication latency and network traffic while improving the performance of latency-sensitive applications [19]. The combination of 6G connectivity with edge intelligence can support real-time applications such as autonomous vehicles, industrial robotics, intelligent transportation systems, immersive XR, and digital twins. In addition, non-terrestrial networks, including satellite and aerial platforms, can complement terrestrial infrastructure to provide wider coverage and resilient connectivity [20].

The potential applications of 6G extend across industrial, commercial, public, and societal domains. In smart factories, 6G can support real-time industrial sensing, autonomous robots, predictive maintenance, and digital twins. In smart cities, it can enable intelligent transportation, environmental monitoring, connected infrastructure, and city-scale digital twins. In healthcare, 6G can support continuous monitoring, remote diagnosis, robotic assistance, and other advanced telemedicine services. Immersive AR/XR, holographic interaction, autonomous vehicles, intelligent IoT, and public-safety systems are additional applications that can benefit from the high throughput, low latency, reliability, and sensing capabilities envisioned for 6G [5], [6].

Despite its considerable potential, the development and deployment of 6G networks involve several challenges. These include the availability and management of high-frequency spectrum, propagation losses at THz frequencies, energy consumption, complex network architectures, infrastructure cost, cybersecurity, privacy, interoperability, and global standardization [8], [9]. The integration of AI also creates challenges related to data privacy, model reliability, computational complexity, explainability, and security. Therefore, future research must address both the technological capabilities and the practical limitations of 6G to ensure that next-generation networks are secure, sustainable, reliable, and economically viable.

Overall, 6G networks represent a transition toward intelligent, ubiquitous, and highly adaptive wireless communication systems. The convergence of THz communication, ultra-massive MIMO, RIS, AI, edge computing, sensing, and non-terrestrial connectivity provides the technological foundation for this transition. This paper therefore focuses on the enabling technologies, intelligent connectivity mechanisms, emerging applications, challenges, and future research directions of 6G networks.

The development of mobile communication has progressed through several generations, with each generation addressing new requirements in terms of capacity, data rate, latency, reliability, and connectivity. While 5G introduced enhanced mobile broadband, massive machine-type communication, and ultra-reliable low-latency communication, the rapid emergence of AI-driven applications, immersive communication, autonomous systems, digital twins, and highly connected environments has created the need for capabilities beyond those targeted by 5G [1], [2]. The transition toward 6G is consequently motivated by the need to support future applications requiring extremely high throughput, very low and predictable latency, massive device density, ubiquitous connectivity, and intelligent network operation.

6G is envisioned as an AI-native and intelligent communication architecture rather than simply a higher-speed version of 5G. Saad et al. identified applications, technological trends, and open research problems that form the foundation of the 6G vision [3]. Similarly, Letaief et al. emphasized the importance of AI-empowered wireless networks in achieving the flexibility and intelligence expected from future communication systems [4]. The attached literature identifies AI, edge intelligence, federated learning, deep reinforcement learning, and explainable AI as important directions for integrating intelligence into 5G and 6G networks.

A key requirement of 6G is ultra-high data-rate communication. Future applications such as holographic communication, immersive extended reality, high-resolution sensing, and real-time digital twins are expected to generate enormous quantities of data. To address these requirements, researchers have investigated the use of higher-frequency spectrum, particularly the terahertz (THz) band, which can provide significantly larger bandwidth than conventional frequency bands [5], [6]. However, THz communication introduces challenges including severe path loss, molecular absorption, beam alignment, and limited propagation distance.

Another fundamental requirement is ultra-low and predictable latency. Future applications such as autonomous transportation, industrial robotics, remote healthcare, and interactive XR require not only low average latency but also predictable network behavior. Recent 6G research highlights deterministic latency and tight jitter control as important capabilities for real-time robotics, digital twins, autonomous systems, and closed-loop industrial applications.

Related Work on 6G Enabling Technologies

Several researchers have investigated the technologies required to achieve the 6G vision. One important research direction is massive MIMO and ultra-massive MIMO. Increasing the number of antenna elements enables advanced beamforming, spatial multiplexing, improved spectral efficiency, and higher network capacity [7], [8]. The literature also discusses ultra-dense networks, nano-antenna arrays, beam tracking, and base-station coordination as important technologies for achieving high data rates in future wireless systems.

