5G Millimeter-Wave and Device-to-Device Integration

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Outline

• 5G communication Networks
• Why we need to move to higher frequencies?
• What are the characteristics of mmWave band communications?
• What are the challenges in using mmWave?
• How mmWave challenges can improve D2D communication performance?
• Challenges of D2D mmWave
• Hybrid D2D network
• Simulation Result
5G networks

<table>
<thead>
<tr>
<th>Network Specification</th>
<th>5G</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Data Rate</td>
<td>10 Gb/s</td>
<td>100 Mb/s</td>
</tr>
<tr>
<td>Mobile Data Volume</td>
<td>10 Tb/s/km(^2)</td>
<td>10 Gb/s/km(^2)</td>
</tr>
<tr>
<td>E2E Latency</td>
<td>5 ms</td>
<td>25 ms</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>10% current consumption</td>
<td></td>
</tr>
<tr>
<td>Number of Devices</td>
<td>1 M/km(^2)</td>
<td>1 k/km(^2)</td>
</tr>
<tr>
<td>Mobility</td>
<td>500 km/h</td>
<td>-</td>
</tr>
<tr>
<td>Reliability</td>
<td>99.999%</td>
<td>99.99%</td>
</tr>
</tbody>
</table>
Existing solutions to improve network capacity:

- **Increase Available BW**
  - Carrier Aggregation
  - Cognitive Radio
- **Spectrum Reuse**
  - D2D Communication
  - Small Cell network
- **Increase Spectral Efficiency**
  - Massive MIMO
  - Spectrum Sharing

Even though some of these techniques can boost performance significantly, there is no clear roadmap on how to achieve the so far defined 5G performance targets.
• Microwave band is referred to as Sweet spot due to its favorable propagation characteristics
• Low frequency bands have been almost used up
• It is difficult to find sufficient frequency bands in the microwave range for 5G improvements
• mmWave with high bandwidth can be a potential solution for 5G communication
• However, wave propagation in mmWave band has specific characteristics that should be considered in design of network architecture
mmWave Characteristics

Atmospheric Absorption
- Raindrops are roughly the same size as the radio wavelengths (millimeters) and therefore cause scattering of the radio signal
- The rain attenuation and molecular absorption characteristics of mmWave propagation limit the range of mmWave communications

mmWave Characteristics

High Propagation Loss and Sensitivity to Blockage
- mmWave communication suffers from high propagation loss $PL \propto f^2$
- Electromagnetic waves have weak ability to diffract around obstacles with a size significantly larger than the wavelength
- For example, blockage by a human attenuate the link budget by 20-30 dB
- Only LOS communication is efficient.

<table>
<thead>
<tr>
<th>Frequency Band (GHz)</th>
<th>PLE- LOS</th>
<th>PLE- NLOS</th>
<th>Rain Attenuation @200 m (dB)</th>
<th>Oxygen Absorption @200 m (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>1.8~1.9</td>
<td>4.5~4.6</td>
<td>0.9</td>
<td>0.04</td>
</tr>
<tr>
<td>38</td>
<td>1.2~2</td>
<td>2.7~3.8</td>
<td>1.4</td>
<td>0.03</td>
</tr>
<tr>
<td>60</td>
<td>2.23</td>
<td>4.19</td>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>73</td>
<td>2</td>
<td>2.45~2.69</td>
<td>2.4</td>
<td>0.09</td>
</tr>
</tbody>
</table>

$F(d) = PL(d_0) + 10n \log_{10} \frac{d}{d_0}$

Path-loss Exponent (PLE)

NLOS suffer from high attenuation
mmWave Characteristics

Directivity

- To combat severe propagation loss, high gain, directional antennas are employed at both transmitter and receiver.
- Beamforming is a key enabling technology of mmWave communication.
- With a small wavelength, electronically steerable antenna arrays can be realized as patterns of metal on circuit board.

IBM Breakthrough Could Alleviate Mobile Data Bottleneck

IBM: The packaged transceiver operates at frequencies in the range of 90-94 GHz. It is deployed as a unit tile, combining 4 phased array ICs and 64 dual-polarized antennas.

Directional antenna
High gain at one direction
very low gain in all other directions

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IEEE RFIC 2014 Seattle, WA
D2D Communication

D2D communication allows mobiles to establish a direct connection without traversing the eNodeB (or BS).
D2D is a key component in the context of IoT, since a substantial fraction of the traffic is generated and consumed locally.
Eliminating the eNodeB from the transmission path leads to:
• Higher spectral efficiency
• Lower signaling overhead
• Higher energy efficiency
• Increase the coverage of cell edge UEs
• Reduce the traffic load of BS

However, these gains can only be achieved if we can overcome several challenges faced by D2D communication.
D2D Communication

Main problem in D2D: *Interference Management*

- **D2D over ISM band (using WiFi)**
  - Devices compete to achieve channel access
  - Little interference control
  - Quality of communication is not guaranteed.

