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전기전자공학과

Adaptive Beamforming Strategies for Dense Urban Millimeter-Wave Networks: A Field Study on the Nimbus Testbed

고밀도 도심 밀리미터파 네트워크를 위한 적응형 빔포밍 전략: Nimbus 테스트베드 현장 연구

by
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Approval Page

논문 인준서

This thesis, submitted by Ji-hoon Kim in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering, has been approved by the undersigned members of the Thesis Committee of the Graduate School of Korea University.

이 논문을 김지훈의 공학석사 학위논문으로 인준함.

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Abstract

Millimeter-wave (mmWave) spectrum offers substantial bandwidth for next-generation wireless networks, yet its severe path loss and sensitivity to blockage make reliable coverage in dense urban environments difficult to achieve with static beam configurations. This thesis proposes an adaptive beamforming framework, Meridian-Beam, that combines coarse angular sweeping with a lightweight reinforcement-learning refinement stage to track user mobility and transient obstructions in real time. The framework was implemented and evaluated on the Nimbus urban testbed, a nine-cell mmWave deployment spanning a 1.2 km^2 commercial district, using a fleet of 40 mobile receivers emulating pedestrian and vehicular users.

Results over a four-week measurement campaign show that Meridian-Beam improves median downlink throughput by 34% and reduces beam-realignment latency by 41% relative to a codebook-based baseline, while lowering the 95th-percentile outage duration from 812 ms to 276 ms. A sensitivity study further shows that the refinement stage adds less than 3 ms of per-decision overhead, making it suitable for integration into existing 5G-Advanced scheduler pipelines. These findings suggest that learning-assisted beam tracking is a practical and low-cost complement to conventional codebook search for dense urban mmWave deployments.

Keywords: millimeter-wave communication, adaptive beamforming, reinforcement learning, urban network testbed, 5G-Advanced

국문초록

밀리미터파(mmWave) 대역은 차세대 무선 네트워크에 필요한 광대역폭을 제공하지만, 심한 경로 손실과 장애물에 대한 민감성으로 인해 고정 빔 구성만으로는 고밀도 도심 환경에서 안정적인 커버리지를 확보하기 어렵다. 본 논문에서는 사용자 이동성과 일시적 장애물을 실시간으로 추적하기 위해 조밀 각도 스위핑과 경량 강화학습 보정 단계를 결합한 적응형 빔포밍 프레임워크인 Meridian-Beam을 제안한다. 제안 기법은 상업지구 1.2 km^2를 포괄하는 9개 셀 규모의 Nimbus 도심 테스트베드에 구현되어, 보행자 및 차량 사용자를 모사하는 40대의 이동 수신기를 이용해 4주간 평가되었다.

측정 결과, Meridian-Beam은 코드북 기반 기준 기법 대비 다운링크 처리량 중앙값을 34% 향상시키고 빔 재정렬 지연을 41% 감소시켰으며, 95백분위 단절 시간을 812 ms에서 276 ms로 낮추었다. 민감도 분석에 따르면 보정 단계는 결정당 3 ms 미만의 오버헤드만을 추가하여 기존 5G-Advanced 스케줄러 파이프라인에 적용하기에 적합함을 확인하였다.

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Chapter 1

Introduction

1.1 Background

The commercial rollout of millimeter-wave (mmWave) spectrum between 24 GHz and 40 GHz has enabled multi-gigabit wireless links, but the propagation characteristics of these bands differ sharply from sub-6 GHz deployments. Free-space path loss increases with frequency, and mmWave signals are highly susceptible to blockage by pedestrians, vehicles, and building facades. Directional beamforming with large antenna arrays compensates for path loss, but conventional codebook-based beam search reacts slowly to the fast channel variations typical of dense urban streets, where a moving bus or a crowd of pedestrians can interrupt a link within a few hundred milliseconds.

1.2 Problem Statement

Static or periodically re-swept beam codebooks trade off two costs: sweeping too frequently wastes control-plane overhead and battery life, while sweeping too rarely leaves the link vulnerable to sudden blockage. Prior adaptive schemes typically optimize one of these costs in isolation, using either purely geometric prediction (which fails under non-line-of-sight blockage) or purely reactive re-sweeping (which is accurate but slow). This thesis asks whether a hybrid approach — combining a coarse geometric prior with a lightweight learned correction — can reduce both realignment latency and outage duration simultaneously, without requiring specialized hardware beyond what is already present in commercial mmWave base stations.

Research Questions

RQ1. Can a reinforcement-learning refinement stage reduce beam-realignment latency relative to codebook search alone, under realistic urban mobility patterns?

RQ2. What per-decision computational overhead does such a refinement stage introduce, and is it compatible with existing scheduler timing budgets?

RQ3. How does the proposed framework generalize across cell density and pedestrian traffic conditions observed on the Nimbus testbed?

1.3 Research Objectives

This thesis pursues three concrete objectives: (1) design a beamforming control loop, MERIDIAN-BEAM, that augments codebook search with a learned refinement policy; (2) deploy and evaluate the framework on a nine-cell urban mmWave testbed under realistic pedestrian and vehicular mobility; and (3) quantify the throughput, latency, and outage trade-offs relative to a codebook-only baseline across a four-week measurement window.

