Towards Hybrid Electronic-Mechanical Beamforming for IEEE 802.11ad

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***Abstract*—Electronical beamforming (EBF) is an enabling technology for millimeter-wave (mmWave)-based communication; it is used by standards like IEEE 802.11ad known as WiGig. As WiGig commercial off-the-shelf solutions must be inexpensive, the EBF cannot be freely controlled; instead the beamforming is chosen from a small set of preconfigured configurations, which limits its gain. In this paper, we propose hybrid WiGig (`hWiGig`), which provides an additional mechanical steering on top of the WiGig's EBF by enabling physical rotation of the mmWave antenna array. A proof of concept prototype is implemented and used to quantify its gain. Experimental results reveal a large improvement in terms of throughput, especially in NLOS environments with a gain of up to $13.4\times$. Moreover, random strategies which test only a few physical orientations achieve still high performance gain which underlines `hWiGig` practical relevance.**

***Index terms*—** millimeter-wave, beamforming, 802.11ad

I. Introduction

The demand for higher throughput wireless communications continues to grow, in line with the increasing number of connected devices online. Recent reports forecasted that in 2023 the total number of networked devices worldwide will have exceeded more than three times the global population [1]. Moreover, a third of these connections will be realized over wireless links. This calls for a more efficient use of the available wireless spectrum and requires innovative engineering solutions to maximize spectrum efficiency, while maintaining low cost. However, the sub-6 GHz spectrum, traditionally used for wireless communications, is almost saturated and there is little room for innovation. As such, carrying communications over higher frequencies is inevitable. In this regard, millimeter-wave (mmWave) arises as a promising solution [2].

mmWave has many GHz of available spectrum and very high degree of spatial reuse. These properties can help to meet the high throughput demands. However, due to operation in higher frequencies, millimeter waves propagate in highly directional paths and require line-of-sight (LoS) links for optimal operation. To achieve this, mmWave communications exploit (highly directional) steerable antenna arrays that can focus the signal toward a desired direction – a concept known as *beamforming* [2], [3]. In this regard, beamforming is seen as an enabling technology for 5G cellular communications [3] and for WiFi (IEEE 802.11ad known as WiGig) [4], [5]. Beamforming in mmWave is implemented as a process known as electronical beamforming (EBF), where the main beam is re-calibrated electronically to aim in the direction of the desired destination (e.g., a receiver). The re-calibration process involves steering of the beam at runtime by controlling each antenna element. Searching all beam configurations can be very time intensive, therefore, low-cost WiGig solutions often use a codebook of a small set of preconfigured configurations from where a beamforming configuration can be selected. Limiting the selection to a subset of possible configurations incurs a penalty on potential gain for WiGig's EBF. Another limiting factor is the signal blockage from co-located chipsets on the antenna array that causes shielding in certain directions [4].

To overcome practical limitations of the potential gain of EBF in WiGig, in this paper, we propose `hWiGig`. `hWiGig` is a hybrid electronic-mechanical beamforming solution for WiGig, that uses mechanical steering of the antenna array besides EBF. As such, `hWiGig` extends beamforming options beyond the restrictions of the EBF codebook and can improve beamforming performance. `hWiGig` can be implemented using commercial off-the-shelf (COTS) hardware and is suitable for static and low-mobility scenarios, therefore, providing performance gain at virtually no additional cost.

Contributions: `hWiGig` extends WiGig's EBF with mechanical steering, thus, enabling dynamic change of the physical rotation of the mmWave antenna array. It is of practical relevance as testing only a few random physical orientations is sufficient to achieve high performance gain, which is especially high in NLOS environments.

II. Related Work

The role of beamforming as an enabling technology for mmWave has stimulated the research community to focus on the development of more efficient and practical solutions to enhance it. Generally speaking, the solution space can include algorithmic solutions that improve the standard-defined beamforming procedures; and hybrid solutions that benefit from multi-technology and/or hardware enhancements.

Steinmetzer et al. [4] presented an IEEE 802.11ad platform based on the TP-Link Talon AD7200 router using the same WiGig chipset (i.e., Qualcomm QCA9500) as in our prototype. They modify the sector sweeping algorithm in IEEE 802.11ad chip's firmware, and propose a compressive path tracking algorithm, where the measurements on a random subset of sectors are used to estimate the optimum sector. This approach improves the selection for the optimal sector over the standard-defined deterministic algorithm.

