



# Millimeter Wave Ad Hoc Networks: Noise-limited or Interference-limited?

**Hossein Shokri-Ghadikolaei** and Carlo Fischione

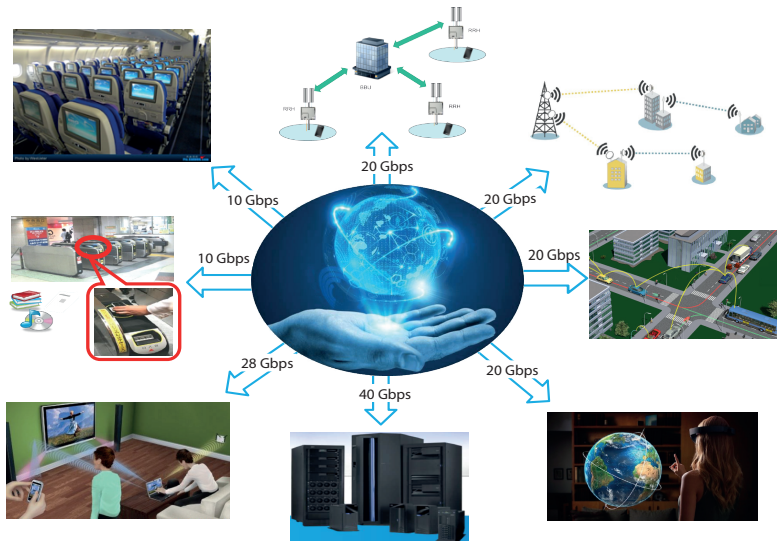
December 2015

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IEEE Global Communications Conference, San Diego, CA, USA, 2015.

# Growing interests in mmWave communications



1. Introduction
2. System Model
3. Interference Analysis
4. Throughput and Delay Analysis
5. Concluding remarks

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# Characteristics of mmWave communications

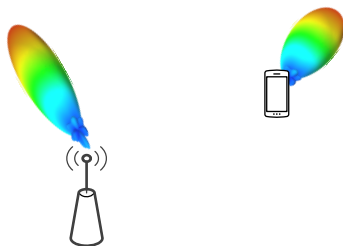


- High path-loss, large bandwidth, short wavelength
- **Blockage:** High penetration loss, e.g., 20-35 dB by the human body
- **Deafness:** Misalignment between transmitter and receiver

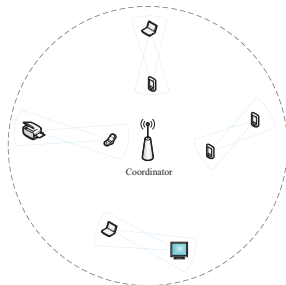
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\*S. Rangan, T. Rappaport, and E. Erkip, "Millimeter wave cellular wireless networks: Potentials and challenges," *Proc. IEEE*, Mar. 2014.

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- **Blockage:** High penetration loss, e.g., 20-35 dB by the human body
- **Deafness:** Misalignment between transmitter and receiver
  - beam-training overhead\*
  - negligible hidden node and exposed node problems!
  - significant spatial gain



\* H. Shokri-Ghadikolaei, L. Gkatzikis, and C. Fischione, "Beam-searching and transmission scheduling in millimeter wave communications," *IEEE ICC*, 2015.



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A fundamental question

Does mmWave networks operate in noise-limited regime?

- High path-loss, large bandwidth, short wavelength
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## A fundamental question

Does mmWave networks operate in noise-limited regime?

- mainstream belief: **YES!**

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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  - a novel blockage model to capture angular correlation of LoS events

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



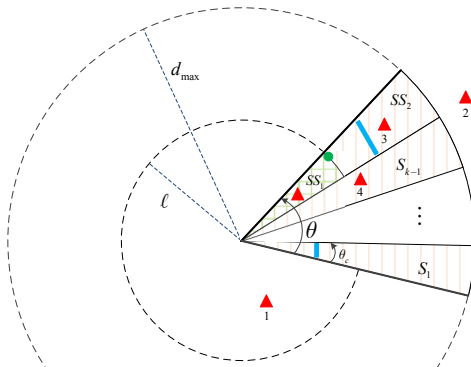
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  - collision probability, per-link throughput, area spectral efficiency, and delay
- How to optimize mmWave networks?
  - operating beamwidth, fairness, and short-term and long-term resource allocations
- How to design MAC?
  - collision-aware hybrid MAC and collision notification signal

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- Homogenous Poisson network of transmitters and obstacles
  - inhomogeneous Poisson network of non-blocked interferers
- Slotted ALOHA
- Similar beamwidth for all devices
- Deterministic wireless channel
- **Interference model:** protocol model of interference, impenetrable obstacles, no reflection
  - very simple yet accurate interference model\*

\* H. Shokri-Ghadikolaei, C. Fischione, and E. Modiano, "On the accuracy of interference models in wireless communications," submitted, 2015.

