LAYING THE FOUNDATIONS FOR MILLIMETRE-WAVE CELLULAR NETWORKS: CHANNEL CHARACTERISTICS AND MODELLING

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Overview
Overview

• Centre for Wireless Innovation
• Future Cellular: Some of the challenges
• Motivations for moving towards mm-wave frequencies
• Examples of mmWave channel studies at QUB:
  • User equipment (UE) to evolved NodeB (eNB) channel
  • UE to ceiling-mounted access point (AP) channel
  • Device-to-device (D2D) channel characteristics
• Stochastic geometry modelling of D2D communications
• Summary
Centre for Wireless Innovation (CWI)
ECIT - THE INSTITUTE OF ELECTRONICS, COMMUNICATIONS AND INFORMATION TECHNOLOGY

TECHNOLOGIES FOR A FUTURE DIGITAL SOCIETY

CSIT - CENTRE FOR SECURE INFORMATION TECHNOLOGIES
  SECURING OUR DIGITAL TOMORROW

CWI - CENTRE FOR WIRELESS INNOVATION
  NEW TECHNOLOGIES FOR MOBILE, MEDICAL AND SPACE

DSSC - CENTRE FOR DATA SCIENCE AND SCALABLE COMPUTING
  COMPUTING SYSTEMS FOR THE DATA-DRIVEN SOCIETY
CWI is home to:

- 60 Academics & Research Assistants
- Extensive T&M capability to 700 GHz
- Far-field, near-field and reverberation chambers
- State of the art wireless channel characterisation capabilities
- Suite of high performance electromagnetic simulation platforms
Centre for Wireless Innovation

**MOBILE (5G & Beyond)**
- Physical Layer Modelling
- mmWave Enabling Technologies (eMBB)
- Massive MIMO
- Signal Processing
- Machine Type Communications (mMTC)
- Ultra Dense Networks (URLLC)

**MEDICAL**
- Wearable & Implantable Systems
- Antennas & Propagation in Biomedical Applications

**SPACE**
- mmWave Antennas & Filters
- Self-Steered & Retrodirective Antennas
Future Cellular: Some of the Challenges
Higher frequencies: Will infrastructure designs require more base stations due to distance-dependent losses?

Larger numbers of co-located, high-bandwidth mobile data users e.g. City centres

Spectrum in short supply, therefore need higher spectral efficiency (use of massive MIMO, LSA, LAA). Also more devices = more interference

Pressure to lower carbon emissions (both UE and eNodeBs)

Operators are constantly looking for ways to offload network traffic to other networks e.g. WiFi
Motivations for Moving Towards mmWave Frequencies
Motivations for Moving Towards mmWave Frequencies

Global Mobile Data Traffic Drivers

<table>
<thead>
<tr>
<th>Mobile Momentum Metrics</th>
<th>2015</th>
<th>2020</th>
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</thead>
<tbody>
<tr>
<td>More Mobile Users</td>
<td>4.8 Billion</td>
<td>5.5 Billion</td>
</tr>
<tr>
<td>More Mobile Connections</td>
<td>7.9 Billion</td>
<td>11.6 Billion</td>
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<tr>
<td>Faster Mobile Speeds</td>
<td>2.0 Mbps</td>
<td>6.5 Mbps</td>
</tr>
<tr>
<td>More Mobile Video</td>
<td>55% of Traffic</td>
<td>75% of Traffic</td>
</tr>
</tbody>
</table>

Source: Cisco VNI Global Mobile Data Traffic Forecast, 2015–2020
Motivations for Moving Towards mmWave Frequencies

Global Mobile Data Traffic Growth / Top-Line
Global Mobile Data Traffic will Increase 7-Fold from 2016–2021

Source: Cisco VNI Global Mobile Data Traffic Forecast, 2016–2021
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Motivations for Moving Towards mmWave Frequencies (e.g. 60 GHz)

- **Low interference** – due to favourable propagation characteristics, this will allow many cellular users to be co-located.

- **Between 5 – 7 GHz of ‘clear’ bandwidth** available worldwide and high propagation losses will enable high frequency reuse between co-located cellular devices.

