Revolutionizing Wireless Connectivity with Cross-Band Metasurfaces

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ABSTRACT

Current network technology encounters difficulties in establishing seamless indoor connections, particularly in higher frequency bands such as Wi-Fi 5GHz and mmWave, which suffer from severe signal attenuation caused by inevitable occlusions. To surmount this challenge, tunable metasurfaces emerge as a promising solution by redirecting incoming waves to circumvent obstacles. However, the absence of a theoretical framework hinders the design of metasurfaces that can effectively operate across multiple frequency bands. This work attempts to provide a general method for cross-band metasurface design, extend wireless link coverage by using a new metasurface prototype called CrossFlit, which can maximize the link quality with efficient aperture usage and low cost. our proof of concept implementation is for Wi-Fi 5 GHz and mmWave bands. The empirical evaluation demonstrates that CrossFlit can enhance widely used mmWave and Wi-Fi links simultaneously.

1 INTRODUCTION

The rapid growth of the Internet of Things (IoT) drives a wide range of smart applications like virtual reality, high-resolution video streaming, smart homes, and mobile health apps. These applications rely on wireless connectivity that is fast, widespread, and power-efficient. To meet these requirements in the next generation of wireless communications, it is essential to combine Sub-6GHz and mmWave frequencies. However, there are still many areas indoors where wireless coverage is limited. This is primarily due to obstacles such as walls and furniture, which cause significant power loss along the line-of-sight path, especially for mmWave frequencies in the tens of GHz range. Even lower frequency Wi-Fi struggles to penetrate multiple walls or floors. To overcome signal attenuation and enable seamless wireless connections, we need to improve communication links across different frequency bands that experience severe path loss.

Metasurfaces are being explored to manipulate signal propagation and transform the radio environment [1–3], but most existing designs are limited to a single frequency band, requiring separate surfaces for different bands and leading to bulkiness and high maintenance costs. To address this, a metasurface capable of optimizing multiple frequency bands, such as Wi-Fi 5 GHz and mmWave, is urgently needed. This would meet diverse application requirements and enable seamless network switching for users.

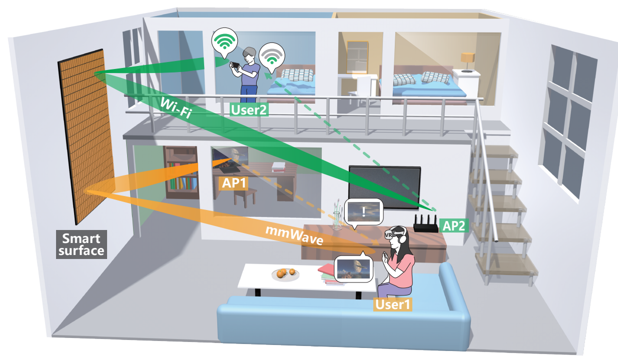
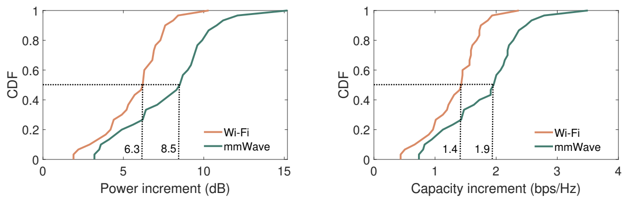


Figure 1: Motivating example of CrossFlit.

This paper introduces CrossFlit, a low-cost tunable metasurface that operates across multiple frequency bands. CrossFlit is designed to reflect incoming waves and redirect them in desired directions, making it suitable for both single-link and multi-link scenarios. It addresses coverage blind spots in wireless links by optimizing more attenuated frequency bands through beam redirection. By utilizing the "bad interaction" of multiple resonance parameters, CrossFlit achieves independent control over disparate frequency bands, enabling real-time radio environment optimization. The concept can be applied to different frequency bands beyond those discussed in this paper. As depicted in the conceptual illustration in figure 1, CrossFlit can optimize widely used mmWave and Wi-Fi links simultaneously, improving the VR experience and internet quality for users in blind spot of the AP.

