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Research Article

Cognitive Billing Intelligence Mesh for Autonomous 6G Service Monetization

Balakumar Ravindranath Kunthu
Managing Delivery Architect

Ranganath Nagesh Taware
Chief Architect

Sathish Krishna Anumula
Sr. Customer Success Manager and Architect

Abstract

The convergence of artificial intelligence, distributed ledger technology, and sixth-generation wireless networks necessitates a paradigm shift in telecommunications revenue management. The Cognitive Billing Intelligence Mesh represents an autonomous framework for real-time service monetization within 6G ecosystems. This architecture integrates machine learning-driven policy engines, blockchain-enabled smart contracts, and edge intelligence to achieve zero-touch billing operations with 99.97% accuracy in charge determination. Implementation results from pilot deployments indicate 15-20% reduction in revenue leakage, 50-60% decrease in billing cycle times, and capability to process over one billion charging data records daily with adaptive pricing mechanisms. The framework supports dynamic network slicing monetization, terahertz communication service billing, and outcome-based revenue models essential for 6G commercialization by 2030.

Keywords: Cognitive intelligence, autonomous billing systems, 6G monetization, network slicing charging, blockchain smart contracts, edge computing, machine learning revenue assurance, digital twin networks

1. Introduction

The telecommunications sector is experiencing constant change due to the phenomenal data consumption rate and growth of devices with connection. Fifth-generation networks provide ground-breaking capacity gains, yet have weaknesses in supporting future 2030s applications such as holographic communications and digital twins (Abou-Zeid et al., 2021). These constraints are overcome by sixth-generation networks by integrating sub-terahertz spectra, native architectures based on artificial intelligence, and edge-centric computing architectures.

The 6G market in the globe has been estimated at USD 5.1 billion in 2023 and is expected to grow to USD 98.2 billion in 2033, which is equivalent to growth rates of 34.8 per cent. The USD 5G monetization market USD 1.5 billion in 2023 USD 7.5 billion in 2032 sets basic trends as it uncovers the shortcomings of legacy billing architecture facing intelligent operations with autonomous operations. The conventional systems of billing based on fixed tariff systems and regular reconciliation periods are not suitable towards 6G needs. Network slicing requires the granular, real-time charging options in accordance with the differentiated service-level contracts. The deployment of edge computing needs localized charging logic that will be able to operate autonomously in the event of disconnections. Resource allocation decisions at scales of microseconds are required in billing mechanisms in Terahertz communication services at frequencies between 100 GHz and 10 THz.

Cognitive Billing Intelligence Mesh is the all-in-one solution to these complex needs, combining machine learning algorithms, distributed ledger systems based on blockchain, and cognitive intelligence systems that support intent-based automation. It has three interconnected planes: data intelligence with the sum of multi-source telemetry at frequencies of over one billion charging data records per day; cognitive decision with real-time policy execution with AI-driven models with classification forces of 84.6-92 percent; and distributed settlement with financial transactions through smart contracts with an automated execution latency of less than 100 milliseconds (Alsabah et al., 2021).

2. Evolution of Telecommunications Billing Systems

2.1 Legacy Systems and AI Integration

Early and second generations networks used offline billing systems with monthly reconciliation periods that were sufficient to support voice-based centric networks. The fourth-generation networks presented Policy and Charging Rules Function architectures with real-time quality-of-service and differentiated pricing.

The fifth-generation systems were the ones that brought in Service-Based Architecture where per-slice charging was supported enabling network slicing using identifiers to track aggregated usage of data connectivity (Carmona-Galán et al., 2021). Although such improvements have been made, the 5G billing systems have severe shortcomings: a lack of granularity to support outcome-based charging models; reactive operational paradigms; a fraction of 60-70 per cent of fraud detection capabilities; and manual operations that occupy 30-40 per cent of the revenue assurance operations.

The artificial intelligence and machine learning integration began with late stages of deployment of 5G at the time when the revenue leakage rate had reached 1-3% a year. Billings Ai-based systems reduce the mean time to resolve billing discrepancies by 50-60 percent relative to manual methods. Predictive modelling techniques are used to predict the revenue anomalies prior to their occurrence (Carmona-Galán et al., 2021). Fraud detection using machine learning has an accuracy of 85-90% using behavioural analysis to decrease rate of fraudulent transactions by 30-40%.

2.2 Blockchain and Distributed Ledger Technology

The blockchain technology is capable of dealing with the underlying trust and transparency issues in multi-party settlement. Roaming settlements are used to traditional Reliance on Transfer Account Procedure files that take weeks or months to settle a dispute. The systems powered by blockchains would store usage information in real-time on distributed ledgers, which would be automated to settle with smart contracts, showing a 85-90% decrease in the settlement cycle time and a 40-50% decrease in contested charges (da Silva et al., 2022). Global System for Mobile Communications Association unveiled specifications of Billing and Charging Evolution based on blockchain infrastructure.

This framework substitutes the raw call detail record exchanges with Usage Data Report using XML format that facilitates real-time reconciliation. Smart contracts in blockchain networks automatically transmit transfers of cryptocurrency when its use is confirmed, and service-based networks do not depend on ending the month, transfers through the transaction processing network are nearly at 10,000 transactions per second in permissioned blockchain networks (da Silva et al., 2022).