- **High data rates** – potentially in excess of 2 Gbps will facilitate multichannel streaming applications including uncompressed video.

- **Small-size of product** – construction of truly miniaturised antenna arrays are feasible ($\lambda = 5$ mm).
Motivations for Moving Towards mmWave Frequencies (e.g. 60 GHz)

- **Hardware** suitable for use in user equipment (UE) still some **distance away** in the future (e.g. power requirements etc.).

- Between 5 – 7 GHz of ‘clear’ bandwidth available... **Everyone else is thinking the same** (likely to be significant competition from other wireless users e.g. WiGig, IoT etc.)

- **Higher signal propagation** losses at mm-wave frequencies mean that innovative system design will be required to support marginal links (e.g. non-line of sight) and overcome shadowing induced by the user.
Oxygen Absorption

- Frequency vs attenuation at sea level
- Green circles indicate regions with attenuation due to oxygen absorption marginally above that for free space
- Blue circles indicate frequencies which suffer significant attenuation
- At 60 GHz attenuation due to oxygen absorption ~12 dB/km meaning that a 100 m link would lose ~1.2 dB due to this effect
- Only really an issue for medium to long range systems
- Here we are interested in short-range mm-wave communications such as those found in small-cells which will occur over tens of metres

Signal Coverage: 2.45 GHz vs 60 GHz

Simulated signal coverage from wireless device on person 13’s front left chest at 2.45-GHz within indoor environment.

Receiver grid of isotropic antennas at height 1 m, with resolution 0.5 * 0.5m.
Signal Coverage: 2.45 GHz vs 60 GHz

Simulated signal coverage from wireless device on person 13’s front left chest at 60-GHz
Examples of mm-wave Channel Studies at QUB
UE to eNB Channel at 60 GHz for Small Cell Deployments
UE to eNB Channel at 60 GHz for Small Cell Deployments

Some key questions:

• How does user handling of the terminal impact the UE to eNB channel at 60 GHz?

• How is the link affected by typical use cases e.g. voice call, “texting” or UE carried in a pocket?

• How are these links affected by the orientation of the user relative to the eNB (i.e. shadowing)?

• How does user movement effect the channel?
Experiments conducted in this study were all carried out at an operating frequency of 60 GHz.

- In-package antennas (realistic for UE devices)
- The TX unit was configured to deliver a continuous wave signal with a maximum Equivalent Isotropically Radiated Power (EIRP) of +10.9 dBm.
Experiments: Measurement Setup and Environments

- Mobile line-of-sight (LOS) and non-LOS (NLOS) channel conditions were considered: the user walked towards and away from the eNB in a straight line.

- NLOS channel conditions only occurred when the direct signal path between the UE and eNB was obstructed by the user’s body.

- Three different environments
  - Indoor Hallway
  - Indoor Open Office Area
  - Outdoor Car Park
Some Typical Use Cases

Texting (Hand)

Pocket

Voice Call (Head)
Key points:
- Antenna radiation patterns distorted for all three use cases compared to free space.
- Forward gain for pocket location not as significantly affected compared to ‘held’ positions (i.e. hand and head).
- Shadowing of the user’s head clearly evident (angles between 30° and 150° compared to 210° and 330°).

Path Loss and Body Shadowing

Hypothetical eNodeB (eNB)

VNA collected samples of the $b_1$ wave quantity at a sample rate of 118 Hz.

Test subject walked towards (LOS) and away (NLOS) from eNB.
Path Loss and Body Shadowing

- Path loss estimated using classical power law in logarithmic form:

\[ P[dB] = P_0 + 10n \log_{10}(d/d_0) + \gamma[dB] + \chi[dB] \]

- \( P_0 \) represents the path loss at the reference distance (\( d_0 \))
- \( n \) is the path loss exponent which indicates the rate at which the path loss increases with distance
- \( d \) is the transmitter-receiver separation distance
Path Loss and Body Shadowing

• Path loss estimated from raw received signal power using linear regression performed in MATLAB.
• Body shadowing factor (BSF) calculated as the difference between $P_0$ for the LOS and NLOS conditions.
Path Loss and Body Shadowing

