Challenges and Solutions for Networking in the Millimeter-wave Band

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Demands for extremely high data rates
How to meet this demand

- Bandwidth scarcity in UHF (below 3GHz)
  - LTE (20 MHz), LTE-A (100 MHz), 802.11ac (160 MHz)

- Huge bandwidth in millimeter wave (mmWave)
  - 802.11ad (around 7 Ghz @60 GHz): 350x LTE bandwidth, 40x 802.11ac bandwidth
  - 107x more bandwidth in mmWave bands w.r.t UHF

Figure: The wireless spectrum
How to meet this demand

Growing interests in mmWave communications

- ECMA 387 (2008), IEEE 802.15.3c (2009), WiGig (2011), IEEE 802.11ad (2012)
- Jan. 2015: FCC and Ofcom released notice of inquiries for mobile communications in mmWave bands
- May 2015: IEEE established a new study group for mmWave communications (IEEE 802.11ay)
  - minimum 20 Gbps data rate, 1000 m range, 100 Gbps possible rate
Outline

1. Introduction

2. Fundamentals
   A. Characteristics of mmWaves
   B. Blockage
   B. Deafness
   D. Hardware

3. Interference Modeling

4. Beam-forming, Access Initialization

5. MAC Layer Design

6. Association and Relaying

7. MmWaves for Cellular Networks

8. MmWaves for Short Range Networks

9. Impact on Higher Layers (Transport)
Characteristics of mmWaves

Figure: Millimeter-wave spectrum


- 3-300GHz spectrum → mmW bands ($\lambda$ ranges from 1-100mm)
- 60GHz band is an unlicensed spectrum
- Large amount of spectral bandwidth: 7GHz
- Achievable data rates > 2Gbps
Characteristics of mmWaves

- 10–300 GHz
- High atmospheric absorption (only at certain frequencies)
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Characteristics of mmWaves

- 10–300 GHz
- High atmospheric absorption (only at certain frequencies)
- Large bandwidth

Figure 1. Channelization of 802.15.3c and unlicensed bands around the globe.

Characteristics of mmWaves

- 10–300 GHz
- High atmospheric absorption (only at certain frequencies)
- Large bandwidth
- Short wavelength

Wafer-scale antenna: 64 elements in 8-12GHz (left) and 1024 elements in 50-75GHz (right)

Characteristics of mmWaves

- 10–300 GHz
- High atmospheric absorption (only at certain frequencies)
- Large bandwidth
- Short wavelength

\[ \text{SNR} = \frac{P_{\text{tx}}}{\sigma} \left( \frac{\lambda}{4\pi R} \right)^2 \]
Characteristics of mmWaves

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$$\text{SNR} = \frac{P_{tx}}{\sigma} \left( \frac{\lambda}{4\pi R} \right)^2$$

- Around 10–20 dB extra noise power, compared to UHF networks, due to higher bandwidth
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$$\text{SNR} = \frac{P_{tx}}{\sigma} \left( \frac{\lambda}{4\pi R} \right)^2 G_{tx}$$

- Around 20 dB smaller captured energy at receiver antenna
Characteristics of mmWaves

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\[
\text{SNR} = \frac{P_{tx}}{\sigma} \left( \frac{\lambda}{4\pi R} \right)^2 G_{tx} G_{rx}
\]

- Around 20 dB smaller captured energy at receiver antenna
Characteristics of mmWaves

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- Large bandwidth
- Short wavelength

We need beamforming both at transmitter and at receiver
Characteristics of mmWaves

- Narrow beams
- Interference immunity
- Deployment of multiple independent links in close proximity
- Point-to-point mesh networks

Figure: Beam comparison
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9. Impact on Higher Layers (Transport)
Variation in Received Power with 32mW transmit power at 5.1GHz (left) and 60GHz (right). M. R. Williamson et al., “Investigating the effects of antenna directivity on wireless indoor communication at 60 Ghz”, IEEE PIMRC, 1997

- Does not penetrate most solid materials → extra spatial isolation
- Coverage is defined by the perimeter of the room
- Frequency reuse is viable
- Implicit security
Blockage

- High penetration loss, e.g., 35 dB by the human body*
- Mostly line-of-sight (LoS) communication (extra loss by first-order reflection**)
Blockage

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- Mostly line-of-sight (LoS) communication (extra loss by first-order reflection)
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9. Impact on Higher Layers (Transport)
Misalignment between transmitter and receiver

- sensitivity to any source of movements (e.g., self-rotation and wind)
- significant spatial gain
- negligible hidden node and exposed node problems!
Misalignment between transmitter and receiver

- sensitivity to any source of movements (e.g., self-rotation and wind)
- significant spatial gain
- negligible hidden node and exposed node problems!
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9. Impact on Higher Layers (Transport)
Power consumption and device complexity is an issue

Components with the highest power consumption are A/D converters, low noise and power amplifiers, and voltage controlled oscillators.

Power consumption in A/D converters is proportional to the signal bandwidth and exponential in sampling accuracy (quantization).

A/D conversion of high bandwidth mmWave signals is an issue, especially for high precision A/D.

