Dense mmWave networks: Study of problems and its solutions

Arunkumar Ravichandran
Department of Electrical and Computer Engineering
University of California, San Diego
arravich@eng.ucsd.edu

Abstract

In this paper, the lateral interference problem caused by 802.11ad consumer hardware in a dense mmWave network is discussed in detail and the problem is solved using the pose and location information of the client. The Signal to Interference Ratio (SIR) for all clients were maximized using the proposed solution. Also, classification of the beams as good and bad beams based on the statistical information is shown to help in reducing the computational complexity of the proposed algorithm. WiFi band was used to assist the 802.11ad network in transmitting the control plane information to a larger cell size.

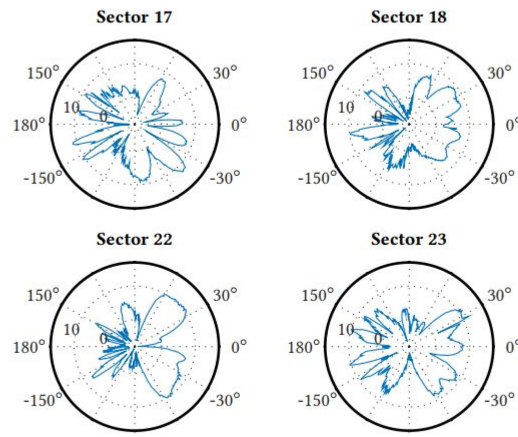

Figure 1. Beampatterns for different sectors of a Talon 2700AP is shown

1. Introduction

Millimeter-wave (mmWave) wireless technology is a disruptive networking technology. They are capable to provide multi-Gbps connectivity for bandwidth intensive applications, such as wireless backhaul [6], cordless virtual reality(VR) [1] etc. New devices based on mmWave standard 802.11ad started to arrive [13] and multiple research demonstrated the advantages of 802.11ad in point-to-point communication links. Due to these advances, mmWave technology is being adopted to the 5G-NR standard[11]. However, the signal propagation properties of 60 GHz band is significantly different from that of 2.4 and 5 GHz bands. [4]

mmWave signals attenuate quickly as distance increases. Hence highly directional antennas were used to focus their power to avoid the attenuation. Since the antenna emitted pencil-beam, only when the transmitters and receivers beams are well-aligned communication was possible. Initially horn antennas requiring mechanical steering was used to identify the best beam alignment. Now-a-days phased-array antennas which can be steered electronically are being used. There is however a significant delay in finding the best beam alignment which is not suitable for deployment of 802.11ad in a highly mobile environment.

To discover the best beam for link establishment to a station, AP will do a rough search of the antenna radiation domain. [18, 7] From the feedback provided by the stations present in that sweep sector, best sector is identified and iteratively that sector is divided again to search for best beam link establishment. The main drawback in this method is it requires feedback from the clients which is mandatory for the next sector level sweep. This causes high overhead in the network.

mmWave beams, even though they are directional in nature, the consumer grade electronically-steerable antennas doesn't produce a perfect mainlobe.[10] As seen in Figure 1, there will be significant side-lobes which will cause interference in other clients. Apart from the interference caused due to main-lobe from a incompatible standard, side-lobe interference is a huge problem in mm-wave networks. So best beam pattern is not the one which increases the throughput between the client and AP but the one beam pattern which also reduces the side-lobe interference for other clients. Side-lobe interference is short-lasting; However to solve this problem, based on the IEEE 802.11ad standard, a beam sweep would be triggered to find the next beam pattern which is interference free. Duration of a beam weep based on 802.11ad standard is 100ms to 1s[20, 17]. Initiating beam sweeps to avoid this intermittent side-lobe interference would cause a significant performance downgrade.

In this paper, a 60GHz network architecture assisted by the sub-6 GHz WiFi spectrum is proposed. The WiFi spectrum would help in data-offloading and act as a control plane to send various information among different APs and Clients in a dense mmWave network to coordinate among each other.

The co-ordination among the APs using the WiFi is different from the IEEE 802.11ad FST which would just help in data-offloading. Control frames are transmitted via the wide coverage WiFi band and the high speed data frames are transmitted using the 60GHz band simultaneously as they wouldn't cause any interference to each other.

