Coverage and Capacity Analysis of mmWave Cellular Systems

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Why millimeter wave?

- Huge amount of spectrum possibly available in mmWave bands
- Technology advances make mmWave possible for low cost consumer devices
- mmWave research is as old as wireless itself, e.g. Bose 1895 and Lebedew 1895
The importance of antennas at mmWave

millimeter wave band

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>2.1</td>
</tr>
<tr>
<td>7 (unic)</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

spatial multiplexing & beamforming

28 GHz

37 / 42 GHz

60 GHz

E-Band

just beamforming

... to 300 GHz

spatial multiplexing for spectral efficiency

multiple data streams

isotropic radiator

isotropic radiator

mmWave aperture

TX

RX

sub-6GHz aperture

Spatial multiplexing for spectral efficiency


several GHz of spectrum is promising but found in many separate bands

2.1 GHz

28 GHz

37 / 42 GHz

60 GHz

E-Band

... to 300 GHz

Differentiating features of mmWave cellular
Large antenna arrays result in
- Large-dimensional precoding/combining matrices
- High channel estimation, training, and feedback overheads unless smart algorithms exploited

Need to design low-complexity precoding and channel estimation algorithms
Different communication channel bandwidth

Large channel bandwidth (high noise power, low SNR before beamforming)
- Implementing random access, channel training and estimation functions is challenging

Broadband channels coupled with delay spread
- Equalization would likely be required at the receiver
- Hardware constraints may make it difficult to perform equalization entirely in baseband

Need new algorithms and architectures for broadband communication
**Hardware constraints**

- Cost, power, and complexity limit the # of RF chains (high-resolution ADCs)
  - Signal processing can not be done entirely in the baseband
- Analog beamforming usually uses a network of phase shifters
  - Additional constraints: Constant gain and quantized angles

**MIMO transceiver DSP algorithms need to incorporate new constraints**
## Channel characteristics

<table>
<thead>
<tr>
<th></th>
<th>sub-6 GHz Wifi or Cellular</th>
<th>mmWave Wifi</th>
<th>mmWave 5G (???)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bandwidth</td>
<td>1.4 MHz to 160 MHz</td>
<td>2.16 GHz</td>
<td>100 MHz to 2 GHz</td>
</tr>
<tr>
<td># antennas @ BS or AP</td>
<td>1 to 8</td>
<td>16 to 32</td>
<td>64 to 256</td>
</tr>
<tr>
<td># antennas at MS</td>
<td>1 or 2</td>
<td>16 to 32</td>
<td>4 to 32</td>
</tr>
<tr>
<td>delay spread</td>
<td>100 ns to 10 us</td>
<td>5 to 47 ns</td>
<td>12 to 40 ns</td>
</tr>
<tr>
<td>angle spread</td>
<td>1° to 60°</td>
<td>60° to 100°</td>
<td>up to 50°</td>
</tr>
<tr>
<td># clusters</td>
<td>4 to 9</td>
<td>&lt; 4</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>orientation sensitivity</td>
<td>low</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>small-scale fading</td>
<td>Rayleigh</td>
<td>Nakagami</td>
<td>non-fading or Nakagami</td>
</tr>
<tr>
<td>large-scale fading</td>
<td>distant dependent + shadowing</td>
<td>distant dependent + shadowing</td>
<td>distant dependent + blockage</td>
</tr>
<tr>
<td>path loss exponent</td>
<td>2-4</td>
<td>2 LOS, 2.5 to 5 NLOS</td>
<td>2 LOS, 3.5 to 4.5 NLOS</td>
</tr>
<tr>
<td>penetration loss</td>
<td>some</td>
<td>varies</td>
<td>possibly high</td>
</tr>
<tr>
<td>channel sparsity</td>
<td>less</td>
<td>more</td>
<td>more</td>
</tr>
<tr>
<td>spatial correlation</td>
<td>less</td>
<td>more</td>
<td>more</td>
</tr>
</tbody>
</table>

Some channel characteristics can be leveraged in the signal processing...
**Sensitivity to blockages**

- **blockage due to buildings**
  - line-of-sight
  - non-line-of-sight

- **hand blocking**

- **self-body blocking**

- **blockage due to people**

**Need models for these forms of blockage**
MmWave cellular system analysis


MmWave performance analysis

Need to incorporate directional beamforming
- RX and TX communicate via main lobes to achieve array gain
- Steering directions at interfering BSs are random