- Path loss exponents for LOS lower than that anticipated for free-space ($n = 2$). Mixture of antenna gain and where applicable “wave-guiding” effect
- NLOS path loss exponents generally much lower due to dominating effect of body shadowing

<table>
<thead>
<tr>
<th>Environments</th>
<th>TX Positions</th>
<th>$D_{SN}$ (dB)</th>
<th>$n$</th>
<th>$P_0$(dB)</th>
<th>$n$</th>
<th>$P_0$(dB)</th>
<th>$n$</th>
<th>$P_0$(dB)</th>
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<tbody>
<tr>
<td>Hallway</td>
<td>Head</td>
<td>18.1</td>
<td>1.40</td>
<td>48.7</td>
<td>0.29</td>
<td>66.5</td>
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<tr>
<td></td>
<td>Hand</td>
<td>13.0</td>
<td>1.60</td>
<td>51.1</td>
<td>1.95</td>
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<td>9.1</td>
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<td>1.30</td>
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<td>Hand</td>
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<td>0.24</td>
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<td>Car park</td>
<td>Head</td>
<td>2.1</td>
<td>1.90</td>
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<td>72.6</td>
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Path Loss and Body Shadowing

- Body shadowing a significant factor, up to 30 dB loss when moving from LOS to NLOS (Pocket, car park)
- “Texting” or hand use case less effected by human body shadowing

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<th>BSF (dB)</th>
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<td>59.1</td>
<td>0.61</td>
<td>88.5</td>
<td>29.4</td>
</tr>
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</table>

Shadowed and Small-Scale Fading

- Shadowed fading obtained by first removing path loss and then averaging using a moving window of 7 samples (equivalent to 10 wavelengths)
- Modelled as a gamma distributed random variable with parameters $\alpha$ (shape) and $\beta$ (scale)
- Small-scale fading obtained by removing path loss and shadowed fading from raw received signal power...
Shadowed Fading

Hallway

Small-scale Fading

• The **Rice fading model** has traditionally been used to describe small-scale fading for **LOS** channel conditions, while the **Nakagami-\(m\) fading model** is synonymous with the characterization of **NLOS** channels.

• Probability density function (PDF) and cumulative distribution function (CDF)
  
  ➢ Rice fading channel

\[
f_R(r) = \frac{2(K+1)rI_0\left(2\sqrt{\frac{K(K+1)r^2}{\Omega}}\right)}{\Omega \exp\left(K + \frac{(K+1)r^2}{\Omega}\right)}, \\
F_R(r) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(K+1)r^2}{\Omega}}\right)
\]

  ➢ Nakagami-\(m\) fading channel

\[
f_R(r) = \frac{2m^{m-1}r^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{mr^2}{\Omega}\right), \\
F_R(r) = \frac{\gamma\left(m, \frac{mr^2}{\Omega}\right)}{\Gamma(m)}
\]
Path Loss and Body Shadowing

- Strong dominant signal component ($K > 1$) for all of the LOS scenarios
- Hand position consistently provided the lowest $K$ values across all of the environments
- For the NLOS scenarios, the $m$ parameter was always found to be greater than 2.
- This result suggests that clustered multipath contributions may have been responsible for shaping the small-scale fading contribution.

<table>
<thead>
<tr>
<th>Environments</th>
<th>TX Positions</th>
<th>$s$</th>
<th>$\sigma$</th>
<th>$K$</th>
<th>$m$</th>
<th>$\Omega$</th>
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<td>0.26</td>
<td>6.9</td>
<td>2.46</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Fading Characterization of UE to Ceiling-mounted AP Communications at 60 GHz
Experiments: Measurement Setup and Environments

- 7.5 dBi on-chip antenna in-package
- EIRP of 10.9 dBm
- Channel sampling frequency of 2 kHz
- Receive bandwidth of 86 kHz
Experiments: Measurement Setup and Environments

- An indoor hallway environment
- Mobile channel conditions
  - LOS – Walked towards the AP
  - NLOS – Walked away from the AP
- Imitated three different use cases
  - Making a voice call (head)
  - Sending a text message or operating an app (hand)
  - Carrying a device (pocket)
Second-order Statistics

- Level crossing rate (LCR) is defined as the average number of times a fading envelope crosses a given signal level with a positive slope within a certain period of time.