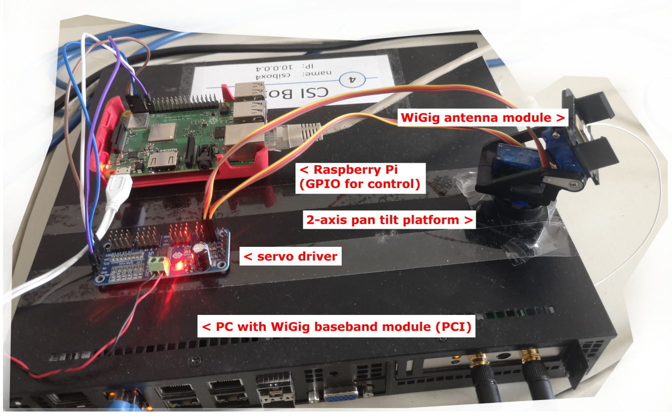

Fig. 1: Prototype of `hWiGig` with WiGig antenna array mounted on a 2-axis pan/tilt platform for mechanical steering.

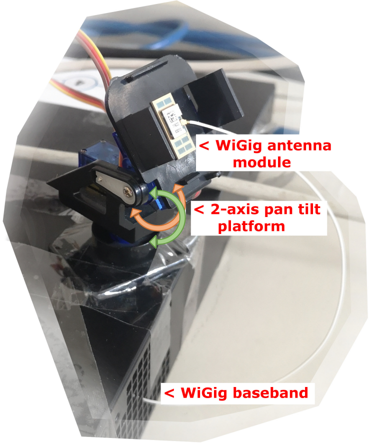

Fig. 2: `hWiGig`'s key component is the 2-axis mechanical rotation of the WiGig antenna module.

Polese et al. [6] propose a deep learning-based beam management framework that does not require explicit coordination between the TX and the RX for beamforming. Instead, while passively eavesdropping ongoing transmissions between the TX and other RXs, the RX collects statistical data about the channel and uses a convolutional neural network (CNN) to identify the beams in the codebook of the TX. It identifies the beams by Angle-of-Arrival (AoA) and unique features found in the waveform when it is transmitted by a specific beam. This information is then used by the RX to steer its receive beam toward the TX for maximum beamforming gain. Salehi et al. [7] also use machine learning techniques to improve mmWave beamforming. They use a combination of non-RF sensor data (e.g., GPS, camera, and LiDAR) in a Federated Learning (FL) architecture to find the best sector for downlink transmission from a mmWave base station to a vehicle. The vehicles locally initialize a supervised learning task and do model training, before sending model weights for global optimization at the Base Station (BS). The BS returns an update with optimized global model weights to the vehicles. This approach eliminates the traditional TX-RX coordination procedures for beamforming. Experimental results using the same TP-Link Talon AD7200 60GHz mmWave radio as in [4] show 52.75% decrease in sector selection time compared to the standard IEEE 802.11ad selection algorithm.

Sur et al. [8] propose an out-of-band solution that takes advantage of WiFi channel state information for beamforming in 60 GHz mmWave. This is made possible by the multi-band chipset of an access point (AP) that implements both technologies. Essentially, whenever a change in the SNR is detected, this approach tries to predict the shift towards the best beam for the mmWave link by analyzing series of time-domain spatial snapshots of the WiFi channel, therefore eliminating the overhead of probing for beamforming.

Different to the above, Park et al. [9] follow a hardware-assisted approach to improve beamforming in mmWave. Specifically, they deploy an RF lens antenna which acts as a passive beamforming equipment, providing high antenna gain at low additional hardware cost.

III. 802.11ad Beamforming

Beamforming uses the concept of electromagnetic interference to improve wireless connectivity by focusing the signal toward a specific receiving device [10]. This is achieved by combining the elements of an antenna in such a way that in certain directions the signals interfere constructively, while in other directions interference is destructive. Beamforming is usually an electronic process, where the beam can be recalibrated electronically to aim in a new direction.

With the IEEE 802.11ad (WiGig) standard, WiFi is able to use the mmWave spectrum at 60 GHz. Here, the usage of EBF is of paramount importance in order to overcome the high signal attenuation of the mmWave spectrum. However, in order to keep WiGig solutions inexpensive the EBF cannot be freely controlled. Instead, standard beam-training algorithms are used, which probe a set of pre-defined antenna patterns and select the best configuration with respect to metrics like signal strength or SNR [4]. As an example, a standard 802.11ad AP like the Talon AD7200 uses a pattern set with 35 configurations, which can be fully tested within a very short time duration, even for mobile systems [5].

IV. `hWiGig` Prototype

`hWiGig` extends commodity WiGig solutions with an additional mechanical steering, which is enabled by the physical rotation of the mmWave antenna array. The mechanical steering is fully transparent to the electronic beamforming used by the WiGig chip and is controlled in software via a simple API, i.e., `rotate2angle(theta,phi,v)` with `theta` and `phi` being the horizontal and vertical angles, respectively, and `v` the rotation speed. As changes to the physical antenna orientation take a considerable amount of time, i.e., a few hundred microseconds, such changes are rarely made.