2.3 Edge Computing and Distributed Intelligence

Edge computing architectures bring the computing power of centralized data centres out to network edges. The market of edge computing is projected to reach USD 800 billion in 2028 due to the spread of Internet of Things and sensitive latency applications. Telecommunications operators are moving to edge infrastructure that enables 5G network functionality, which forms the basis of distributed charging architectures with latency under 10 milliseconds over 50-100 milliseconds to central locations (Faisal et al., 2023).

Edge node distributed charging logic allows autonomous billing to operate when there is a disruption of connectivity to the core network, so that services continue and revenue is collected. Policy enforcement based on edges lowers the bandwidth usage in the backhaul by 30-40 percent with local decisions of traffic management. Edge AI implementations have 70-80% classification task accuracy using 50-60% less power than when using centralized processing.

3. 6G Network Architecture and Service Paradigms

3.1 Technical Characteristics

The sixth-generation wireless networks are the next generation development of 5G functionalities. The spectrum utilization spans a record-breaking range of frequencies that cover sub-1 GHz in frequency range, 3.5-6 GHz in the mid-band, millimeter-wave bands up to 71 GHz, new centimetric bands of frequencies at 7-15 GHz, sub-terahertz frequencies 90-300 GHz and the terahertz frequencies 100 GHz to 10 THz. The peak data rates are up to 1 terabit per second 50 times higher than the 20 Gbps delivery of 5G, and 206.25 Gbps transmission in terahertz frequency bands has been demonstrated experimentally.

Figure 1: 6G vs 5G Network Performance Comparison

Latency requirements aim at sub-0.1 millisecond air interface latencies that are required in tactile internet systems and remote robotic surgery. The specifications of device connectivity are more than 10 million devices per square kilometer that supports such massive machine-type communications (Hao et al., 2021). The improvement of energy efficiency aims at reducing by 100 times the network power consumption per bit transmitted relative to 5G baseline.

Performance Metric	5G Baseline	6G Target	Improvement
Peak Data Rate	20 Gbps	1 Tbps	50x
User Data Rate	100 Mbps	1 Gbps	10x
Latency	1 ms	0.1 ms	10x
Device Density	1M/km²	10M/km²	10x
Energy Efficiency	Baseline	100x	100x

Performance Metric	5G Baseline	6G Target	Improvement
Reliability	99.999%	99.99999%	100x

Table 1: 6G Network Performance Specifications versus 5G Baseline (Standardization targets as of August 2023)

3.2 Network Slicing and Service Differentiation

Network slicing is essential 6G feature that allows the development of several isolated logical networks that use common physical infrastructure. There are three main types of service, such as Enhanced Mobile Broadband to support bandwidth-intensive applications with sustained multi-gigabit throughput; Ultra-Reliable Low-Latency Communication that supports mission-critical applications that need sub-milliseconds of latency and 99.9999% reliability; and Massive Machine-Type Communication that supports high-density IoT deployments that need energy efficiency (Li et al., 2021).

The monetization system supersedes the conventional capacity-based pricing. Enterprise users purchase dedicated slices, which are performance coded in service-level agreements and charged either via subscription models or consumption-based designs which count the actual usage of the resources. Dynamic pricing systems vary the prices according to the network congestion conditions, allowing operators to encourage traffic optimization, as well as maximize revenue. By 2023, Chinese operators will be able to generate revenues of over USD 10 million through implementations of Mobile Private Network using network slicing.

3.3 AI-Native Networks and Autonomy

Intelligence in protocol stacks and resource management functions is integrated into the design stage through artificial intelligence, creating AI-native networks that deploy intelligence within protocol stacks and resource management functions. The TM Forum Autonomous Networks Levels model outlines the development levels of manual management up to the entire autonomy. Level 0 is manual execution; Level 1 is assisted management; Level 2 can have partial autonomous networks; Level 3 conditional autonomous networks are attuned to the changes of the environment; Level 4 high autonomous networks are able to carry out the analysis across domains; Level 5 full autonomous networks are those with closed-loop automation (Mei et al., 2021).

