Predictive Beam Management in 5G mmWave using NMS-Hosted AI with Smart Contract-Based Policy Enforcement

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ABSTRACT

Millimeter-wave 5G networks rely on directional beamforming to overcome severe path loss and maintain reliable high-data-rate communication. Managing beams reliably is a challenge. This is because mobility, blockages and rapid changes in channels can often misalign beams and degrade links in dense deployments [1], [2]. Conventional methods for beam sweeping and measurement help keep connectivity, but they create a signaling overhead and don't scale well as beam codebooks and deployment density increase [3]. This paper presents a framework for beam management driven by Network Management Systems (NMS). It uses Simu5G to create traces that are then sent to an external NMS. These traces are refined using AI to predict beams. The proposed architecture relies on a quantized graph neural network for predicting the top K beams. This approach does not require changes to the existing RAN control system.

To address concerns of trust, policy compliance, and multi-stakeholder interoperability, a blockchain-based smart contract layer is introduced as a non-real-time governance mechanism. Rather than participating in latency-critical beam selection, the smart contract selectively validates and enforces policy constraints on a subset of AI-generated decisions, ensuring auditability and secure control without impacting real-time performance.

In a stadium scenario, with 7 gNBs, 500 UEs, 64-beam codebooks and 28 GHz operation, this framework aims to reduce beam failures, CSI-RS overhead and boost spectral efficiency compared to regular sweeping.

Keywords: 5G, beam management, Simu5G, network management system, smart contracts, artificial intelligence. Blockchain, Radio Access Network, decentralized RAN automation, Key Performance Indicators, Configuration Management, Graph Neural Network, Radio Intelligent Controller, INET Framework, OMNeT++.

I. INTRODUCTION

The rapid increase of 5G New Radio in the Frequency Range 2 (millimeter-wave spectrum) has created a means for using high data rates and a high-capacity environment; however, the ability to meet these capabilities is directly dependent on accurately and reliably achieving beam alignment between the gNB (base station) and the UE (user equipment) in the event of movement and blockage conditions [1], [2].

In practical deployments, it is not uncommon for beam misalignment and delayed beam recovery to have a negative impact on the user experience, particularly in challenging environments, such as a stadium, dense urban corridors, and transportation hubs [1], [3].

Conventional 5G beam management relies on periodic beam sweeping, measuring, reporting, and refining procedures to identify suitable transmit and receive beam directions [3]. Even though conventional beam management procedures are effective, the exhaustive or semi-exhaustive nature of these methods will result in an excessive amount of control overhead and increased time delays for decision making as a function of the number of beams, the number of users utilizing the beams, and the varying and continually changing characteristics of the environment.

Artificial Intelligence (AI) has the potential to provide a viable alternative for predictive beam management by utilizing historic SINR (signal-to-interference plus noise ratio) patterns, mobility and motion context, and spatial correlation to create future beam selections [3], [5]. However, many of the existing (AI-based) methods are tightly integrated with either RAN (radio access network) native or RIC (Radio Intelligent Controller)-based control loops, thereby limiting their usability in brownfield deployments, and reducing their ability for external OSS (operations support system) and/or NMS (network management system)-based automation.

To overcome these limitations, this paper proposes a new architecture powered by NMS which externalizes intelligence from the RAN to NMS. The NMS receives the simulation data generated through Simu5G, which it processes and refines using an AI Model to generate Top-K recommendations for beam development. These top-K recommendations will be executed during the fast decision loop and will be validated through an additional layer of Smart Contract to enforce non-real-time policy enforcement and validate the decisions from the RAN with several goals: *ensuring level of consistency across

ISBN: 978-81-689089-0-1

beams; *providing an auditable system; and *enabling cross vendor trust).

The key contributions of this work include the following:

1) Developed a NMS-centric orchestration architecture for beam management using RAN data derived from simulations that is independent of the traditional tightly coupled RAN control loops;
2) Developed an AI based refinement engine to provide Top-K predictions for beam development, which reduces search complexity and minimizes the overall signaling overhead;
3) Developed policy aware Smart Contracts that validate beam decision-making (not in real time), thereby providing an auditable and consistent mechanism for implementing beam decisions across multi-vendor environments;
4) Conducted comprehensive evaluations that demonstrate improvements in spectral efficiency, signaling overhead and beam reliability levels with respect to conventional beam sweeping and conventional AI prediction based methods.

