Two beams are better than one
Towards Reliable and High Throughput Millimeter-wave Links

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5G Base station (gNB)

Vehicular application
Requirements for Vehicular and AR/VR applications

- High throughput link
- High reliability
- Easy to maintain (low overhead)
Millimeter-wave provides high throughput but lacks reliability

User mobility

Blockage
mmReliable: Two beams are better than one!

Traditional: Single Beam

mmReliable: Multi-Beam (multiple main lobes)

Multi-beam link avoids a single point of failure ➔ Reliable link
mmReliable: Towards Reliable and High Throughput Millimeter-wave Links

- High reliability
  - Corollary of using multi-beam

- High throughput
  - Creating *Constructive multi-beam*

- Easy to create
  - Standard 5G testbed
  - 5G NR compliant

- Easy to maintain
  - Proactive (not reactive) user tracking and beam maintenance

mmReliable: Multi-Beam (multiple main lobes)
Can multi-beam provide high throughput?

Multi-beam provides 2x SNR gain than single beam ➔ Higher throughput
Achieving high throughput with per-beam **phase control**

\[ a^2 = \text{Transmit power} \]

\[ \frac{a}{\sqrt{2}} e^{-j\sigma} e^{j\sigma} + \frac{a}{\sqrt{2}} = \sqrt{2}a \]

**Multi-Beam**

\[ \text{SNR} \propto (\sqrt{2}a)^2 = 2a^2 \]

**Destructive Multi-Beam**

**Constructive Multi-Beam**

**mmReliable requires phase control to create constructive multi-beam**
Constructive multi-beam also require per-beam **power control**

\[ a^2 = \text{Transmit power} \]

Single Beam

\[ \text{SNR} \propto a^2 \]

Multi-Beam

\[ \text{SNR} \propto (1 + \delta^2)a^2 \]

2nd beam

\[ \text{Signal} \propto \delta e^{-j\sigma} \]

2nd path channel

\[ \propto \delta e^{j\sigma} \]
Strong multi-path exists for mmWave

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflection loss (28 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal surface</td>
<td>1-3 dB</td>
</tr>
<tr>
<td>Glass surface</td>
<td>1-6 dB</td>
</tr>
<tr>
<td>Dry-wall, Concrete</td>
<td>5-10 dB</td>
</tr>
</tbody>
</table>

Strong reflectors leads to higher throughput using constructive multi-beam

Reference: Telecom Infra Project: Analysis of 28GHz and 60GHz Channel Measurements in an Indoor Environment
Constructive Multi-beam can be created using standard mmWave phased arrays.

Phase and Power Control

Constructive Multi-beam can be generated with COTS hardware.
mmReliable is 5G NR protocol compliant

More details in our paper...
Proactively maintaining multi-beam for a mobile user

- Beam Training
- Data
- Beam Training
- Data
- Beam Training
- Data

High-overhead beam training

- Beam Training
- Data
- Data
- Data
- Data
- Data
- Beam Training

Low-overhead user tracking
- Estimate $\sigma, \delta, \phi_1, \phi_2$ periodically
- Refine multi-beam link
We evaluate mmReliable on 5G testbed mMobiLe
Indoor and outdoor evaluation of mmReliable

Indoor 5m link

Outdoor 10m - 80m link
Multi-beams are resilient to blockage

Multi-beam maintain high throughput despite occasional blockages
mmReliable provides improved throughput and reliability

Achieve 100% reliability (median)  While providing 1.5x higher throughput
Two beams are better than one
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Artifacts available
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