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   B. Set of Dominant Interferers
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9. Impact on Higher Layers (Transport)
Lack of understanding of interference behavior and fundamental performance limitations, especially at medium access control (MAC) layer

- limited knowledge on modeling, performance evaluation, available degrees of freedom, design constraints

The consequences are

- No standard for mmWave cellular networks

- Poor mmWave standards in short range networks
  - 802.15.3c and 802.11ad: maximum data rate 7 Gbps, while 100 Gbps could be achieved (802.11 ay)!
We propose a new index to quantify accuracy of any interference model under any network scenario.

We investigate the impact of directionality and blockage of mmWave networks on the accuracy of existing interference models.

We develop a simple yet accurate interference model for performance analysis and protocol development.

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9. Impact on Higher Layers (Transport)
The first step to analyze many performance indicators: introducing an interference model
Signal to interference plus noise ratio

$\mathcal{I}$: set of interferers

$p_i$: transmission power of transmitter $i$

$\sigma$: power of white Gaussian noise

$g_{ij}^{\text{Tx}}$: antenna gain at transmitter $i$ toward receiver $j$

$g_{ij}^{\text{Rx}}$: antenna gain at receiver $j$ toward transmitter $i$

$g_{ij}^{\text{Ch}}$: channel gain between transmitter $i$ and receiver $j$

\[
\gamma_i = \frac{p_i g_{ii}^{\text{Tx}} g_{ii}^{\text{Ch}} g_{ii}^{\text{Rx}}}{\sum_{j \in \mathcal{I}} p_i g_{ij}^{\text{Tx}} g_{ij}^{\text{Ch}} g_{ij}^{\text{Rx}} + \sigma}.
\]
Signal to interference plus noise ratio

\[ \gamma_i = \frac{p_i g^\text{Tx}_{ii} g^\text{Ch}_{ii} g^\text{Rx}_{ii}}{\sum_{j \in I} p_i g^\text{Tx}_{ij} g^\text{Ch}_{ij} g^\text{Rx}_{ij}} + \sigma. \]

outage event: \( \gamma < \beta \), where \( \beta \) is the SINR threshold.

- Accuracy/simplicity tradeoff
- **Modeling** \( I \): protocol model, interference ball model, physical model
- **Modeling other components**: sidelobe gain, reflection, penetration loss
Signal to interference plus noise ratio

\[ \gamma_i = \frac{p_i g_{ii}^{\text{Tx}} g_{ii}^{\text{Ch}} g_{ii}^{\text{Rx}}}{\sum_{j \in I} p_i g_{ij}^{\text{Tx}} g_{ij}^{\text{Ch}} g_{ij}^{\text{Rx}}} + \sigma. \]

Interference model similarity (IMS) index

For any constant \( 0 \leq \xi \leq 1 \), any interference model \( x \) with SINR \( \gamma^x \), and any reference interference model \( y \) with SINR \( \gamma^y \), we define the interference model similarity index as

\[ S_{\xi,\beta}(x \parallel y) = 1 - \xi \Pr[\gamma^x > \beta \mid \gamma^y \leq \beta] - (1 - \xi) \Pr[\gamma^x \leq \beta \mid \gamma^y > \beta]. \]


Definition

\[ S_{\xi,\beta}(x\|y) = 1 - \xi \Pr[\gamma^x > \beta \mid \gamma^y \leq \beta] - (1 - \xi) \Pr[\gamma^x \leq \beta \mid \gamma^y > \beta] . \]

- \( S_{\xi,\beta}(x\|y) \in [0, 1] \), where higher values show higher similarity between \( x \) and \( y \).

- If we consider an accurate model for \( y \), \( S_{\xi,\beta}(x\|y) \) gives the accuracy of interference model \( x \).

- With \( \xi = \Pr[\gamma^y \leq \beta] \), \( S_{\xi,\beta}(x\|y) \) is the probability of having correct outage decisions under \( x \).

- There is a relationship between \( S_{\Pr[\gamma^y \leq \beta],\beta}(x\|y) \) and the Bhattacharyya distance, used for bounding detection error probability.
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9. Impact on Higher Layers (Transport)
Set of dominant interferers

- protocol model
- interference ball model
- physical model
Set of dominant interferers

- protocol model
- interference ball model
- physical model

- omni-directional
- no blockage
Set of dominant interferers

- protocol model (very simple, not accurate)
- interference ball model
- physical model

- omnidirectional
- no blockage
Set of dominant interferers

- protocol model *(very simple, not accurate)*
- interference ball model *(complicated, accurate)*
- physical model

- omnidirectional
- no blockage
Set of dominant interferers

- protocol model (very simple, not accurate)
- interference ball model (complicated, accurate)
- physical model (very complicated, very accurate)

- omnidirectional
- no blockage
Set of dominant interferers

- protocol model (very simple, not accurate)
- interference ball model (complicated, accurate)
- physical model (very complicated, very accurate)

- directional
- blockage
Set of dominant interferers

- **protocol model** *(very simple, not accurate)*
- interference ball model *(complicated, accurate)*
- physical model *(very complicated, very accurate)*

- directional
- blockage
Set of dominant interferers

- protocol model (very simple, not accurate)
- interference ball model (complicated, accurate)
- physical model (very complicated, very accurate)

- directional
- blockage
Set of dominant interferers

- protocol model (very simple, not accurate)
- interference ball model (complicated, accurate)
  - physical model (very complicated, very accurate)

- directional
- blockage
Set of dominant interferers

- protocol model (very simple, accurate)
- interference ball model (complicated, very accurate)
- physical model (very complicated, very accurate)

- directional
- blockage
Set of dominant interferers

Set of dominant interferers


- omnidirectional, no blockage, SINR threshold = 5 dB
Set of dominant interferers

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9. Impact on Higher Layers (Transport)
We consider physical model of interference. We consider infinite penetration loss in $x$, and sweep penetration loss in $y$. 