Also to help in the location estimation and new beam assignment, theta and phi information from the IMU sensors, beam sector used, MCS used and received signal strength would be transmitted periodically or due to significant change in parameters as a broadcast frame. This would be received by the all APs and clients which would help in updating their database. The location information was roughly evaluated from the client using the IMU sensors present in the mobile devices like Smartphones. Using the location, elevation and azimuthal angle information algorithm was proposed to estimate the beam sector to be used by an AP which would minimize the side-lobe interference and would maximize the received signal strength at the client.

The Beam sectors were identified to be a good or bad beam sector to be assigned to a client. The location information of all clients, side-lobe interference to other clients and number of clients present in a particular area were used to compute the bad beam votes for a beam pattern. This method requires statistical information to help in the computation.

In this paper, a method to reduce the beam searching delay is also proposed. When a client moves or the pose of the client changes, based on the estimated location information, best beam pattern is identified by the earlier algorithms to maximize the SIR. This possible beam to be used by the AP is sent to the client using the WiFi band to reduce the time taken in beam searching. This proposed solution is similar to the 802.11v BSS transition management mechanism where channel searching delay is reduced. Using MATLAB, the proposed solutions were studied.

2. Related Work

mmWave consumer devices have a significant amount of side-lobe power[15] which might cause interference in nearby clients. To overcome this, side-lobe interference should be estimated for a client and beams should be chosen in such a way that the SIR is reduced.

A hierarchical beam searching algorithm shown in Figure 2 was proposed in 802.11ad standard to discover the best beam for link establishment to a station. AP will do a rough search of the antenna radiation domain. From the feedback provided by the stations present in that sweep sector, best sector is identified and iteratively that sector is divided again to search for best beam link establishment. The main drawback in this method is it requires feedback from the clients which is mandatory for the next sector level sweep. This causes high overhead in the network.

In [15], Adaptive Beam Switching algorithm was introduced in which instead of performing a full beam sweep, the nodes probe beampatterns which are likely to avoid interference. Similarities in the side lobes of beampatterns are studied to evaluate the performance of all beampatterns. Whenever a node sends such an individual probe, the probability of interference-free transmission table for that beampattern and the probability of similar beampatterns are also updated thereby reducing the delay in beam search and avoiding lateral interference. In this method, the location information is not being used. The stablization will increase as the number of probes increase thereby high amount of overhead is present in this.

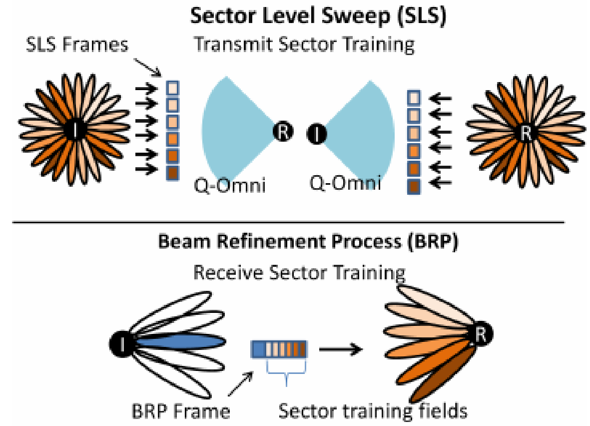

Figure 2. Beamforming stages proposed in 802.11ad network is shown

In [19], pose-information assisted 802.11ad network was introduced to assist in the mobility. Using the location and pose information the beam were found which would improve the Signal-to-Leakage Ratio(SLR). The pose information is collected from the IMUs present in the mobile device and based on that AP with best beam alignment is chosen. Pose information is also used to determine the best AP and best beam pattern for the client. PIA also describes a method to assign beams with weaker side lobes for better spatial reuse. However in this 802.11ad control plane is used which already suffers from directionality losses. Hence in our research we are using the omni-directional WiFi as the control plane which has higher coverage area too. Also in this paper, location information was being estimated from the 802.11ad beams RSSI. In our method, we initially estimate the location information of the client based on the 802.11ad beam RSSI and correlate that with the WiFi RSSI. Thus accurate location information is available after which we will use the step counting algorithm running in the smartphone with an accelerometer to estimate the location of the client from the AP and send that to the AP using WiFi as control plane.

