CoBF: Coordinated Beamforming in Dense mmWave Networks

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ABSTRACT

With MIMO and enhanced beamforming features, IEEE 802.11ay is poised to create the next generation of mmWave WLANs that can provide over 100 Gbps data rate. However, beamforming between densely deployed APs and clients incurs unacceptable overhead. On the other hand, the absence of up-to-date beamforming information restricts the diversity gains available through MIMO and multi-users, reducing the overall network capacity. This paper presents a novel approach of "coordinated beamforming" (called CoBF) where only a small subset of APs are selected for beamforming in the 802.11ay mmWave WLANs. Based on the concept of uncertainty, CoBF predicts the APs whose beamforming information is likely outdated and needs updating. The proposed approach complements existing per-link beamforming solutions and extends their effectiveness from link-level to network-level. Furthermore, CoBF leverages the AP uncertainty to create MU-MIMO groups through interference-aware scheduling in 802.11ay WLANs. With extensive experimentation and simulations, we show that CoBF can significantly reduce beamforming overhead and improve network capacity for 802.11ay WLANs.

CCS CONCEPTS

• **Networks** → **Network experimentation**; **Wireless local area networks**; • **Hardware** → **Beamforming**.

KEYWORDS

mmWave; Beamforming; WLAN

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1 INTRODUCTION

Building upon the current 802.11ad standard [2], the IEEE 802.11ay [3] refines the PHY and MAC specifications to enable the next generation of 60 GHz millimeter-wave (mmWave) WLANs. With the newly introduced support for multiple-input multiple-output (MIMO) and flexible channelization, 802.11ay can provide up to 100 Gbps of data rate. Such high data rates will make it possible to support hundreds of densely deployed devices in WLANs and their bandwidth-hungry applications, such as immersive volumetric video streaming, augmented and virtual reality (AR/VR), robotic manufacturing, etc.

Scaling the WLAN infrastructure to hundreds of IoT and edge computing devices will require the dense deployment of access points (APs) in future mmWave WLANs. However, dense deployment of APs and clients in mmWave 802.11ay WLANs poses a critical challenge where the beamforming (BF) between a large number of clients and APs incurs a formidable overhead. Frequent beamforming between APs and clients is necessary to adjust the beams reacting to blockages and mobility. If up-to-date beamforming information is available, it is possible to dynamically determine the AP-client association and allocate network resources in an efficient way. But frequent BF can take a significant amount of time. For example, in 802.11ay, it takes approximately 5ms to train the downlink transmitter (Tx) and receiver (Rx) sectors of one AP to all its clients. With ten collocated APs, the overhead could be approximately 50ms which would consume half of the 100ms beacon interval (BI) just for the BF.

In this paper, we present CoBF, a coordinated beamforming system that addresses the problem of high beamforming overhead in dense mmWave WLANs. Our key idea is that if we can identify only a small subset of APs that need to perform BF in each BI, we can reduce the BF overhead at the network level while ensuring that the BF information is up-to-date. To identify the subset of APs, we introduce a concept of uncertainty which is the probability that an AP's beams to its clients have changed significantly since its last BF. We develop a prediction model where APs which performed BF recently can predict the uncertainty of other APs. Then the APs with high uncertainty can be selected for BF. In addition, we use the network-level uncertainty to dynamically choose the number of APs that need to perform BF in each BI, allowing CoBF to adapt to the network dynamics seamlessly. Furthermore, the uncertainty value is leveraged for interference management, multi-user multiple input, multiple output (MU-MIMO) grouping, and scheduling.

2 SYSTEM OVERVIEW

Fig. 1 shows a high-level overview of CoBF. We assume a centrally-managed enterprise WLAN scenario where APs are connected to a controller through a high-speed backhaul. CoBF consists of three important modules: (i) the uncertainty prediction module, (ii) the BF AP selection module, and (iii) uncertainty-aware scheduler with MU-MIMO grouping. CoBF executes the following steps:

(1) At the start of a BI, a small subset of selected APs perform BF using enhanced beacon frames to train their downlink Tx and

