# Fundamentals of Medium Access Control Design for Millimeter Wave Networks

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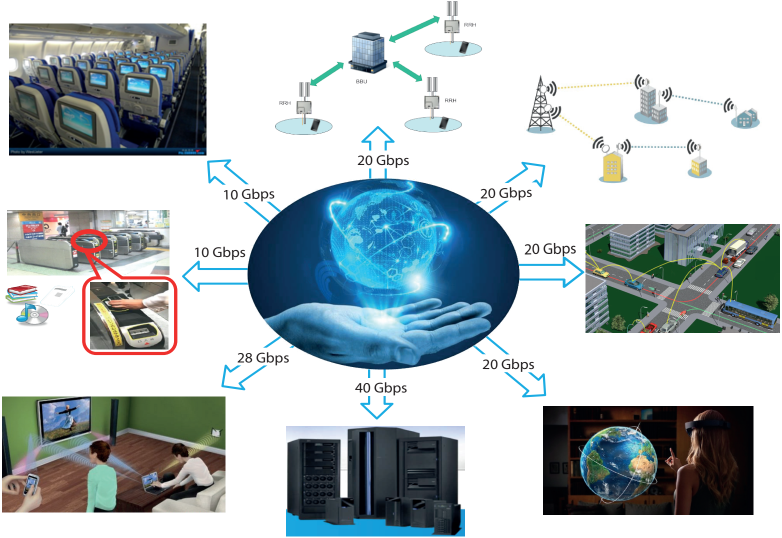
# Demands for extremely high data rates wireless access



# How to meet this demand

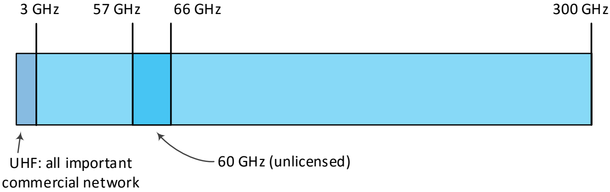



Figure: The wireless spectrum

- 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

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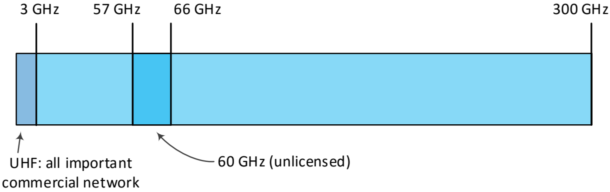


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- Growing interests in mmWave communications
  - ECMA 387 (2008), IEEE 802.15.3c (2009), WiGig (2011), IEEE 802.11ad (2012)
  - Jan. 2015: FCC and Ofcom released notice of inquiries for mobile communications in mmWave bands
  - May 2015: IEEE established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

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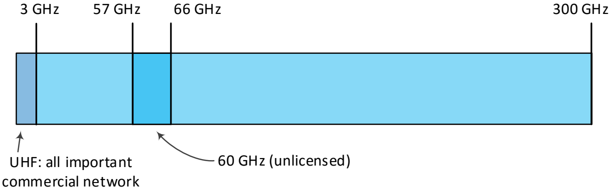


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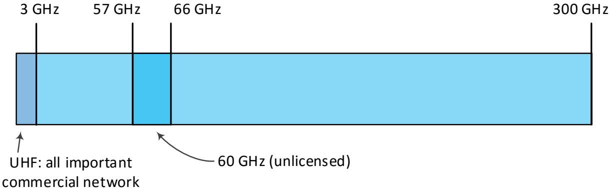


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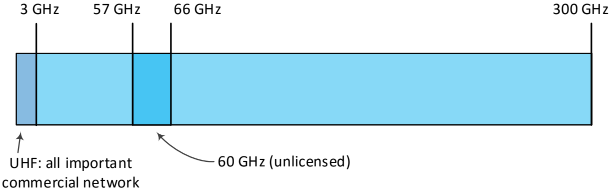


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# Outline

1. Overview of mmWave systems and contributions
2. Fundamental performance analysis
    A. Alignment overhead
    B. Interference
    C. Throughput
3. MAC design guidelines for future mmWave networks
    A. Ad hoc networks
    B. Cellular networks
4. Concluding remarks

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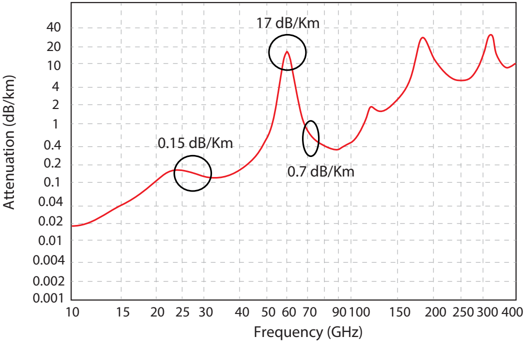


T. S. Rappaport, et al., "State of the art in 60-GHz integrated circuits and systems for wireless communications," *Proc. IEEE*, Aug. 2011.

# Characteristics of mmWave frequencies

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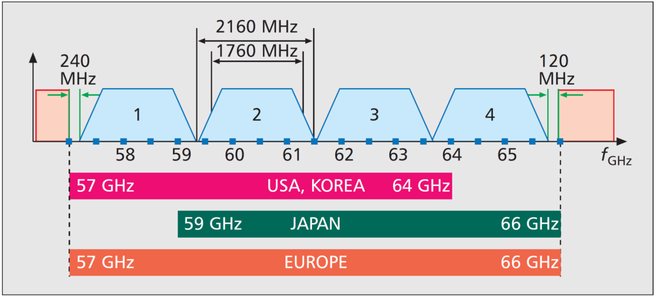


**Figure 1.** *Channelization of 802.15.3c and unlicensed bands around the globe.*

- T. Baykas, et al., "IEEE 802.15.3c: the first IEEE wireless standard for data rates over 1 Gb/s," *IEEE Commun. Mag.*, 2011.

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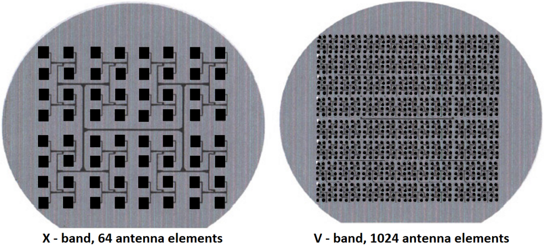


Wafer-scale antenna: 64 elements in 8-12GHz (left) and 1024 elements in 50-75GHz (right)

http://electronicdesign.com/communications/build-phased-array-wafer-boost-antenna-performance

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We need beamforming both at transmitter and at receiver

# Blockage

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

*S. Rangan, et al., "Millimeter wave cellular wireless networks: Potentials and challenges," *Proc. IEEE*, Mar. 2014.

**S. Geng, et al., "Millimeter-wave propagation channel characterization for short-range wireless communications," *IEEE Trans. Veh. Technol.*, 2009.

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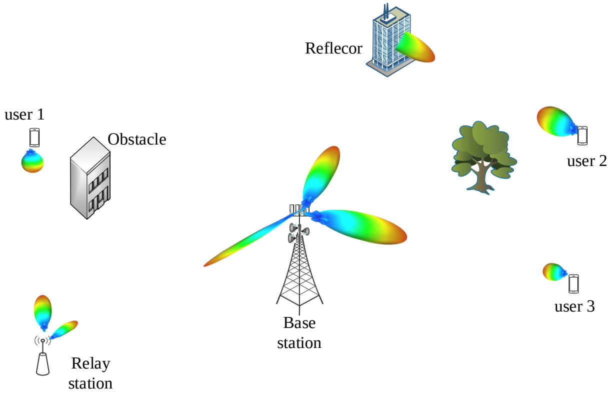
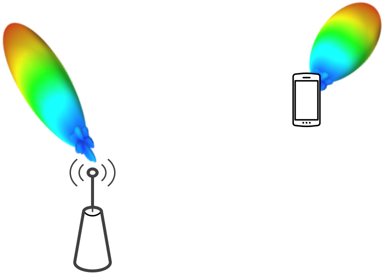


# Deafness

- 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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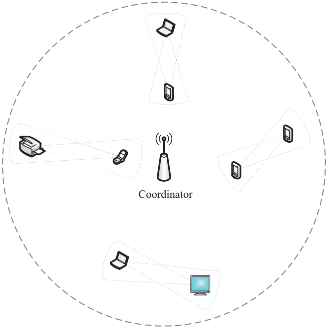

# Research gap in mmWave cellular networks

Lack of understanding of network 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)!

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# Thesis contributions (1/2)

- How to mathematically model mmWave network behaviors?
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  - collision probability, per-link throughput, area spectral efficiency, delay, and coverage

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- How to optimize mmWave networks?
  - operating beamwidth, fairness, and short-term and long-term resource allocations

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- How to optimize mmWave networks?
  - operating beamwidth, fairness, and short-term and long-term resource allocations
- How to design MAC?
  - alignment-throughput tradeoff, collision-aware hybrid MAC, and collision notification

Detailed list of contributions

# Thesis contributions (2/2)

[J1] H. Shokri-Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Trans. Commun.*, 2015, to appear.