Compressive sensing based beam searching algorithms were introduced [9, 12] to reduce the delay in initial beam forming. One such method is where the AP sends multiple beacons using a different phase mapped to an antenna element. The right alignment of the beam is found by comparing the feedbacks of multiple compressive beacons. These compressive scanning algorithm requires complex hardwares to compute the best beam with a lesser delay. This method will introduce a computational overhead and hence cause significant delay unless the algorithm is hardcoded into a ASIC instead of letting the host to perform the computations.

Agile-link algorithm [2] suggested a hashing function to identify the best beam alignment. This hashing function would hash the spatial directions to bins. Each bin represents the energy obtained from all directions. Another iteration of hashing is done to identify if any bin doesnt have energy due to collision. Voting is done to see which has the strongest path. This method doesnt discuss about the number of beacons required to identify the correct beam alignment direction. Also the beam searching problem is only discussed in this paper. The side-lobe interference problem is not accounted for in this research paper.

A WiFi assisted 802.11ad network was proposed [16] where best beam setting was found with zero probing overhead using the WiFi profile. A proactive blockage detection was introduced where a blockage would affect the 802.11ad CSI profile whereas the WiFi CSI profile would be unaffected. We are planning to use the same method in our paper to identify blockage.

3. Dense mmWave networks

3.1. Impact of side-lobe interference:

In this section, the impact of side-lobe is analysed using MATLAB and their results are presented. We use the Talon 2700 data set [14]. This dataset had the RSSI and SNR values for the Talon 2700AP for different beam patterns, client locations indicated using theta and phi. The measurements of the RSSI data for different sectors,theta and phi which was done in an anechoic chamber. Selected beampatterns of a Talon 2700 AP is generated from the measured values present in the Talon 2700 dataset and are shown in Figure 1. Commercial phased-arrays antennas present in 802.11ad APs are not perfectly directional. Each beam pattern will have a main lobe with higher strength along with side lobes of weaker strength. We consider a scenario where there are 3 APs and 5 clients. We assign random beam pattern to be used with each Client-AP pair and random location, pose information is assigned to the clients to simulate a real world scenario. Due to clients connected to nearby APs, we saw a significant drop in the signal strength. Then we calculated the SIR for the client which had the RSS drop and figured out the side-lobe for certain beampatterns were so high that could cause shadowing of the client. At some locations and some beam patterns, we observed very low SIR which would contribute to a less MCS thereby a very low throughput.

3.2. Avoidance of side-lobe interference:

Side-lobe interference can be avoided by choosing a beam pattern that cause less interference to other clients. This might cause throughput performance degradation for the client whose beam pattern was changed. We propose an algorithm which tries to find a balance between these two. This is a joint AP selection and beam selection problem. The main objective is to find the optimal AP and optimal beam assignment which maximizes the link quality and also increases the spatial reuse.

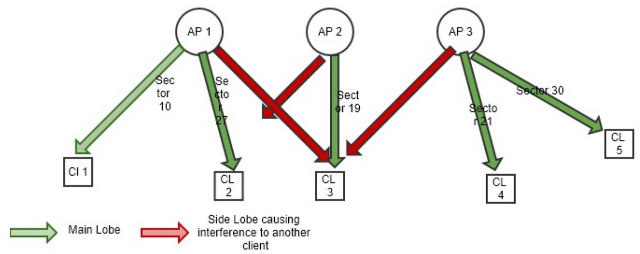

Figure 3. Multi-client dense mmwave network is shown where there are 3 APs and 5 clients; The beampattern of the APs causing side-lobe interference is shown