- Average fade duration (AFD) is defined as the average time duration that a fading envelope is found below a given signal level.
  - Rice fading channel
    \[
    N_R(r) = \frac{f_m \sqrt{2\pi (K + 1)r^2} I_0 \left(2\sqrt{\frac{K(K+1)r^2}{\Omega}}\right)}{\sqrt{\Omega} \exp \left(K + \frac{(K+1)r^2}{\Omega}\right)}, \quad T_R(r) = \frac{\exp \left(K + \frac{(1+K)r^2}{\Omega}\right) \left[1 - Q \left(\sqrt{2K}, \sqrt{2 \frac{(1+K)r^2}{\Omega}}\right)\right]}{f_m \sqrt{2\pi (K+1)r^2} I_0 \left(2\sqrt{\frac{K(1+K)r^2}{\Omega}}\right)}
    \]
  - Nakagami-\(m\) fading channel
    \[
    N_R(r) = \frac{f_m \sqrt{2\pi}}{\Gamma(m)} \left(\frac{mr^2}{\Omega}\right)^{m-\frac{1}{2}} \exp \left(-\frac{mr^2}{\Omega}\right), \quad T_R(r) = \frac{\gamma \left(m, \frac{mr^2}{\Omega}\right) \left(\frac{\Omega}{mr^2}\right)^{2m-1} \exp \left(\frac{mr^2}{\Omega}\right)}{f_m \sqrt{2\pi}}
    \]
To extract the small-scale fading from the channel data for analysis, all measurements were normalized with respect to the local mean which was calculated by averaging over a distance of 10 wavelengths.

The parameter estimates for the Rice and Nakagami-$m$ fading models were obtained using MLE.

To ascertain the most probable model between Rice and Nakagami-$m$ distributions, the second-order Akaike information criterion was employed.
Parameter Estimates

<table>
<thead>
<tr>
<th>Channel Conditions</th>
<th>UE Positions</th>
<th>Rice</th>
<th>Nakagami-m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>s</td>
<td>σ</td>
</tr>
<tr>
<td>LOS</td>
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<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Hand</td>
<td>0.91</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Pocket</td>
<td>0.99</td>
<td>0.40</td>
</tr>
<tr>
<td>NLOS</td>
<td>Head</td>
<td>0.87</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Hand</td>
<td>0.93</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Pocket</td>
<td>0.85</td>
<td>0.66</td>
</tr>
</tbody>
</table>

- There existed a dominant signal component ($K > 1$) for the LOS cases over all of the UE positions.
- The pocket position had higher $K$ parameter estimates than those for the head and hand positions, suggesting that there existed stronger dominant signal components in the pocket-to-AP channels compared to others.
Parameter Estimates

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- There existed a strong dominant signal component ($K > 1$) for the LOS cases over all of the UE positions.
- The pocket position had higher $K$ parameter estimates than those for the head and hand positions, suggesting that there existed stronger dominant signal components in the pocket-to-AP channels compared to others.
- A strong dominant signal component existed even for the NLOS hand case, suggesting that the hand UE position typically had a quasi-LOS with the AP.
The highest $m$ parameter was observed at the pocket and hand positions for the LOS and NLOS channel conditions respectively.

Nevertheless, across all the LOS and NLOS scenarios, the $m$ parameters were greater than 1, indicating that the NLOS channel conditions were subject to less severe fading than those experienced in Rayleigh fading channels ($m = 1$).
The Nakagami-\(m\) distribution was chosen as the best model with the exception of the LOS pocket case.

For the LOS scenarios, the direct signal path between the UE and AP was obscured by the user’s hand for the head and hand positions whereas there existed the direct signal link between UE and AP for the pocket position.