Fig. 1 shows the full prototype, which is based on inexpensive COTS hardware components. It consists of a standard PC (Intel Xeon) equipped with a WiGig baseband module with the WiGig antenna module mounted on a 2-axis pan tilt platform to allow mechanical steering (Fig. 2). The two low-cost servos

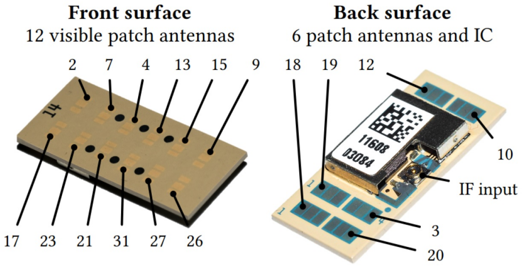

Fig. 3: Phased array antenna of the Qualcomm QCA9500 WiGig chipset [11].

of the platform are controlled using a servo driver, which in turn is controlled by an embedded computer (Raspberry PI) via GPIO interface. For the WiGig chipset, we selected the Qualcomm QCA9500, which is a FullMAC IEEE 802.11ad solution [4]. The chip is connected to an antenna array module with 32 antenna elements used for beam steering by changing phase shifts and amplitudes on each array element (Fig. 3). Note, that the chip's proprietary firmware has full control over the antennas and the handling of MAC layer operations [4]. The device driver *wil6210* shipped together with Ubuntu 18 was left unchanged, i.e., the proprietary beam selection and rate control was used.

V. Evaluation

A. Methodology

We evaluated the feasibility of `hWiGig` using our prototype (Fig. 1). In particular, we wanted to quantify its gain as compared to a pure WiGig solution, which is using EBF only. We analyzed the performance of a point-to-point mmWave link in an office environment for four scenarios:

- `LOS1`: very short link (1 m) with clear LOS and both nodes placed on a desk (with possible ground reflection),
- `LOS2`: same as `LOS1` but with the RX node placed 30 cm above the table,
- `NLOS1`: link distance of 2 m and NLOS, i.e., LOS path obstructed by two obstacles (each covered with aluminum foil),
- `NLOS2`: link distance of 1.5 m and NLOS, but only single obstruction in LOS path.

Note, the `LOS1` and `LOS2` scenarios represent optimal conditions whereas the `NLOS1` and `NLOS2` are challenging due to the absence of a LOS component, i.e., communication happens over reflected path(s).

As our objective is to quantify the gain from the additional mechanical steering on top of EBF, the following setup was used. The TX node was a `hWiGig` node, which was able to mechanically rotate into one of the 625 possible antenna orientations with a step size of 5°, i.e. $\theta \in \{-60^\circ \ldots +60^\circ\}$ and $\phi \in \{-60^\circ \ldots +60^\circ\}$, which we will refer to as field of view (FoV). In contrast, the RX node was a standard WiGig solution without the possibility of mechanical steering.

As performance metric, we selected TCP throughput, which we measured over the duration of 10 s using the `iperf` tool for each selected physical antenna orientation. In order to avoid interference and external influence (e.g., walking people), all experiments were performed during the night in an empty office room using channel 1 (58.320 GHz).

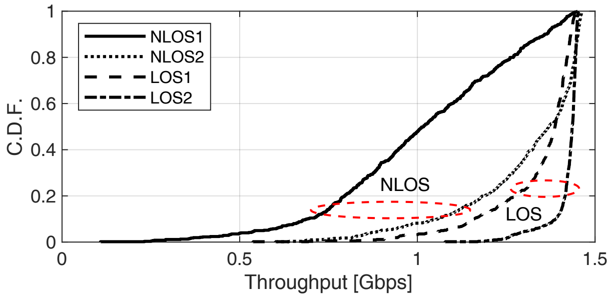

Fig. 4: CDF of TCP throughput over all 625 measured antenna orientations of the `hWiGig` TX node.

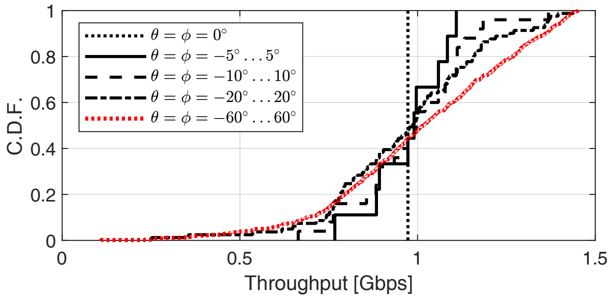

Fig. 5: FoV strategies: impact of α for `NLOS1`.