\* H. Shokri-Ghadikolaei *et al.*, "What Is the right interference model in millimeter wave networks?," submitted, 2015.



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

# Blockage model

circle: intended transmitter

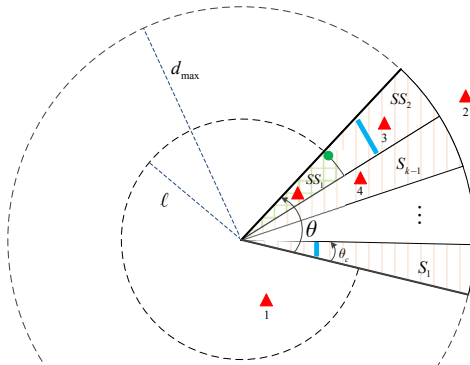
triangle: unintended transmitters

rectangle: obstacles

$\theta$ : beamwidth

$\theta_c$ : coherence angle

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



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## Proposition

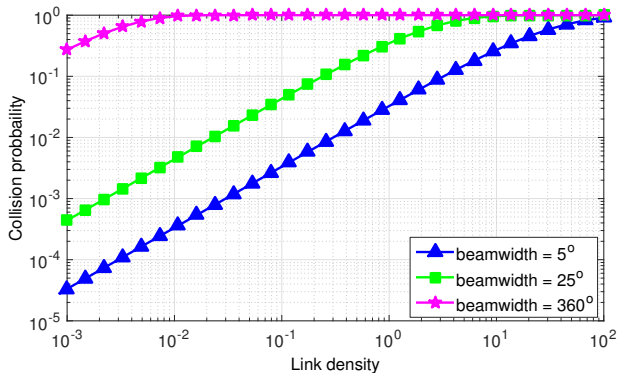
Let  $\lambda_t$  and  $\lambda_o$  be the density of the transmitters and obstacles per unit area. Let  $\rho_a$  be the transmission probability. Let  $d_{\max}$ ,  $\theta$ , and  $\theta_c$  be the interference range, beamwidth, and coherence angle, respectively. Let  $\lambda_I = \rho_a \lambda_t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

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

and can be tightly bounded as

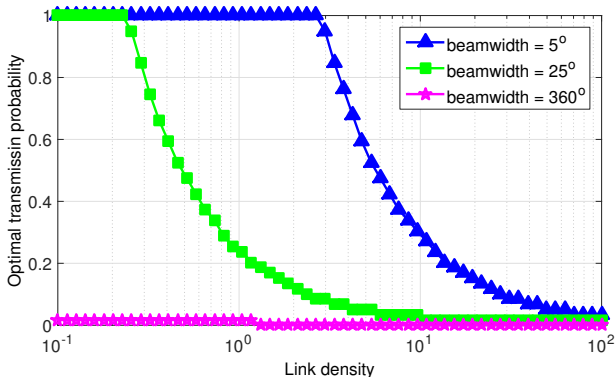
$$1 - \left( \frac{\lambda_o + \lambda_I e^{-(\lambda_o + \lambda_I) \theta_c d_{\max}^2 / 2}}{\lambda_o + \lambda_I} \right)^{\lceil \theta / \theta_c \rceil} \leq \rho_c \leq 1 - e^{-\lambda_I \theta_c d_{\max}^2 / 2} \left( \frac{\lambda_o + \lambda_I e^{-(\lambda_o + \lambda_I) \theta_c d_{\max}^2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

# Collision probability





# Collision probability



- 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

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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  $A_x = \theta_c x^2/2$ . Then, the per-link throughput and the area spectral efficiency (ASE) of slotted ALOHA and those of TDMA are

$$r_{\text{S-ALOHA}} = \int_{\ell=0}^{d_{\max}} \rho_a e^{-\lambda_o A \ell} (1 - \rho_c |\ell|) \frac{2\ell}{d_{\max}^2} d\ell,$$