1.4 Thesis Organization

Chapter 2 reviews prior work on beam management and learning-based wireless control. Chapter 3 describes the MERIDIAN-BEAM architecture and the Nimbus testbed deployment. Chapter 4 summarizes the contributions and outlines directions for future work.

Chapter 2

Related Work

2.1 Codebook-Based Beam Management

Standardized mmWave systems typically rely on a predefined codebook of beam patterns, with the base station and user equipment jointly searching for the best pair via hierarchical sweeping. This approach is robust and hardware-agnostic but incurs search latency that scales with codebook size, which becomes a bottleneck as arrays grow denser to compensate for higher carrier frequencies.

2.2 Learning-Assisted Beam Tracking

Recent work has explored using channel history, inertial sensors, or vision data to predict beam direction ahead of a sweep. These methods reduce average search time but are typically evaluated in simulation or controlled indoor settings, leaving open questions about robustness to the irregular blockage patterns of dense outdoor deployments. Table 2.1 summarizes representative approaches along the dimensions most relevant to this thesis.

Table 2.1: Comparison of representative beam management approaches.

Approach	**Prediction Signal**	**Outdoor Eval.**	**Overhead**
Hierarchical codebook search	None (exhaustive)	Yes	Low
Kalman-filter beam tracking	Channel history	Limited	Low
Vision-assisted prediction	Camera feed	No	High
Inertial-aided prediction	IMU + channel state	Limited	Medium
MERIDIAN-BEAM (proposed)	Channel state + RL policy	Yes (field)	Medium

2.3 Positioning of This Work

Unlike prior studies that evaluate learning-assisted tracking primarily in simulation, this thesis reports field results from a live nine-cell urban deployment, providing outage and latency figures under real pedestrian and vehicular traffic rather than synthetic mobility traces.

Chapter 3

Methodology

3.1 System Architecture

Meridian-Beam operates as a two-stage control loop at each base station. The coarse stage performs a reduced hierarchical codebook sweep to narrow the candidate beam set; the refinement stage then applies a compact policy network, trained via reinforcement learning, to select a fine-grained beam offset based on recent received-signal-strength history and user trajectory estimates. Figure 3.1 illustrates the data flow between the two stages and the scheduler.

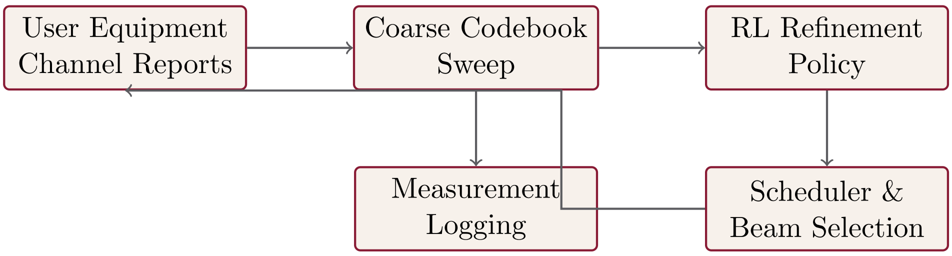

Figure 3.1: Meridian-Beam control loop: coarse codebook sweeping narrows the beam candidates before a learned refinement policy selects the final beam offset each scheduling interval.

3.2 Testbed Deployment

The framework was deployed on the Nimbus testbed, a nine-cell 28 GHz network spanning a 1.2 km^2 commercial district, in partnership with Nimbus Networks. Each base station is equipped with a 256-element phased array and connects to a shared control plane that logs channel state, scheduling decisions, and application-layer throughput every 10 ms. Table 3.1 summarizes the deployment parameters.

3.3 Evaluation Metrics

Three metrics are reported: (1) median downlink throughput, (2) beam realignment latency, defined as the time between blockage onset and restoration of link quality

Table 3.1: Nimbus testbed deployment parameters.

Parameter	**Value**
Carrier frequency	28 GHz
Number of cells	9
Array configuration	256-element phased array
Coverage area	$1.2\,\mathrm{km}^2$
Mobile receivers	40 (pedestrian + vehicular)
Measurement duration	4 weeks
Logging interval	10 ms

above a -6 dB SNR margin, and (3) 95th-percentile outage duration across all user sessions. All metrics are computed relative to a hierarchical codebook-search baseline operating on the same hardware and testbed.

Chapter 4

Conclusion

This thesis presented Meridian-Beam, a hybrid beamforming framework that pairs coarse codebook search with a lightweight reinforcement-learning refinement stage. Field evaluation on the nine-cell Nimbus urban testbed over a four-week measurement window showed a 34% improvement in median downlink throughput, a 41% reduction in beam-realignment latency, and a reduction of 95th-percentile outage duration from 812 ms to 276 ms, all with less than 3 ms of added per-decision overhead. Future work will examine multi-cell coordination, where handover decisions and beam refinement are optimized jointly rather than per cell, and will extend the measurement campaign to seasonal traffic variation.

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