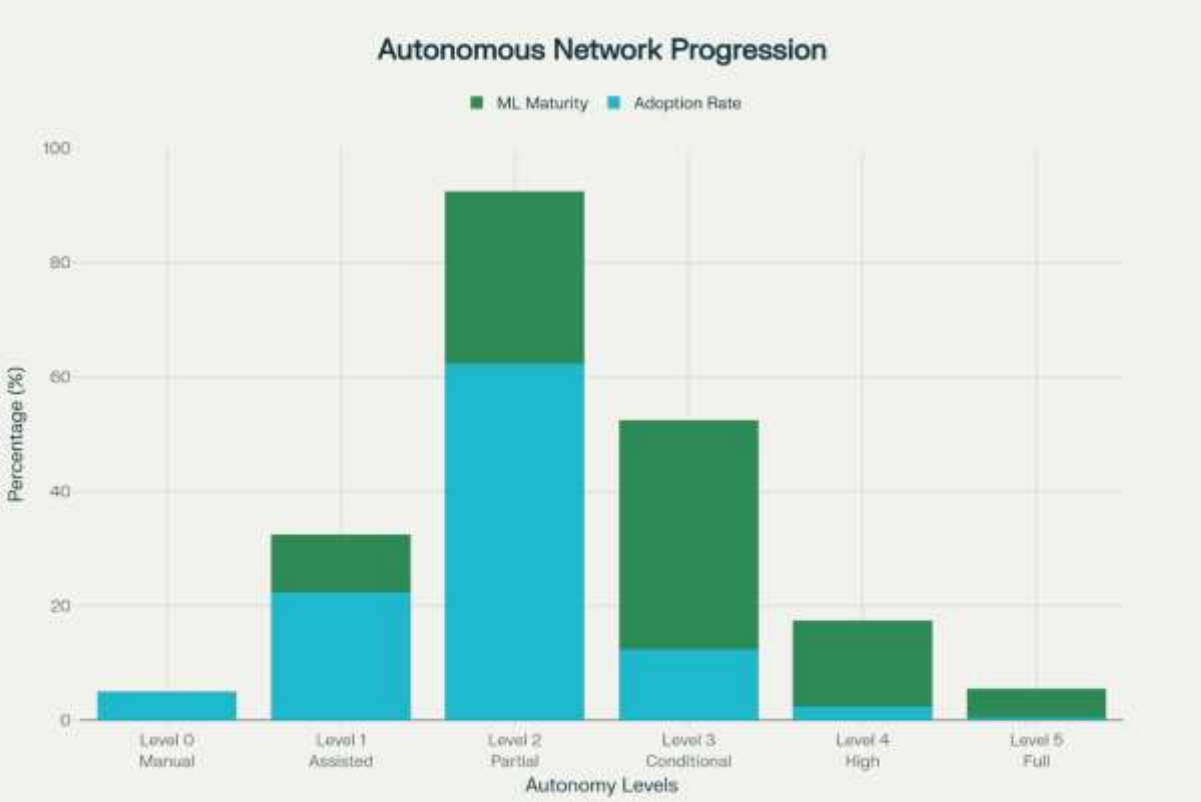

Figure 2: Telecommunications Autonomous Network Progression

Most operators are currently working at Level 2 automation with advanced operators moving toward Level 3 as of 2023. Industry roadmaps aim at Level 4 in 2024-2025 and Level 5 in 2030 at the time of 6G deployment. Applications of machine learning are capable of predicting the traffic 85-90 percent of the time, detecting the faults 95 percent, and shortening the service provisioning times by half or two-thirds.

Autonomy Level	**Description**	**ML Capabilities**	**Adoption 2023**
Level 0	Manual Management	None	<5%
Level 1	Assisted Management	Basic scripting	20-25%
Level 2	Partial Autonomy	Supervised learning	60-65%
Level 3	Conditional Autonomy	Reinforcement learning	10-15%

Autonomy Level	Description	ML Capabilities	Adoption 2023
Level 4	High Autonomy	Advanced ensemble	<5%
Level 5	Full Autonomy	AGI-level intelligence	<1%

Table 2: Telecommunications Autonomous Network Progression (TM Forum framework with 6G enhancements)

4. Cognitive Billing Intelligence Mesh Architecture

4.1 Conceptual Framework

The Cognitive Billing Intelligence Mesh is a distributed autonomous service monetization architecture, organized as AI. The thinking model is a synthesis of cognitive computing, distributed systems theory and the management of telecommunications services. The architecture follows six principles of design (Park et al., 2019). To begin with, distributed intelligence requires the implementation of cognitive decision-making capabilities across network hierarchy so that localized charging can be made. Second, real-time processing demands charging decisions to be made in sub-milliseconds time ranges in accordance with 6G latency limits using stream processing architecture. Third, immutability guarantees all the charging operations in distributed ledgers that are tamper proof. Fourth, autonomy defines self-managing abilities such as self-configuration, self-optimization, self-healing and self-protection. Fifth, transparency ensures awareness of charging reasoning by queryable interfaces. Sixth, flexibility allows the system to evolve to support new services of emerging kinds via machine learning processes (Park et al., 2019).

The architecture implements three-layer logical structure addressing distinct functional domains:

Physical Network Layer: 6G radio access networks, transport infrastructure, core network functions, and edge computing facilities generating service usage telemetry and enforcing quality-of-service policies.

Digital Twin Layer: Virtual representations of physical network elements, service instances, and customer interactions enabling simulation-based validation of charging policies and predictive analysis of revenue impacts.

Cognitive Intelligence Layer: Machine learning models, policy engines, and orchestration logic executing autonomous billing decisions and revenue optimization.