Reconfigurable Intelligent Surfaces (RIS) have also received considerable attention as an enabling technology for 6G. RIS can dynamically manipulate the wireless propagation environment by controlling the reflection of electromagnetic waves. This capability can improve coverage, signal quality, energy efficiency, and communication reliability, particularly in environments where direct communication links are obstructed. In particular, research on Intelligence-enabled 6G highlights RIS, THz communications, and edge AI as crucial technological elements of future networks. Another significant area of research is edge and fog computing. When sending massive volumes of data to centralized computers, traditional cloud computing may cause delays. By bringing processing closer to endpoints and data sources, edge computing overcomes this constraint. Edge intelligence in 6G can provide low-latency based services, predictive maintenance, compute offloading, intelligent resource allocation, and real-time inference. AI-based resource optimization encompassing cloud infrastructure, edge nodes, a 5G/6G cells, and IoT devices is highlighted in the literature that is attached.

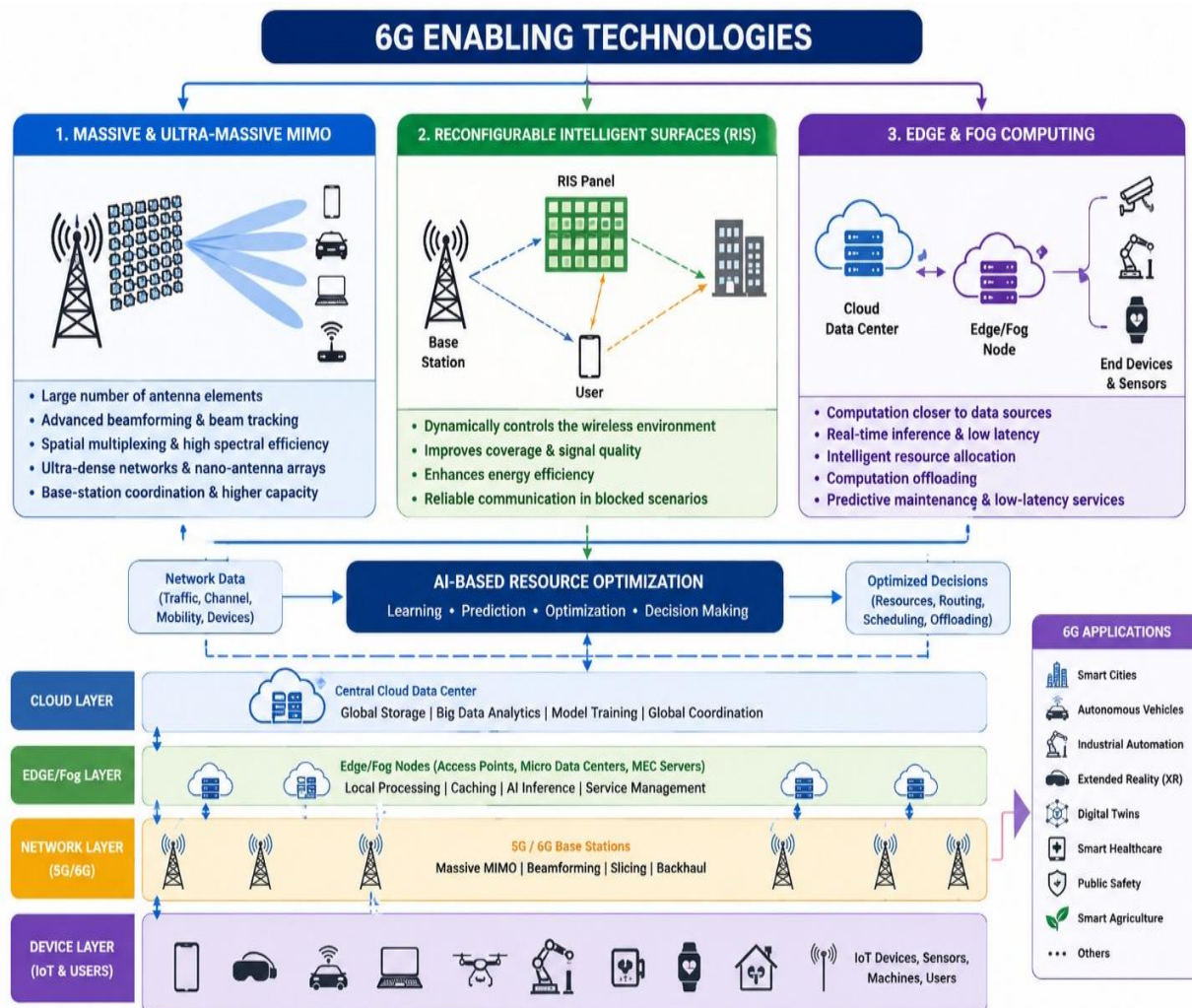


Figure 1:6G Enabling Technologies

Intelligent Connectivity in 6G

AI has also been investigated for 6G network optimization and autonomous management. AI and machine-learning algorithms can assist with traffic prediction, resource allocation, network slicing, beamforming, channel estimation, mobility management, and security. Deep reinforcement learning, federated learning, and edge AI are particularly relevant because they can enable distributed decision-making while reducing dependence on centralized processing.

