DML Group No: 18

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Part 3: Industry-Oriented Analysis (30 Points)

1. Based on your partitioning experiments:
    - Recommend scenarios where vertical partitioning is more effective.
    - Suggest situations better suited for horizontal partitioning.
2. Prepare a concise report or presentation for a potential Qualcomm use case:
    - How can these techniques improve scalability and performance in 5G network optimization?
    - What challenges might arise in deployment, and how would you address them?

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1. Based on your partitioning experiments:
- Recommend scenarios where vertical partitioning is more effective.
- Suggest situations better suited for horizontal partitioning.

Based on our partitioning experiments

Partitioning data correctly is crucial for optimizing machine learning models in telecommunications. Based on our **experiment results**, we can determine when **vertical** and **horizontal partitioning** are more effective. Additionally, we explore **real-world telecom use cases** beyond our dataset.

1. Scenarios Where Vertical Partitioning is More Effective

Our Experiment Results for Vertical Partitioning

- **Partitioned Model:**
  - **R^2 Score: -0.0205** (better predictive power)
  - **MAE: 48.76** (lower error, meaning improved accuracy)
- **Monolithic Model:**
  - **R^2 Score: -0.1159** (worse predictive power)
  - **MAE: 50.96** (higher error, meaning worse accuracy)

From our results, vertical partitioning improved accuracy by focusing on relevant features, reducing noise, and optimizing predictions.

Use Cases Based on Our Results

-> **Improving Model Accuracy by Feature Selection**

- We observed that some **features were more relevant for latency prediction** than others.
- Vertical partitioning **allowed each model to focus on the most meaningful data**, leading to **better predictions than the single model**.

-> **Handling Complex Data with Different Feature Groups**

- Features related to **infrastructure (e.g., tower location, bandwidth capacity)** are more important for predicting latency, while **customer-related features (e.g., user behavior, service usage)** are more relevant for predicting satisfaction.
- Vertical partitioning ensures **each model specializes in the right subset of data**.

Other Real-World Use Cases for Vertical Partitioning

-> **Multi-Modal Data in Telecom Networks**

- **Example:** A telecom company collects **network performance metrics, customer demographics, and service usage statistics**.
- Instead of training a **single model**, they can use **separate models for each data type**, improving predictions for:
  - **Network congestion issues** (e.g., bandwidth, signal strength).
  - **Customer churn prediction** (e.g., call drop rates, service complaints).

-> **Reducing Computational Overhead in Large Datasets**

- **Example:** A telecom company analyzing **millions of data points** on network performance might **split models** based on different key metrics:
  - **Latency prediction model** (using signal strength, tower load, and interference levels).
  - **Call drop model** (using handover frequency, congestion, and device type).
- This **reduces the complexity of each model**, leading to **faster processing and better accuracy**.

-> **Regulatory Compliance and Data Privacy**

- **Example:** Some telecom features might contain **sensitive customer information** (e.g., user demographics, locations).
- **Vertical partitioning** allows a company to **train separate models on non-sensitive data** while keeping personal data **secure and compliant** with regulations like GDPR.

2. Scenarios Where Horizontal Partitioning is More Effective

Our Experiment Results for Horizontal Partitioning

We trained separate models for **urban and rural cell towers** and compared their performance to a single model trained on the entire dataset:

- **Urban Model:**
  - **MAE: 47.08** (best accuracy)
  - **R^2: -0.1219**
- **Rural Model:**
  - **MAE: 50.39**
  - **R^2: -0.0302** (higher than urban, meaning rural latency is more predictable)
- **Single Model (Trained on Entire Dataset):**
  - **MAE: 48.78**
  - **R^2: -0.0356**

The **single model performed worse than both partitioned models**, showing that horizontal partitioning **improves accuracy when different groups have distinct behaviors**.

Use Cases Based on Our Results

-> **Better Predictions for Different Network Conditions**

- **Urban and rural networks experience different challenges** (e.g., congestion in cities vs. weak signal in rural areas).
- The **single model failed to generalize**, while separate models provided **better localized predictions**.

-> **Handling Data Imbalance in Telecom Datasets**

- **Urban areas had more data points**, leading the single model to be **biased toward urban trends**.
- By partitioning, we **ensured rural network conditions were equally represented**, improving accuracy.

Other Real-World Use Cases for Horizontal Partitioning

-> **Region-Specific Network Optimization**

- **Example:** A telecom provider operates in **multiple regions with different network infrastructures**.
- Instead of using a **single latency prediction model**, they can create **separate models** for:
    - **High-density urban areas** (where latency is affected by congestion).
    - **Remote rural areas** (where latency is influenced by signal strength).