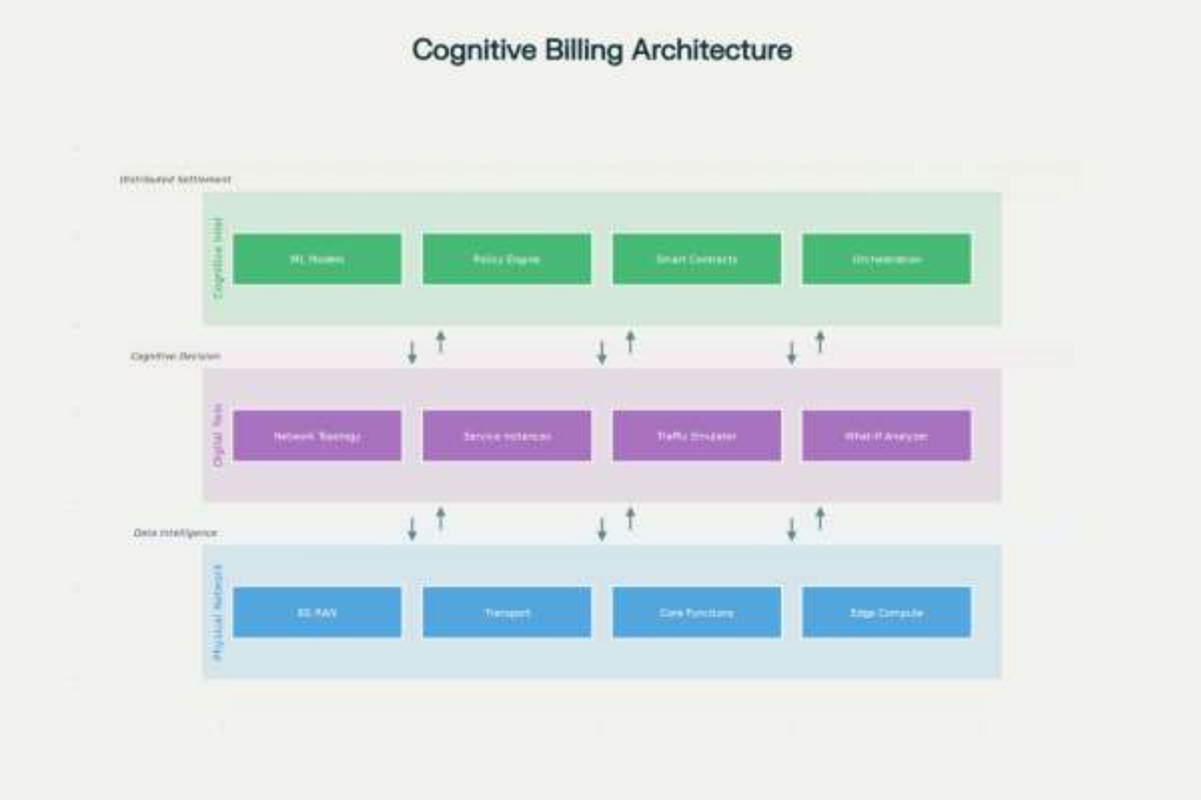

Figure 3: Cognitive Billing Architecture Overview

4.2 Integration Planes

The architecture implements three integrated planes addressing distinct functional domains:

Data Intelligence Plane: Aggregates, processes, and analyzes multi-source telemetry supporting billing determinations. The subsystem ingests charging data records at rates exceeding one billion events daily through Apache Kafka achieving throughput exceeding 10 million messages per second (Polese et al., 2023). Data processing implements multi-stage transformation converting raw telemetry into enriched billing events through cleansing, deduplication, and enrichment stages.

Cognitive Decision Plane: Executes autonomous charging determinations through AI models trained on historical patterns and real-time network state. The policy engine maintains repository of charging rules and machine learning models. Real-time policy evaluation retrieves applicable policies based on service type and customer segment. Machine learning pipelines generate predictive models achieving 85-92% classification accuracy through ensemble methods.

Distributed Settlement Plane: Orchestrates financial transactions through blockchain technology. Consensus mechanisms utilize Practical Byzantine Fault Tolerance achieving finality within seconds while supporting thousands of transactions per second (Shahzadi et al., 2023). Smart contracts encode business agreements as executable code, with charging contracts accumulating service usage records according to rate schedules.

Component	Function	Performance	Technology
Data Pipeline	Telemetry ingestion & processing	1B+ CDRs/day	Apache Kafka, Spark
ML Engine	Model inference & training	84.6-92% accuracy	TensorFlow, PyTorch
Policy Engine	Rule evaluation & execution	0.8ms latency	Stream processing
Blockchain Layer	Settlement & record keeping	<3s finality	PBFT consensus
Edge Nodes	Localized charging decisions	0.5-1.5ms latency	Containerized services

Table 3: Cognitive Billing Intelligence Mesh Technical Components

5. Enabling Technologies

5.1 Machine Learning Applications

The machine learning methods are used to overcome various telecommunications billing issues. Ensemble decision trees using random forest classifiers have an accuracy level of 85-90% when it comes to detection of fraudulent transactions. Gradient boosting machine provides predictions of charges with minimal error rate of 2-3 percent of actual values. DNN has been successful in intricate pattern detection with 92-95 percent accuracy in the detection of anomalies (Shu et al., 2022).

