Scalable Peer-to-Peer mmWave Communication

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***Abstract*—mm-Wave is an attractive high-speed wireless communication paradigm that also has strong sensing applications owing to large available bandwidths. Such high frequencies come with the need for mandatory beamforming to achieve appreciable SNR, enforcing the need for sector sweep. The overhead of sector sweep can be eliminated for peer-to-peer communication by leveraging sensing capabilities at the access point (AP). The AP can facilitate the peer-to-peer connection establishment by informing the intended device about the location of its peers. This way, the device can directly beamform to it's peers without performing a neighbour discovery sector-sweep. We present the RADAR-assisted mm-Wave peer-to-peer communication paradigm where an mm-Wave RADAR co-located with the AP provides the necessary information to its clients for establishing a connection among themselves without undergoing sector sweep.**

***Index Terms*—mm-Wave, peer-to-peer communication, RADAR, beamforming, sector sweep, machine learning**

I. Introduction

Millimeter wave technology is an attempt to push the capacity of wireless networks into the realm of wired networks. mm-Wave network designs aim to provide high throughout, low latency, and high reliability. The high pathloss of the mm-wave frequency mandates beamforming, and hence beam sweeping is a key requirement for network discovery. The sequential measurement of SNR during beam sweep for identification and high-speed communication is an overhead that is seen not only between an AP and nearby stations, but also between two stations attempting to talk to one another. The bottom line of the sector sweep stage is that line-of-sight (LoS) communication is desirable and produces the highest SNR.

The high bandwidth of mm-Wave makes it useful for sensing applications as well. These days, RADAR integration with communication transceivers are becoming popular, and the RADAR, alongside the AP, can be used to localize the various client positions. The localization results can be used by the AP to create beams only in the identified positions without performing a scan. The localization data can also be transmitted to the clients so that they can perform direct peer-to-peer transactions without going through the AP.

This report presents a RADAR-assisted solution to mm-Wave peer-to-peer communication. The setup consists of a master WiFi device that is augmented with an mm-Wave RADAR and two client devices that want to communicate with one using the localization results provided to them. To get the orientation of the devices with respect to one another, all three devices are enabled with orientation readings through a magnetometer.

II. System Design

A. Hardware Set-up

The proposed system consists of different hardware modules such as one RADAR assisted master WiFi Device and two client devices. Client devices are emulated with the help of routers configured as stations, a processing platform such as personal computer or Raspberry Pi and one Inertial Measurement Unit (IMU) device to get magnetometer reading. Fig 1 illustrates the proposed setup further.

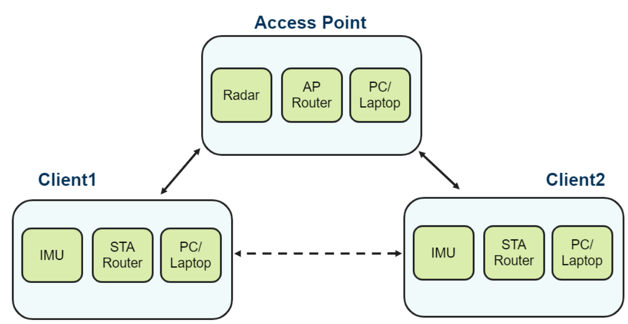

Fig. 1. System Setup

B. Steps of communication

In our proposed design, there are 5 steps involved.

- Step1: Radar identifies both the clients and tracks them while they are in range using DBScan [1] and Hungarian algorithm [2]. AP requests both clients to acknowledge themselves. [Fig 2]
- Step2: Clients respond with their identity such as IP address. [Fig 2].
- Step3: AP sends each client's location to both the clients. [Fig 3].
- Step4: Both clients compute each other's beamforming angle relative to themselves. [Fig 3].
- Step5: Clients beam-form to one another. [Fig 3].