We consider physical model of interference. We consider zero reflection coefficient in $x$, and sweep reflection coefficient in $y$. 

No sidelobe gain

- We consider physical model of interference. We consider zero sidelobe gain in $x$, and sweep sidelobe gain in $y$.

![Graph showing the accuracy index vs. sidelobe gain for different values of $\lambda_t$, $\theta$, and $\beta$.]

Applications of the simplified interference model

- **A conclusion:** Neglecting finite penetration loss, reflection loss, and sidelobe gain only marginally decrease the accuracy of the resulting interference model.

- We have applied this simple interference model to
  - develop on-demand interference management protocol [TCOM’15]
  - analyze collision probability [Globecom’15]
  - analyze per-link throughput [Globecom’15]
  - evaluate area spectral efficiency [TCOM’16]
  - evaluate throughput-delay tradeoff [TCOM’16]
  - characterize interference graph of mmWave networks [RepC’16]
  - develop a novel collision notification signal [Netw’15]
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9. Impact on Higher Layers (Transport)
We introduced a new framework to assess the accuracy of any interference model under any network scenario.

Directionality and blockage allow major simplification of interference model.

Protocol model of interference is sufficiently accurate.

Neglecting finite penetration loss, reflection loss, and sidelobe gain only marginally decrease the accuracy of the resulting interference model.

The resulting simplified interference model allows investigating of fundamental performance metrics and designing proper protocols for mmWave networks.
Application areas of the proposed index goes much beyond the studies of this presentation

Extend the fundamental design principles of wireless networks when directionality and blockage appear

New blockage and reflection models

Fall-back, relay, reflection, direct link: what should a transmitter do upon appearance of obstacle(s)?
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   B. Numerical Examples

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10. Simulation Environments
Association and Relaying
Association and Relaying
Association and Relaying

- Goal: Maximize some clients utility, such as the sum of clients throughput or the minimum of the client’s throughput

- Ideal solution: Distributed algorithms for client-relay association

- Current solution: association based on the RSSI


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10. Simulation Environments
System Model

- Client $i \in \mathcal{M} = \{1, \ldots, M\}$, relay $j \in \mathcal{N} = \{1, \ldots, N\}$ and AP $k \in \mathcal{K} = \{1, \ldots, K\}$

- Achievable rate at distance $d$ is

$$r_{ij} = W \log_2 \left(1 + \frac{P_T G_R G_T \lambda^2 d_0^\eta}{16\pi^2 (N_0 + I) W d_{ij}^\eta} \right),$$
Throughput benefit from client $i$

$$a_{ik} = r_{ik}, \quad a_{ijk} = \min\{r_{ij}, r_{jk}\}$$

Total throughput

$$u = \sum_{(i,k) \in A} a_{ik}x_{ik} + \sum_{(i,j,k) \in A} a_{ijk}x_{ijk},$$

Binary decision variables $x_{ik} = 1$ if client $i$ is associated to AP $k$ and $x_{ik} = 0$ otherwise. Moreover, $x_{ijk} = 1$ if client $i$ is associated to relay $j$, then to AP $k$ and $x_{ijk} = 0$ otherwise.
Max Throughput Problem Formulation

\[ \text{maximize} \quad u \]
\[ \{x_{ik}\}, \{x_{ijk}\} \]
\[ \text{s.t.} \quad \sum_{(i,k) \in A} x_{ik} + \sum_{(i,j,k) \in A} x_{ijk} = 1, \quad \forall i \in \mathcal{M}, \]
\[ \sum_{(i,j,k) \in A} x_{ijk} \leq 1, \quad \forall j \in \mathcal{N}, \]
\[ x_{ijk}, x_{ik} = \{0, 1\}, \quad \forall (i, j), (i, j, k) \in \mathcal{A}, \]

- **Variable:** \( x_{ik}, x_{ijk} \)
- **Constraints:** a) client needs to be assigned to one AP, b) relay can only be assigned to one client-AP pair, c) binary decision variables
Solution Method Challenges

- **Existing MILP solvers are centralized**
- Typically based on global branch and bound algorithms ⇒ the worst-case complexity grows exponentially with the problem size
- **Even small** problems, with a few tens of variables, can take a very long time
- **Our approach:** Asymmetric Assignment Problem + Auction-based algorithm ⇒ decentralized
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10. Simulation Environments
Numerical Examples