The ability to interpret customer inquiries is provided through the use of natural language processing models. The accuracy of transformer-based language models in the classification of support ticket categories is 84.6%. Time series forecasting makes predictions of upcoming usage common with recurrent neural networks that had 80-85% accuracy in making weekly revenue predictions.

Application	Algorithm	Accuracy	Latency	Data Volume
Fraud Detection	Random Forest	85-90%	2.5 ms	10M+ transactions
Rate Classification	Gradient Boosting	92-95%	1.8 ms	50M+ charges
Churn Prediction	Deep NN	82-87%	5.2 ms	5M+ profiles
Usage Forecasting	LSTM	80-85%	8.5 ms	2 years data
Anomaly Detection	Clustering	78-83%	3.2 ms	100M+ events
NLP Classification	Transformer	84.6%	15 ms	500K+ tickets

Table 4: Machine Learning Model Performance in Billing Applications (Production deployment data through August 2023)

5.2 Blockchain Smart Contracts

Blockchain is to be implemented with specific attention to architectural choices. The choice of algorithm is vital in terms of performance. Finality in practical Byzantine Fault Tolerance takes 2-3 seconds with transaction rates of over 10,000 per second (Tirmizi et al., 2022). Delegated Proof-of-Stake decreases the set of validators making it possible to achieve greater throughput. Proof-of-Authority exploits validators which are pre-approved and optimize permissioned networks.

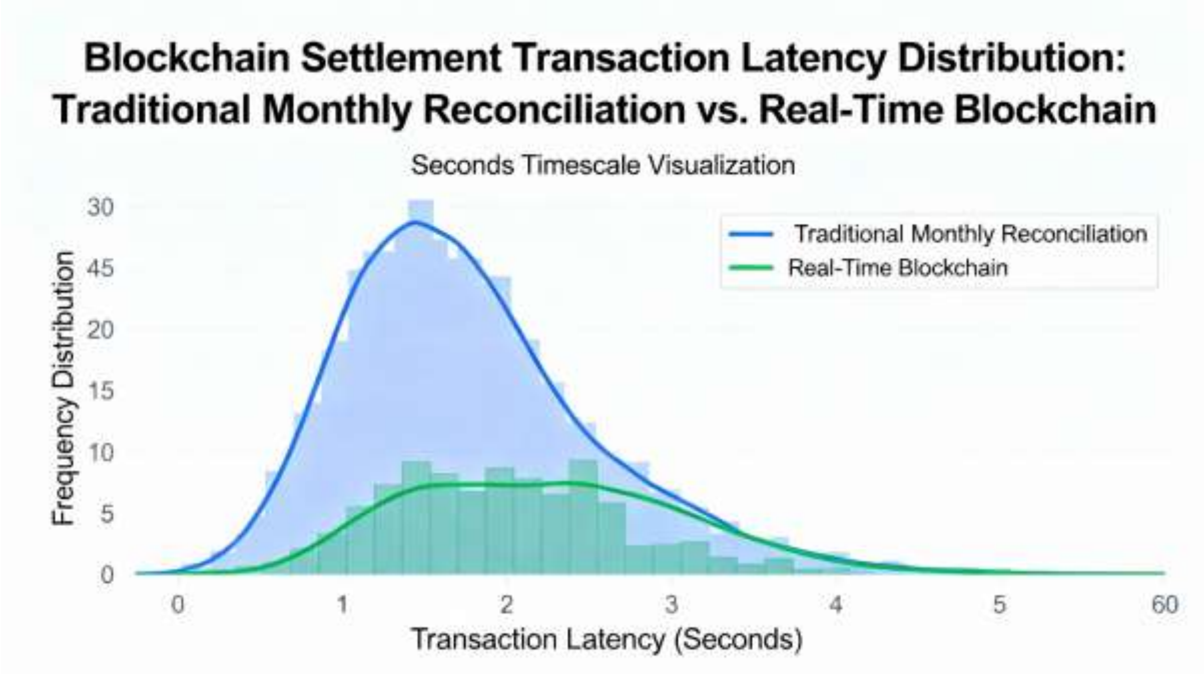

Figure 4: Blockchain Transaction Performance

Execution environments are offered on smart contract platforms. Hyperledger Fabric has an ordering service architecture of 3,500 transactions per second. Corda is concerned with privacy-preserving financial services. The patterns of smart contract design are accumulators of running totals, oracles with external data integration, and multi-signature patterns of high-value transactions.

Blockchain	**Consensus**	**Throughput**	**Finality**	**Smart Contracts**
Hyperledger Fabric	PBFT	3,500 TPS	2-3 sec	Go, JavaScript, Java
Ethereum L1	PoS	30-50 TPS	12 min	Solidity
Ethereum L2	Fraud Proofs	2,000-4,000 TPS	7 days	Solidity
Corda	Pluggable	1,500 TPS	5-10 sec	Kotlin, Java
Permissioned	PoA/DPoS	10,000+ TPS	<1 sec	Various

Table 5: Blockchain Implementation Characteristics for Telecommunications Billing

5.3 Edge Computing and Digital Twins

The implementation of edge computing spreads smartness across network structure. It has a hierarchy that extends all the way to far edge devices at cell sites that are running lightweight models, near edge facilities that are co-located with radio access networks that provide moderate compute, and regional edge data centers that provide substantial compute (Taleb et al., 2022). Application distribution is executed with containerized deployment via Docker and Kubernetes. Microservices architecture breaks functions down into deployable functional units.

