Beamsteering and Beam-tracking System for Vehicle-to-vehicle (V2V) Wireless Communication

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Some of the challenges in V2V communication include:

- Interference
- Signal Attenuation
- Mobility and Dynamic Topology
- Limited Bandwidth
- Security and Privacy

- Energy Consumption
- Line-of-Sight (LoS) Issues
- Regulatory and Spectrum Allocation
- Weather Conditions
Challenges

Feeding Loss, planar and compact structure, High speed

More than One UAV

Beam Misalignment (AoA/AoD), Atmospheric attenuation, propagation loss, path loss -> Low Gain

Line-of-Sight (LoS) required, small wavelength -> reflects back

Fig. Distributed system for UAV-to-UAV communication
RINGS: Mobility-driven Spectrum-Agile Resilient mmWave Communication Links for Unmanned Aerial Vehicle Traffic Management in the Sky

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Collaborators: PI Dr. Namuduri (UNT), Co-PI Dr. Xiang (UNM)

Illustration of an air corridor

Use case for Vehicle-to-Vehicle and Vehicle-to-Ground communication

**RQ1:** How to efficiently design the phased-array antenna to achieve the maximum gain, bandwidth, steering angle, and minimum beamwidth?

**RQ2:** How to implement an efficient control algorithms to automatically track and steer the beam through Electrical Beamforming and Mechanical steering?
Millimeter wave (mmWave) Band

Millimeter wave (mmWave) frequency refers to the range of electromagnetic waves with wavelengths between **1 and 10 millimeters** and corresponding frequencies between **30 and 300 gigahertz** (GHz).

![Frequency Bands](https://www.everythingrf.com/community/s-band)

When the wavelength is large compared to the size of a raindrop, scattering is predominant.

Conversely, when the wavelength is small compared to the raindrop's size, attenuation due to absorption is predominant.
Millimeter wave (mmWave) Band
Pros and Cons of Millimeter wave (mmWave) Band Utilization

**Pros**

**Wider bandwidth:** Provision to utilize a wider spectrum (30 GHz – 300 GHz).

**High directionality:** mmW band results in smaller apertures, and compact form factor antennas have narrower beam widths, resulting in more directional beam patterns.

**Less congested:** mmW bands are less congested compared to UWB bands.

**Compact form factor:** size reduces as frequency increases.

**Higher data rates:** mmW bands facilitate higher data rates

**Cons**

**Higher atmospheric attenuation**
Millimeter frequency bands experience high atmospheric attenuation due to peak energy absorption by oxygen and water vapor molecules, reducing signal strength during EM wave propagation.

**More prone to external noise**
Interference: Higher frequency signals are more prone to interference from other sources.

HAL open-source article – comprehensive analysis on mmWave communication systems.

https://wiki.dfrobot.com/What_is_mmWave_Millimeter_Wave

https://www.microwavejournal.com/articles/66
3-millimeter-wave-satellite-remote-sensing
Millimeter wave (mmWave) Array

Why mmWave antenna arrays?

**High gain:** mmWave antenna arrays result in improved gain.

**High directionality:** of radiation beam can be attained.

**Higher data rates:** mmW antenna arrays facilitate higher data rates.

**Enhanced beam steering:** mmW arrays facilitate efficient beam steering.

Source

1 × N array

- Power consumption: Antenna arrays can consume more power.
- Side lobe and back lobe issues associated with the design complexity.
- Complexity in feeding network.

N = No. of antenna elements
Where, N = 1, 2, 3, ..., 8.


https://www.metaswitch.com/knowledge-center/reference/
In phased array antennas, the phase of the signal emanating from the individual elements is fixed.

This would give a signal that would be right angles to the axis or plane of the antenna.

By controlling and varying the phase of the signals to the antenna elements, it is possible to provide different directive patterns.