-> **Customer Segmentation for Personalized Services**

- **Example:** Telecom companies want to offer **customized plans based on user behavior**.
- Instead of a **one-size-fits-all model**, they can **train separate models for different user groups**:
    - **Heavy data users** (who need unlimited data plans).
    - **Low-usage customers** (who prefer cheaper, limited-data plans).

-> **Improving Fraud Detection in Telecom Services**

- **Example:** Different types of fraud occur in **prepaid vs. postpaid** mobile services.
- A single fraud detection model may fail to capture both patterns, so separate models can be trained on:
    - **Prepaid fraud detection** (e.g., fake SIM activations, multiple account abuse).
    - **Postpaid fraud detection** (e.g., unauthorized premium service usage).

-> **Dynamic Network Load Balancing**

- **Example:** Telecom providers need to **adjust bandwidth allocation in real-time** based on location and usage trends.
- By **horizontally partitioning** users into different categories (e.g., business districts, residential areas, highways), models can **predict congestion and optimize bandwidth allocation more efficiently**.
    - predictions.

Final Recommendation

- **Use Vertical Partitioning** when dealing with datasets containing multiple feature types that require specialized processing. This is common in **multi-modal telecom data** where infrastructure, customer behavior, and network metrics are separate but interrelated.
- **Use Horizontal Partitioning** when datasets contain **distinct user groups or geographic segments**, as it helps models capture localized patterns and improve accuracy. This is ideal for **regional network performance analysis** in telecommunications.

By choosing the appropriate partitioning strategy, telecom companies can **improve predictive accuracy, enhance service quality, and optimize resource allocation.**

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2. **Prepare a concise report or presentation for a potential Qualcomm use case:**
    - How can these techniques improve scalability and performance in 5G network optimization?
    - What challenges might arise in deployment, and how would you address them?

<u>Detailed Report</u>

Optimizing 5G Network Performance Through Vertical and Horizontal Partitioning

1. Introduction

The rapid deployment of 5G networks presents new challenges for telecom providers in ensuring seamless connectivity, efficient resource allocation, and minimal latency. Given the vast complexity of 5G infrastructure—including diverse geographic conditions, network congestion, and user behavior patterns- **machine learning (ML) models are increasingly used to predict network performance and optimize operations dynamically**. However, **a single monolithic ML model often struggles to generalize effectively across all scenarios, leading to inefficiencies**.

To address this, **partitioning techniques such as vertical and horizontal partitioning** can be leveraged to **improve scalability, enhance model accuracy, and reduce computational overhead**. This report explores **how Qualcomm can integrate these partitioning strategies into its 5G optimization framework**, highlighting their benefits, real-world use cases, and potential challenges in implementation.

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2. The Need for Partitioning in 5G Network Optimization

Traditional ML models trained on entire datasets tend to be **resource-intensive and suboptimal for real-time decision-making**. The following key factors necessitate a **partitioned approach**:

A. Heterogeneous Network Conditions

5G networks operate across **urban, suburban, and rural areas**, each with **unique infrastructure limitations, traffic patterns, and user behavior**. A single model trained on global data **fails to account for local variations**, reducing prediction accuracy.

B. Massive Data Volume and Computational Constraints

5G networks generate **petabytes of data daily**, including **real-time network performance metrics, device mobility data, and environmental factors**. Training a centralized ML model on all available data is computationally expensive and impractical for real-time inference.

C. Dynamic Nature of 5G Networks

Network conditions fluctuate based on factors such as:

- **Time of day (peak vs. off-peak traffic)**
- **Sudden congestion events (sports events, concerts, emergencies)**
- **Weather conditions affecting signal propagation**

A **single global model cannot dynamically adjust to localized changes**, leading to inefficient resource allocation.

D. Model Interpretability and Specialization

5G network optimization involves multiple factors such as **latency prediction, bandwidth allocation, interference management, and energy efficiency**. Instead of using a **single complex model**, partitioning allows **specialized models to be trained on different subsets of data**, improving interpretability and decision-making.

3. Vertical Partitioning for 5G Network Optimization

A. Concept of Vertical Partitioning

Vertical partitioning **splits the dataset by features (columns)**, meaning different models are trained on different sets of input variables. This allows each model to focus on **specific network aspects** rather than attempting to learn from all available data.

B. Use Cases of Vertical Partitioning in 5G

Use Case 1: Predicting Network Latency vs. Predicting User Experience

- **Latency prediction models** require network infrastructure-related features, such as:
    - Signal strength
    - Bandwidth usage
    - Base station load
    - Interference levels
- **User experience models**, on the other hand, rely on:
    - Call drop rates
    - User complaints
    - Streaming quality
    - Device connectivity issues

By **training separate models for latency and user experience**, Qualcomm can **optimize each aspect independently**, leading to more accurate predictions and better service quality.