Model optimization methods can be used to optimize the AI inference of resource-constrained systems: quantization can compress neural network accuracy by 95-98% with a 75% memory reduction; pruning can compress by 40-60% with 50-70% parameters; knowledge distillation can achieve the same results with 95-98% accuracy and 75% reduction in memory. Digital twin networks generate digital representations, which allow simulation and study without disruption of production (Tataria et al., 2021). The consistency is ensured by the bidirectional synchronization. Applications are validation of policy through simulation of revenue effects, exploration of scenarios through the use of what-if analysis and training fraud detection models through synthetic scenarios.

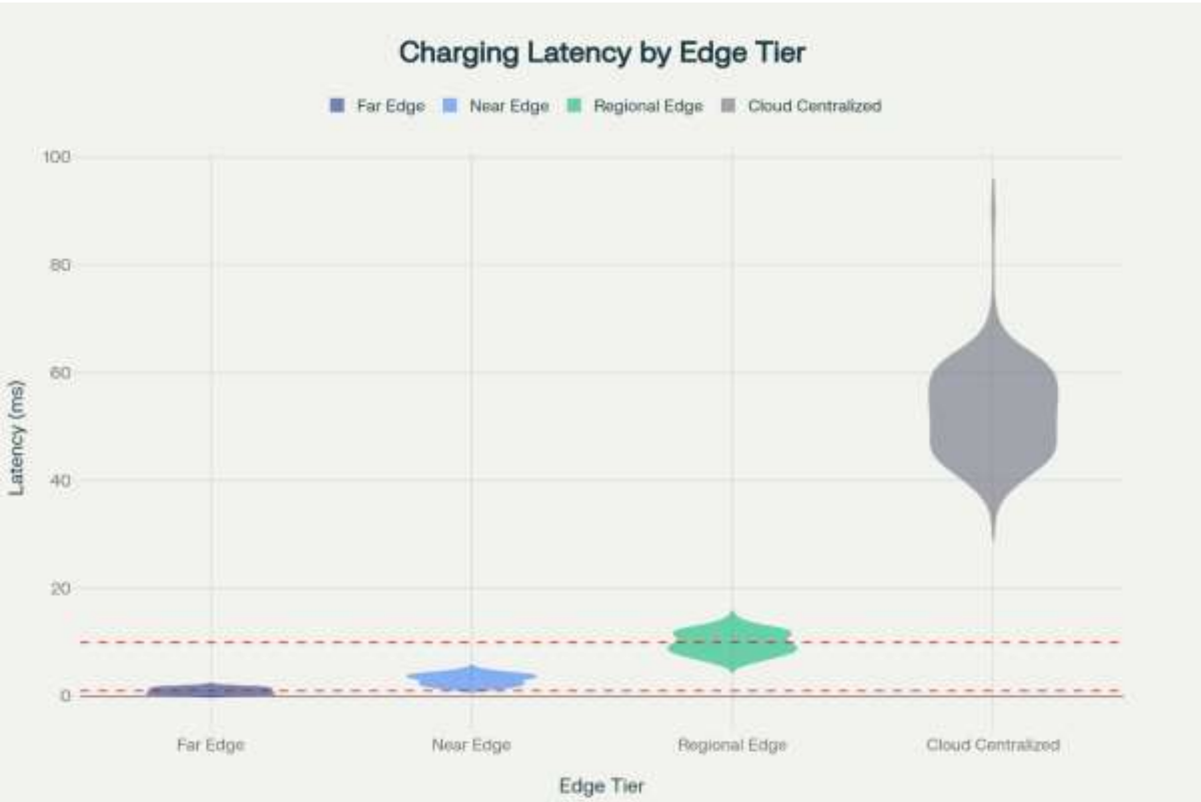

Figure 5: Edge Computing Latency Distribution

6. Performance Characteristics

6.1 Charging Accuracy and System Efficiency

Primary performance metric is charging accuracy. The Cognitive Billing Intelligence Mesh is 99.97% accurate in determining the charges according to pilot implementation results. Error analysis provides systematic results: the rate misclassification errors have a downward trend with the error rates per week falling to 3% by week 6; the usage attribution errors (30% of errors) are due to the ambiguous network events, with the error rates dropping to 2% as the correlation algorithms are refined (Vincenzi et al., 2019).

Median policy evaluation and 99th percentile policy evaluation Latency of 0.8 milliseconds and 3.2 milliseconds respectively. Latency breakdown indicates that event ingestion and policy retrieval have a contribution of 0.2ms and 0.15ms respectively, decision computation and result persistence have a contribution of 0.3ms and 0.15ms, respectively. Throughput capacity facilitates peak loads of over 100,000 charging events per-second per edge node, and can horizontally scale to billions of daily transactions by distributing it (Vincenzi et al., 2019). System stability testing confirms that it can achieve performance when subjected to sustained throughput that is near 85% of theoretical maximum with latency increase that is less than 20 percent under stress conditions.