II. RELATED WORK

Beam management has been widely studied in mmWave and 5G-Advanced systems because directional links are highly sensitive to mobility, blockage, and fast channel variation [2], [3]. Operational studies have shown that practical beam management can experience notable failure behaviour in real deployments, reinforcing the need for more predictive and adaptive methods [1].

AI and ML methods have been explored for predictive beam selection, beam recovery, and beamforming optimization, including approaches that use historical measurements, spatial context, and learned correlations across users and beams [5]. These methods reduce dependence on exhaustive sweeping, but they are often embedded inside centralized control frameworks or assume direct integration with the RAN [5].

Blockchain and smart contracts have also been explored for decentralized control, verification, and trusted execution in telecom and distributed systems [6]. Yet their application to beam management remains relatively limited compared with use cases such as slicing or spectrum coordination, which gives this work a useful novelty point at the intersection of AI prediction, NMS orchestration, and decentralized enforcement..

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

The considered network consists of a set of gNBs and a set of user equipment operating in a mmWave environment with a finite beam codebook per gNB. At each decision interval, the serving gNB selects one beam for each UE based on measured or inferred channel quality, where the objective is to maintain high SINR and minimize beam failure events.

The beam selection objective can be expressed as choosing the beam that maximizes link quality for a given user and serving cell under interference and noise constraints. In conventional search-based beam management, the decision complexity grows with the size of the beam codebook because many candidate beams must be examined repeatedly.

B. Problem Statement

In millimeter wave 5G networks managing beams is required to keep the link reliable. This is because the signals are highly directional and can be easily blocked or disrupted by movement. The usual ways of managing beams such as scanning all beams regularly create a lot of overhead for the network and do not work well with large numbers of beams especially in busy and changing environments like stadiums.

At the time using artificial intelligence to predict which beams to use has shown promise but it is hard to make it work in real-world networks that already exist [3]. This is because it is complicated to integrate and it is hard to trust that it will work correctly with equipment from vendors and operators. Specifically there is no way to make sure that decisions made by external systems are reliable can be reviewed and follow the networks rules.

Therefore, the key problem is to make beam management more efficient and responsive while also making sure that any new system, for making decisions can be trusted verified and used within the existing network infrastructure.

C. Proposed Decision Model

Instead of searching the full beam set at every cycle, the proposed system predicts a top-K candidate subset from recent Simu5G-derived measurements such as SINR vectors, UE position, and mobility context. The blockchain layer then validates the candidate action through a consensus rule before the NMS pushes the selected beam configuration toward the network side.

IV. PROPOSED ARCHITECTURE

The proposed architecture consists of four logical components: data generation from a simulation, ingestion of that data into an NMS, prediction of candidate beams with AI, and validation of those beams against policies through a smart contract, indicated in figure 1 below.

ISBN: 978-81-689089-0-1

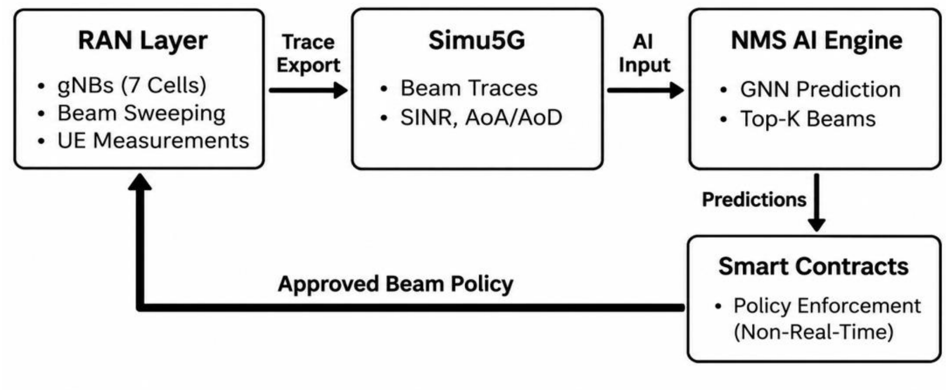

Fig. 1. NMS-driven AI Architecture with Policy-Enforced Smart Contract Layer.

Simu5G produces outputs that are both beam-level vectors (e.g., SINR) and scalars (e.g., beam indices, mobility context), which are exported through files. These files are used in a downstream process.

When the NMS receives these outputs periodically, it uses an external orchestration layer called "Data Pipeline" to ingest them and process them via a series of filtering, feature construction, and aggregation steps to create input features for an AI model. The AI model is implemented as a quantized Graph Neural Network (GNN) and outputs a reduced top-k set of candidate beams for each UE in a fast decision loop with minimal search complexity and control overhead.