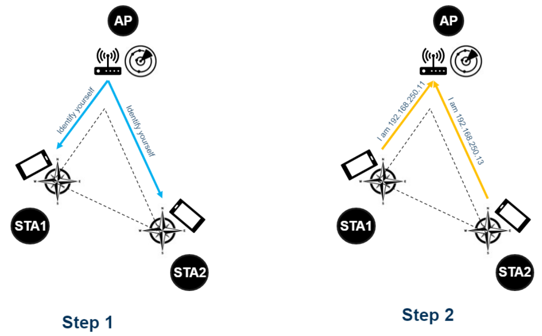

Fig. 2. Steps of communication

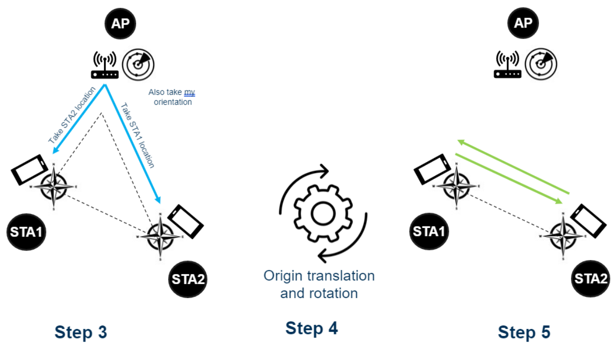

Fig. 3. Steps of communication

III. Algorithm

A. Radar Clustering

The radar is used to locate the mobile clients in real-time. It continuously scans the environment and performs DBSCAN to form clusters. To track the trajectory of mobile clients, it uses Hungarian algorithm. Using the Hungarian algorithm allows the tracking of correlation between frames using a distance measure and eliminating those clusters that do not persist. Noise is largely uncorrelated and are eliminated in this process.

B. Beam Angle Computation

At a given time, the AP and the clients have different headings. This results in different frames of reference for them thus making the beam angle computation a non-trivial problem. The mobile client computes its own beam angle and its peer's angle using magnetometer information of itself, its peer, and the AP.

Let the frame of reference of the AP be considered the global frame of reference for this setup. The position of the AP is $(0, 0)$. The coordinates of the clients, STA 1 and STA 2, are (x_1, y_1) and (x_2, y_2) respectively. The angle between the two clients is given as,

$$\gamma = tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \tag{1}$$

Data: frame data (x, y, z, doppler, frame number, points) from the radar
Result: (x,y) coordinates of each identified cluster
Initialization: $eps \leftarrow 0.15$; $minpts \leftarrow 250$; $alpha \leftarrow 0.25$; $L2 \leftarrow 10000$; $thresh \leftarrow 5$; $maxFails \leftarrow 10$;
while *True* **do**

1. Retrieve frame data from the radar socket.
2. DB-SCAN clustering on frame data and find centroids for the clusters.
3. Use the Hungarian Algorithm for correlation between frames generated as tracks.
4. Identify valid stations from the tracks.
5. Associate each track with the station's IP address and build an IP-track dictionary.
6. Use the IP-track dictionary to set Tx-Sector values on the AP.
7. Use the IP-track dictionary to send the latest (x,y,z) values to the respective stations.

end

Algorithm 1: RADAR clustering algorithm

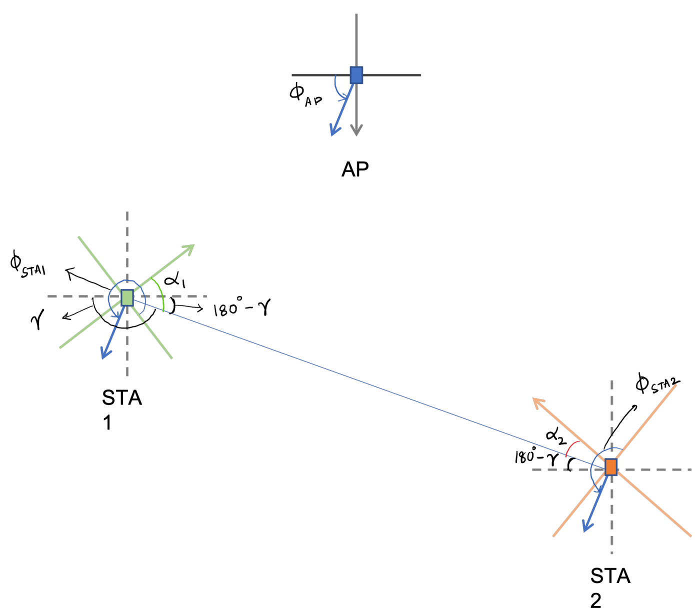

Fig. 4. Diagram for angle computation

The angle of the headings of the AP, STA1, and STA2 and the magnetic north of the earth are ϕ_{AP}, ϕ_{STA1} and ϕ_{STA2} respectively. All angles in this calculation are in degrees and in the range of $[0, 360]$.

Using geometry, it can be shown that the required beam angles for STA 1 and STA 2 to communicate with each other are,

$$\alpha_1 = 90° + \phi_{AP} - \phi_{STA1} - \gamma \tag{2}$$

$$\alpha_2 = 270° + \phi_{AP} - \phi_{STA2} - \gamma \tag{3}$$

where, α_1 is the beam angle from STA 1 and α_2 is the beam angle from STA 2. Once the beam angles are computed, they are mapped to the corresponding Tx sector values of the Mikrotik routers [5].