- Consider a multi-user multi-cell environment

- **Compare** distributed auction algorithm to
  - Random association
  - RSSI-based association (IEEE 802.11)
  - Optimal association (IBM CPLEX)

- **Measure**
  - Throughput, $u$, v.s. the numbers of clients and relays
  - Convergence analysis v.s. the numbers of clients, relays and APs
  - $\epsilon$-optimal analysis, convergence and $M\epsilon$ boundary
Topologies

- SNR operating point at a distance $d$ from any AP

$$\text{SNR}(d) = \begin{cases} 
P_0 \lambda^2 / (16\pi^2 N_0 W) & d \leq d_0 \\
P_0 \lambda^2 / (16\pi^2 N_0 W) \cdot (d/d_0)^{-\eta} & \text{otherwise}
\end{cases}$$

- Radius of each cell $r$ is chosen such that $\text{SNR}(r) = 10$ dB

- Clients and relays are uniformly distributed at random, among the circular cells
Throughput Analysis

- Varying the number of clients

Figure: Throughput of AUCTION, OPTM, RAND, and RSSI. (a) $\log u$ vs. number of clients with 3 APs and 30 relays; (b) $\log u$ vs. number of clients with 5 APs and 50 relays; (c) $\log u$ vs. number of clients with 7 APs and 70 relays.
Throughput Analysis

- Varying the number of relays

**Figure:** Throughput of AUCTION, OPTM, RAND, and RSSI. (a) \( \log u \) vs. number of relays with 3 APs and 150 clients; (b) \( \log u \) vs. number of relays with 5 APs and 250 clients; (c) \( \log u \) vs. number of relays with 7 APs and 350 clients.
\( \epsilon \)-optimal Analysis

**Figure:** Convergence and maximum distance from the optimal objective value of the Max Throughput Optimization problem, \( u \), when \( \epsilon \) varies.

(a) Number of iterations vs. \( \epsilon \); (b) \( \Delta_{\text{max}} \) vs. \( \epsilon \).
This part of the presentation is entirely based on the paper

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   C. Resource Allocation and Interference Management
   D. Spectrum Sharing
   E. Some Takeaways

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Control Channels

- Used for synchronization, cell search, user association, channel estimation, coherent demodulation, scheduling grant notification
Fall-back tradeoff: sending control messages over mmWave or UHF frequencies
Fall-back tradeoff: sending control messages over **mmWave** or UHF frequencies

- **Pros**: using single transceiver
- **Cons**: high attenuation and blockage
Fall-back tradeoff: sending control messages over mmWave or UHF frequencies

Pros: larger coverage and higher link stability
Cons: double radios (one for data and one for control messages), not useful for channel estimation at mmWave
Directionality tradeoff: establishing a control channel in omnidirectional, semi-directional, or fully-directional communication modes
Directionality tradeoff: establishing a control channel in omnidirectional, semi-directional, or fully-directional communication modes

- Pros: no spatial search (good for broadcasting)
- Cons: shorter communication range
Directionality tradeoff: establishing a control channel in omnidirectional, semi-directional, or *fully-directional* communication modes

- **Pros:** longer communication range, less interference
- **Cons:** spatial search to mitigate deafness
## Available Options and Design Aspects

<table>
<thead>
<tr>
<th>Option</th>
<th>Control Channel</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Possible PHY-CCs</th>
</tr>
</thead>
</table>
| 1      | Omnidirectional in mmWave band | (1) No need for spatial search  
(2) No deafness problem | (1) Very short coverage  
(2) Subject to mmWave link instability | (1) Broadcast channel inside small cells  
(2) Multicast channel inside small cells  
(3) Random access channel |
| 2      | Semi-directional in mmWave band | (1) Longer coverage  
(2) Energy-efficient transmission  
(3) Efficient use of spatial resources | (1) Extra complexity due to spatial search  
(2) Protocol complexity due to deafness and blockage  
(3) Subject to mmWave link instability | (1) Multicast channel inside small cells  
(2) Synchronization channel inside small cells  
(3) HARQ feedback channel  
(4) Uplink/downlink shared channel  
(5) Uplink/downlink dedicated channel  
(6) Random access channel |
| 3      | Fully-directional in mmWave band | Similar to option 2 | Similar to option 2 | (1) Synchronization channel inside small cells  
(2) HARQ feedback channel  
(3) Uplink/downlink shared channel |
| 4      | Omnidirectional in UHF band | (1) Macro-level coverage  
(2) No need for spatial search  
(3) No deafness problem  
(4) Link stability | (1) Hardware complexity due to the need for two radios  
(2) Inefficient use of spatial resources  
(3) Introduction of inter- and intra-cell interference in control plane | (1) Macro-level control plane  
(2) Macro-level synchronization channel  
(3) Macro-level Broadcast channel  
(4) Macro-level Multicast channel  
(5) Macro-level random access channel |
Assumptions: 50 kHz bandwidth for control channels, independent Poisson point processes for UEs and for LoS BSs, 30 dBm transmit power, 0 dB SNR threshold, and sector antenna model
Lower coverage with larger beamwidths (due to reduced antenna gain)

- more severe at 72 GHz → higher directionality level is required at 72 GHz
Minimum BS density to ensure 97% coverage