After completing inference, the NMS will forward selected subsets of AI-generated decisions to the Smart Contract Layer through an oracle interface. The Smart Contract Layer will not be involved in real-time beam selection but will validate each of the AI generated beam selections against predefined policies (e.g., confidence threshold, stability constraint, and beam configuration) based on non-real-time processing, as indicated in figure 2 and 3 below

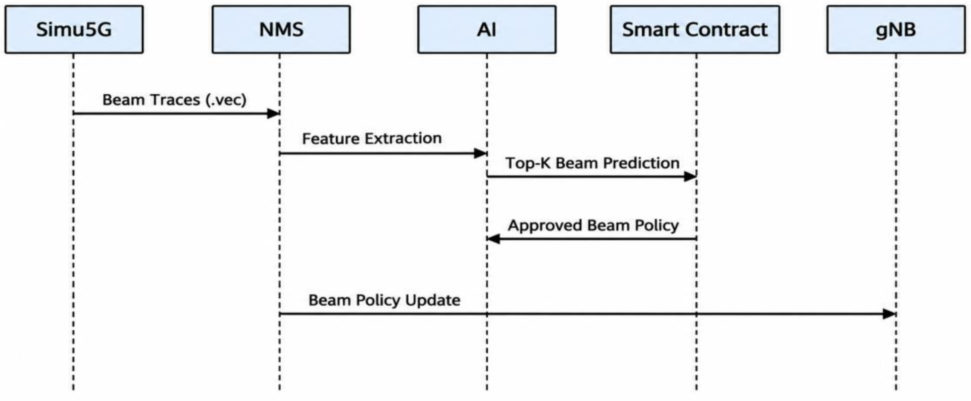

Fig. 2. Sequence flow showing periodic policy enforcement of AI generated beam decisio

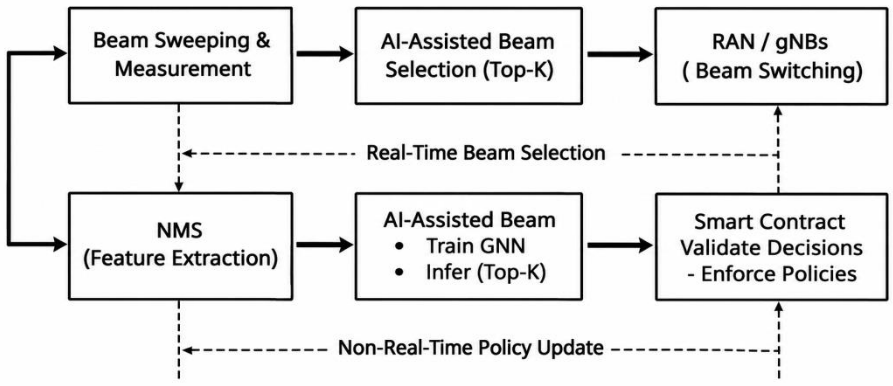

Fig. 3. Two-Stage Beam Management Process.

ISBN: 978-81-689089-0-1

Immutable recording allows validated decisions to be auditable and trusted across different domains, but real-time beam selection will still be based on the AI model in the NMS pipeline. Separating fast decisions and slow policy enforcement facilitates the practical deployment of low-latency operation while adding a verifiable governance layer.

V. SIMULATION SETUP AND METHODOLOGY

The evaluation scenario uses Simu5G with OMNeT++ and INET Framework, modeling a stadium-like deployment with 7 gNBs arranged in a hexagonal layout and 500 mobile UEs distributed over a 500 m × 200 m area. The system operates in the FR2 band at 28 GHz with 400 MHz bandwidth, numerology 3, hybrid beamforming, and 64 beams per panel, enabling realistic evaluation of highly directional beam dynamics.

UEs follow a random waypoint mobility model with speeds between 0.5 m/s and 2 m/s, while the channel is configured using a 3GPP urban model with blockage effects. The simulation runs for 300 seconds, during which beam-level metrics such as SINR, beam indices, and mobility context are logged and exported for external processing.

An external NMS periodically ingests these simulation outputs to construct feature vectors, including SINR history, beam usage patterns, and UE mobility attributes. These features are used by an AI model based on a graph neural network (GNN) to predict a reduced Top-K set of candidate beams for each UE, thereby limiting the search space and reducing control overhead.

Key metrics reflect the relationship between AI output and system performance. The predicted top K beams produce a smaller number of candidate beams that must be evaluated by the system, reducing the CSI-RS signaling overhead. The final beam determined from this reduced candidate set directly influences link quality and subsequently leads to increased spectral efficiency. Confidence scores associated with AI-derived predictions are filtered through policy rules to eliminate unreliable decisions and reduce the occurrence of beam failures by improving overall reliability.