B. Results

1) Quantifying the potential gain: Fig. 4 shows the CDF of the TCP throughput over all 625 physical antenna orientations for the four different scenarios. We see that the distribution of the throughput values is the highest for `NLOS1` and `NLOS2` scenarios. For `NLOS1`, we see that in the optimal orientation of the TX node the throughput is 1.45 Gbit s^{-1} as compared to just 0.1 Gbit s^{-1} in the worst case orientation, which is an improvement by a factor of 13.4×. This can be explained by the inability of the WiGig's EBF to find the optimal beamforming configuration in scenarios with blockage of the LOS path. Hence, the gain of `hWiGig` over baseline can be up to a factor of 13.4× if we assume the baseline to operate in the worst configuration, i.e. physical antenna orientation with the lowest throughput. But even if we assume the average case for baseline the improvement is 1.43×.

In the `LOS1` and `LOS2` scenarios, the gain from `hWiGig` is smaller, since the gain from EBF is sufficient to operate the link on the highest data rate. In the case of `LOS1`, the gain is 2.7× if we compare against the worst case and only 9% against the average case. In `LOS2`, the gain is even smaller at around 1.35× as compared to the worst case.

2) Impact of field of view: In Fig. 5, we analyze the impact of the FoV of the TX node on the achievable link performance for the `NLOS1` scenario. We see that by increasing the FoV the amount of measured physical antenna orientations increases

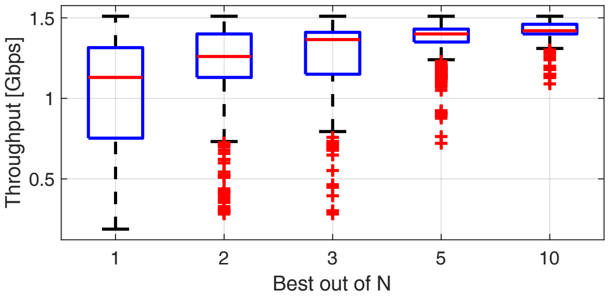

Fig. 6: Random strategy: select the best out of N configurations for `NLOS1`.

and, therefore, the performance gain as the best configuration can be chosen from a larger set of antenna orientations. Even with only small FoV of $\theta = \phi = -10^\circ \dots 10^\circ$, which contains only 9 configurations the potential gain is large compared to baseline with only one configuration, i.e., $\theta = \phi = 0^\circ$.

3) Selection strategies for physical orientation: Evaluating all physical antenna orientations is practically infeasible as it takes a considerable amount of time to mechanically steer and measure all possible configurations. This is challenging even in environments with low mobility. Random strategies where N configurations are tested from which the best one is selected are of practical use as long as N is kept small. The results for $N = 1, 2, 3, 5$ and 10 and the `NLOS1` scenario are shown in Fig. 6. We can see that by increasing N not only the median throughput could be increased but also the variation can be significantly reduced. Already with $N = 5$ the median throughput corresponds to 96.5% of the optimally achievable value when all configurations are exhaustively tested.

VI. Discussion

So far, we analyzed `hWiGig` in a fully static environment where no mechanical reconfigurations were needed once the optimal physical orientation was found. However, even in environments with low mobility (e.g., indoor office space with fixed mmWave deployment but moving people who may cause shadowing) frequent mechanical reconfigurations are needed. This is challenging as it takes hundreds of microseconds or even seconds to change the physical orientation of the antenna array depending on the angle by which the physical orientation has to be changed. Note, our ultra low-cost prototype has an angular velocity of $\omega = 60^\circ/s$ which can be improved by using more expensive high-performance servos. Therefore, we believe the area of application to be limited to static deployments like mmWave links used in backhaul networks.

Also, our `hWiGig` prototype itself can be improved. Instead of mechanically rotating the antenna array, another option is to have the antenna array fixed but deploy a mmWave RF lens in front that is rotated. This would reduce the mechanical stress on the coaxial connection between the antenna array and the baseband chip. Such a fixed RF lens for mmWave was proposed and demonstrated by Park et al. [9] for mmWave MIMO systems in order to achieve high antenna gain with low hardware cost.

VII. Conclusion

We presented `hWiGig`, which provides an additional mechanical steering on top of the electronic beamforming used in modern 802.11ad WiGig radios. Results from experiments reveal a significant gain in throughput, which was the largest in NLOS environments with strong signal blockage. Here we achieved a gain of up to 13.4×.

As future work we plan to extend our evaluations by analyzing the gain in configurations where both sides of the mmWave link, i.e., transmitter and receiver, are equipped with `hWiGig`. In addition, we plan to quantify the gain is a point-to-multipoint scenario, i.e., one node (typically AP) communicating with multiple nodes (typically end systems). Finally, we want to also study the advantages in the interference channel, i.e., multiple co-located and possibly interfering P2P links.

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