C. End to end communication

Fig 5 shows the complete system architecture for the end-to-end communication between the clients. To facilitate the steps mentioned in Section II.B, sockets are created in the devices. There is one socket between the AP and mobile station where the AP acts as the client and the mobile client acts as the server. This link is used to transmit the current locations of the stations to the mobile station. A second socket is created between the two stations where station 1 acts as the client and station 2 acts as the server. Station 1 computes the Tx sector value required for station 2 and transmits that information through the created socket.

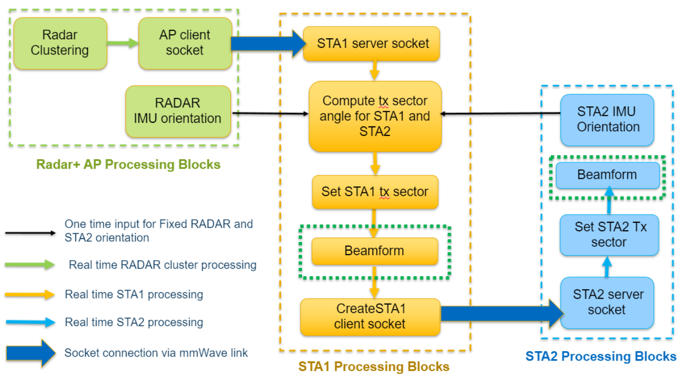

Fig. 5. Processing blocks in different hardware

IV. Experimental Setup

Table I mentions the hardware components that are used in our experimental set-up. There are two underlying assumptions for implementing our experimental set-up to reduce complexity. 1) The three devices are always in range of one another and 2) Z-axis is not relevant in beam selection – simplifies trajectory creation. Furthermore, due the limitation of the hardware we have faced several challenges to implement the design.

- 3-way communication is not possible. The Mikrotik routers cannot communicate in station mode, and mesh cannot be established.
- Mapping all clients with AoA vs. peer-to-peer comm – either one is possible, but not both simultaneously. Experimentation with IMU device MPU9250 [3] shows that the magnetometer data is very noisy. For better magnetometer heading readings, we use the high-end IMUs in smartphones and manual assessment to identify the orientation.
- Dead reckoning not feasible with these IMU MPU9250.
- Beam sweeping at AP is not avoidable. AP could beam form to all clusters from RADAR instead of beam sweep.

But due to lack of client mapping for all STA, we can't distinguish active clusters from inactive.

TABLE I
Hardware components

Device	Model
RADAR	RETINA-4SN
60 GHz AP router	MikroTik wAPx3
IMU	MPU9250
Phone's magnetometer	AK009918C

A. IMU magnetometer accuracy estimation

Fig 6 shows the difference in accuracy of the magnetometer readings between MPU 9250 IMU device and Phone's IMU. We see that the IMUs used in phones are much more reliable. As the objective of this report is not to rectify the IMU readings using various techniques, we resort to the accuracy of the smartphone IMU readings through visual inspection and user input of the magnetometer heading into the algorithm.

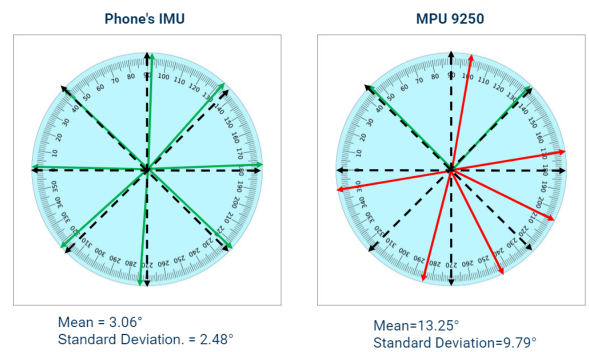

Fig. 6. IMU Accuracy measurement

B. Router SINR Profiling

We use two Mikrotik WAP 60G WiFi routers for mm-Wave communication. The router can be used in both AP mode and STA mode. Fig 7 shows the RSSI measurement at the STA for different beams from the AP. We see that LoS beam provides an RSSI of $-56dB$, while other NLoS beams also produce similar RSSI readings. This happens because the Tx-power of the transmitting router is not controllable with the devices original perating system (RouterOS). The device is designed for communicating in a 300m range, whereas our experiments are conducted within 5m. Despite attenuation, strong beams and sidelobes allow high-RSSI connectivity through reflection.