The smart contract layer operates as a non-real-time policy enforcement and validation mechanism. Instead of participating in latency-critical beam selection, it selectively validates a subset of AI-generated decisions based on predefined rules such as confidence thresholds and policy constraints, and records approved actions to ensure auditability and cross-domain trust.

Three approaches are evaluated: (i) conventional exhaustive beam sweeping, (ii) AI-only prediction using the Top-K beam selection strategy, and (iii) the proposed hybrid framework combining AI-based prediction with smart contract-based policy enforcement. Performance is assessed using key performance indicators including spectral efficiency, CSI-RS overhead, and beam failure rate, reflecting improvements in efficiency, control signaling reduction, and reliability.

VI. RESULTS AND DISCUSSION

The results from the evaluation of the proposed framework demonstrate that it has achieved the best normalized spectral efficiency compared to the three other approaches (conventional sweeping, AI only prediction). In comparison to both conventional sweeping and AI only predictions, the proposed framework illustrates that utilizing AI driven beam prediction and policy aware validation increases the consistency of the outcome of each selection thereby converting the quality of the prediction to a more consistent outcomes.

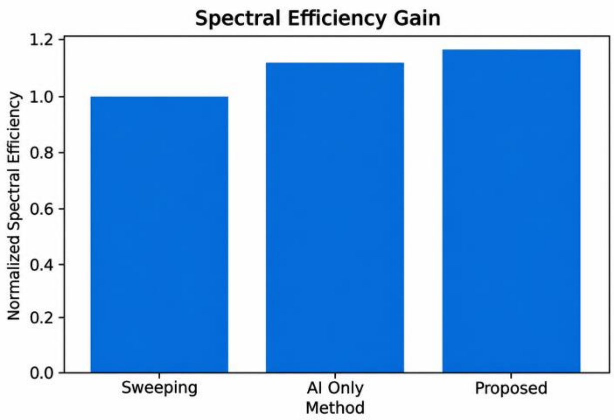

Fig. 4. Normalized spectral efficiency comparison for sweeping, AI-only, and the proposed method.

As shown in Figure 4, normalized spectral efficiency comparisons for conventional sweeping methods, AI only method, and the proposed hybrid method (AI Prediction Guided with Policy Aware Validation) reveal that AI based Top-K prediction has increased the efficiency of the selected beam by eliminating unnecessary exploration. Additionally, the additional validation layer provides a stable and more consistent execution of each selection due to the increased stability of the selection process.

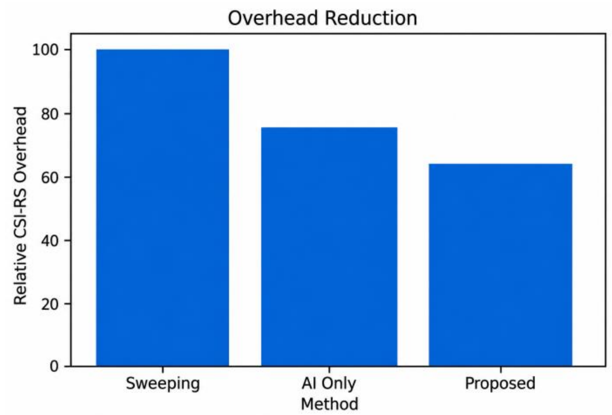

Fig. 5. Relative CSI-RS overhead for the evaluated beam management methods.

CSI-RS Overhead / Signaling Overhead for the proposed framework, illustrated in Figure 5, indicates that the proposed framework has significantly reduced the

ISBN: 978-81-689089-0-1

signaling overhead versus the periodically swept selection method and also marginally reduced the overhead as compared to the AI based Top-K prediction. As such, this is consistent with the design objective to terminate all exhaustive beam searches by utilizing a prediction guided candidate selection for the purpose of reducing the control signaling (overhead).

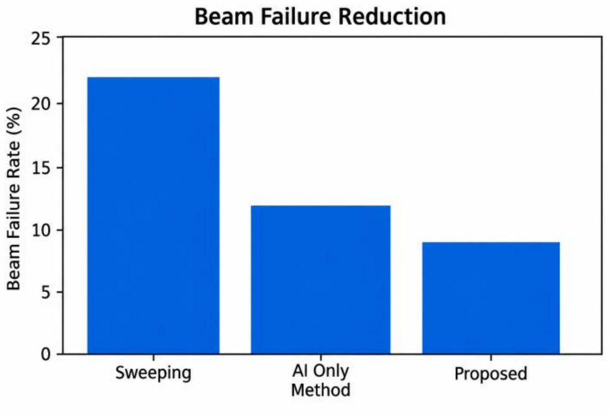

Fig. 6. Beam failure rate comparison across sweeping, AI-only, and proposed decentralized control.