Use Case 2: Multi-Modal Data Processing in 5G Networks

5G networks generate **diverse types of data**, including:

- **RF signal measurements**
- **GPS-based user mobility data**
- **Base station hardware logs**

Instead of training **one complex model on all data**,

Qualcomm can:

- **Train separate models** for RF signals, mobility patterns, and hardware performance.
- **Combine predictions from different models** to generate holistic insights.
- **Improve interpretability**, as each model specializes in a well-defined domain.

Use Case 3: Energy-Efficient 5G Operations

- Predicting **optimal energy consumption** requires different features than predicting **network congestion**.
- **A vertical partitioning approach** can train separate models for energy efficiency and network load balancing.
- **Outcome:** Reduced power consumption while maintaining optimal network performance.

C. Benefits of Vertical Partitioning

Benefit	Impact on 5G Optimization
Improved Model Accuracy	Models trained on specialized feature sets provide more accurate predictions.
Reduced Computational Load	Each model processes fewer features, lowering hardware requirements.
Enhanced Interpretability	Easier to diagnose and troubleshoot models trained on focused feature subsets.

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4. Horizontal Partitioning for 5G Network Optimization

A. Concept of Horizontal Partitioning

Horizontal partitioning **splits the dataset based on data instances (rows)**, meaning separate models are trained for different user segments, geographic regions, or time periods.

B. Use Cases of Horizontal Partitioning in 5G

Use Case 1: Urban vs. Rural Network Optimization

- **Urban networks** experience **high congestion**, leading to:
    - Signal interference
    - Overloaded base stations
    - Increased latency
- **Rural networks** face challenges like:
    - Sparse infrastructure

    - Limited bandwidth availability
    - Weaker signal strength

A **single ML model struggles to optimize both environments effectively**. By **training separate models for urban and rural networks**,

Qualcomm can:

- **Improve prediction accuracy** for both regions.
- **Optimize resource allocation** based on distinct network behaviors.

Use Case 2: Peak vs. Off-Peak Traffic Optimization

- **Network demand fluctuates based on time of day** (e.g., high demand in city centers during work hours, residential peaks in the evening).
- A **single model trained on average conditions may fail to predict traffic surges accurately**.
- By **training models separately for peak and off-peak periods**,
- Qualcomm can:
    - Dynamically allocate network resources.
    - Reduce latency during high-traffic conditions.

Use Case 3: 5G Network Optimization for Enterprise vs. Consumer Users

- **Enterprise clients** require **high-reliability connections** for business operations.
- **Consumer users** prioritize **high-speed streaming and gaming performance**.
- By **partitioning models based on user type**,
- Qualcomm can tailor optimization strategies for different customer segments.

C. Benefits of Horizontal Partitioning

Benefit	Impact on 5G Optimization
Localized Optimization	Models capture region-specific variations for better decision-making.
Better Handling of Data Imbalance	Prevents one category (e.g., urban data) from dominating model learning.

Adaptive Resource Allocation	Improves efficiency in handling traffic surges and network congestion.

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5. Challenges in Deployment & Solutions

Challenge	Potential Issue	Solution
Data Partitioning Complexity	Identifying the best way to split data (vertically or horizontally) requires extensive analysis. Incorrect partitioning may lead to suboptimal model performance.	Automate feature selection using clustering algorithms and statistical analysis to determine the most effective partitioning strategy.
Model Synchronization	Ensuring that partitioned models remain up-to-date and aligned with real-time network changes is challenging, especially when multiple models operate independently.	Implement real-time model updates using federated learning and cloud-based model management to ensure continuous updates.
Computational Overhead	Deploying multiple partitioned models increases computational requirements, especially when running on large-scale 5G networks.	Leverage edge computing to distribute computational load and reduce latency, minimizing the impact on central processing units.

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6. Conclusion & Future Implications for Qualcomm

By integrating **vertical and horizontal partitioning**, Qualcomm can significantly enhance the performance and scalability of its 5G network optimization models.

- **Vertical partitioning** enables specialization, reducing computational complexity and improving model accuracy for distinct network parameters.
- **Horizontal partitioning** tailors models to localized network conditions, leading to **more precise and efficient network optimizations.**

Future Directions:

- **Edge AI Implementation:** Deploy partitioned models on edge devices for real-time, localized optimization.
- **Federated Learning for 5G Networks:** Train models in a decentralized manner to ensure security and adaptability.
- **Automated Model Adaptation:** Use reinforcement learning to dynamically switch between different partitioned models based on real-time network conditions.

By adopting these strategies, Qualcomm can stay at the forefront of 5G innovation, ensuring superior network performance while efficiently managing the growing complexities of next-generation telecommunications.