---

**Model Selection**

| Channel Conditions | UE Positions | \(s\) | \(\sigma\) | \(K\) | \(\Omega\) | \(f_m\) (Hz) | Rank | \(m\) | \(\Omega\) | \(f_m\) (Hz) | Rank |
|--------------------|-------------|------|-----|------|-----|-------|-----|-----|------|-------|-----|-----|
| **LOS**            | Head        | 0.90 | 0.61 | 1.12 | 1.56 | 140.5 | 2   | 1.28 | 1.56 | 108.3 | 1   |
|                    | Hand        | 0.91 | 0.59 | 1.19 | 1.53 | 100.2 | 2   | 1.33 | 1.53 | 77.7  | 1   |
|                    | Pocket      | 0.99 | 0.40 | 3.02 | 1.31 | 94.3  | 1   | 2.00 | 1.31 | 65.4  | 2   |
| **NLOS**           | Head        | 0.87 | 0.65 | 0.90 | 1.60 | 148.5 | 2   | 1.21 | 1.60 | 118.2 | 1   |
|                    | Hand        | 0.93 | 0.57 | 1.35 | 1.50 | 99.6  | 2   | 1.38 | 1.50 | 75.5  | 1   |
|                    | Pocket      | 0.85 | 0.66 | 0.83 | 1.61 | 212.6 | 2   | 1.19 | 1.61 | 171.8 | 1   |
Model Selection

- The Nakagami-\(m\) distribution was chosen as the best model with the exception of the LOS pocket case.
- For the LOS scenarios, the direct signal path between the UE and AP was obscured by the user’s hand for the head and hand positions whereas there existed the direct signal link between UE and AP for the pocket position.
- For the NLOS scenarios, the Nakagami-\(m\) fading model was selected in all of the NLOS cases.

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<tbody>
<tr>
<td></td>
<td>s</td>
<td>(\sigma)</td>
<td>(K)</td>
</tr>
<tr>
<td>LOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>0.90</td>
<td>0.61</td>
<td>1.12</td>
</tr>
<tr>
<td>Hand</td>
<td>0.91</td>
<td>0.59</td>
<td>1.19</td>
</tr>
<tr>
<td>Pocket</td>
<td>0.99</td>
<td>0.40</td>
<td>3.02</td>
</tr>
<tr>
<td>NLOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>0.87</td>
<td>0.65</td>
<td>0.90</td>
</tr>
<tr>
<td>Hand</td>
<td>0.93</td>
<td>0.57</td>
<td>1.35</td>
</tr>
<tr>
<td>Pocket</td>
<td>0.85</td>
<td>0.66</td>
<td>0.83</td>
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</table>
Data Fitting - CDF
Data Fitting – LCR & AFD
Millimetre-Wave Device-to-Device Communications
Future Cellular Networks: Why Device-to-Device Communications?

• Advantageous to use network users themselves as relays by employing device-to-device (D2D) communications

• By (cooperatively) transmitting from UE to UE, we can:
  ✓ Extend the range of infrastructure networks *(less eNodeBs required)*
  ✓ Increase capacity where it is needed most *(high densities of users)*
  ✓ Reuse frequencies over shorter distances *(higher spectral efficiency)* and reduce interference
  ✓ Users simultaneously connected to multiple networks *(readily off-load data)*
  ✓ Reduce the transmit power at both eNodeB and UE *(save energy)*
D2D Communications

Some key questions:

• How are the wireless links in D2D communications impacted by human body movement and shadowing?

• Can we use instantaneous connectivity information at different frequencies to indicate how closely located people are within a D2D network?

• How we go beyond existing routing technologies to incentivise the participation of resources for D2D networking?

• How does network performance vary with UE density?