Figure 6 presents the beam failure rate for each of the evaluated beam selection methods. The proposed framework demonstrates the lowest beam failure rate of all methods examined, and therefore, benefits the user with improved link reliability, which is critical in mmWave environments where mobility and blockage will frequently interrupt beam alignment.

In addition, although the pure-AI predictions had less search complexity than an AI-over-Assisted-Prediction from one set of data for a given individual, the predictions were no better than random chance at providing consistent decisions on dynamic conditions. Furthermore, the addition of smart contract layer dramatically increases the reliability of AI-based decision making by establishing policy rules (e.g., thresholds for levels of confidence and stability) and selectively validating the AI's decision output. Furthermore, validation of AI's decision output is completed outside of the high latency portion of the control loop to ensure that real-time beam actions are not inhibited.

In terms of actual implementation, these results indicate that the overall system architecture maintains balanced performance with appropriate amounts of trust. In other words, the AI inference operates quickly to make real-time decisions while the smart contract layer is used as a governance mechanism – allowing for auditing and coordination across multiple distributed entities without introducing a significant increase in latencies.

VII. WHY NMS-DRIVEN DECENTRALIZATION INSTEAD OF RIC-CENTRIC CONTROL

RIC-centric designs are valuable in O-RAN settings, but they generally assume a control ecosystem that may not exist in brownfield or mixed-vendor deployments. They also tend to keep intelligence closely coupled with the RAN control plane, which can complicate deployment for external OSS or NMS vendors seeking RAN-agnostic optimization.

The proposed NMS-driven design works outside the RAN ecosystem by pulling only the required data, refining it with AI, and using smart contracts for trusted execution. This makes the approach attractive for network operators and OSS vendors that want verifiable automation without redesigning the RAN stack.

VIII. CONCLUSION

This paper introduces an NMS-driven framework that implements predictive beam management for 5G mmWave networks. The framework uses simulation-based data as input and implement AI-assisted beam prediction with policy-aware smart contract validation. The framework was evaluated in a realistic stadium mobility environment using Simu5G where it demonstrated improved spectral efficiency, lower signaling overhead, and fewer beam failures than either conventional sweeping or baseline AI-prediction methods.

A major architectural contribution of this research is to decouple the real-time intelligence layers of the NMS (network management system) from the governance layers of NMS. The AI layer, hosted within the NMS, is able to generate fast beam predictions with an efficient reduced Top-K search space to support rapid scalable decision-making. In contrast, the smart contract layer provides non-real-time enforcement and validation of policies, selectively checking AI-derived decisions for compliance, consistency, and auditability without introducing latency into time-sensitive operations.

This hybrid approach creates a practical solution for building trusted and scalable RAN optimization capabilities in environments with multiple stakeholders. By merging data-based intelligent decision-making with decentralized policy measurement, the proposed framework provides a sound basis for autonomous, verifiable network-control systems which will be critical components of 5G-Advanced and future 6G-enabled networks [5], [6].

IX. FUTURE WORK

Future work can extend the proposed framework by introducing continuous learning and faster adaptation to meet the dynamic conditions. The AI engine can be powered by reinforcement learning, and federated learning to improve the scalability.

The smart contract based policy enforcement can improve with the context and situation introduction. The smart contact performance is another area that can be improved. Additionally incorporating multi-cell coordination and interference-aware beam management in dense deployments can improve the performance.

ISBN: 978-81-689089-0-1

ACKNOWLEDGEMENT

We would like to thank the esteemed faculty of Gautam Buddha University for providing the valuable guidance that significantly enhanced our work. We also extend our gratitude to Aircom International Pvt. Ltd. for their encouragement and support.

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Cite this article as:

Ranjan, Anurag and et.al. "Predictive Beam Management in 5G mmWave using NMS-Hosted AI with Smart Contract-Based Policy Enforcement", Proceedings of 13th international conference on Microelectronics, Circuits and Systems, Micro2026 (Vol-II)

Displayed as online on 21st August 2026.

Link: http://actsoft.org/science/micro2026-pro/342-micro2026.pdf

ISBN: 978-81-689089-0-1