[J2] H. Shokri-Ghadikolaei and C. Fischione, "The transitional behavior of interference in millimeter wave networks," *IEEE Trans. Commun.*, submitted, 2015.

[J3] H. Shokri-Ghadikolaei, C. Fischione, P. Popovski, and M. Zorzi, "Design aspects of short range millimeter wave networks: A MAC layer perspective," *IEEE Netw.*, submitted, 2015.

[C1] H. Shokri-Ghadikolaei and C. Fischione, "Millimeter wave ad hoc networks: Noise-limited or interference-limited?," in Proc. *IEEE Global Communications (GLOBECOM)* Workshop, San Diego, Dec. 2015.

[C2] H. Shokri-Ghadikolaei, Y. Xu, L. Gkatzikis, and C. Fischione, "User association and the alignment-throughput tradeoff in millimeter wave networks," in Proc. *IEEE Research and Technologies for Society and Industry (RTSI)*, Turin, Italy, Sept. 2015.

[C3] H. Shokri-Ghadikolaei, L. Gkatzikis, and C. Fischione, "Beam-searching and transmission scheduling in millimeter wave communications," in Proc. *IEEE International Conference in Communications (ICC)*, London, UK, Jun. 2015.

[R1] H. Shokri-Ghadikolaei, C. Fischione, and E. Modiano, "Interference models similarity index," *KTH Tech. Rep.*, 2015, available upon request.

[R2] H. Shokri-Ghadikolaei, C. Fischione, and E. Modiano, "Abstract interference analysis of millimeter wave networks," *KTH Tech. Rep.*, 2015, available upon request.

[R3] Y. Xu, H. Shokri-Ghadikolaei, and C. Fischione, "Distributed association and relaying in millimeter wave networks," *KTH Tech. Rep.*, 2015, available upon request.

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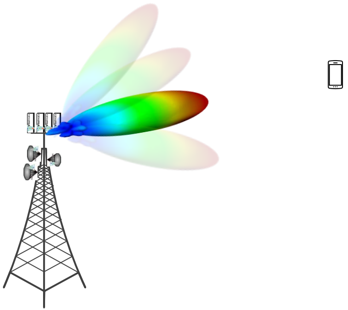
# Fundamental performance analysis

## Impacts of blockage and directionality on MAC

- **Complicated link establishment phase**
- Reduced multiuser interference



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### Essential questions

1. How to abstract the impact of beamwidth on the network performance?
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1. How to abstract the impact of beamwidth on the network performance?
2. What is the optimal beamwidth?
   - from SINR (transmission rate) maximization perspective: the narrowest beam!

# Fundamental performance analysis

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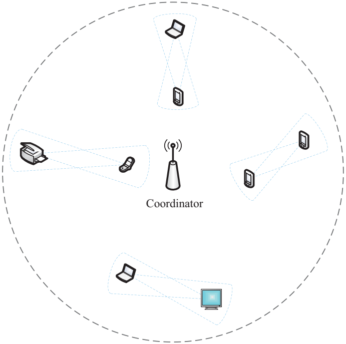

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- Does mmWave networks operate in noise-limited regime?

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### A fundamental question

- Does mmWave networks operate in noise-limited regime?
  - mainstream belief: YES!

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**A conclusion**

Blockage and directionality challenge our “very good” understanding of wireless networks, available models for performance evaluation, and their accuracies

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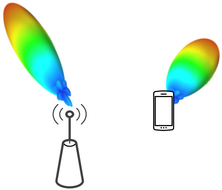
# Interplay between beamwidth and throughput



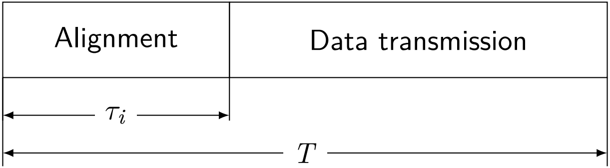
| Alignment | Data transmission |
| --- | --- |

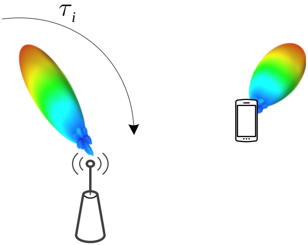
## Alignment phase

- Analog beamforming in current mmWave standards
  - beamforming → alignment of the Tx and Rx beams!
  - alignment by a sequence of pilot transmissions!
- Hybrid beamforming in future mmWave networks

▸ more info

# Interplay between beamwidth and throughput




$\tau_i$ : alignment time of device $i$

$T$ : time slot duration

$r_i$ : transmission rate of device $i$

Achievable throughput of link (Tx-Rx pair) $i = (T - \tau_i)\, r_i$

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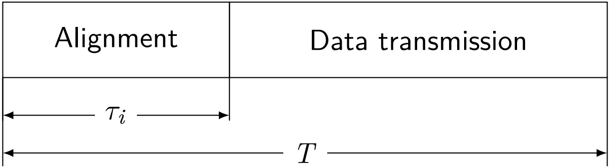


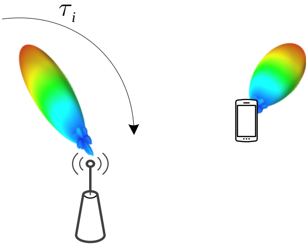


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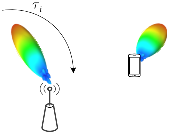
# Alignment procedure


$T_p$ : single pilot transmission overhead

$\psi_i^t$ : sector-level beamwidth of transmitter of link $i$

$\psi_i^r$ : sector-level beamwidth of receiver of link $i$

$\varphi_i^t$ : beam-level beamwidth of transmitter of link $i$

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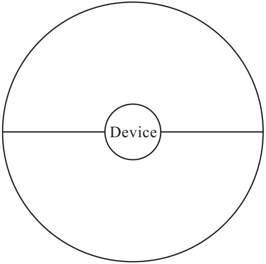


quasi-omni pattern

J. Wang, *et al.* "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, 2011.

# Interplay between beamwidth and throughput


Alignment overhead : $$\tau_i\left(\varphi_i^t, \varphi_i^r\right) = \left\lceil \frac{\psi_i^t}{\varphi_i^t} \right\rceil \left\lceil \frac{\psi_i^r}{\varphi_i^r} \right\rceil T_p$$

# Interplay between beamwidth and throughput

| Alignment | Data transmission |
|---|---|

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Antenna gain (transmitter) : $g_{i,j}^t\left(\varphi_i^t\right) = \begin{cases} \frac{2\pi-(2\pi-\varphi_i^t)z}{\varphi_i^t}, & \text{main lobe} \\ z, & \text{sidelobe} \end{cases}$

Antenna gain (receiver) : $g_{i,j}^r\left(\varphi_i^r\right) = \begin{cases} \frac{2\pi-(2\pi-\varphi_j^r)z}{\varphi_j^r}, & \text{main lobe} \\ z, & \text{sidelobe} \end{cases}$

depends on the topology and beamwidth

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$$\mathrm{SINR}_i = \frac{p_i g_{i,i}^t g_{i,i}^c g_{i,i}^r}{\sum_{\substack{k=1 \\ k \neq i}}^{N} p_k g_{k,i}^t g_{k,i}^c g_{k,i}^r + n}$$

# Interplay between beamwidth and throughput

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$$
\begin{aligned}
\underset{\varphi^t,\varphi^r,\mathbf{p}}{\text{maximize}} \quad & R = \sum_{i=1}^{N} \left(1 - \frac{\tau_i}{T}\right) \log_2\left(1 + \mathrm{SINR}_i\right), && \text{(1)} \\
\text{s.t.} \quad & \varphi_i^t \leq \psi_i^t, & 1 \leq i \leq N, \\
& \varphi_i^r \leq \psi_i^r, & 1 \leq i \leq N, \\
& \psi_i^t \psi_j^r T_P / T \leq \varphi_i^t \varphi_j^r, & 1 \leq i, j \leq N, \\
& 0 \leq p_i \leq p^{\max}, & 1 \leq i \leq N.
\end{aligned}
$$

$N$: number of links
$p^{\max}$: maximum transmission power

# Interplay between beamwidth and throughput

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How to solve? start from single link scenario $(N = 1)$

# Main results for single link scenario

$$\begin{aligned}
\underset{\varphi^t,\varphi^r,\mathbf{p}}{\text{maximize}} \quad & R = \sum_{i=1}^{N=1} \left(1 - \frac{\tau_i}{T}\right) \log_2\left(1 + \mathrm{SINR}_i\right), \\
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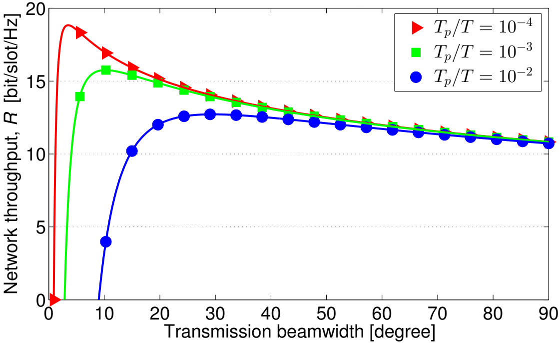
\end{aligned}$$