When a phase difference is applied, the signals will constructively combine at an angle that is different from the perpendicular ($\theta=90^\circ$).
Electrical Beamsteering for Planar Array

- Radiation Pattern for “n” of antenna element:

\[ A(k) = a_0 e^{jk\delta_0} + a_1 e^{jk\delta_1} + \ldots + a_{n-1} e^{jk\delta(n-1)} \]

- Magnitude
- Distance between element

\[ d\phi = dsin\theta \Rightarrow dt = \frac{2\pi dsin\theta}{\lambda} \quad d < \lambda/2 \]

Maximum allowed \( d\phi = k \times L_s \times \sqrt{\epsilon_r} \)

\[ k = \frac{2\pi}{\lambda} \]
Electrical Beamsteering for Planar Array

- Cheap
- Low power
- Frequency dependent
- Higher frequency => BW
- High Insertion loss
- Number of PS => higher IL
- Larger size
- Varactor diode, switched line => FET

- Costly
- Digital Domain -> time delay
- ADCs and DACs for each channel
- Most efficient
- Power consumption
- Wide BW = signal splitting in channels
- Delayed lines

- Reduces the no. of digital phase shifters
- Low loss
Mechanical Beam Steering:

- The antenna is mechanically steered to focus the beam in the desired direction.
- Planar phased array patch antennas can be rotated along the radiation plane to focus the beam in a desired direction along with electrical steering (e.g. Doppler weather radar).
- In end-fire antenna arrays, the single elements can be individually rotated to steer the beam mechanically.
- Vivaldi antennas are suitable end-fire antennas as they have large BW and unidirectional radiation patterns.

Tracking Techniques

(1) Target detection, (2) Range of the target, (3) Finding elevation and azimuth angles, (4) Finding Doppler frequency shift

Sequential Lobing

Angular Tracking

Conical Scanning

Figures were collected from various sources on the internet.
Amplitude Comparison Monopulse Systems

- The monopulse systems use the sum pattern on transmit, whereas the sum and difference patterns are used together on receive.

- The difference in the amplitudes obtained from these two beams (i.e. the difference beam) gives the angular error.

- Phase difference between the sum pattern and the difference pattern provides the direction of the angular error.

\[
\Delta \frac{\text{difference voltage}}{\Sigma \text{sum voltage}}
\]

\[
\text{Re}\{\frac{\Delta}{\Sigma}\} = \frac{\Delta}{\Sigma} \cos \delta
\]

Figures were collected from various sources on the internet.
Tracking Techniques

Amplitude Systems  Comparison  Monopulse  Phase-Comparison Monopulse Systems

- The two antenna beams point in the same direction.
- The projection of the target on each beam and the amplitudes of the returns from the target received by each of these antennas are the same.

\[
\frac{\Delta}{\Sigma} \approx k_s \theta, \quad |\theta| \leq \frac{\theta_B}{4}
\]

\(k_s\) is the monopulse slope constant

\(\theta_B\) is the half power beamwidth

Figures were collected from various sources on the internet.
Highly Compact End-Fire mmWave Vivaldi Antenna for V2V Communication

**Design architecture**

**Envisioned case scenario of antennas placed on drones**

**Measurement setup in anechoic chamber**

**Key criteria considered for design:**
- Highly compact
- Suitable to deployment on drone
- High Gain

**Design specifications:**
- Size – 25 mm × 13 mm (3.3 λ × 1.7 λ)
- Realized Gain – 11.4 dBi
- Polarization – Linear polarization
- Half power beam width – 60°

**Measurement results**

- **S-parameter**
  - Frequency (GHz): 26.8 GHz, 54.0 GHz
  - FBW = 67.32%

- **Gain sweep across band**
  - Max Gain (dBi): 12.05 dBi, 11.40 dBi

- **Farfield radiation plots (Normalized)**
  - H-plane at 40.4 GHz
  - E-plane at 40.4 GHz
Highly Compact End-Fire mmWave Vivaldi Antenna for V2V Communication

Specific observations

- Metal materials utilized between the flares resulted in enhanced gain performance.
- Corrugations incorporated in the design results in better S11 performance.

Antenna dimensions: $25 \times 13 \times 0.324 \text{ mm}^3$ ($3.33\lambda \times 1.73\lambda \times 0.04\lambda$).

- Wider bandwidth (>50% FBW)
- High gain (>10 dBi)
- Compact and simple design (< $3\lambda \times 3\lambda$)
- Wide beam steering range (>± 60 degrees)
Highly Compact End-Fire mmWave Vivaldi Antenna for V2V Communication

mmWave Vivaldi antenna array analysis

Schematic of $1 \times N$ mmWave Vivaldi antenna array analysis.

