Random Access Protocol for Massive MIMO:

Strongest-User Collision Resolution (SUCR)

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Motivation

- *Massiveness* of 5G Networks and Beyond
  - Massive number of user equipments (UEs), intermittent activity
  - Massive total data traffic
  - Massive differences in traffic between UEs (mobile broadband, internet-of-things, etc.)

Connection Issue

How to connect and disconnect that many UEs from the network?

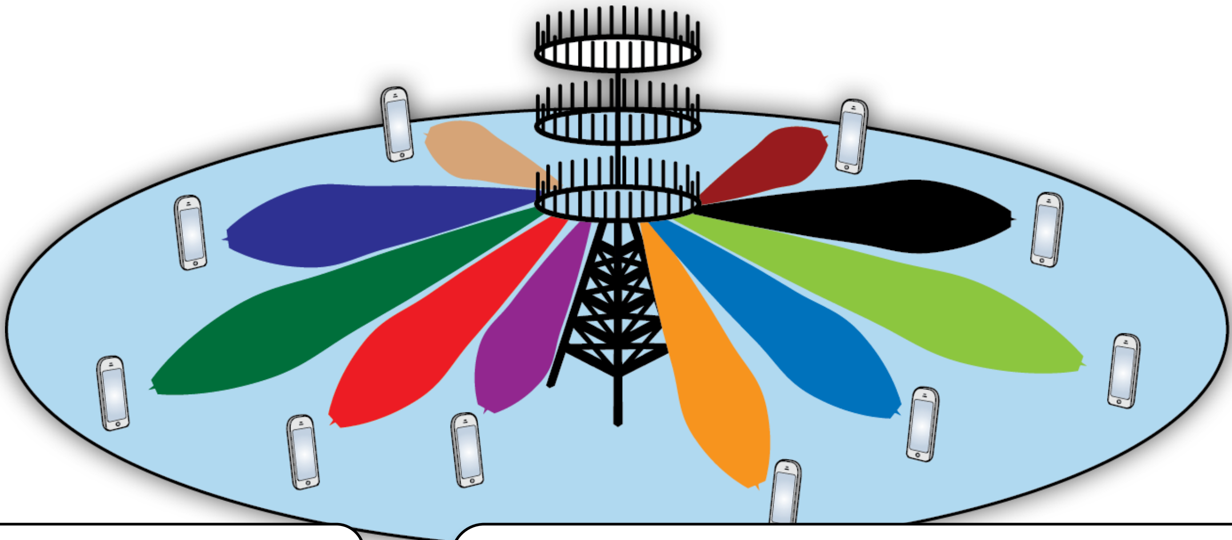
LTE Random Access Solution Not Enough

More users → More access contention → Requires more overhead

5G Physical Layer Solution

Massive MIMO (multiple-input multiple-output)

- M antennas at the base station (e.g., $M = 100$)
- K UEs are associated with the base station
- Pilot sequences are key to separate UEs by spatial beamforming
- Number of pilots limited by channel coherence: τ_c channel uses



Achieves high throughput by multiplexing of many UEs

Massive number of UEs in a cell

$K \gg \tau_c$: *Cannot pre-associate pilots with UEs*

Pilot Allocation for Intermittent User Activity

Studied in paper at ICASSP 2016

Two Approaches

1. Uncoordinated pilot allocation
   - Each UE sends data using a randomly selected pilot sequence
   - Pros: No access procedure
   - Cons: Creates intra-cell pilot contamination, UE↔stream identification
   - Good for **short packages** and **best-effort services**?