## Proposition

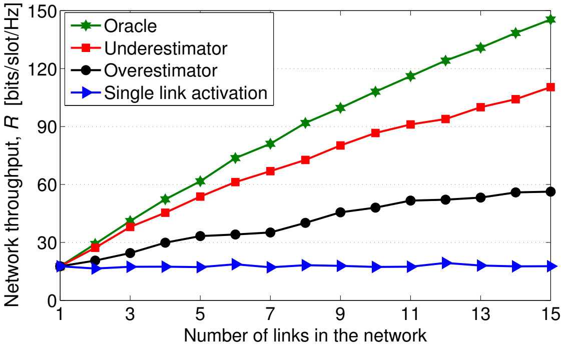
Let $\varphi_i^t$ and $\varphi_i^r$ be beam-level beamwidths of transmitter and receiver $i$. Define $\varphi_i = \varphi_i^t \varphi_i^r$. Consider optimization problem (1) for a single link scenario. Then, the optimal antenna beamwidths $\left(\varphi_i^t\right)^*$ and $\left(\varphi_i^r\right)^*$ are well approximated by hyperbola $\left(\varphi_i^t\right)^* \left(\varphi_i^r\right)^* = \varphi_i^*$, where $\varphi_i^*$ is the unique solution of $\partial R / \partial \varphi_i = 0$.

# Single link scenario




- We always have a hat! $\rightarrow$ *The alignment-throughput tradeoff*
  - high beam-searching overhead with narrow beams (do not use pencil-beams!)
  - low antenna gain with wide beams (do not use very wide beams!)
- Performance improvement with reduced pilot transmission overhead

# Multiple links scenario



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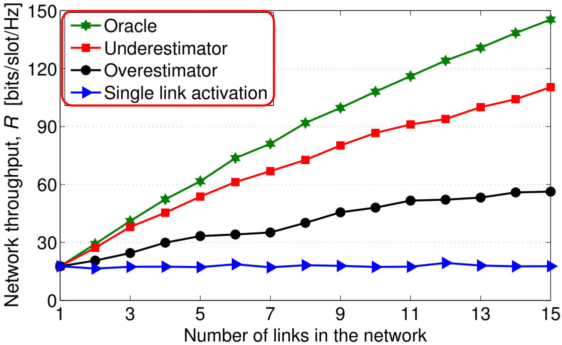
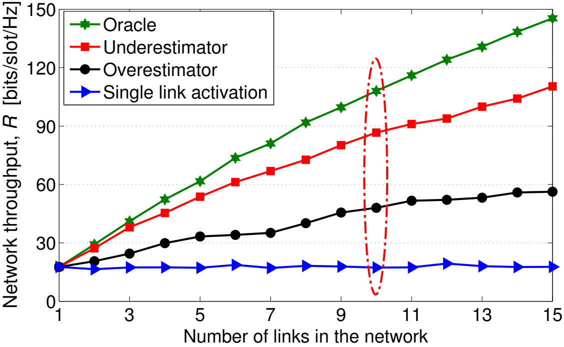



- **Oracle:** the solution of optimization problem (1)
- **Underestimator:** all links are activated!
- **Overestimator:** independent-set based scheduling (no multiuser interference)
- **Single Link Activation:** only the link of the highest SNR is activated

describing algorithms

# Multiple links scenario




- Inefficiency of activating only one link per slot (existing standards)
  - inefficiency increases with the number of links
  - with 10 links, 525%, 401%, and 177% performance enhancement by the Oracle, interference under-estimator, and over-estimator, respectively
- Non-negligible multiuser interference (gap between under-estimator and Oracle)

describing algorithms

# Outline

# Blockage model

- The first step of evaluating the interference: introducing a blockage model

# Blockage model

circle: intended transmitter

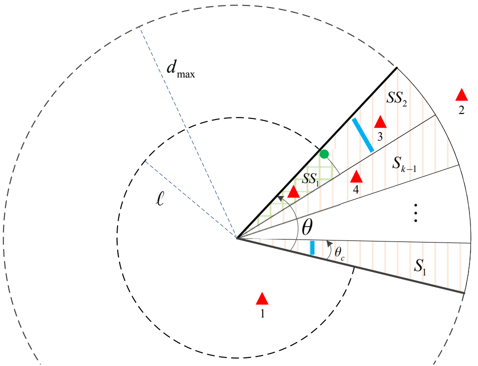
triangle: unintended transmitters

rectangle: obstacles

$\theta$: beamwidth

$\theta_c$: coherence angle

$k = \lceil \theta/\theta_c \rceil$



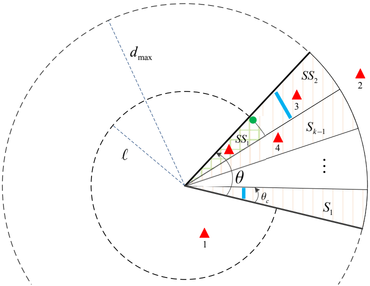

- *Coherence angle* $\theta_c$: the angular interval over which LoS conditions are correlated
- No correlation between LoS condition events in different coherence angle intervals

# Some assumptions

- Homogenous Poisson network of transmitters and obstacles
  - inhomogeneous Poisson network of non-blocked interferers
- Slotted ALOHA
- Similar beamwidth for all devices
- Impenetrable obstacles
- Deterministic wireless channel

Protocol model for interference ▸ accuracy of this model

# Approach sketch




1. Different coherence angles (sectors) are independent, first, find the collision probability for a given sector
   - note difference between the last sector and the rest

2. For a given sector, find the probability that the nearest interferer appears before the nearest obstacle

* Analytical approach: stochastic geometry and stochastic ordering

# Main results

## Proposition

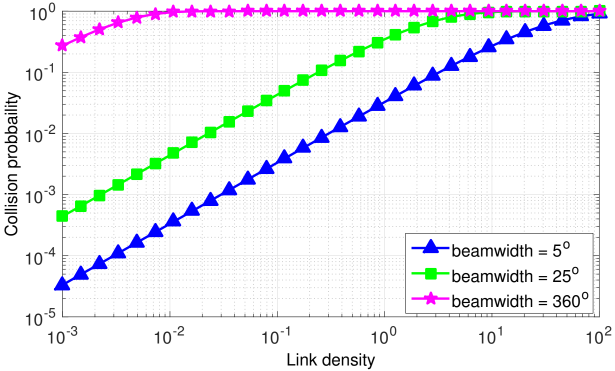
Let $\lambda_t$ and $\lambda_o$ be the density of the transmitters and obstacles per unit area. Let $\rho_a$ be the transmission probability. Let $d_{\max}$, $\theta$, and $\theta_c$ be the interference range, beamwidth, and coherence angle, respectively. Let $\lambda_I = \rho_a \lambda_t \theta / 2\pi$. Then, the collision probability given an intended transmitter at distance $\ell$ is

$$\rho_{c|\ell} = 1 - \left( \frac{\lambda_o + \lambda_I e^{-(\lambda_o+\lambda_I)A_{d_{\max}}}}{\lambda_o + \lambda_I} \right)^{\lceil \theta/\theta_c \rceil - 1} \times \left( e^{-\lambda_I A_\ell} - \frac{\lambda_I}{\lambda_o + \lambda_I} \left( e^{-(\lambda_o+\lambda_I)A_\ell} - e^{-(\lambda_o+\lambda_I)A_{d_{\max}}} \right) \right) , \quad (2)$$

and can be tightly bounded as

$$1 - \left( \frac{\lambda_o + \lambda_I e^{-(\lambda_o+\lambda_I)\theta_c d_{\max}^2/2}}{\lambda_o + \lambda_I} \right)^{\lceil \theta/\theta_c \rceil} \le \rho_c \le 1 - e^{-\lambda_I \theta_c d_{\max}^2/2} \left( \frac{\lambda_o + \lambda_I e^{-(\lambda_o+\lambda_I)\theta_c d_{\max}^2/2}}{\lambda_o + \lambda_I} \right)^{\lceil \theta/\theta_c \rceil - 1} .$$

# Collision probability



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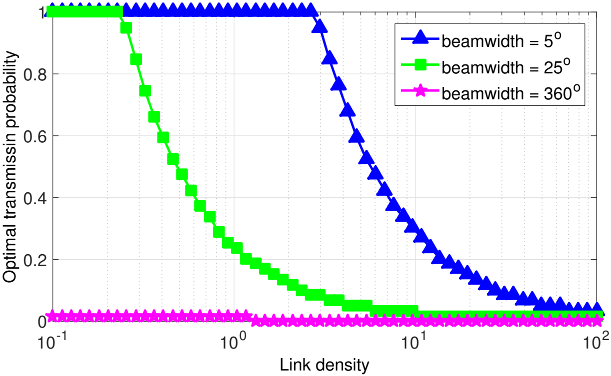