First we present the flowchart of an algorithm which is greedy(figure 4) and calculate the Signal-to-Interference Ratio (SIR) of the clients. In this algorithm, all client tries to establish link with all APs. The algorithm tries to find best AP and best sector by searching in the Talon 2700 dataset. Then based on the chosen sector and AP, we find the interference caused at the clients due to other APs. Then SIR was calculated for all the clients. In Talon 2700 dataset, the RSSI and SNR values presented in the data file are measured in an anechoic chamber by placing the receiver at a distance of 3m. To compensate for the distance, a Frii's path loss model is used as suggested in [3] to identify the client original path loss at the client. In the proposed solution, SIR calculation would be done globally which would assign AP and beams to the client in such a way that maximizes the SIR. Two datastructures are maintained to compute the Interference map of this dense mmWave network. AP-Strength-MAP is a datastructure which would calculate the RSSI of the AP-Client pair. Interference-map is a data structure to fill the interference at a client i due to other clients. As mentioned in the flow-chart(Figure 5) the AP-strength-map and interference-map would be calculated. This would allow us to calculate the SIR of all clients for different beam patterns. As we calculate that, we can try to maximize the SIR and find the optimal beam pattern which is reducing the leakage and increasing the throughput.

PIA describes a similar method where SIR calculation is deemed computationally in-scalable and hence they use Signal-to-Leakage ratio. Here they mention the Leakage as signal received by an undesired client. Since the algorithm is running in a Talon 2700AP, the interference calculation done in Algorithm 2 mentioned in Figure 5 is similar to what was discussed in PIA[19].

3.3. Location and Pose information estimation:

Location and Pose information would be used to identify best beam pattern and best AP for a client. In our paper, we only consider the LOS beampatterns. We assume that the AP and client are present in a place which doesn't have any environmental reflectors. The initial pose information of the client would be found during the beam searching phase. The

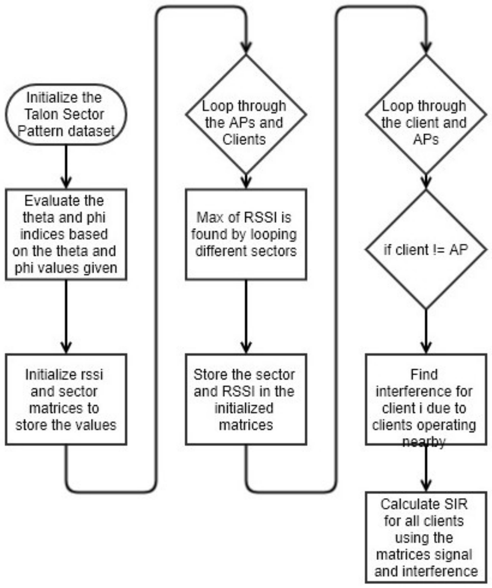

Figure 4. Local optimum based SIR calculation and AP/Beam assignment algorithm

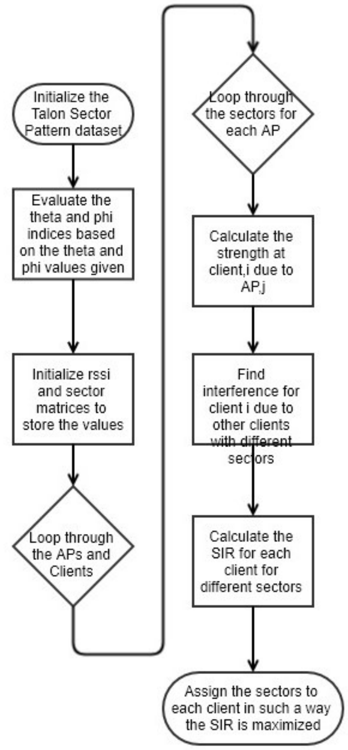

Figure 5. Global optimum based SIR calculation and AP/Beam assignment algorithm

probes would be sent by the client in different theta and phi to find the best beam pattern during the beamforming phase. These probes can be used to identify the theta and phi of the client wrt to the AP. This evaluated theta and phi would be sent to the client for calibration. As the client moves, the new theta and phi change would be updated at the client and if there is a significant change, the new theta and phi would be sent as a broadcast. We chose WiFi to send this data so that it's received by all the APs and clients present in the vicinity and therefore in our next implementation we can try to avoid the central controller to store all these client information in a central database.