Ultra-dense network in Option 1 (omnidirectional-mmWave): one BS in every 14x14 m²

- one BS in every 31x31 m² in Option 2
- one BS in every 75x75 m² in Option 3 (fully-directional-mmWave)
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Functionalities

- Specifies how a user should connect (UE1) to the network and preserve (UE2) its connectivity
Functionalities

- Specifies how a user should connect (UE1) to the network and preserve (UE2) its connectivity

Initial access
1. Synchronization and cell search
2. Extract of system information
3. Random access

Mobility management
1. Handover
2. Beam tracking
Coverage Asymmetry Problem

- A mismatch between the ranges at which a link with reasonable data rate can be established and the range at which a broadcast synchronization signal along with cell identity can be detected.
A mismatch between the ranges at which a link with reasonable data rate can be established and the range at which a broadcast synchronization signal along with cell identity can be detected.

10x difference between the ranges of control and data plane, assuming 30 dBi more (combined Tx-Rx) antenna gains at data plane and path-loss exponent of 3.

![Graph showing coverage gain with different path-loss exponents and antenna gains.](image-url)
A mismatch between the ranges at which a link with reasonable data rate can be established and the range at which a broadcast synchronization signal along with cell identity can be detected.

- Omnidirectional-mmWave may not be a good option for initial access.
- Fully-directional-mmWave requires beam alignment, so not the best option for initial access phase where users do not know where they should listen to!
Two-step Synchronization and Initial Access Proposal

- **First step:** macro-cell BS broadcasts periodic time-frequency synchronization signals with an *omnidirectional-UHF* control channel (option 4)
  - small-cell BSs and users will be synchronized in time (fine) and in frequency (coarse)
  - existing procedure and signaling of LTE can be used here
  - macro-cell ID is embedded in these signals

- **Second step:** small-cell BSs performs a period spatial search using a sequence of directional pilot transmissions on a *semi- or fully-directional-UHF* control channel (options 2 or 3)
  - second-step can be initiated either by BSs (cell-centric) or by users (user-centric)
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- existing procedure and signaling of LTE can be used here
- macro-cell ID is embedded in these signals

Second step: small-cell BSs performs a period spatial search using a sequence of directional pilot transmissions on a semi- or fully-directional-UHF control channel (options 2 or 3)
- second-step can be initiated either by BSs (cell-centric) or by users (user-centric)

Main features

pros: substantial reduction in the search space
cons: dual-band operation (it is compatible with recent standards)
**Assumptions:** same parameters as before, small-cell BSs individually divide 2D space into \(\lceil\frac{2\pi}{\theta}\rceil\) sectors (\(\theta = \text{beamwidth}\)), randomly uniformly sort them, and send synchronization signals toward sectors sequentially (one sector per epoch)
Lower synchronized delay for semi-directional-mmWave option

Is this lower delay (only, on average, one epoch in many cases) significant when we consider substantial coverage reduction by semi-directional-mmWave option?
Delay converges to \((\lceil 2\pi/\theta \rceil + 1)/2\) for sparse deployment of BSs

Delay converges to 1 for ultra dense deployment of BSs
Mobility Management

- Frequent handovers due to vulnerability to obstacle and any source of movement (e.g., wind, user mobility)

- Very poor performance of RSSI-based association

- Multiple associations
  - UE2 can be connected to both BS2 and BS3

- Beam-tracking
Frequent handovers due to vulnerability to obstacle and any source of movement (e.g., wind, user mobility)

Very poor performance of RSSI-based association

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Beam-tracking
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8. MmWaves for Short Range Networks

9. Impact on Higher Layers (Transport)
Channelization and Scheduling

- **Time-frequency-space** resource block

- Scheduling using grouping (with hybrid analog-digital beamforming)
  - orthogonality in space among different groups, orthogonality in time-frequency domains within one group

- **Dynamic cell**: small-cell BSs dynamically group UEs together and form new cells so that
  1) individual UE’s demands are met (QoS provisioning)
  2) some levels of fairness in ensured (network utility maximization)
  3) every UE is categorized in multiple groups (connection robustness)
Table: Performance comparison of transmission schemes in mmWave cellular networks with 2 base stations and 30 users

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Directionality in mmWave gives significant gains for
- network sum rate
- minimum per-link throughput
- fairness
Optimal association with fairness guarantees

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Optimal association with fairness guarantees

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- Directionality in mmWave gives significant gains for
  - network sum rate, minimum per-link throughput, fairness
Directionality in mmWave gives significant gains for

- network sum rate,
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**What is the main source of these gains?**
Optimal association with fairness guarantees