Intelligent connectivity is one of the defining characteristics of 6G. Future networks are expected to continuously adapt their operation according to user requirements, application characteristics, network conditions, and environmental information. AI-native mechanisms can dynamically optimize radio resources, scheduling, routing, coverage, and computing resources. Such capabilities allow different applications to receive differentiated connectivity according to their latency, reliability, throughput, and security requirements.

The integration of terrestrial and non-terrestrial networks (NTNs) is another important direction. Satellites, unmanned aerial vehicles, and terrestrial infrastructure can cooperate to provide broader and more resilient connectivity. This architecture is particularly relevant to rural regions, remote environments, mobility corridors, emergency response, and other scenarios where conventional terrestrial infrastructure may be unavailable or unreliable.

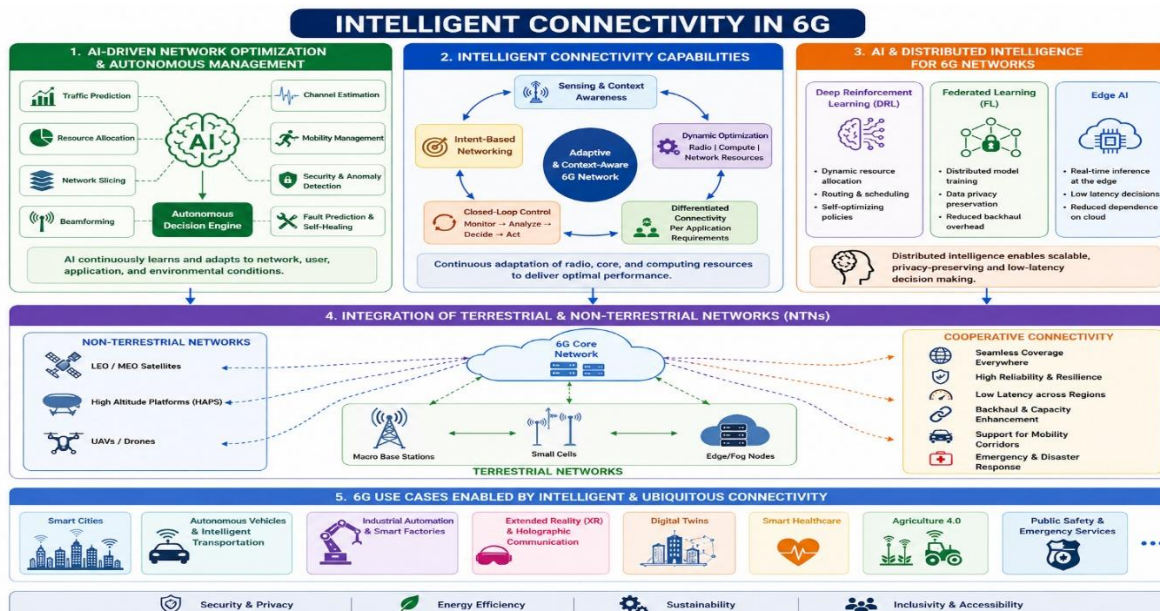


Figure 2: Intelligent Connectivity in 6G

AI Integration in 6G Networks: Framework and Outcomes

Artificial Intelligence (AI) is expected to become a native component of 6G architecture rather than an external optimization tool. Unlike previous wireless generations, 6G integrates AI across cloud, edge, network infrastructure, and end devices to enable autonomous communication, intelligent sensing, and real-time decision-making. AI-driven networking allows the communication system to continuously learn from traffic patterns, user behavior, channel conditions, environmental sensing, and application requirements, thereby improving network efficiency and service quality.

AI Integration Framework in 6G

AI at Device Layer

Smartphones, IoT devices, autonomous vehicles, robots, and wearable sensors perform on-device AI inference for local intelligence and reduced latency.

Edge AI Layer

Edge servers execute low-latency AI tasks such as traffic prediction, resource allocation, beam management, and distributed learning near users.

Cloud Intelligence Layer

Cloud platforms train large AI models, coordinate network-wide optimization, and maintain global knowledge across distributed network elements.

AI-Native Network Control Layer

AI orchestrates network slicing, mobility management, fault prediction, security analytics, spectrum allocation, and self-healing operations.