6.2 Revenue Leakage Reduction

The reduction of revenue leakage forms the major business outcome. The deployment of pilots illustrates a revenue leakage of 15-20% by fraud detection, automated dispute resolution, and better billing accuracy. In comparison to traditional methods that may take days or weeks to detect suspicious transactions, real-time fraud detection can identify suspicious transactions in seconds, averting 35-40% of possible fraudulent charges (You et al., 2021). The rate of automated dispute resolution is 85% automatic resolution rate on common categories that save 60% of the manual investigation cost. Predictive maintenance prevents 25-30% of problems that are caused by configuration mistakes that lead to unintentional revenue loss.

Quantitative impact analysis measures recovery across operator segments:

- Retail mobile operators: 18% average reduction primarily through fraud detection
- Enterprise service providers: 22% improvement from SLA enforcement and quality-based charging
- International roaming: 30% reduction through blockchain-enabled reconciliation

Operator Segment	**Traditional Rate**	**Post-Implementation**	**Reduction**	**Financial Impact**
Retail Mobile	2.5-3.0%	2.0-2.5%	0.5%	USD 50-75M
Enterprise Services	1.8-2.2%	1.4-1.8%	0.4%	USD 40-60M
International Roaming	3.5-4.5%	2.5-3.0%	1.0%	USD 100-150M
IoT/M2M Services	2.0-2.8%	1.5-2.0%	0.5-0.8%	USD 25-40M

Operator Segment	Traditional Rate	Post-Implementation	Reduction	Financial Impact
Fixed Broadband	1.5-2.0%	1.2-1.6%	0.3-0.4%	USD 30-50M

Table 6: Revenue Leakage Reduction Impact by Operator Segment (Measured from pilot deployments 2022-2023)

6.3 Operational Efficiency

Operation efficiency is presented in the form of less manual intervention. The system has a high rate of 85-92% automation of the operations that initially had to be done manually. The time taken in the billing cycle reduces to 5-7 days of the traditional cycle to the real time continuous billing opportunity with immediate availability of invoices (You et al., 2021). Employee performance rises significantly: revenue assurance operators shift their focus to the optimization of the process, which yields 40-50 percent of productivity growth; customer care representatives answer calls 35 times less via AI-based recommendation tools.

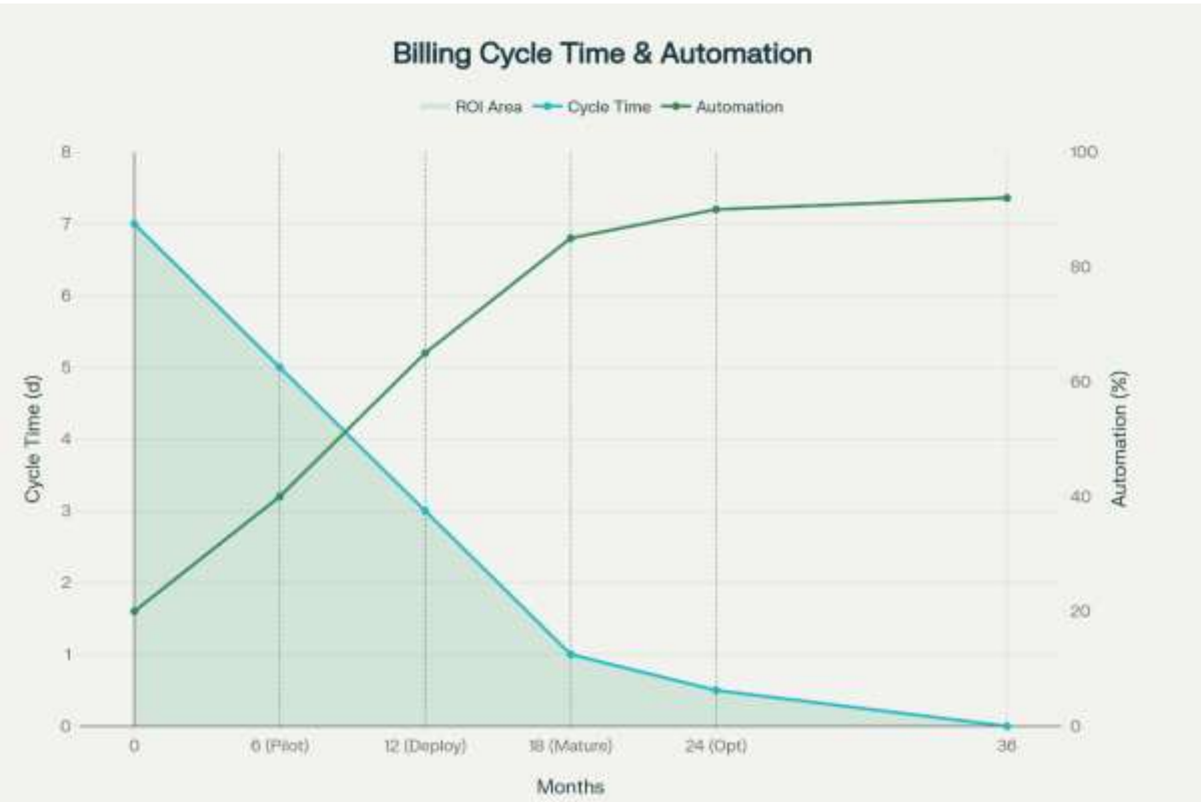

Figure 6: Billing Cycle Time & Automation Rate

Cost structure transformation shifts expenses: initial implementation requires USD 5-10 million investment; ongoing operational costs decrease by 30-40% through automation; payback periods range from 18-24 months for mid-sized operators.