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The performance of both semi- and fully-directional operations improves with the number of RF chains per BS, but in a directionality level, and limited interference. The mmWave characteristics of a mmWave system are very high attenuation, vulnerability to obstacles, and sparse-scattering environments, high robustness to deafness, high channel reliability, and long connection robustness demands revisiting the complex tradeoffs among throughput enhancement, fairness, and efficiency of a directional PHY-CC on mmWave band providing a large number of degrees of freedom to form different cells and inter-cell interference cancelation. As stated in Section V-B, the current interference-limited architecture leads to a significant throughput gain over existing omnidirectional communication with a limited number of RF chains per BS. For future studies, focus on the changes required at the various MAC layer aspects, especially at the MAC layer. This paper investigated the special characterizes of mmWave systems, were identified, and initial solution approaches, based on the changes required at the various MAC layer aspects, especially at the MAC layer. This paper investigated the special characterizes of mmWave systems, were identified, and initial solution approaches, based on the changes required at the various MAC layer aspects, especially at the MAC layer.
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The performance of both semi- and fully-directional operations improves with the number of RF chains per BS, but in a limited number of RF chains provides to highlight that a proper scheduling with fully-directional operation, while improving the fairness among the UEs. The complex tradeoffs among throughput enhancement, fair scheduling, and high connection robustness demands revisiting the current interference-limited architecture. An example was introduced in Section V-B, providing the potential of mmWave systems to improve the reliability of an omnidirectional PHY-CC on microwave band and the efficiency of a directional PHY-CC on mmWave band, leveraging the potential of mmWave systems to improve the reliability of an omnidirectional PHY-CC on microwave band and the efficiency of a directional PHY-CC on mmWave band. This number increases with the directionality level, allowing previously robustness to deafness, high channel reliability, and long range are necessary, for instance, in initial access procedures. Massive MIMO and in coordination among BSs during handovers. A semi- or fully-directional PHY-CC on mmWave band is also mandatory and in coordination among BSs during handovers. A semi- or fully-directional PHY-CC on mmWave band is also mandatory.

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The performance of both semi- and fully-directional operations improves with the number of RF chains per BS, but in a trajectory to boost link budget in mmWave band, provides a large sensitivity to the angle of arrival. Evaluations showed that a relatively small number of pilot symbols is sufficient for initial access procedure leveraging macro-level coverage and in coordination among BSs during handovers. A semi- or fully-directional operation, while improving the fairness among the UEs, leads to a significant throughput gain over existing omnidirectional operation. The mmWave vulnerabilities to obstacles, sparse-scattering environments, high channel capacity, and limited interference. The mmWave characteristics of a mmWave system are very high attenuation, severe multipath delay spread, and high path loss. Inter-cell interference cancelation. As stated in Section V-B, leveraging the potential of mmWave systems to improve the efficiency of a directional PHY-CC on mmWave band for future studies.
Interference management

- Intra-cell interference → can be mitigated by proper scheduling and beamforming

- Inter-cell interference: very challenging at traditional cellular networks, especially at cell edges → can be mitigated by directional communications (in the limit of large antennas either at the BSs or at the UEs, the inter-cell interference goes to zero)

- Reactive (on-demand) interference management

- Interference is prominent in omnidirectional control channels
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9. Impact on Higher Layers (Transport)

C. Fischione, J. Widmer | MmWaves Networking | MmWaves for Cellular Networks | Spectrum Sharing
Is spectrum sharing beneficial?

Technological enabler:
Beamforming (analog, digital, hybrid)

Information sharing:
Coordination (no, partial, full)

Amount of spectrum shared (no, partial, full)

Sharing architecture (infrastructure, core network, ...)

Performance gain

Protocol overhead
Sharing architectures

**Figure:** Arcatures for spectrum pooling between two network operators. (a) interface at the RAN (base station), (b) interface at the core network (CN), (c) RAN sharing, (d) CN sharing, (e) via a spectrum broker, (f) uncoordinated.

1. Optimal association with sharing and full coordination ($P_1$)

2. Optimal association with sharing and no inter-operator coordination ($P_2$)

3. Optimal association with no sharing ($P_3$)

4. Practical association with sharing and no coordination (RSSI)
Rate model

- Average rate that UE $u$ can get from BS $b \in \mathcal{B}_z$ is

$$r_{bu} = E \left[ W_z \log \left( 1 + \frac{P}{I_1 + I_2 + I_3 + W_z \sigma^2} \right) \right],$$  \hspace{1cm} (1)

- $P$: desired power
- $I_1$: intra-cell interference
- $I_2$: inter-cell interference
- $I_3$: inter-operator interference
- $\sigma^2$: noise power spectral density
Optimal association with sharing and full coordination

$\mathcal{P}_1: \text{maximize } \sum_{\mathbf{X}} [f_1(\mathbf{X}), f_2(\mathbf{X}), \ldots, f_{Z}(\mathbf{X})]$ \hspace{1cm} (9a)

subject to analog beamforming design , \hspace{1cm} (9b)

\[
\sum_{b \in \mathcal{B}_z} x_{bu} = 1 , \ \forall u \in \mathcal{U}_z, 1 \leq z \leq Z , \hspace{1cm} (9c)
\]

\[
\sum_{u \in \mathcal{U}_z} x_{bu} \leq N_r , \ \forall b \in \mathcal{B}_z, 1 \leq z \leq Z \hspace{1cm} (9d)
\]

\[x_{bu} \in \{0, 1\} , \ \forall b \in \mathcal{B}, u \in \mathcal{U}, \hspace{1cm} (9e)\]

\[x_{bu} = 0 , \ \forall b \in \mathcal{B}_k, u \in \mathcal{U}_z, k \neq z, 1 \leq z, k \leq Z, \hspace{1cm} (9f)\]