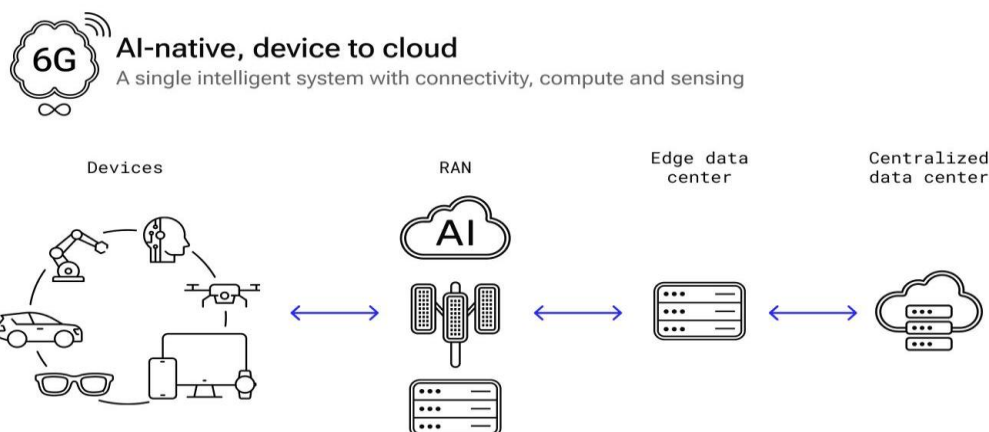


Figure 3. AI-Native Integration Architecture for 6G Networks.

The figure 3 illustrates AI intelligence distributed across cloud, edge servers, terrestrial base stations, satellites, UAVs, IoT devices, autonomous vehicles, smart factories, and healthcare systems.

AI Techniques Used in 6G Networks

AI Technique	Role in 6G Networks
Machine Learning (ML)	Traffic prediction, anomaly detection, channel estimation.
Deep Learning (DL)	Beamforming optimization, modulation recognition, signal classification.
Federated Learning	Privacy-preserving distributed model training across devices.
Deep Reinforcement Learning (DRL)	Dynamic spectrum allocation, routing optimization, network slicing.
Explainable AI (XAI)	Transparent AI decisions for security and resource management.
Generative AI	Intelligent network configuration, digital twin simulation, service orchestration.

AI-Based Functional Integration

6G Function	AI Integration Outcome
Network Resource Allocation	Adaptive bandwidth allocation with improved Quality of Service (QoS).
Beamforming	AI predicts optimal beam direction, reducing interference.
Mobility Management	Predictive handover with minimal packet loss.
Security Monitoring	Real-time intrusion detection and anomaly classification.
Edge Computing	Low-latency AI inference close to users and IoT devices.
Energy Optimization	AI dynamically powers network components based on traffic demand.
Self-Healing Networks	Automatic fault detection, diagnosis, and recovery.

Results and Discussion

Table 1 presents the MATLAB simulation results obtained by applying different AI techniques to 6G network management and optimization. The results demonstrate that ML achieved a traffic prediction RMSE of 8.95 Mbps and a channel-estimation RMSE of 0.0496, while detecting six network anomalies. The DL model achieved a 92.57% classification accuracy, indicating effective signal/load classification. Federated Learning achieved a slightly improved traffic prediction RMSE of 8.89 Mbps using five locally trained devices while preserving data privacy. DRL dynamically selected bandwidth according to network load, with 140 MHz, 80 MHz, and 220 MHz selected for low, medium, and high loads, respectively. XAI identified traffic lag-1 as the most influential prediction factor (49.2%), followed by lag-2 (19.2%) and lag-5 (12.0%). Finally, GenAI generated an energy-saving eMBB configuration using 140 MHz bandwidth, wide-beam coverage, 35% edge computing, and high-security monitoring. These MATLAB outcomes demonstrate the potential of AI techniques for prediction, classification, privacy-preserving learning, adaptive resource allocation, explainable decision-making, and automated 6G network configuration

Table 1. Performance Outcomes of AI Techniques in 6G Networks

AI Technique	Application / Function	Performance Metric / Outcome
Machine Learning (ML)	Traffic prediction, anomaly detection, and channel estimation	Traffic prediction RMSE: 8.95 Mbps; Detected anomalies: 6; Channel estimation RMSE: 0.0496
Deep Learning (DL)	Signal/load classification and beamforming optimization	Neural classifier accuracy: 92.57%