- mmWave networks exhibit full range of behaviors from noise-limited to interference-limited
  - ✓ important parameters: density of transmitters, size and density of obstacles, beamwidth, MAC protocol

▸ diverse collision domain size

# Outline

# Main results

## Proposition

Let $\lambda_t$ and $\lambda_o$ be the density of the transmitters and obstacles per unit area. Let $\rho_a$ be the transmission probability. Let $d_{\max}$, $\theta$, and $\theta_c$ be the interference range, beamwidth, and coherence angle, respectively. Let $A$ denote the area over which scheduler regulates the transmissions of the transmitters. Define $A_{\mathrm{x}} = \theta_c \mathrm{x}^2/2$. Then, the per-link throughput and the area spectral efficiency (ASE) of slotted ALOHA and those of TDMA are

$$r_{\textsf{S-ALOHA}} = \int_{\ell=0}^{d_{\max}} \rho_a e^{-\lambda_o A_\ell} \left(1 - \rho_{c|\ell}\right) \frac{2\ell}{d_{\max}^2} \, \mathrm{d}\ell \,,$$

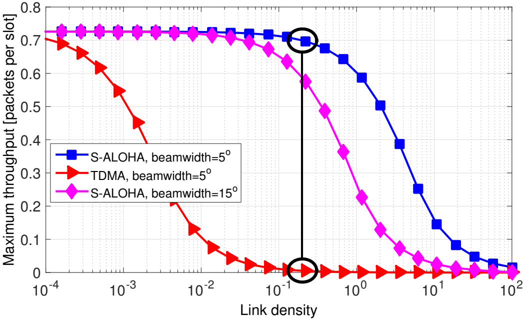
$$\mathrm{ASE}_{\textsf{S-ALOHA}} = \frac{1 + A\lambda_t}{A} \int_{\ell=0}^{d_{\max}} \rho_a e^{-\lambda_o A_\ell} \left(1 - \rho_{c|\ell}\right) \frac{2\ell}{d_{\max}^2} \, \mathrm{d}\ell \,,$$

$$r_{\textsf{TDMA}} = \left(\frac{1 - e^{-\lambda_t A}}{\lambda_t A}\right) \left(\frac{1 - e^{-\lambda_o A_{d_{\max}}}}{\lambda_o A_{d_{\max}}}\right) \,,$$

and

$$\mathrm{ASE}_{\textsf{TDMA}} = \frac{1 - e^{-\lambda_o A_{d_{\max}}}}{A \lambda_o A_{d_{\max}}} \,.$$

# TDMA vs slotted ALOHA




- Significant spatial gain
  - 5000x throughput gain with transmitter density 0.11

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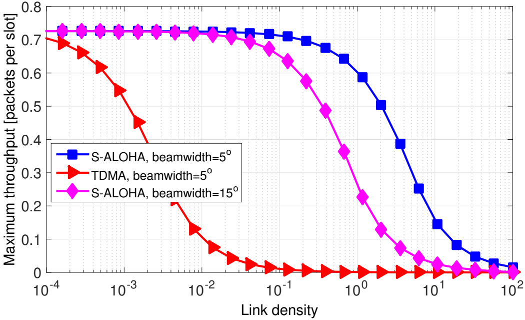


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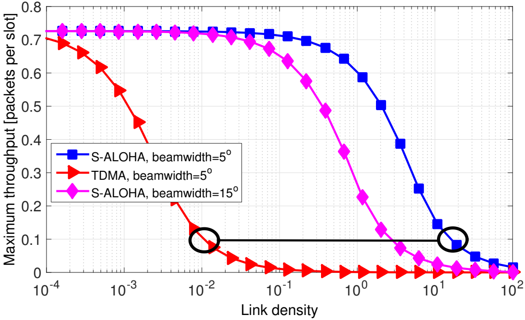
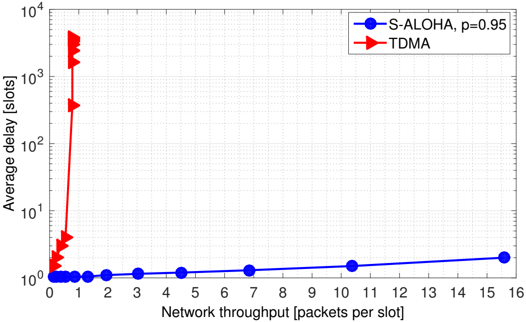


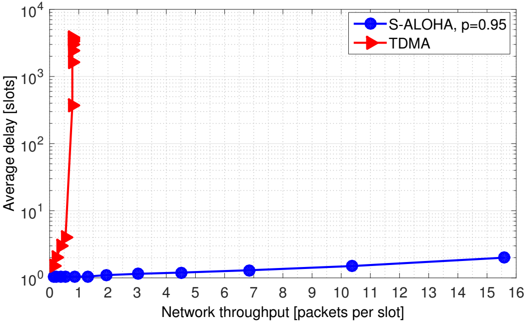

- Significant spatial gain
  - 5000x throughput gain with transmitter density 0.11
  - optimal transmission probability is 1 in many cases! (very simple slotted ALOHA)
  - around 1000x denser network with the same per-link throughput!

# TDMA vs slotted ALOHA




- Saturation of TDMA channel (with around 10 transmitters)
  - instability of transmitters' queues in TDMA
- How great a simple slotted ALOHA can be!

# TDMA vs slotted ALOHA

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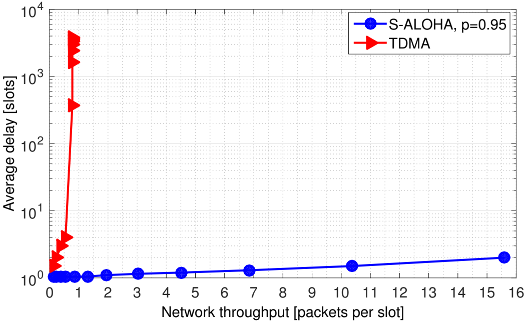


- Saturation of TDMA channel (with around 10 transmitters)
  - instability of transmitters' queues in TDMA
- How great a simple slotted ALOHA can be!
- Why should we serve traffic in TDMA phase? $\rightarrow$ collision-aware hybrid MAC

# Fundamental performance analysis (final comments)

- Beam training overhead
  - important in beam training codebook design
  - important in link establishment phase
- The transitional behavior of interference
  - important in interference management and resource allocation protocols
- Diverse collision domain size
  - important in retransmission policy and resource allocation protocol

# Outline

1. Overview of mmWave systems and contributions
2. Fundamental performance analysis
   A. Alignment overhead
   B. Interference
   C. Throughput
3. MAC design guidelines for future mmWave networks
   A. Ad hoc networks
   B. Cellular networks
4. Concluding remarks

# 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

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# 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?)

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  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 12% channel utilization efficiency
- With 100 Mbps data rate, the channel utilization efficiency increases to 83%

# Ad hoc networks (short-term resource allocation)

| CSMA/CA | TDMA |
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- 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)

| CSMA/CA | TDMA |
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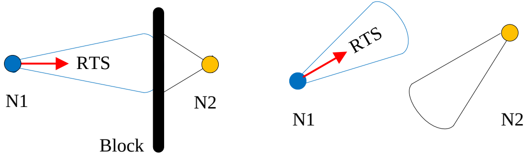
- Revise collision-based phase: minimal use of collision avoidance messages (why?)
- Make the collision avoidance procedure more smart




Random backoff is not a good solution to solve blockage or deafness!