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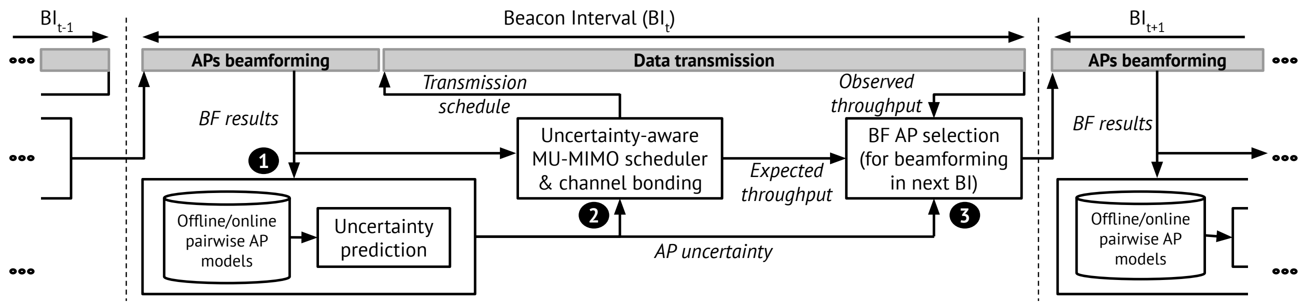

Figure 1: CoBF **system overview.**

Rx sectors of all antennas on the AP and all clients. The updated BF information is input to the uncertainty prediction module. The module consists of AP uncertainty prediction models which can be trained online or offline and then looked up during the run-time. Based on the BF information of the APs that performed the BF, the module predicts the uncertainty (i.e., the probability of significant change in BF information) for other APs.

(2) The current BF information and the predicted AP uncertainty values are input to the uncertainty-aware scheduler. The scheduler uses this information to calculate SINR with intra-/inter- interference in a probabilistic manner to perform Tx and Rx sector selection, MU-MIMO grouping, and scheduling. The calculated schedule is then executed by the APs during the data transmission interval.

(3) The AP uncertainty is also input to the BF AP selection module, which ranks the APs based on predicted uncertainty. Based on the feedback ratio of observed throughput to expected throughput and the predicted uncertainty, a subset of APs (more if the ratio is small, less otherwise) is selected for BF in the next BI. The process is repeated, creating a closed-loop, feedback-based coordinated BF and scheduling system for 802.11ay WLANs.

3 CONTRIBUTIONS AND RESULTS

We implement and evaluate CoBF using extensive real-world experiments and large-scale trace-driven simulations. First, we use commodity 802.11ad devices enhanced with Rx beamforming implementation by modifying the wil6210 driver [7] to evaluate the uncertainty prediction model and the effectiveness of coordinated BF. Second, we use the Remcom InSite [4] mmWave channel simulator to evaluate CoBF in large, densely deployed WLAN scenarios. Our evaluation shows that:

- The coordinated beamforming improves the network throughput by 30.8% compared to the default beamforming of 802.11ad with a 71% reduction in beamforming overhead in our testbed with 4 APs. Furthermore, the mean difference in AP-client SNR (Signal to Noise Ratio) is observed to be less than 1 dB for the sector selected by our coordinated beamforming scheme and the scheme where all APs perform beamforming.
- CoBF with MU-MIMO can achieve up to 5.5 times higher average throughput and 4.2 times lesser beamforming overhead with limited control latency compared to the default 802.11ay beamforming scheme where all APs perform beamforming in each beacon interval.
- The warwalking efforts required to build the uncertainty model are reasonably small. For example, approximately 120 warwalking steps are required in a room of 198 m^2 area in the experiment scenario. Our results also show that carefully updating the training data using an online approach is feasible, eliminating the need for the time-consuming warwalking process. The online model achieves a comparable performance in terms of uncertainty prediction.
- We evaluate the control latency of CoBF and find that our uncertainty based beamforming and centralized scheduling incur much smaller latency overhead compared to the time taken by default exhaustive beamforming of 802.11ad/ay.
- CoBF can be combined with existing link-level beamforming schemes to achieve 7.9%, 9.3%, and 15.9% network throughput increment with CoBF + compressive sensing [5], CoBF + UbiG [6] and CoBF + MUTE [1] respectively compared to CoBF + 802.11ay link-level BF.

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