Location information can be estimated by using the MUSIC algorithm [8] in WiFi interface as well as using the RSSI of the 802.11ad probes[5] received at multiple APs. In PIA[19], 3 APs are used to find the location information using the 802.11ad beams. However our method offers a better solution as we are able to compare the location information calculated from multiple APs using 2 bands. Using the information of position of different APs, RSSI of 802.11ad beams and RSSI of WiFi beams at the APs, we can correlate the correct result. The location information found by this method is coarse and not accurate at many instances which might affect the throughput estimation for a particular beampattern. Once the initial location information is found, we use the step counting method to find the location information of the client. The smartphone with accelerometer and IMU sensors can be used to count the amount of distance the mobile device has travelled and the direction of the motion can be found. By conducting experimental results, we can find statistically the threshold of the distance and the direction change which would affect the throughput. Thereby only when there is a significant movement, the change in location would be updated to the APs via the WiFi interface.

As the location information is updated to the AP, the controller runs the SIR calculation algorithm to evaluate the best beam for this current location. When this SIR calculation is running, we use the change in direction to reduce the search size. If the theta and phi remains same and only the distance changes, we try to find the best AP which is nearby to the client and make the client to roam to the other AP and assign a best beampattern by running SIR calculation algorithm. However when there is a significant change in the theta and phi information of the client, the SIR calculation algorithm would be run to find the next possible beam. PIA suggests that when there was a change in the distance the throughput didn't affect. However when there was a change in the pose information, the throughput was affected. These results was also seen in the MATLAB simulation using the Talon 2700AP beampatterns dataset. As mentioned in the [19], the threshold for the distance was around and the threshold for pose information was . We can use this threshold information to classify whether a beam is good or bad based on the side-lobe leakage.

3.4. Bad beam evaluation

It was seen from MATLAB simulations and in other papers [10, 15] that side-lobe interference would cause a significant impact like shadowing of client. As we saw the beam pattern for all 34 sectors in the talon 2700AP dataset, we found that certain beam patterns had higher side-lobe strength compared to certain beam-patterns having negligi-

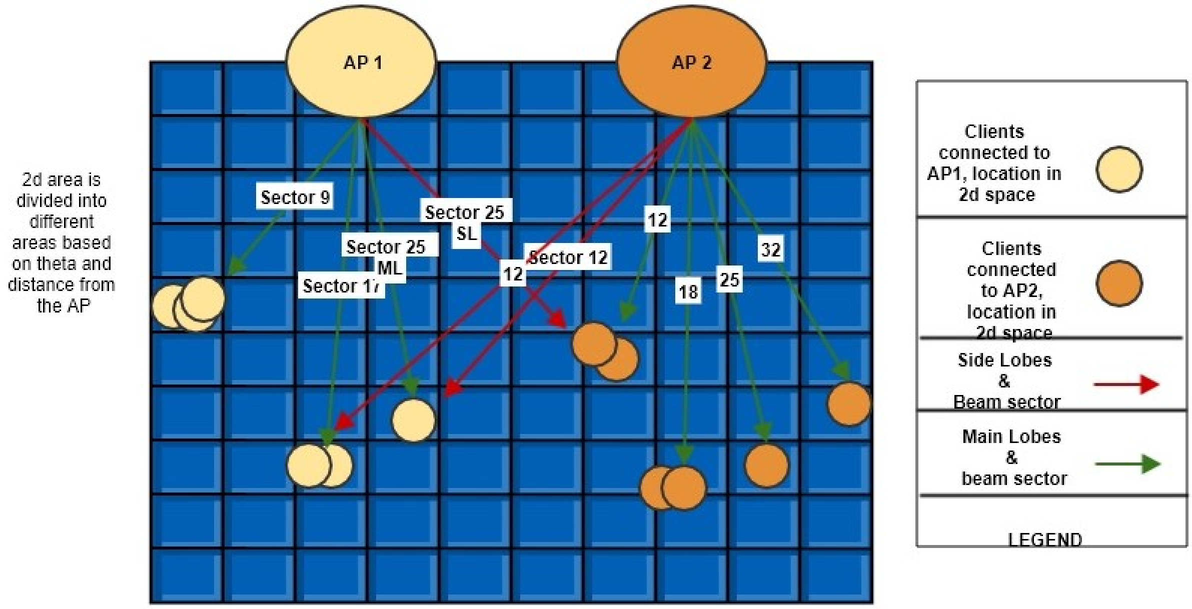

Figure 6. Local optimum based SIR calculation and AP/Beam assignment algorithm

ble side-lobes which wouldn't cause any interference. Thus this led us to evaluate which are the beam patterns having high side-lobe interference causing significant impact to a overall SIR.