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How to identify a collision? collision notification message

collision notification message

# Cellular networks (long-term resource allocation)

Table: Performance comparison of transmission schemes in mmWave cellular networks with 2 base stations and 30 users

| Communication Mode | # RF chains per BS | Network sum rate | Minimum rate | Jain's fairness index |
|---|---|---|---|---|
| Fully-directional | 3 | 151.48 | 3.76 | 0.94 |
| | 6 | 322.74 | 7.73 | 0.89 |
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- Directionality in mmWave gives significant gains for
  - network sum rate, minimum per-link throughput, fairness
- **What is the main source of these gains?**

# Cellular networks (long-term resource allocation)

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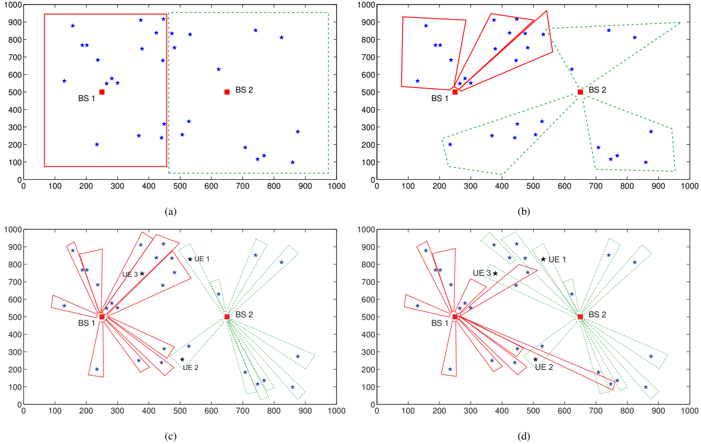


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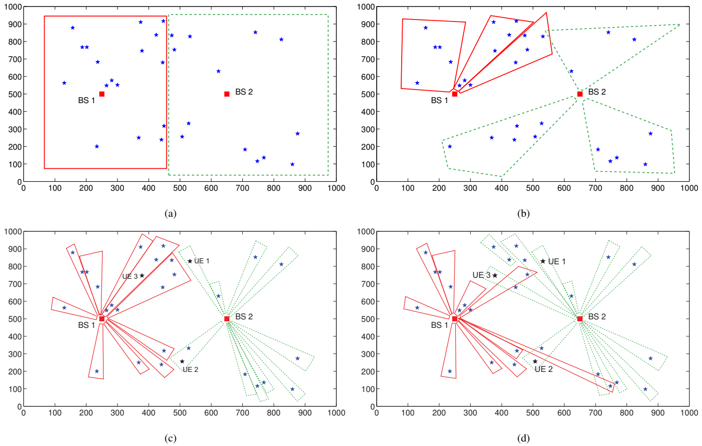

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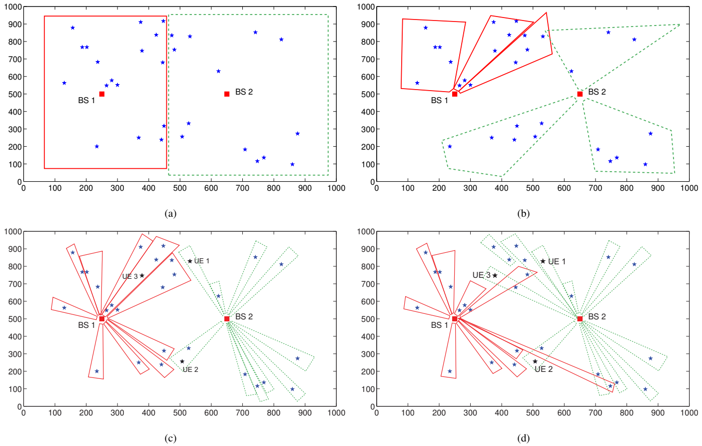

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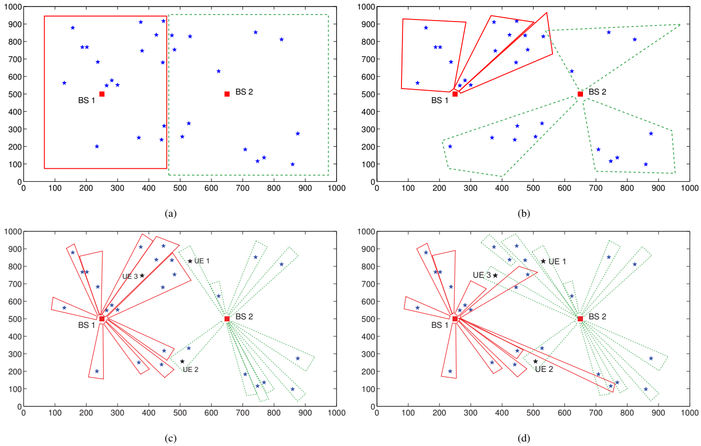


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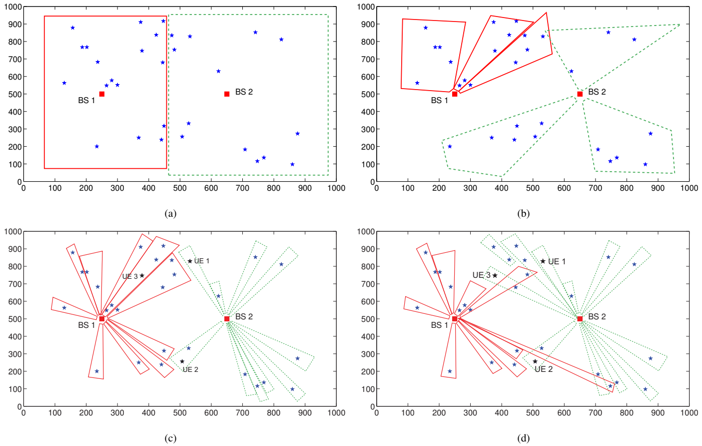

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# Some takeaways of mmWave communications (1/2)

- **Distinguishing properties:** huge bandwidth, high penetration loss, high noise power, many antennas

- **Impacts on performance:** alignment-throughput tradeoff, reduced interference footprint, high signaling cost

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- **Impacts on performance:** alignment-throughput tradeoff, reduced interference footprint, high signaling cost

  misunderstanding: mmWave networks are noise-limited!

  This holds only for specific applications (such as backhauling). The network performance is mostly limited by LoS interference, signaling overhead, or link establishment overhead.

# Some takeaways (2/2)

- **New design principles:**
  - in ad hoc networks: hybrid MAC, collision notification
  - in cellular networks: association, reactive interference management

# Future works

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

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Work on mmWave networks!

# Useful links

IEEE 802.11ay task group:
http://www.ieee802.org/11/Reports/tgay_update.htm

Our mmWave communications group (LinkedIn):
http://www.linkedin.com/grp/home?gid=6957585

Our system-level mmWave simulator (ns3):
http://github.com/igodip/test-module

NYU mmWave channel module (ns3):
http://github.com/mmezzavilla/ns3-mmwave

# Special thanks to

ROYAL INSTITUTE
OF TECHNOLOGY

# Fundamentals of Medium Access Control Design for Millimeter Wave Networks

Hossein Shokri-Ghadikolaei

September 2015

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Stockholm, Sweden

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# Backup slides!

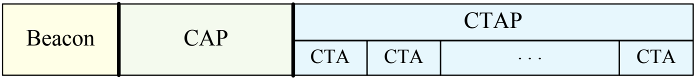
# Hybrid MAC

- diverse applications, different QoS levels
  - low-data-rate event-driven monitoring
  - high-data-rate low-delay low-jitter video streaming

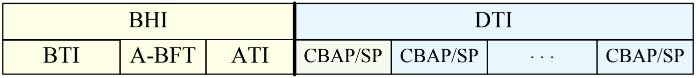
| MAC protocol | Pros | Cons |
|---|---|---|
| TDMA | – no interference<br>– simplicity | – network-wide synchronization<br>– no spatial gain |
| STDMA | – no interference<br>– spatial gain | – knowledge of exact topology<br>– NP-hard problem |
| CSMA | – simplicity<br>– local synchronization<br>– spatial gain | – hidden and exposed node problems |
| CSMA/CA | – simplicity<br>– local synchronization<br>– spatial gain | – collision avoidance overhead |

# Hybrid MAC

- diverse applications, different QoS levels
  - low-data-rate event-driven monitoring
  - high-data-rate low-delay low-jitter video streaming
- hybrid CSMA/CA-TDMA approach




Superframe of IEEE 802.15.3c




Beacon interval of IEEE 802.11ad

H. Shokri-Ghadikolaei, et al., "Design aspects of short range millimeter wave wireless networks: A MAC layer perspective," *IEEE Network*, submitted, 2015.

# Contributions

- proposing a novel blockage model to capture the angular correlation of line-of-sight condition
- deriving closed-form expressions for collision probability, per-link throughput, and area spectral efficiency of slotted ALOHA and those of TDMA
- proposing the new concept of *dynamic cell*
- proposing four options to realize physical control channel for mmWave cellular networks
- proposing a novel two-stage synchronization procedure (macro-level time-frequency synchronization in UHF bands and micro-level spatial synchronization in mmWave bands) for mmWave cellular networks, along with its delay and coverage analysis

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# Contributions

- extending the concept of *grouping* compatible with hybrid beamforming architecture of mmWave networks
- illustrating the tradeoff among throughput enhancement, fair scheduling, and high connection robustness
- formulating a long-term resource allocation problem to enhance per-link and network throughput with macro-level load balancing
- proposing a novel collision notification message, along with a new protocol, to solve the prolonged backoff time problem in mmWave networks with random access
- raising the necessity of on-demand executions of control messages

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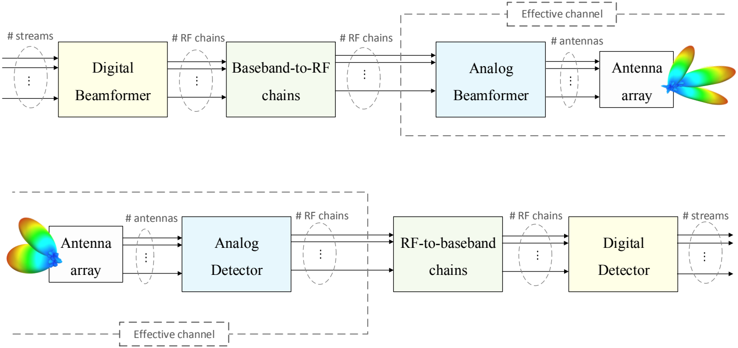
# Beamforming