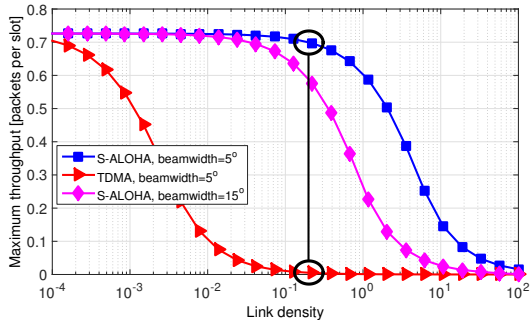
$$\text{ASE}_{\text{S-ALOHA}} = \frac{1 + A\lambda_t}{A} \int_{\ell=0}^{d_{\max}} \rho_a e^{-\lambda_o A \ell} (1 - \rho_c |\ell|) \frac{2\ell}{d_{\max}^2} d\ell,$$

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

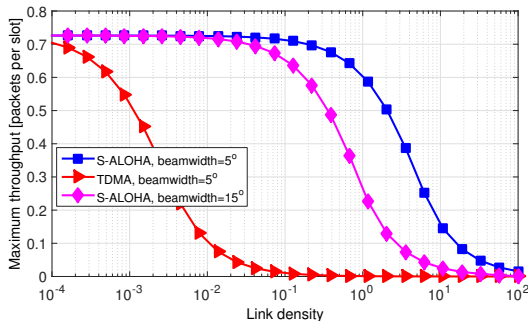
and

$$\text{ASE}_{\text{TDMA}} = \frac{1 - e^{-\lambda_o A d_{\max}}}{A \lambda_o A d_{\max}}.$$

# Per-link throughput

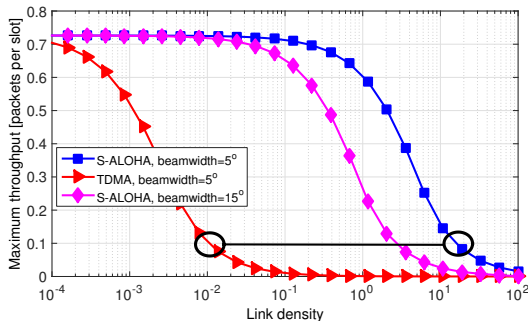


- Significant spatial gain
  - 5000x throughput gain with transmitter density 0.11



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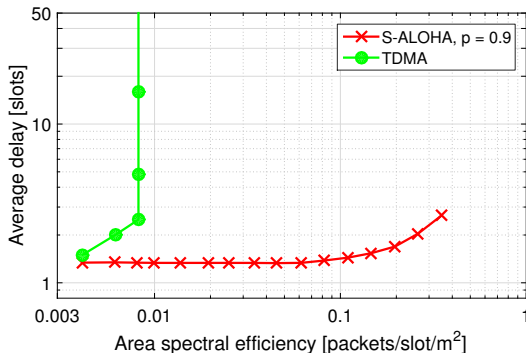
- 5000x throughput gain with transmitter density 0.11
- optimal transmission probability is 1 in many cases! (very simple slotted ALOHA)



- Significant spatial gain

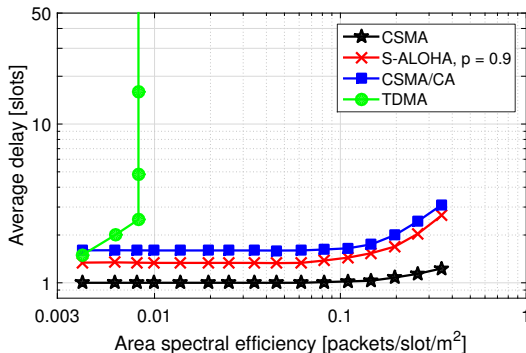
- 5000x throughput gain with transmitter density 0.11
- optimal transmission probability is 1 in many cases! (very simple slotted ALOHA)
- around 1000x denser network with the same per-link throughput!