CST estimated absolute gain (dBi) values for $1 \times N$ array

<table>
<thead>
<tr>
<th>Antenna Array</th>
<th>Absolute Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 8$</td>
<td>18.8</td>
</tr>
<tr>
<td>$1 \times 7$</td>
<td>17.4</td>
</tr>
<tr>
<td>$1 \times 6$</td>
<td>16.8</td>
</tr>
<tr>
<td>$1 \times 5$</td>
<td>16.1</td>
</tr>
<tr>
<td>$1 \times 4$</td>
<td>15.3</td>
</tr>
<tr>
<td>$1 \times 3$</td>
<td>14.5</td>
</tr>
<tr>
<td>$1 \times 2$</td>
<td>13.4</td>
</tr>
<tr>
<td>$1 \times 1$ (Single Element)</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Friss pathloss estimations for 1 to 30 m distance range,

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Friis pathloss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.88</td>
</tr>
<tr>
<td>10</td>
<td>46.88</td>
</tr>
<tr>
<td>20</td>
<td>52.90</td>
</tr>
<tr>
<td>30</td>
<td>56.42</td>
</tr>
</tbody>
</table>

- Considering 40 GHz center frequency, the wavelength ($\lambda$) is 0.00749481 m, which is 7.49481 mm, and that of ($\lambda/2$) is 3.747405 mm.

- Friss pathloss estimations for 1 to 30 m distance range,

Friis Equation

$$\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda^2}{4\pi d^2} \right)$$
A Beam-Steerable Compact V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication

12 x 1 Array – Improved Efficiency

Geometry of the Improved 12 x 1 Array.

- Taper length [6]:
  \[ L = \frac{n\lambda_g}{4} \]
  \[ \text{And } \lambda_g = \frac{c}{f\sqrt{\varepsilon_r}} \]
  \[
  \begin{cases}
  \text{Were,} \\
  \lambda_g \text{ is the guided wavelength and } f \text{ is the design frequency, and.} \\
  n = 1,2,3,\ldots
  \end{cases}
  \]

A Beam-Steerable Compact V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication

**Measurement Result**

- A compact and highly efficient SIW-based beam-steerable leaky wave antenna operating in the V-band is proposed.
- The designed antenna covers a wide band of frequency ranging from 56.3 GHz to 63.4 GHz and has a frequency scanning angle of 38° within the operating bandwidth.
- The proposed antenna has the smallest dimension of 3.24 × 0.2 cm, making it highly compact and low profile with a side lobe level of -12.7 dB.
- Average half-power angular Beam-width: 12.1°
A Beam-Steerable Compact V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication

12 x 1 Array – SIW to GCPW

FBW = 6.05%
Rad. Effici. > 89%
Tot. Effici. > 80%
A Beam-Steerable Compact V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication

12 x 1 Array – SIW to GCPW

Max. Gain= 13.5 dBi

Beam-Steering= 37°
A High Gain SIW Elliptically Polarized Antenna for Millimeter-Wave Applications

A High Gain SIW Elliptically Polarized Antenna for Millimeter-Wave Applications

Measurement Result

- Stable gain: 8.34 dBi
- BW: 48.5-62.3 GHz
- Side lobe Level: -8 dB
- Efficiency: > 86%

A High Gain SIW Elliptically Polarized Antenna for Millimeter-Wave Applications

- Stable gain: 8.34 dBi
- BW: 48.5-62.3 GHz
- Side lobe Level: -8 dB
- Efficiency: > 86%

Fig. 2 x 2 Array
A High Gain SIW Elliptically Polarized Antenna for Millimeter-Wave Applications

- Peak gain: 9.5 dBi
- Multi Band: 54.4 GHz-55.8 GHz, 60 GHz-61.5 GHz, 63.6 GHz-66.6 GHz, 69 GHz-70.5 GHz, and 83.5 GHz-89 GHz
- Efficiency: > 90%
- Total BW: 13.5 GHz
- Linear Polarization=> V-band
- CEP=> W-band
- Compact Size: 23.15 mm x 21.4 mm

Fig. Antenna Performance
Future Work

Tracking system development

1) Dual Circularly polarized arrays for tracking and communication
2) Adjustable beam coverage area depending on the target’s distance and velocity
3) A reconfigurable beamwidth control scheme to achieve the best tradeoff between the array gain and the accuracy of the tracking.

• Design of phased array antenna for variable spacing between elements excited using variable voltage controller–> To **reduce** grating lobe.
• Implementation of hybrid beamforming technique with designed phased array (> ±45°).
• Modification of Bow-tie patch element to achieve higher gain (>25 dBi) and circular polarization.
• Using GCPW feeding network to achieve **dual polarization**.
• Substrate analysis–> Efficient, Cost Effective, and Robust–> To **analyze scanning loss and enhance coverage range.**
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