• How much do the proposed D2D communications enhance the capacity of the infrastructure-based network?
D2D Operating Distances

Outdoors, Both Persons Facing Towards One Another, Voice Call

2.45 GHz, 5.8 GHz, 60 GHz

>50 m
D2D Operating Distances

Outdoors, Both Persons Facing Away from Each Other, Voice Call

- 60 GHz: 5 m
- 5.8 GHz: 30 m
- 2.45 GHz: >50 m
Pedestrian Shadowing a 60 GHz D2D Link

Outdoors, 10 m link, person intersecting direct line of sight path
Pedestrian Shadowing a 60 GHz D2D Link

Outdoors, 10 m link, person intersecting direct line of sight path

Deep fades of >30 dB possible

Significant fading events can last between 50 and ~500 ms
• We looked at two generalised fading models, namely κ-μ and η-μ
• LOS: κ-μ fading model:

\[
\kappa = \frac{\text{Total power of dominant components}}{\text{Total power of the scattered components}}
\]

\[
f_p(\rho) = \frac{2\mu (1+\kappa)^{\frac{\mu+1}{2}}}{\kappa^{\frac{\mu-1}{2}} \exp(\mu \kappa)} \rho^\mu \exp\left(-\mu (1+\kappa) \rho^2\right) l_{\mu-1}\left(2\mu \sqrt{\kappa (1+\kappa) \rho}\right)
\]

μ is related to the number of multipath clusters
NLOS: $\eta-\mu$ fading model:

Format 1: $\eta$ is the scattered wave power ratio between the in-phase and quadrature components

$$ h = \frac{2+\eta^{-1}+\eta}{4} \quad \text{and} \quad H = \frac{\eta^{-1}-\eta}{4} $$

Format 2: $\eta$ is the correlation coefficient between the scattered wave in-phase and quadrature components of each cluster of multipath

$$ h = \frac{1}{1-\eta^2} \quad \text{and} \quad H = \frac{\eta}{1-\eta^2} $$

$$ f(\rho)_P = \frac{4\sqrt{\pi}\mu^{\mu+\frac{1}{2}}h^\mu}{\Gamma(\mu)H^{\mu-\frac{1}{2}}} \rho^{2\mu} \exp(-2\mu h \rho^2) I_{\mu-\frac{1}{2}}(2\mu H \rho^2) $$

$\mu$ is related to the number of multipath clusters
D2D Communications: Special Cases

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$\kappa$-\mu</th>
<th>$\eta$-\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh</td>
<td>$\kappa \rightarrow 0, \mu = 1$</td>
<td>$\eta = 1, \mu = 0.5$</td>
</tr>
<tr>
<td>Rice</td>
<td>$\mu = 1$</td>
<td></td>
</tr>
<tr>
<td>Nakagami-$m$</td>
<td>$\kappa \rightarrow 0, \mu = m$</td>
<td>$\eta = 1, \mu = m/2$ or $\eta \rightarrow 0, \mu = m$</td>
</tr>
<tr>
<td>Hoyt (Nakagami-$q$)</td>
<td>$\mu = 0.5$</td>
<td>$\eta \rightarrow 0, \mu = 0.5$ or $\eta \rightarrow \infty, \mu = 0.5$</td>
</tr>
<tr>
<td>One-sided Gaussian</td>
<td>$\kappa \rightarrow 0, \mu = 0.5$</td>
<td></td>
</tr>
</tbody>
</table>
D2D Communications: Example Data Fits

\[ \kappa = 5.27, \mu = 1.13, \Omega = 1.14 \]

Text-to-Text

LOS

5 m

5 m
D2D Communications: Example Data Fits

Text-to-Text

NLOS

\[ \sigma = 0.83 \]
\[ \eta = 1.00, \mu = 0.85, \Omega = 1.48 \]
D2D Communications Over Generalised Fading Channels

D2D links provide higher rates than those of the cellular link when the spectrum partition factor is appropriately chosen.

As anticipated, spectral efficiency improves with an increase in the $\kappa$ parameter.
Summary

• Many challenges lie ahead with the development of future cellular networks.
• Operating communications at millimetre-wave frequencies will go some way to addressing many of these.
• Nonetheless at these frequencies, it is extremely important that careful consideration is given as to the impact of human activity.
• For example how the UE is held, and how the device is used/positioned.
• Furthermore, whether an optical LOS with the eNB can reliably be achieved and the magnitude of body shadowing (often as great as 30 dB).
Summary

- Device-to-device communications also offer an exciting opportunity to mitigate many of the challenges.
- Nonetheless, the wireless links in D2D networks will also be impacted by human activity.
- Possibly more so, due to the low elevation of the transmitter and receiver.
Thank You!