# Area spectral efficiency vs delay



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

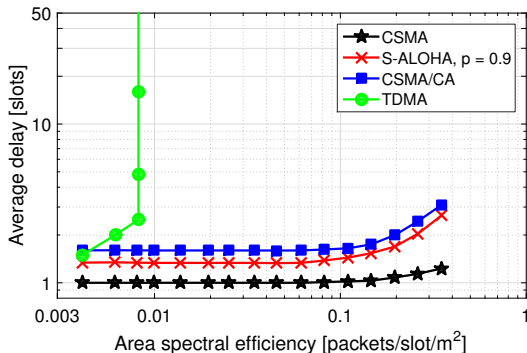
# Comparison with other MAC protocols



- Poor performance of CSMA/CA due to inefficient collision avoidance procedure
  - significant control and data rate mismatch (27.7 Mbps control vs 6.7 Gbps data rate)
- Superior performance of CSMA
  - due to negligible hidden and exposed node problems

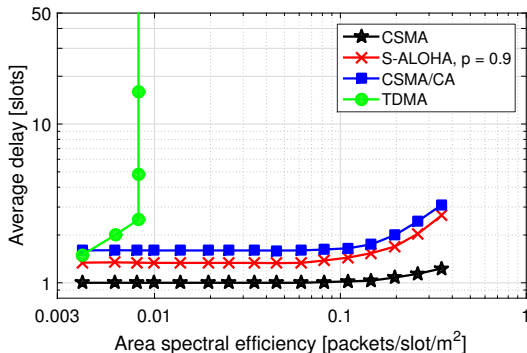


# Comparison with other MAC protocols



- Why should we serve traffic in TDMA phase?

# Comparison with other MAC protocols



- Why should we serve traffic in TDMA phase? → collision-aware hybrid MAC\*

\* H. Shokri-Ghadikolaei and C. Fischione, "The transitional behavior of interference in millimeter wave networks and its impact on medium access control," submitted, 2015.

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

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- Blockage and directionality affect all aspects of mmWave networks
  - simple interference model
  - low multiuser interference footprint
  - transitional behavior of interference
  - high signaling cost
  - collision-aware hybrid MAC
- MmWave networks are barely noise-limited!
  - only for specific applications, e.g., wireless backhauling
  - mostly limited by LoS interference, signaling overhead, or link establishment overhead

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IEEE 802.11ay task group:

[http://www.ieee802.org/11/Reports/tgay\\_update.htm](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>



# Millimeter Wave Ad Hoc Networks: Noise-limited or Interference-limited?

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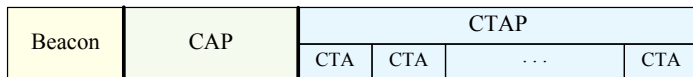
# Backup slides!



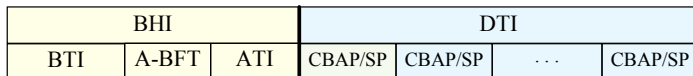
- diverse applications, different QoS levels
  - low-data-rate event-driven monitoring
  - high-data-rate low-delay low-jitter video streaming

| MAC protocol | Pros  | Cons   |
|--------------|---|--|
| TDMA         | <ul style="list-style-type: none"><li>– no interference</li><li>– simplicity</li></ul>                              | <ul style="list-style-type: none"><li>– network-wide synchronization</li><li>– no spatial gain</li></ul> |
| STDMA        | <ul style="list-style-type: none"><li>– no interference</li><li>– spatial gain</li></ul>                            | <ul style="list-style-type: none"><li>– knowledge of exact topology</li><li>– NP-hard problem</li></ul>  |
| CSMA         | <ul style="list-style-type: none"><li>– simplicity</li><li>– local synchronization</li><li>– spatial gain</li></ul> | <ul style="list-style-type: none"><li>– hidden and exposed node problems</li></ul>                       |
| CSMA/CA      | <ul style="list-style-type: none"><li>– simplicity</li><li>– local synchronization</li><li>– spatial gain</li></ul> | <ul style="list-style-type: none"><li>– collision avoidance overhead</li></ul>                           |