**Digital:** maximum flexility, but unaffordable complexity and cost in mmWave networks

H. Shokri-Ghadikolaei, et al., "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Trans. Commun.*, 2015, to appear.

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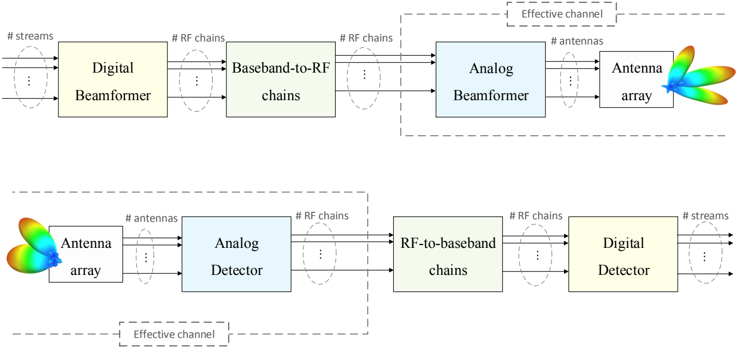
# Beamforming




**Analog:** maximum simplicity (no CSI for beamforming), but no multiplexing gain

H. Shokri-Ghadikolaei, et al., "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Trans. Commun.*, 2015, to appear.

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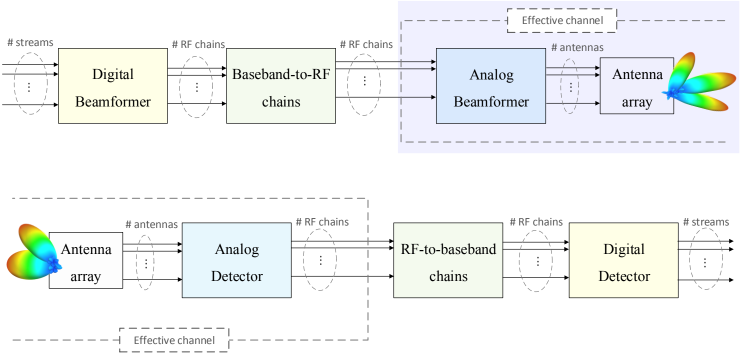
# Beamforming




**Hybrid:** promising solution for mmWave networks due to channel sparsity, multiplexing gain, antenna gain, flexibility, etc.

H. Shokri-Ghadikolaei, et al., "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Trans. Commun.*, 2015, to appear.

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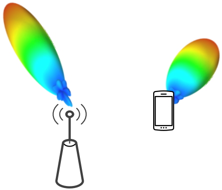
# Interplay between beamwidth and throughput



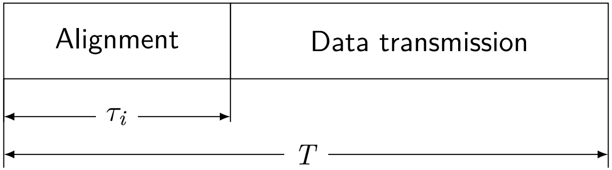
| | |
|---|---|
| Beam training | Data transmission |

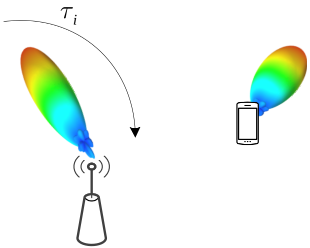
## Beam training phase

- Analog beamforming in current mmWave standards
  - beam training $\rightarrow$ alignment of the Tx and Rx beams!
  - alignment by a sequence of pilot transmissions!
- Hybrid beamforming in future mmWave networks

more info

# Interplay between beamwidth and throughput



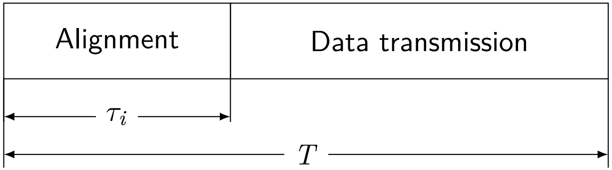

$\tau_i$ : alignment time of device $i$

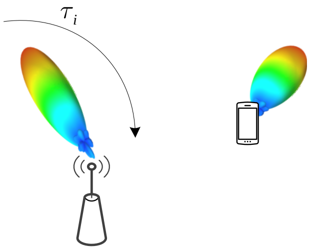
$T$ : time slot duration

$r_i$ : transmission rate of device $i$

Achievable throughput of link (Tx-Rx pair) $i = (T - \tau_i)\, r_i$

# Interplay between beamwidth and throughput

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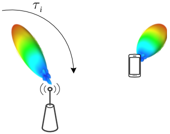
Achievable throughput of link (Tx-Rx pair) $i = (T - \tau_i)\, r_i$

# Alignment procedure

| Alignment | Data transmission |
|---|---|



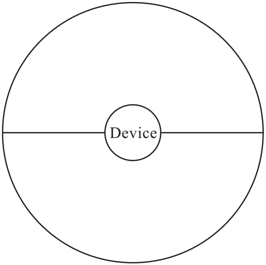

$T_p$ : single pilot transmission overhead

$\psi_i^t$ : sector-level beamwidth of transmitter of link $i$

$\psi_i^r$ : sector-level beamwidth of receiver of link $i$

$\varphi_i^t$ : beam-level beamwidth of transmitter of link $i$

$\varphi_i^r$ : beam-level beamwidth of receiver of link $i$




quasi-omni pattern

J. Wang, *et al.* "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, 2011.

# Interplay between beamwidth and throughput

| | |
|---|---|
| Alignment | Data transmission |

Alignment overhead : $\tau_i\left(\varphi_i^t, \varphi_i^r\right) = \left\lceil \frac{\psi_i^t}{\varphi_i^t} \right\rceil \left\lceil \frac{\psi_i^r}{\varphi_i^r} \right\rceil T_p$

# Interplay between beamwidth and throughput

| Alignment | Data transmission |
|---|---|

Alignment overhead : $\tau_i\left(\varphi_i^t,\varphi_i^r\right)=\left\lceil\frac{\psi_i^t}{\varphi_i^t}\right\rceil\left\lceil\frac{\psi_i^r}{\varphi_i^r}\right\rceil T_p$

Antenna gain (transmitter) : $g_{i,j}^t\left(\varphi_i^t\right)=\begin{cases}\frac{2\pi-(2\pi-\varphi_i^t)z}{\varphi_i^t}\,, & \text{main lobe}\\ z\,, & \text{sidelobe}\end{cases}$

Antenna gain (receiver) : $g_{i,j}^r\left(\varphi_i^r\right)=\begin{cases}\frac{2\pi-(2\pi-\varphi_j^r)z}{\varphi_j^r}\,, & \text{main lobe}\\ z\,, & \text{sidelobe}\end{cases}$

depends on the topology and beamwidth

# Interplay between beamwidth and throughput

| Alignment | Data transmission |
|---|---|

Alignment overhead : $\tau_i\left(\varphi_i^t, \varphi_i^r\right) = \left\lceil \frac{\psi_i^t}{\varphi_i^t} \right\rceil \left\lceil \frac{\psi_i^r}{\varphi_i^r} \right\rceil T_p$

Antenna gain (transmitter) : $g_{i,j}^t\left(\varphi_i^t\right) = \begin{cases} \frac{2\pi - (2\pi - \varphi_i^t)z}{\varphi_i^t}, & \text{main lobe} \\ z, & \text{sidelobe} \end{cases}$

Antenna gain (receiver) : $g_{i,j}^r\left(\varphi_i^r\right) = \begin{cases} \frac{2\pi - (2\pi - \varphi_j^r)z}{\varphi_j^r}, & \text{main lobe} \\ z, & \text{sidelobe} \end{cases}$

$$\mathrm{SINR}_i = \frac{p_i g_{i,i}^t g_{i,i}^c g_{i,i}^r}{\sum_{\substack{k=1 \\ k \neq i}}^{N} p_k g_{k,i}^t g_{k,i}^c g_{k,i}^r + n}$$

# Interplay between beamwidth and throughput

| Alignment | Data transmission |
| --- | --- |

$$\begin{aligned}
\underset{\varphi^t,\varphi^r,\mathbf{p}}{\text{maximize}} \quad & R = \sum_{i=1}^{N}\left(1-\frac{\tau_i}{T}\right)\log_2\left(1+\mathrm{SINR}_i\right), && (2)\\
\text{s.t.} \quad & \varphi_i^t \le \psi_i^t\,, & 1 \le i \le N\,,\\
& \varphi_i^r \le \psi_i^r\,, & 1 \le i \le N\,,\\
& \psi_i^t\psi_j^r\,T_P/T \le \varphi_i^t\varphi_j^r\,, & 1 \le i,j \le N\,,\\
& 0 \le p_i \le p^{\max}\,, & 1 \le i \le N\,.
\end{aligned}$$