$f_z(\mathbf{X})$ is the objective function of operator $z$:

\[
f_z(\mathbf{X}) = \sum_{u \in \mathcal{U}_z} \log r_u = \sum_{u \in \mathcal{U}_z} \log \left( \sum_{b \in \mathcal{B}_z} x_{bu} r_{bu} \right). \hspace{1cm} (10)\]
Numerical results

- Independent Poisson point processes for locations of BSs and UEs
- Four operators, 2 GHz bandwidth, 32 GHz carrier frequency
- Ideal centralized coordination approach (no delay, no loss)
- 6 RF chains at each BS, 1 RF chain at each UE
- BS density of 100 BSs/km², UE density of 600 UEs/km²
- 25 dBm total transmission power at each BS
- We also assume $I_3 = 0$ in both $P_2$ and $P_3$. 
Numerical results

- Interference components vanish when $N_{BS}$ grows large
- For relatively small antenna arrays (traditional sub-6 GHz networks), $I_3$ is large, and neglecting it may result in a highly suboptimal performance
Numerical results

Figure: Full bandwidth sharing performance, with/without inter-operator coordination, assuming analog precoding with $N_{BS} = 256$ and $N_{UE} = 16$ and a carrier frequency of 32 GHz. Baseline is exclusive spectrum allocation ($P_3$).
Is spectrum sharing beneficial?

- Large scale *beamforming* boosts link budget and alleviates multiuser interference
- Higher level of *coordination* inside one (intra-operator) and among different operators (inter-operator) enables better control of the network (by beamforming, load balancing, etc.)
- Pooling more spectrum increases the degrees-of-freedom, but increases the noise power and also the number of interferers (so interference power)
- Sharing architecture greatly affects the performance of spectrum pooling*

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C. Fischione, J. Widmer  |  MmWaves Networking  |  MmWaves for Cellular Networks  |  D. Some Takeaways
Some Takeaways of mmWave Cellular networks

- **Physical control channels**
  - several new tradeoffs (directionality and fall-back tradeoffs)
  - four options to realize a physical control channel

- **Initial access and mobility management**
  - coverage asymmetry problem
  - two-step synchronization procedure
  - user-centric design
  - beam-tracking

- **Resource allocation and interference management**
  - time-frequency-space resource blocks
  - dynamic cell concept
  - load balancing is more important
  - on-demand interference management
  - omnidirectional control channels may be the main bottleneck!
Fall-back, relay, reflection, direct link: what should a transmitter do upon appearance of obstacle(s)?

Full duplex mmWave communications: do higher noise power and pencil-beam operation facilitate self interference cancelation complexities?

Spectrum sharing at mmWave: does less interference facilitates spectrum sharing at mmWave?
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10. Simulation Environments
MmWaves MAC Short Range Standards

- IEEE 802.11ad
- WiGig
- IEEE 802.15.3c
- WirelessHD
- ECMA-387

Important MAC aspects

Ad hoc networks

- Short-term resource allocation
  - hybrid MAC, collision avoidance, collision notification, backoff, retransmission
- Multihop communications

Cellular networks

- Long-term resource allocation
- Physical control channel
  - coverage, reliability, delay, spectral and energy efficiency
- Initial access (synchronization, random access, association)
- Mobility management, interference management
### Important MAC aspects

#### Ad hoc networks

- **Short-term resource allocation**
  - hybrid MAC, collision avoidance, collision notification, backoff, retransmission
  - Multihop communications

#### Cellular networks

- **Long-term resource allocation**
  - Physical control channel
    - coverage, reliability, delay, spectral and energy efficiency
  - Initial access (synchronization, random access, association)
  - Mobility management, interference management
Ad hoc networks (short-term resource allocation)

| CSMA/CA | TDMA |

- Revise the traditional framework: minimal use of TDMA phase
- Revise collision-based phase: minimal use of collision avoidance messages (why?)
Ad hoc networks (short-term resource allocation)

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- Revise collision-based phase: minimal use of collision avoidance messages (why?)
  1. significant control and data rate mismatch (27.7 Mbps control vs 6.7 Gbps data rate)

Illustrative example

- To transmit a data message of 2 KBytes payload plus 8 Bytes header with CSMA/CA of IEEE 802.11ad, we have up to \textbf{12\%} channel utilization efficiency
- With 100 Mbps data rate, the channel utilization efficiency increases to \textbf{83\%}
Ad hoc networks (short-term resource allocation)

| CSMA/CA | TDMA |

Revise the traditional framework: minimal use of TDMA phase

Revise collision-based phase: minimal use of collision avoidance messages (why?)