- 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



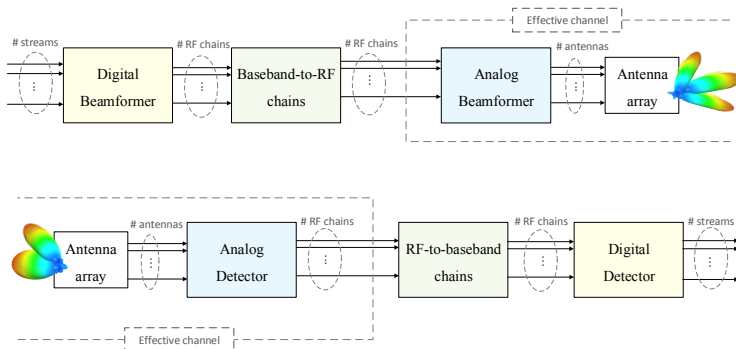
Beacon interval of IEEE 802.11ad

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

- 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

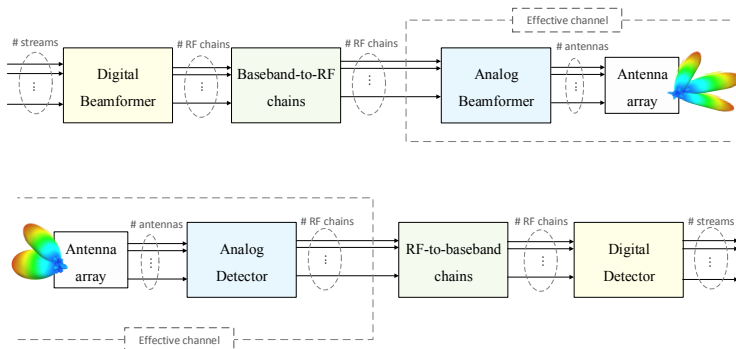
- extending the concept of *grouping* compatible with hybrid beam-forming architecture of mmWave networks
- illustrating the tradeoff among throughput enhancement, fair scheduling, and high connection robustness
- formulating a long-term resource allocation problem to enhance per-link and network throughput 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

# Beamforming

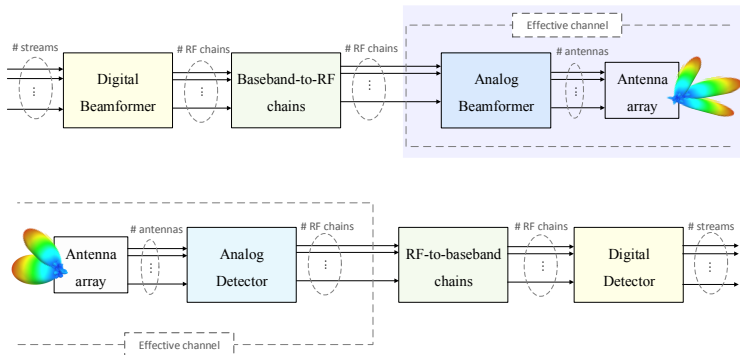


**Digital:** maximum flexibility, but **unaffordable complexity and cost in mmWave networks**

# Beamforming

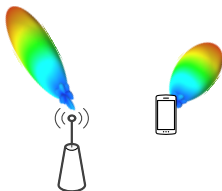


**Analog:** maximum simplicity (no CSI for beamforming), but **no multiplexing gain**



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

# Interplay between beamwidth and throughput



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

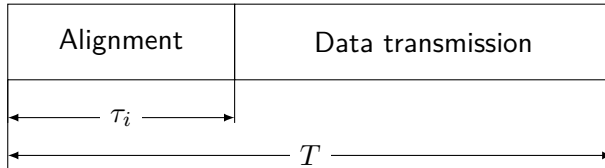
## Beam training phase

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

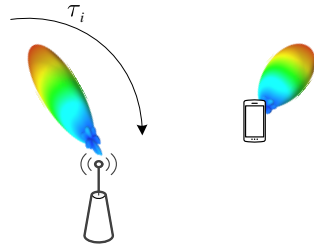
[▶ more info](#)



# Interplay between beamwidth and throughput

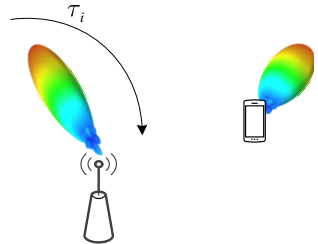
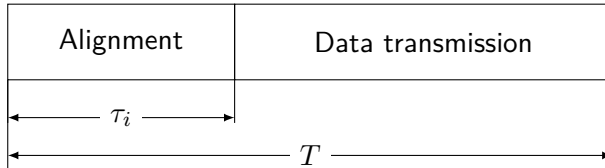