$N$: number of links
$p^{\max}$: maximum transmission power

# Interplay between beamwidth and throughput

| Alignment | Data transmission |
| --- | --- |

$$\begin{aligned} \underset{\varphi^t,\varphi^r,\mathbf{p}}{\text{maximize}} \quad & R = \sum_{i=1}^{N} \left(1 - \frac{\tau_i}{T}\right) \log_2\left(1 + \mathrm{SINR}_i\right), && (2) \\ \text{s.t.} \quad & \varphi_i^t \le \psi_i^t, && 1 \le i \le N, \\ & \varphi_i^r \le \psi_i^r, && 1 \le i \le N, \\ & \psi_i^t \psi_j^r T_P / T \le \varphi_i^t \varphi_j^r, && 1 \le i, j \le N, \\ & 0 \le p_i \le p^{\max}, && 1 \le i \le N. \end{aligned}$$

How to solve? start from single link scenario $(N = 1)$

# Multiple links scenario

- proposing two topology-agnostic approaches to solve (1)
- decomposing *a multiple-link* scenario into *multiple single-link* scenarios
  - substantial reduction of computational complexity
  - a performance loss compared to (6)
- **overestimation of interference**
  - estimate interference in sector-level
  - activate links with negligible sector-level interference (independent set)
  - still NP-hard!
- **underestimation of interference**
  - ignore multiuser interference (noise-limited regime)
  - activate all links at the same time
  - multiple executions of gradient descent algorithm
  - very low signaling overhead!

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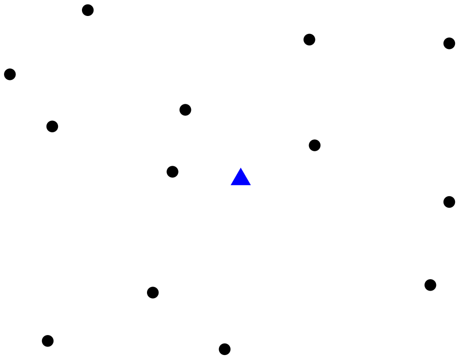
# Right interference model

- interference range model
- interference ball model
- physical model

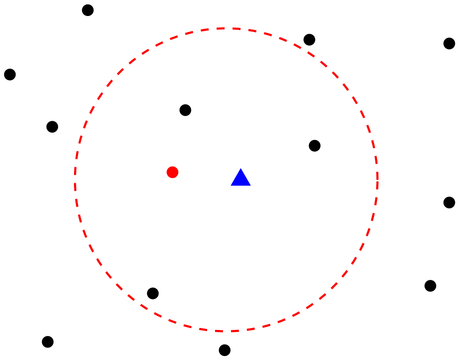


# Right interference model

- **interference range model**
- interference ball model
- physical model

– omnidirectional

– no blockage

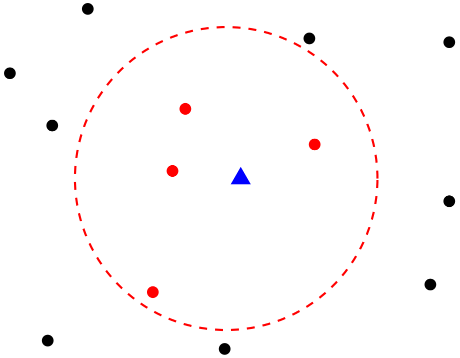


# Right interference model

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

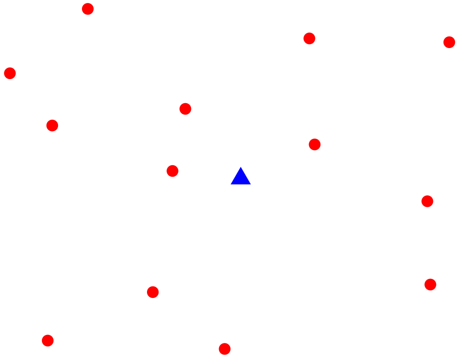
–omnidirectional

–no blockage



# Right interference model

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



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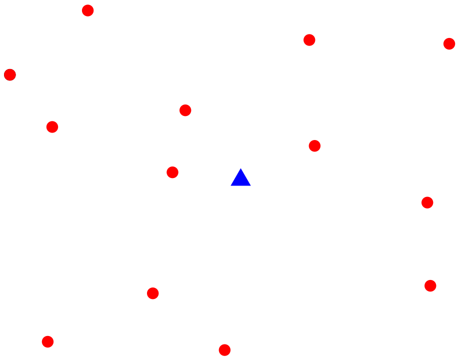

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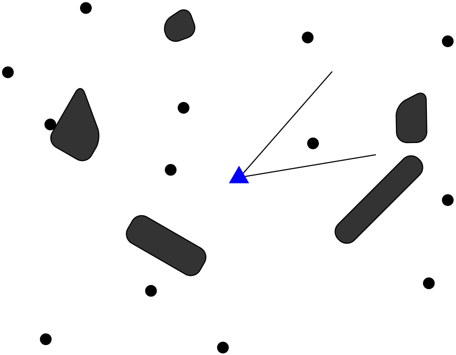

– directional

– blockage

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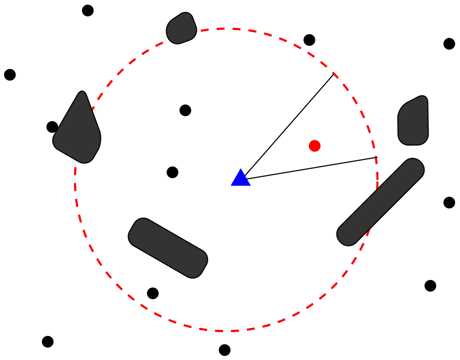
– directional

– blockage



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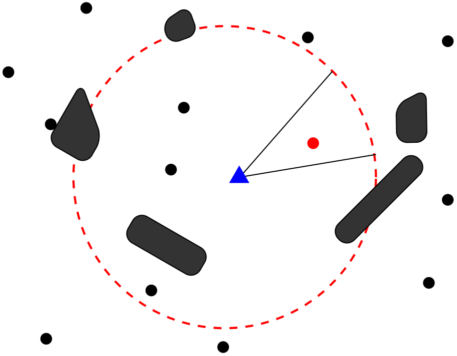
- physical model (very complicated, very accurate)

– directional

– blockage



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- **physical model** (very complicated, very accurate)

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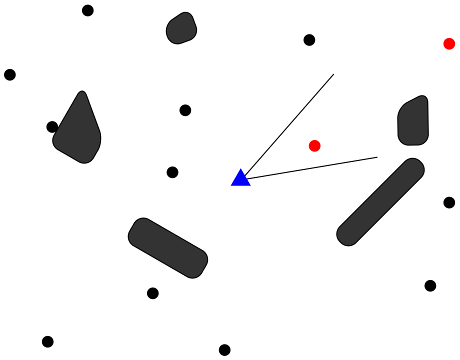
– blockage



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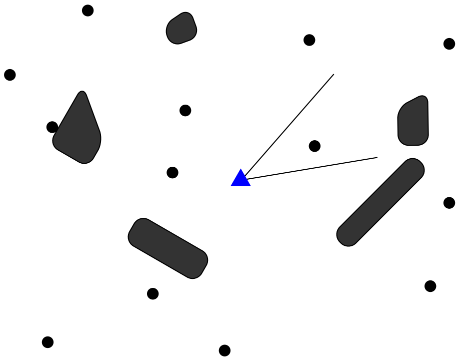

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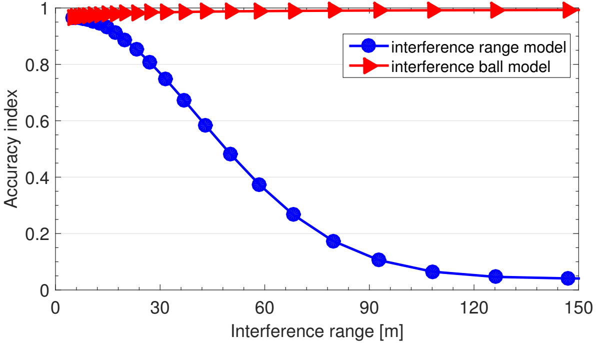


- omnidirectional, no blockage
- 1 transmitter in a 100x100 $m^2$ area
- SINR threshold = 1 dB

H. Shokri-Ghadikolaei, C. Fischione, E. Modiano, "Interference models similarity index," *KTH Tech. Rep.*, Aug. 2015, available upon request.