Need to distinguish LOS and NLOS paths
- Incorporate different characteristics in LOS & NLOS channels
- Better characterize building blockages

Include beamforming + blockage in mmWave cellular analysis
Accounting for beamforming

- Each base station is marked with a directional antenna
  - Antenna directions of interferers are uniformly distributed
  - Assume perfect beam alignment for desired signal link
- Use “sectored” pattern in analysis for simplicity
  - Antenna pattern fully characterized by $\theta$, $M$ and $m$
Incorporating building blockages

Buildings in some cities, e.g. parts of Boston, form regular grids

Other cities have less regular planning

Use the concept of the LOS probability \( p(r) \) to separate LOS/ NLOS links

- A link of length \( r \) is LOS with probability \( p(r) \)
- LOS probability \( p(r) \) is a non-increasing function of the link length \( r \)

Find the LOS probability based on the certain building models

- Using stochastic models from random shape theory*
- Using site-specific maps from geographical information system (GIS) database

General mmWave network model

- Use stochastic geometry* to model BS locations as marked PPP
  - Model the steering directions of BSs as independent marks of the point process
  - User connects to the BS with smallest path loss
- Use distance-dependent LOS probability function \( p(r) \)
  - Different path loss laws (exponents) for LOS and NLOS paths
  - Assume independent LOS probabilities among links

Simplified model for dense networks

- **Approximate LOS region by an equivalent LOS ball**
  - Theorem 1 can be inefficient to compute due to the general form of $p(r)$
  - Simplify a general $p(r)$ as a step function by matching its first moment
  - Enable simplified expressions for further performance analysis

**Fig. 11.** Comparison of mmWave and microwave massive MIMO asymptotic results. The simulations show that mmWave massive MIMO asymptotically achieves better SINR than microwave, as RX beamforming thins the interference, and blockages also improve SINR.

**Fig. 8.**

- Simplified model for dense networks
  - Approximate LOS region by an equivalent LOS ball
  - Less than 5% error in coverage
  - LOS ball model captures most nearby LOS interferers that dominate the performance in dense networks

**Theorem 1**: The probability of a user being in a LOS region can be approximated by an equivalent LOS ball centered at the user, with a radius that is a function of the propagation environment.

**SINR Coverage Probability**

- $\text{SINR threshold in dB}$
- $\text{SINR Coverage Probability}$

- $\text{LOS BS}$
- $\text{NLOS BS}$
- $\text{Typical user}$

- $\text{ISD}=200 \text{ m}, p(t)=e^{-\beta t}, \frac{1}{\beta}=200 \text{ m}$

- $\text{LOS ball approximation}$

- $\text{LOS ball model captures most nearby LOS interferers that dominate the performance in dense networks}$
Results on SINR coverage
SINR coverage of mmWave cellular

Theorem 1 [mmWave SINR Distribution]
The SINR coverage probability (CCDF of SINR) in mmWave networks is
\[ P(\text{SINR} > T) = A_L P_{c,L}(T) + A_N P_{c,N}(T), \]
where the conditional coverage probability by LOS BSs is
\[ P_{c,L}(T) \approx \sum_{n=1}^{N_L} (-1)^{n+1} \binom{N_L}{n} \int_0^\infty e^{-\frac{n \eta L x^{2} L T \sigma^2}{c L M_{l} M_{t}}} Q_n(T,x) - V_n(T,x) f_L(x) \ dx, \]
and the conditional coverage probability by NLOS BSs is
\[ P_{c,N}(T) \approx \sum_{n=1}^{N_N} (-1)^{n+1} \binom{N_N}{n} \int_0^\infty e^{-\frac{n \eta N x^{2} N T \sigma^2}{c N M_{l} M_{t}}} Q_n(T,x) - V_n(T,x) f_N(x) \ dx. \]

SINR coverage expressions for general mmWave networks
- Apply to general building distribution, i.e., LOS probability function \( p(r) \)
- Assume Nakagami fading with different parameters for LOS and NLOS
- Can be simplified in some special cases of \( p(r) \), e.g. step function in the dense network model
Coverage in dense mmWave networks