$\tau_i$  : alignment time of device  $i$   
 $T$  : time slot duration  
 $r_i$  : transmission rate of device  $i$



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

# Interplay between beamwidth and throughput



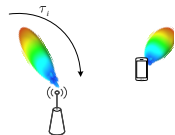
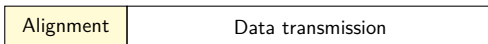
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Achievable throughput of link (Tx-Rx pair)  $i = (T - \tau_i) r_i$

# Alignment procedure



$T_p$  : 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  $i$

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 |
|-----------|-------------------|

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

# Interplay between beamwidth and throughput

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

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

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

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

depends on the topology and beamwidth



# Interplay between beamwidth and throughput

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

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

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

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

# Interplay between beamwidth and throughput



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

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

$N$ : number of links

$p^{\max}$ : maximum transmission power

# Interplay between beamwidth and throughput

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

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

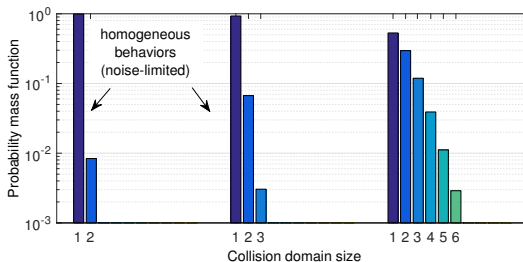
How to solve? start from single link scenario ( $N = 1$ )



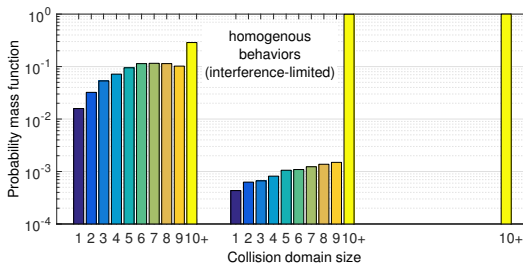
- **Definition:** collision domain of any receiver is the set of unintended transmitters that each of them causes a collision at the receiver

# Distribution of the collision domain size

beamwidth =  $5^\circ$



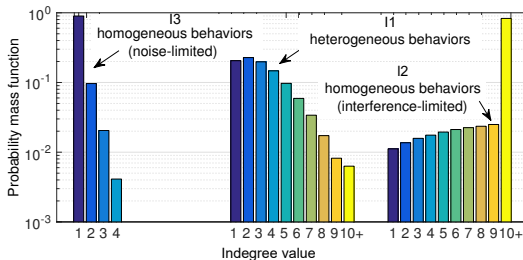
beamwidth =  $360^\circ$



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

# Distribution of the collision domain size

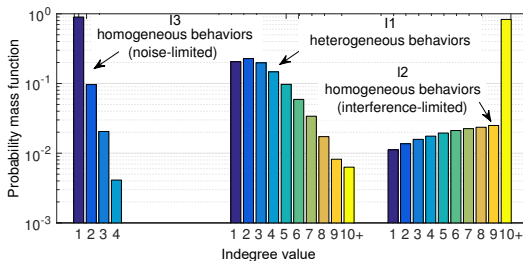
beamwidth =  $30^\circ$



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

# Distribution of the collision domain size

beamwidth =  $30^\circ$

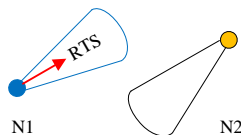
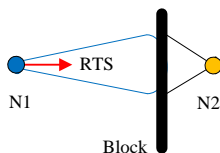


- mmWave networks exhibit much more diverse collision domain sizes than UHF ones!

\*H. Shokri-Ghadikolaei and C. Fischione, "The transitional behavior of interference in millimeter wave networks and its impact on medium access control," submitted, 2015.

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

# Prolonged backoff time

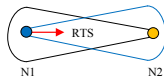


Random backoff is not a good solution to solve blockage or deafness!

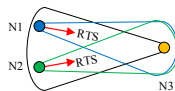
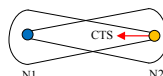
# Prolonged backoff time

A given time

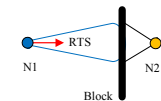
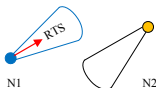
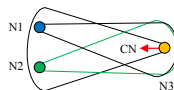
Next step



Scenario (1)



Scenario (2)



Scenario (3)