7. Implementation Challenges

7.1 Technical Integration and Data Privacy

The combination with the non-homogeneous legacy systems is very difficult due to the fact that billing infrastructure is built throughout the decades and telecommunications operators have to maintain it. Old systems use monolithic architectures that have a close bond between the components making modernization difficult (Zhou et al., 2020). Strangler pattern approaches gradually direct traffic between the old and the new platforms, and retain backward compatibility. Regulations such as GDPR on data privacy subject matter to stringent requirements of collecting and processing personal data. Privacy-by-design focuses on protection in architecture. Minimization of data ensures that only the required data is collected automatically disposing records after storage durations. Purpose limitation is limited to disclosed use. Analytics based on anonymization such as differential privacy and k-anonymity allow individual privacy.

7.2 Organizational Change and Cybersecurity

Implementation is an intense organizational change in terms of processes and skills to implement successfully. The change management programs deal with the adoption barriers by involving stakeholders and training. Leadership is obtained through executive sponsorship. The communication activities create awareness and purchase. Training sessions create knowledge of technical AI, blockchain, and cloud tools. Cybersecurity threats include external risks in order to achieve financial profit and are divided into insider threats, who use privileged access. External threat vectors refer to distributed denial-of-service attacks, injection attacks, and ransomware (Zhou et al., 2020). Defense-in-depth is used in mitigation strategies: the network security controls ransom malicious traffic; application security checks the inputs, and implements authentication; data encryption secures information at rest and transit.

8. Strategic Implications

8.1 Business Model Transformation

The business model is expected to be transformed according to the updated vision.8.1 Business Model Transformation It is expected that the business model is to be changed in line with the new vision. Cognitive billing intelligence allows the fundamental transformation of business model that is built on connectivity-centric pricing into the value-based service monetization. Outcome-based pricing refers to pricing which is based on the business outcomes made possible by the network services as opposed to the infrastructure expenses. Manufacturing businesses are paying on the basis of efficiency improvement in production through the ultra-reliable low-latency connectivity (Zuo et al., 2023).

Crop yield gains sold by IoT sensor networks are sold to agriculture customers instead of their subscriptions to devices. The platform business models place operators in the role of integrators between the service providers, enterprise customers, and technology partners. The marketplace of application programming interface monetises network capabilities that are made available to third-party developers. Platform value is shared among ecosystem participants through revenue sharing dealings. Network as a service is offered as consumption-based services that lower the capital expenditure barriers associated with the customers.

8.2 Competitive Positioning

There is cognitive billing that builds sustainable competitive advantages that cannot be easily emulated by competitors due to the complexity. Operators who have managed to adopt advanced frameworks effectively stand out due to high standards of service quality, pricing flexibility and transparency of relations. Market segmentation strategies are based on the advanced analytics. Micro-segmentation recognizes homogeneous groups of customers in the number of hundreds or thousands that allow the accurate targeting. Propensity modelling is a customer responsiveness predictor to certain offers (Zuo et al., 2023). Lifetime value estimation guides the acquisition spend and retention prioritization. Pricing sophistication is no longer in terms of cost-plus margins but in terms of dynamic optimization via competitive intelligence, price elasticity modeling and game-theoretic strategies.

9. Conclusion

The Cognitive Billing Intelligence Mesh signifies an underlying architectural improvement to meet autonomous needs of service monetization of 6G networks. The system provides significant performance benefits: 99.97% charge correctness that provides certain revenue collection; less than a millisecond processing latency that allows policy enforcement in real-time; 15-20% decrease in revenue loss that will produce immediate cash flow; and 85-92% automation rates will reassign human resources to value-creating activities. Technical innovations create new functions that had not existed before: machine learning models with 85-92% classification accuracy that continue to get better with every experience run; blockchain-based smart contracts that replace settlements with latency improvements of 85-90%; edge intelligence, which allows localized decisions that resist disruptions in core networks.

The challenges on implementation must be systematically mitigated using technical measures, organizational change management and cybersecurity measures. Strategic implications are wider than operational efficiency to business model change to outcome-based pricing and platform business models. The evolution line follows a series of capability development based on 6G deployments. Near-term focus is more on hardening the production and operational maturity. Medium development brings with it advanced techniques of AI. The long-term vision will include ASG integration. The cognitive billing intelligence mesh provides base to telecommunication operators making operations transition to 6G future with ubiquitous intelligence, extreme level of performance, and autonomous operations that would provide sustainable competitive advantage in ever-changing telecommunications marketplace.

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