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# Right interference model

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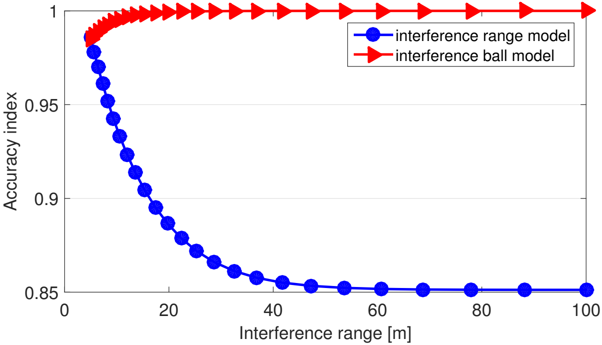


- directional, blockage
- 1 transmitter in a 100x100 $m^2$ area
- 1 obstacle in a 40x40 $m^2$ area with average size 10 m
- SINR threshold = 1 dB

H. Shokri-Ghadikolaei, C. Fischione, E. Modiano, "Interference models similarity index," *KTH Tech. Rep.*, Aug. 2015, available upon request.

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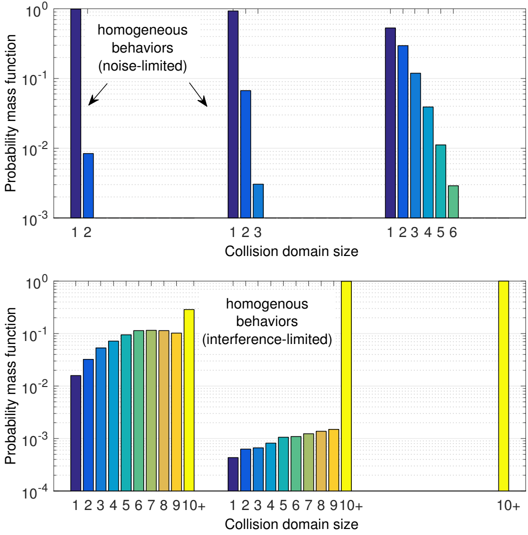
# Distribution of the collision domain size

- **Definition:** collision domain of any receiver is the set of unintended transmitters that each of them causes a collision at the receiver

# Distribution of the collision domain size

beamwidth = 5°

beamwidth = 360°




H. Shokri-Ghadikolaei, C. Fischione, E. Modiano, "Abstract interference analysis of millimeter wave networks," *KTH Tech. Rep.*, available upon request.

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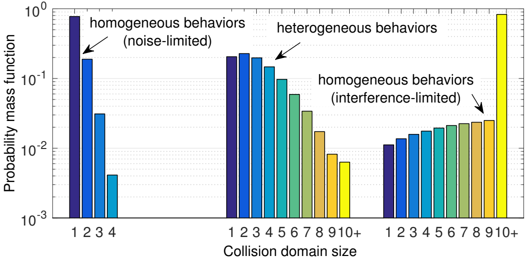
# Distribution of the collision domain size

beamwidth = 30°

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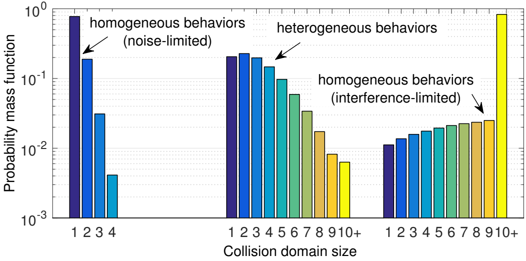


- mmWave networks exhibit much more diverse collision domain sizes than UHF ones!

*H. Shokri-Ghadikolaei and C. Fischione, "The transitional behavior of interference in millimeter wave networks," *IEEE Trans. Commun.*, submitted, 2015.

**H. Shokri-Ghadikolaei, C. Fischione, E. Modiano, "Abstract interference analysis of millimeter wave networks," *KTH Tech. Rep.*, available upon request.

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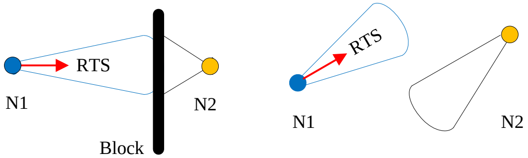
# Prolonged backoff time




Random backoff is not a good solution to solve blockage or deafness!

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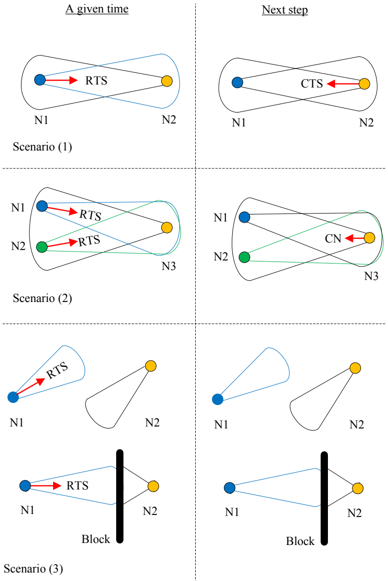
# Prolonged backoff time

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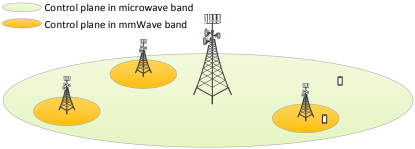
# Physical control channel (essential tradeoffs)

fall-back tradeoff:

(1) **microwave**: better coverage, more reliable, two radios

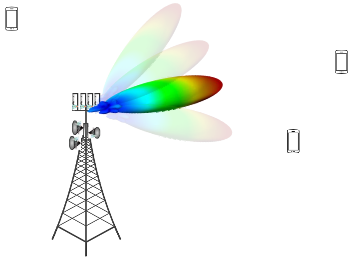
(2) **mmWave**: one radio, short coverage




directionality tradeoff:

(1) **omnidirectional**: no alignment overhead, short coverage

(2) **directional**: spectral and energy efficient, good coverage, alignment overhead



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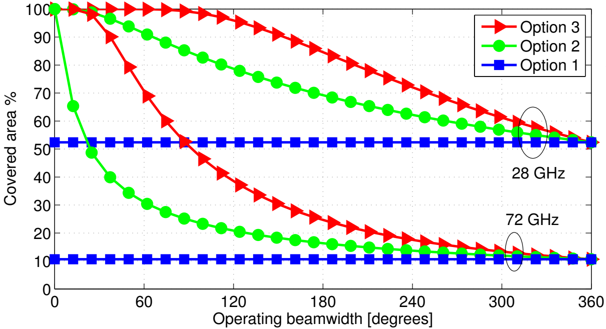
# Physical control channel (coverage of different options)




transmitter density: $10^{-5}$

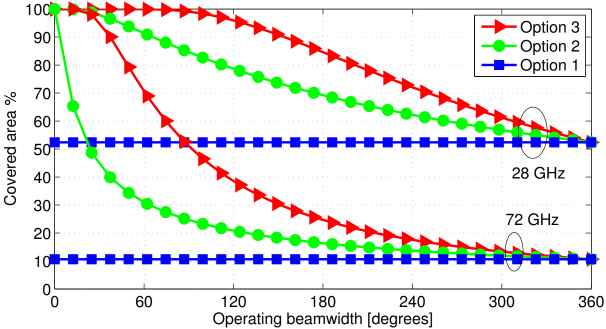
SINR threshold: 0 dB

Option 1: omnidirectional operation of both transmitter and receiver

Option 2: directional operation of either transmitter or receiver (semi-directional)

Option 3: directional operation of both transmitter and receiver (fully-directional)

# Physical control channel (coverage of different options)




transmitter density: $10^{-5}$

SINR threshold: 0 dB

- lower coverage in 72 GHz, mainly due to higher path-loss
- superior performance of fully-directional option

# Two-stage synchronization

- we have *time-frequency-spatial* resource block
  - synchronization in time-frequency-spatial domain
  - joint synchronization in mmWave band is possible*, but not very efficient

- we propose a two stage synchronization:

  (1) macro level time-frequency synchronization in UHF bands using macro base stations

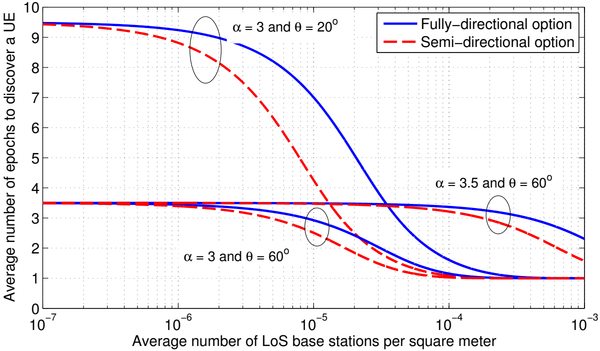
  (2) micro level spatial synchronization in mmWave bands using micro base stations

## Main features

- pros: substantial reduction in the search space
- cons: dual-band operation (it is compatible with recent standards)

*C. Barati, et al., "Directional cell discovery in millimeter wave cellular networks," *IEEE Trans. Wireless Commun.*, 2015, to appear.

# Spatial synchronization overhead




- initial synchronization: a small additional overhead
  - from 1 slot in existing network to 2 slot (with BS density $10^{-5}$)
- afterwards: almost no additional synchronization overhead (beam tracking)