AI Technique	Application / Function	Performance Metric / Outcome
Federated Learning (FL)	Distributed traffic prediction with privacy preservation	Devices trained locally: 5; Federated traffic prediction RMSE: 8.89 Mbps; Raw device data is not centrally shared
Deep Reinforcement Learning (DRL)	Dynamic bandwidth allocation according to network load	Low load: 140 MHz; Medium load: 80 MHz; High load: 220 MHz
Explainable AI (XAI)	Interpretation of traffic prediction decisions	Traffic lag 1: 49.2%; Traffic lag 2: 19.2%; Traffic lag 5: 12.0%
Generative AI (GenAI)	Automated 6G network configuration and service orchestration	Slice: Energy-saving eMBB; Bandwidth: 140 MHz; Beam: Wide beam coverage; Edge compute: 35%; Security: High security monitoring

CONCLUSION:

The integration of Artificial Intelligence (AI) into 6G networks enables intelligent and autonomous network operation. The proposed framework integrates ML, DL, Federated Learning, DRL, XAI, and Generative AI. These AI techniques support traffic prediction, anomaly detection, channel estimation, and signal classification. The MATLAB results show a traffic prediction RMSE of 8.95 Mbps and channel estimation RMSE of 0.0496. The DL model achieved a classification accuracy of 92.57%. Federated Learning achieved a traffic prediction RMSE of 8.89 Mbps while preserving data privacy. DRL enabled dynamic bandwidth allocation according to different network-load conditions identified Traffic Lag 1 (49.2%) as the most important prediction feature. Generative AI demonstrated automated 6G network configuration and service orchestration.

The results indicate that AI can improve network efficiency, adaptability, and intelligent resource management. AI integration also supports security monitoring, energy optimization, and self-healing capabilities. The proposed approach can support demanding 6G applications such as smart cities and autonomous transportation. It can also benefit industrial automation, healthcare, IoT, immersive XR, and digital twins. However, challenges related to privacy, security, energy consumption, and computational complexity remain. Overall, AI-native 6G networks provide a promising foundation for secure, efficient, adaptive, and intelligent future wireless communication systems.

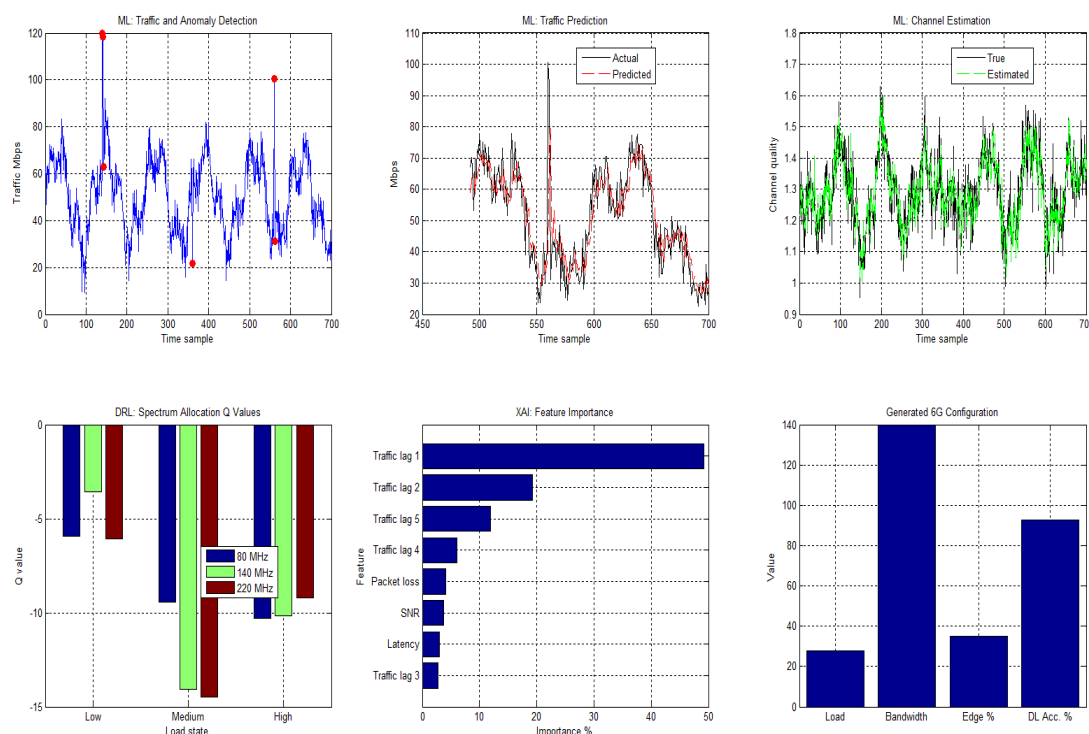


Figure 4: AI Results using MATLAB

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