1. significant control and data rate mismatch (27.7 Mbps control vs 6.7 Gbps data rate)
2. possible zero multiuser interference at the receiver
3. negligible hidden and exposed node problems
Ad hoc networks (short-term resource allocation)

- Revise the traditional framework: minimal use of TDMA phase
- Revise collision-based phase: minimal use of collision avoidance messages (why?)
- Make the collision avoidance procedure more smart

Random backoff is not a good solution to solve blockage or deafness!
Ad hoc networks (short-term resource allocation)

| CSMA/CA | TDMA |

- Revise the traditional framework: minimal use of TDMA phase
- Revise collision-based phase: minimal use of collision avoidance messages (why?)
- Make the collision avoidance procedure more smart

How to identify a collision? collision notification message
Outline

1. Introduction
2. Fundamentals
3. Interference Modeling
4. Beam-forming, Access Initialization
5. MAC Layer Design
6. Association and Relaying
7. MmWaves for Cellular Networks
8. MmWaves for Short Range Networks
   IEEE 802.15.3c
   IEEE 802.11ad
   IEEE 802.11ay
9. Impact on Higher Layers (Transport)
10. Simulation Environments
IEEE 802.15.3c

- IEEE 802.15.3 gives the MAC and PHY specifications for high rate wireless personal area networks (WPAN)
- IEEE 802.15.3c is the amendment to IEEE 802.15.3 to support the operation in mmWave band
- First IEEE wireless standard in 60 GHz band
- It defines
  - An alternative PHY operating in the 60 GHz band
  - Necessary MAC changes to support this PHY
1 Single carrier (SC) mode: optimized for low power and low complexity
2 High-speed interface (HSI): optimized for low-latency bidirectional data transfer
3 Audio/video (AV) mode: optimized for the delivery of uncompressed, high-definition video and audio

These three modes are coordinated by the Common-mode signaling (CMS): it mitigates the interference among the 3 PHY modes. It transmits command frames such as beacon frame and synchronization frame.
### 3 PHY Modes in IEEE 802.15.3c

<table>
<thead>
<tr>
<th></th>
<th>SC PHY</th>
<th>HSI PHY</th>
<th>AV PHY</th>
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</thead>
<tbody>
<tr>
<td><strong>Main usage model</strong></td>
<td>Kiosk downloading, office desktop</td>
<td>Conference ad hoc, office desktop</td>
<td>Video streaming, multivideo streaming</td>
</tr>
<tr>
<td><strong>Data rates</strong></td>
<td>0.3 Mb/s–5.28 Gb/s</td>
<td>1.54–5.78 Gb/s</td>
<td>0.95–3.8 Gb/s</td>
</tr>
<tr>
<td><strong>Modulation scheme</strong></td>
<td>Single carrier</td>
<td>Orthogonal frequency-division multiplexing</td>
<td>Orthogonal frequency-division multiplexing</td>
</tr>
<tr>
<td><strong>Forward error control coding options</strong></td>
<td>Reed Solomon code, low-density parity check codes</td>
<td>Low-density parity check codes</td>
<td>Reed Solomon code, convolutional coding</td>
</tr>
<tr>
<td><strong>Block size/fast Fourier transform size</strong></td>
<td>512</td>
<td>512</td>
<td>512</td>
</tr>
</tbody>
</table>
In IEEE 802.15.3c a network is called a piconet. The piconet coordinator (PNC) broadcasts beacon messages to other devices (DEVs). Time is divided into super-frames, each consisting of 3 portions:

- beacon
- contention access period (CAP)
- channel time allocation period (CTAP)

### Superframe of IEEE 802.15.3c

<table>
<thead>
<tr>
<th>Beacon</th>
<th>CAP</th>
<th>CTAP</th>
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<tbody>
<tr>
<td></td>
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<td>CTA</td>
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<tr>
<td></td>
<td></td>
<td>CTA</td>
</tr>
</tbody>
</table>

C. Fischione, J. Widmer | MmWaves Networking | MmWaves for Short Range Networks | IEEE 802.15.3c
Aggregation

- Frame aggregation to reduce the overhead, e.g., the preamble and PHY/MAC header, by concatenating multiple MAC service data units (MSDUs) to form a frame with a long payload.

- Two aggregation methods defined in IEEE 802.15.3c
  1. Standard aggregation: to support high-speed uncompressed video streaming
     Aggregate both global control information and individual control information for each subframes. Transmission starts when enough MSDUs arrive.
  2. Low latency aggregation: to support delay-sensitive applications such as bidirectional transmission
     Aggregate only global control information. Once an MSDU is available, the transmission starts and zero-length MSDU is sent to fill the gap until new MSDU arrives.
Beamforming

- Two-level analog beamforming training mechanisms, followed by an optional high resolution (HRS) tracking phase:
  1. sector (coarse) level training
  2. beam (fine) level training

- Two beamforming protocols:
  1. On-demand beamforming
     - can be used between two DEVs or between the PNC and a DEV
     - is performed in the CTA allocated to the DEV
  2. Pro-active beamforming
     - only when the PNC is the source of data to one or multiple DEVs
     - sector level training from PNC to DEV takes place in the beacon
     - sector level training from DEV to PNC and the beam level training of both directions takes place in the CTAP
Beam patterns, a) quasi-omni patterns, b) sectors, c) fine beams and d) HRS beams
References

Realizing physical control channels


Initial access and cell search


Mobility management and handover


Interference analysis


References

Resource allocation


Channel measurements


References

Short range networks


Relaying


Spectrum sharing

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Challenges and Solutions for Networking in the Millimeter-wave Band

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