2 SYSTEM OVERVIEW OF CROSSFLIT

CrossFlit is designed to deal with significant signal losses caused by LoS occlusions for wireless links at different frequency bands, pushing wireless link towards seamless connection. A proof of concept demonstrates that CrossFlit is capable of extending communication link coverage in the widely used mmWave and Wi-Fi frequency bands. An



(a) Power increment. (b) Capacity increment.

Figure 2: CrossFlit provides signal improvements to both Wi-Fi and mmWave bands.

overview of our system architecture consists of the following four elements:

Metasurface. The metasurface implemented in this work combines multiple resonant parameters to construct the basic meta-atom that can interact with different bands (e.g., Wi-Fi and mmWave) simultaneously. The metasurface consists of multiple meta-atoms that are activated by bias voltages. By programming the bias voltages, different arrangements and phase differences of the adjacent meta-atoms can be created, tailoring the number and directions of the reflected beams.

FPGA board. The FPGA board is employed to provide dynamic bias voltages for the tunable coding metasurface, so as to achieve real-time programmability for the multiple digital metasurface elements.

Central controller. A centralized controller observes the signal power measured at the receiver, and performs a fast beam-scanning to determine a sequence of bias voltages that maximize the power by finding an optimal beam direction that directs the reflected beam to the receiver.

Endpoints. The endpoint receiver reports its received signal power from the transmitter to the controller, which then determines how to actuate the metasurface by manipulating the coding sequences based on the input voltages.

3 IMPLEMENTATION AND EVALUATION

Implementation. We implement our cross-band metasurface through a conventional printed circuit board (PCB) manufacturing process. The entire metasurface system comprises double-layered printed circuit boards, and the FPGA control system. The metasurface is fabricated with 900 inexpensive functional elements. The FPGA control board is interconnected with each column of meta-atoms on the metasurface through a wire harness. We validate the cross-band performance of CrossFlit with both Wi-Fi and mmWave links by controlled experiments based on USRP and frequency converter. To evaluate the gain achieved by the metasurface when the LoS path is occluded, we place a blocker (wrapped with absorbing material) between the transmitter and receiver to weaken the LoS signal.

Signal improvements. To verify CrossFlit's cross-band ability of enhancing the wireless links, we conduct experiments with both Wi-Fi and mmWave platforms simultaneously, and use default frequency of 5.8 GHz and 25 GHz at two frequency band, respectively. We place the transmitters and metasurface at the constant location, and move receivers across 30 different testing positions in a $5m \times 6m$ meeting room. We control the two layers of metasurface simultaneously and run the fast beam-scanning algorithm to find the optimal beam state for both Wi-Fi and mmWave links, respectively. Figure 2 shows the cumulative distribution function (CDF) of the received power increment and channel capacity increment caused by metasurface. it is clear that CrossFlit has a positive impact on both the Wi-Fi and mmWave bands. For mmWave link, the minimum, median and maximum power improvements are 3.2 dB, 8.5 dB, and 15.2 dB, respectively; and the minimum, median and maximum capacity improvements are 0.7 bps/Hz, 1.9 bps/Hz, and 3.5 bps/Hz, respectively. For Wi-Fi link, the minimum, median and maximum power improvements are 1.9 dB, 6.3 dB, and 10.3 dB, respectively; and the minimum, median and maximum capacity improvements are 0.4 bps/Hz, 1.4 bps/Hz, and 2.4 bps/Hz, respectively. The signal improvements for the Wi-Fi link are a bit smaller, for two main reasons: (i) we use omnidirectional antennas for the Wi-Fi link, so the receiver can obtain additionally benefit from constructive interference from random multipath even without metasurface; (ii) the beamwidth of the metasurface at the lower frequency Wi-Fi band is wider than that at high mmWave band since the metasurface contains fewer meta-atoms that interact with the Wi-Fi band because they are each physically larger. Nevertheless, CrossFlit plays an important role once the LoS path is blocked.

4 ACKNOWLEDGMENTS

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