Theorem 2 [Simplified SINR distribution in dense network]

\[ P_c(T) \approx \rho e^{-\rho} \sum_{\ell=1}^{N} (-1)^{\ell+1} \binom{N}{\ell} \int_{0}^{1} \exp \left( -\frac{2}{\alpha_L} b_k (\ell \eta T \bar{a}_k) \frac{2}{\alpha_L} \Gamma \left( -\frac{2}{\alpha_L}; \ell \eta T \bar{a}_k, \ell \eta T \bar{a}_k s^{\frac{\alpha_L}{2}} \right) \right) dt \]

- In dense network, SINR largely depends on the relative BS density \( \rho \)
  - \( \rho \) is defined as the base station density normalized by the LOS region size
  - \( \rho \) can be considered as the average number of BSs that are LOS to a user
- Asymptotic analysis when networks become ultra dense
  - Performance of dense networks limited by LOS interferers, which are typically strong
  - When LOS exponent no larger than 2, asymptotic SINR converges to 0 in probability

Coverage gain from large arrays

Assume no RX beamforming
Signal bandwidth: 500 MHz
Avg. ISD: 200 m
Avg. LOS range: \(1/\beta = 141\) m
Carrier frequency: 28GHz
Tx antenna input power: 30dBm

**SINR coverage benefits from directional beamforming w/ large arrays**

- Larger directivity improve SINR coverage by boosting signal power
- Small beamwidth reduces the chance of strong interference
Coverage w/ different BS densities

Carrier freq.: 28 GHz
Signal Bandwidth: 500 MHz
Tx power: 30 dBm
Tx directivity gain: 20 dB*
Tx beamwidth: 30 degree*
Rx directivity gain: 10 dB
Rx beamwidth: 90 degree
LOS probability: $p(r) = e^{-\beta r}$
Avg. LOS range: $1/\beta = 200$ m
ISD: average inter-site distance

Noise-limited due to insufficient link budget

Interference-limited as SINR converges to SIR

SINR distribution sensitive to BS density

- SINR not invariant with BS density due to LOS/NLOS links and noise power
- From noise-limited to interference-limited when increasing BS density
- Good coverage achieved when BSs are sufficiently dense

* Beamforming parameter @ 28 GHz from: Z. Pi and F. Khan, “A millimeter-wave massive MIMO system for next generation mobile broadband,” In proc. of Asilomar, Nov. 2012
SINR coverage comparison

28 GHz strategy:
Beamforming @LOS
2 streams enabled by polarization

Mode adaptation @ NLOS
Optimize # of streams
NLOS channel model from [1]
No polarization

73 GHz strategy:
Beamforming w/ 1 stream

Gain from smaller beamwidth @ 73 GHz

Due to larger noise power @ 73 GHz

2 GHz parameters:
Signal bandwidth: 50 MHz
ISD: 500 m
TX power: 46 dBm
4X4 MIMO with ZF receiver

28 GHz parameters:
Signal bandwidth: 500 MHz
TX power: 30 dBm
8-by-8 UPAs at BSs
4-by-4 UPAs at MSs
Each with 4 RF chains

73 GHz parameters:
Signal bandwidth: 2 GHz
TX power: 30 dBm
20-by-20 at BSs
5-by-5 at MSs
Using analog beamforming only
(Same aperture size as 28 GHz)

Building statistics:
LOS range: 70 m
(NYU measurement)
Perfect CSI at TX and RX

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Results on rate
Rate coverage comparison

28 GHz strategy:
- Beamforming @ LOS
- 2 streams enabled by polarization

Mode adaptation @ NLOS
- Optimize # of streams
- NLOS channel model from [1]
- No polarization

73 GHz strategy:
- Beamforming w/ 1 stream

2 GHz parameters:
- Signal bandwidth: 50 MHz
- ISD: 500 m
- TX power: 46 dBm
- 4X4 MIMO with ZF receiver

28 GHz parameters:
- Signal bandwidth: 500 MHz
- TX power: 30 dBm
- Using hybrid beamforming:
  - 8-by-8 UPAs at BSs
  - 2-by-2 UPAs at MSs
  - Each with 4 RF chains

73 GHz parameters:
- Signal bandwidth: 2 GHz
- TX power: 30 dBm
- Using analog beamforming:
  - 20-by-20 at BSs
  - 5-by-5 at MSs
- (Same aperture size as 28 GHz)

Building statistics:
- LOS range: 70 m
- (NYU measurement)

Rate computation:
- 5 dB gap from Shannon
- Clipping not shown in the plot

Gain from larger BW
Gain from dense BS deployment
Gain over conventional cellular system