V. Experimental Results

A. Radar Clustering accuracy

From Fig 8, it can be observed that with an increase in distance from the radar, the accuracy of the radar positioning decreases. The mean error of the clustering algorithm is 20 cm and the standard deviation of the error is 12 cm. This

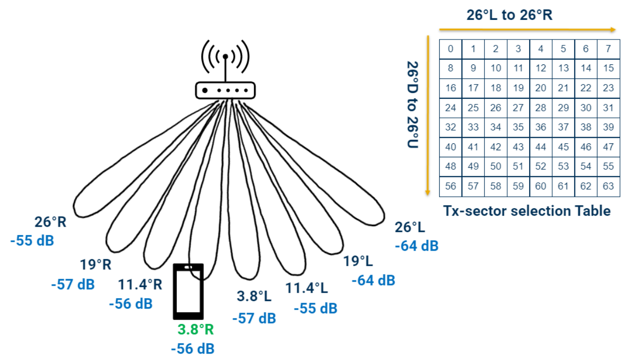

Fig. 7. Router's RSSI profiling

granularity of accuracy is enough for the system to function. Finer clustering than this would improve accuracy but would adversely affect execution time.

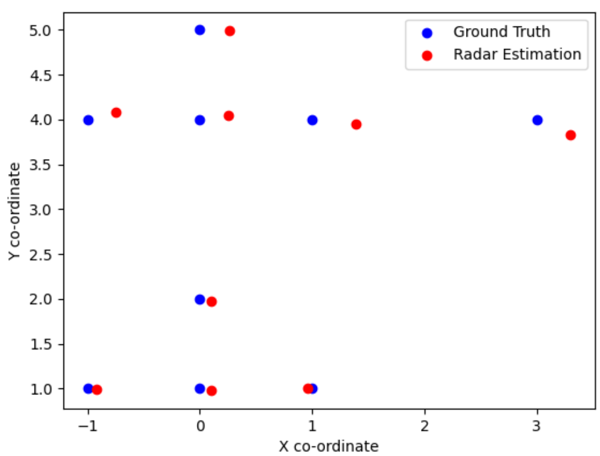

Fig. 8. Radar Clustering location with respect to ground truth

B. SINR vs relative orientation of stations

In this experiment, the heading of one of the stations was fixed at 0° with the magnetic north. The heading of the other station was rotated by 45° each time. 180° means both the stations are facing each other and hence establishing LoS communication. The Tx sector was set to *auto* mode which means the device picks the best beam automatically based on the maximum SNR value.

It can be observed that except for the LoS link, all other orientations have a degradation of around 15 dB from the maximum possible SNR in the set environment.

C. Beam angle selection

This experiment compares the selected beam through the proposed algorithm vs the beam with the maximum SNR for that orientation of the stations. The maximum SNR beam is determined by the beam sweeping from the extreme right

TABLE II
SNR At Different Orientations

Relative orientation (in degrees)	SNR (in dB)
0	-69
45	-68
90	-67
135	-66
180	-51
225	-62
270	-69
315	-70

(beam number 24) to the extreme left (beam number 31) and collecting the SNR values. For simplicity, we ignore the beam numbers that cover the elevation angles and restrict our search between sectors 24 and 31 (See Fig 7 table for sector numbers).

1) Relative orientation of 180°*:* The proposed algorithm computes the Tx sector as 28. From Table IV, it is seen that the maximum SNR is obtained at beam number 27. Beams 27 and 28 are the central beams and have an SNR difference of only 1 dB.

TABLE III
SNR At Different Tx Sectors

Beam number	SNR (in dB)
24	-62
25	-60
26	-55
27	-52
28	-53
29	-59
30	-61
31	-56

2) Relative orientation of 210°*:* The proposed algorithm computes the Tx sector as 31. From Table IV, it is seen that the maximum SNR is obtained at beam number 31. The observed maximum SNR and the selected beam are same in this case.

TABLE IV
SNR At Different Tx Sectors

Beam number	SNR (in dB)
24	-66
25	-65
26	-65
27	-63
28	-62
29	-61
30	-61
31	-60

VI. Conclusion

This report presents a system architecture for direct peer-to-peer communication in mmWave stations. The design and limitations have been explored and the results obtained by implementing a prototype. The proposed algorithm has desirable accuracy.

This work can be extended to compute actual real-time latency reduction by overcoming the current device limitations. This can be explored as part of future work and the testing can be expanded to more than two stations in the system to analyse the scalability in terms of accuracy as well as latency.

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