We maintain a bad-beam-index for all the 34 sectors in a AP. To evaluate the bad beams, we consider a 2d space and we divide the 2d space into different physical areas. The area size is found by results from PIA which suggested del-theta and distance for which there is no impact in performance or for which no beam pattern change is required. Whenever any clientj encounters side-lobe interference due to APi, we increment the bad-beam-index by a factor leakage-impact. Leakage-impact is the result of multiplication of SIR for clientj and number of clients in that physical area. This leakage-impact would tell us how the side-lobe for a particular beam-pattern is affecting the overall system efficiency. Thereby we can try to avoid the beams which has higher leakage impact while doing the beam assignment. The beam-patterns can be ranked based on the descending order of the leakage-impact or the bad-beam-index to identify the bad beams. Also we can find the best beampatterns which has significantly less impact on other clients using the above two matrices.

3.5. Blockage detection and beam selection

Blockage detection in MUST[16] is done using the CSI information from both 802.11ad interface and WiFi interface. The CSI information of 802.11ad would change when there is a blockage but the CSI information of WiFi interface would not see a significant impact. Thus blockage can be identified. Our solution proposes a method where the RSSI of the 802.11ad beam at the client can be used to identify if there is a blockage. If only the RSSI changes but there is no change in theta and phi information of the client, then we can say that there is a LOS blockage. However in scenarios like when the mobile client is in motion, there will be change in pose information which might affect the blockage detection. Hence we go with the idea proposed in the MUST. When there is a blockage, we switch to the WiFi interface for sending data packets.

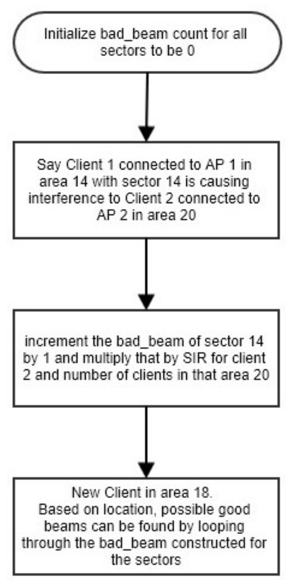

Figure 7. Local optimum based SIR calculation and AP/Beam assignment algorithm

3.6. Reducing the beam search delay

The beam search delay using the 802.11ad standard is around 100ms [20, 17] which is significantly high. As the controller knows the client location and pose information, the controller can trigger the AP to change the beampattern and also make the client to associate to another AP which improves the overall SIR as discussed in section 3.3. The controller is going to choose a set of possible beams which the AP might use for this client and inform this to the client using the WiFi band. Once the client mobility goes beyond the pose threshold and location threshold, the AP would send the possible beam patterns to the client. The client would search in these beam patterns alone instead of doing a full sector sweep. As the client keeps track of the connected APs location and pose, the client knows the different operating sectors. Once the possible operating beam patterns are fed to the client, the client would try to find if there is any energy in these beampatterns and tries to join the AP back. This proposed method requires the location, pose information of client to be known by the AP and viceversa. So this method can't be used when the client is trying to join an AP for the first time.

Future Work

Experimental evaluation of the algorithms This involves implementing the algorithms proposed in section 3 on hardware and evaluate how the algorithm scales on real environment. We are planning to use a smartphone with typical IMU sensors present in it. The AP and the smartphone should have both WiFi interface and 802.11ad interface.

Parameters to be considered In this paper, we didn't consider the non-LOS paths. However in a dense mmWave network deployed inside an indoor environment, there would be a lot of reflectors. The non-LOS reflected beams could cause significant interference to other clients.

Adaptive code-book based side-lobe interference avoidance The code-book for 802.11ad hardware is fixed. However we can exploit the firmware to change the codebook for certain beampatterns. Using this, we can adapt the codebook for beampatterns which cause a significant side-lobe interference for the clients.

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