### Average rate comparison

**Downlink rate at a typical outdoor user**

<table>
<thead>
<tr>
<th>scenario</th>
<th>5% rate (Mbps)</th>
<th>avg rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 GHz with 1TX 1RX</td>
<td>1.3</td>
<td>68</td>
</tr>
<tr>
<td>2 GHz with 4TX 4RX</td>
<td>13</td>
<td>149</td>
</tr>
<tr>
<td>28 GHz with sparse BSs (ISD=400 m)</td>
<td>4.7</td>
<td>1560</td>
</tr>
<tr>
<td>28 GHz with dense BSs (ISD=150 m)</td>
<td>500</td>
<td>8300</td>
</tr>
<tr>
<td>73 GHz with sparse BSs (ISD=400 m)</td>
<td>8.2</td>
<td>4200</td>
</tr>
<tr>
<td>73 GHz with dense BSs (ISD=150 m)</td>
<td>830</td>
<td>14500</td>
</tr>
</tbody>
</table>

**2 GHz parameters:**
- Signal bandwidth: 50 MHz
- ISD: 500 m
- TX power: 46 dBm
- MIMO with ZF receiver

**28 GHz parameters:**
- Signal bandwidth: 500 MHz
- TX power: 30 dBm
- Using hybrid beamforming:
  - 8-by-8 UPAs at BSs
  - 2-by-2 UPAs at MSs
  - Each with 4 RF chains

**73 GHz parameters:**
- Signal bandwidth: 2 GHz
- TX power: 30 dBm
- Using analog beamforming:
  - 20-by-20 at BSs
  - 5-by-5 at MSs
  - (Same aperture size as 28 GHz)

**Building statistics:**
- LOS range: 70 m
  - (NYU measurement)

**Rate computation:**
- 5 dB gap from Shannon
- SINR clipped by 30 dB

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Conclusions
Going Forward with mmWave

- Good rates and coverage can be achieved in dense mmWave networks
  - Mmwave is a small cell solution
  - Will magnify gains of densification

- Many opportunities for further research
  - Analog beamforming algorithms & hybrid beamforming
  - Channel estimation, exploiting sparsity, incorporating robustness
  - Multi-user beamforming algorithms and analysis
  - Microwave-overlaid mmWave systems
  - Going away from cells to a more ad hoc configuration
  - Incorporating mobility

questions?
Performance analysis of mmWave cellular networks [J1,J2, C1,C2]


In [J1], we proposed a stochastic geometry network model that incorporated key features of mmWave cellular systems, including directional beamforming and blockage effects. The downlink rate and SINR distributions was then investigated based on the network model.

Our analyses showed that mmWave performance is much sensitive to the density of base stations: a denser base station deployment is required to achieve comparable SINR coverage to the conventional cellular networks; the comparable SINR translates to a higher achievable rate, due to the larger bandwidth assumed at mmWave.
Select publications (2/4)


In [J2], we showed that dense mmWave networks can achieve comparable coverage and significantly higher data rates than the conventional networks. Moreover, sum rate gains can be achieved using more advanced beamforming techniques that allow multiuser transmission. The insights are derived using the framework proposed in [J1].


We introduced a simplified LOS-ball network model for dense mmWave network analysis. We showed that the performance of dense mmWave networks is largely determined by the average number of LOS base stations that a typical user observes. (Related results also reported in [J1].)
Select publications (3/4)


We developed a cone-blocking model to characterize the blocking effect from cellphone users’ bodies with potential position changes; as human bodies can block mmWave signals causing 20-40 dB attenuation. Based on the network model in [J1], we analyzed the impact of self-body blocking on the SINR coverage and rate under different base station association rules. The results showed that self-body blocking decreases the SINR coverage, and may cause 10% degradation in achievable rates with certain system parameters.
Modeling building distributions w/ random shape theory [J3]


Leveraging concepts from random shape theory, we modeled the distributions of buildings in urban areas as rectangular Boolean schemes, where the certain of the buildings form a Poisson point process, and their sizes and orientations follow certain distributions. Based on the Boolean scheme model, we showed that the probability that a link is not blocked by any buildings decay exponentially with its length, which matches the LOS probability proposed in 3GPP standard. Furthermore, our analysis on system performance showed that SINR and rate performance in cellular networks can benefit from blockage effects, as buildings may block more interference that often comes from longer links.