- **D2D over licensed band**
  - Guaranteed communication quality
  - Require accurate interference management between cellular and D2D users

Several techniques are proposed to solve these challenges. Still D2D link capacity is significantly affected by the network density:

- Insufficient communication bandwidth
- Significant interference caused due to the omni-directional nature of communication
mmWave Shortcomings Advantage for D2D

Some of the mmWave communication challenges are desirable features for D2D communication:

- High path loss
- Directional beam forming
  - Less interference
  - Improve spatial reuse
- High bandwidth
  - Supports high throughput D2D applications

Challenges
- Narrow beam width
- Low antenna height in D2D communication comparing to BS height

Makes devices more vulnerable to blockage which may cause difficulty to fulfill D2D device discovery and beam alignment.

Hybrid communication: works on mmWave in Line-of-Sight (LoS) case and switch back to microwave in case of blockage, and exchange control signaling in microwave to aid the alignment for mmWave.
Beam alignment protocol

1. BS finds that there is a UE who wants to communicate directly with another UE in its cell
2. BS broadcasts this information as a D2D-link-set-up-request to both UEs.
3. DUE pair receive the request and prepare for the beam alignment process (micro wave band)
4. DUE A will send channel probing signals from each of its sectors in a cycle, and B will receive at each of its sectors and keep recording the signal strength \( (A_k \times B_n) \)
5. BS gets the feedback of the power strength from B and convey information to A.
   - **LoS Link:** If the mmWave power received by B in some sector is greater than a minimum power threshold (T), BS will send A the information: mmWave communication.
   - **Blockage:** If none of B’s sectors received enough power higher than the threshold, which shows there are blockages in the link, BS will inform A to communicate with B on micro wave band
6. A begins to communicate with B in micro wave or mmWave.

\[
\begin{bmatrix}
P_{11} & \cdots & P_{1n} \\
\vdots & \ddots & \vdots \\
P_{k1} & \cdots & P_{kn}
\end{bmatrix}
\]
mmWave D2D integration

**Assumptions**

**Location of BSs**: The locations of the BSs form a homogeneous Poisson Point Process (PPP) $\phi$ on the plane with density $\lambda_B$ and all BSs employ constant downlink transmission power $P_B$.

**Location of DUEs**: The D2D users form another homogeneous PPP $\phi$ on the plane with density $\lambda_D$. The DUE reuse the downlink resource of the cellular links.

**Blockage model**: The blockages are modeled as another PPP of buildings independent of the communication network. Each point of the building PPP is independently marked with a random width, length, and orientation.

**Beam-Forming**: In millimeter wave band, antenna arrays at the base stations and DUEs are all adopted for directional communication. Angle gain between the transmitter beam and the receiver beam is denoted as $G(\theta_t, \theta_r)$, and the maximum achievable array gain is $G(0, 0)$. In microwave band they use omni-directional antenna.

**Beam Alignment**: Due to small size of antenna, they can be used in large scale at equipment to obtain high gain communication. The main beams of the transceiver antennas are perfectly aligned with each other when transmission is being carried on.
Converge probability:

$$P = P\{\text{SINR} > T\}$$

**Microwave Mode:**

$$\gamma_{\text{micro}} = \frac{\mu_{\text{micro}} r^{-\alpha} h_{DD}}{I_{BD} + I_{DD} + \sigma^2}$$

**mmWave Mode:**

Probability of blockage: 
$$a = 1 - e^{-\beta d}$$
$$\beta = \frac{2\lambda_{\text{blockage}} E[w] E[L]}{\pi}$$

$$\gamma_{\text{mm}} = \frac{\mu_{\text{mm}} \alpha[0] g(r_0)}{\sigma^2 + \sum_{k=0}^{K-1} \mu_{\text{mm}} \alpha[\theta_k] g(r_k)}$$

**Hybrid Mode:**

$$P(\text{SINR} > T) = a P(\text{SINR}_{\text{mm}} > T) + (1 - a) P(\text{SINR}_{\text{micro}} > T)$$
## Simulation result

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of BSs $\lambda_B$</td>
<td>$1 \times 10^{-6} m^2$</td>
</tr>
<tr>
<td>Density of DUEs $\lambda_D$</td>
<td>$1 \times 10^{-5} m^2$</td>
</tr>
<tr>
<td>Density of Blockages</td>
<td>$1 \times 10^{-5} m^2$</td>
</tr>
<tr>
<td>Transmitting power of BS $\mu_B$</td>
<td>30dBm</td>
</tr>
<tr>
<td>Transmitting power of DUE in micro wave $\mu_{micro}$</td>
<td>23dBm</td>
</tr>
<tr>
<td>Transmitting power of DUE in mmWave $\mu_{mm}$</td>
<td>23dBm</td>
</tr>
<tr>
<td>SINR threshold $T$</td>
<td>-10dB</td>
</tr>
<tr>
<td>Microwave Path loss exponent</td>
<td>3</td>
</tr>
<tr>
<td>mmWave path loss</td>
<td>4</td>
</tr>
<tr>
<td>Noise Power</td>
<td>-87dB</td>
</tr>
<tr>
<td>Average blockage width</td>
<td>50m</td>
</tr>
<tr>
<td>Average blockage length</td>
<td>50m</td>
</tr>
<tr>
<td>Carrier frequency in mmWave</td>
<td>28 GHz</td>
</tr>
</tbody>
</table>
Simulation Result

Coverage vs D2D distance

Coverage vs D2D link distance
References