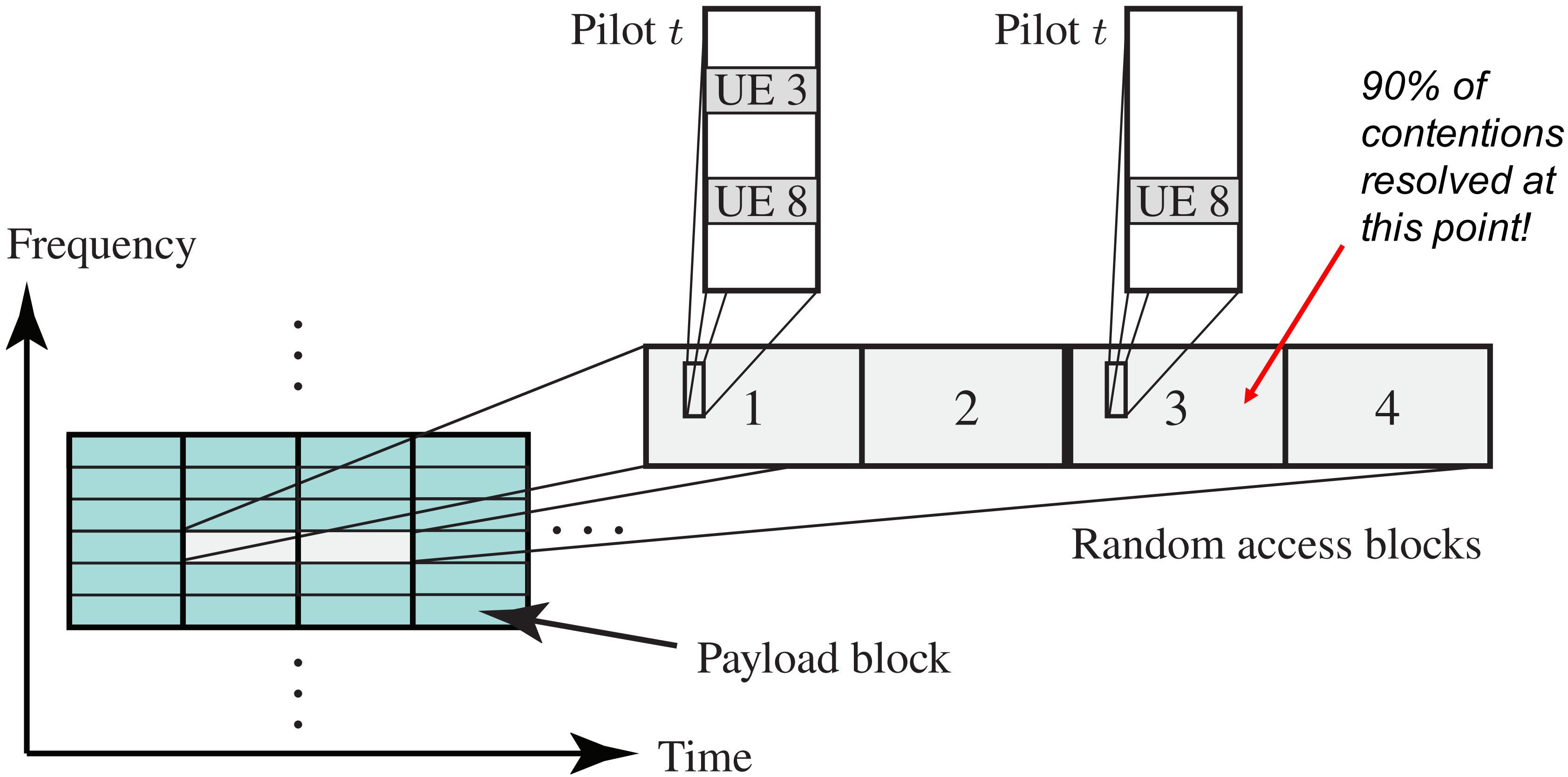
2. Coordinated pilot allocation
   - Each UE asks for a “protected” pilot sequence using random access
   - Pros: Separates access and data – no intra-cell pilot contamination
   - Cons: Random access collisions must be resolved
   - Good for **long packages** and **high-rate/robust services**?

Can we exploit Massive MIMO characteristics?

Focus of this presentation!

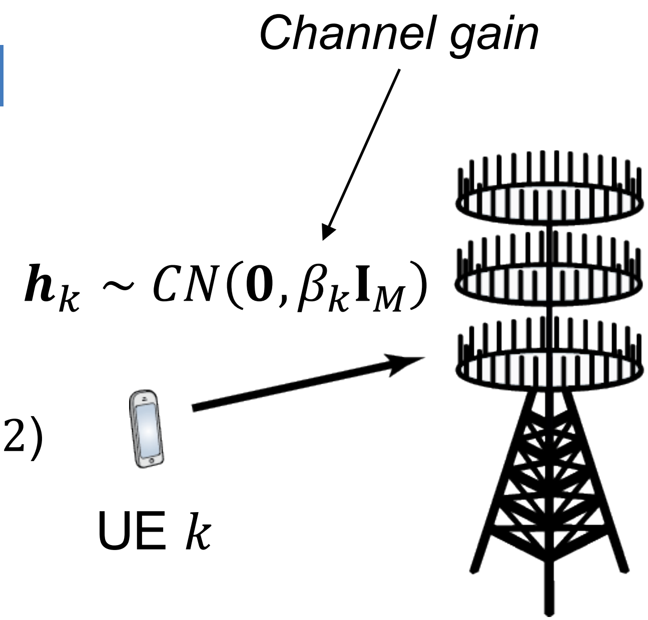
Proposed Frame Structure

- Two types of resource blocks
  1. Payload blocks ← Operated as in classic Massive MIMO
  2. Random access blocks



System Model

- Preliminaries
  - K UEs want to connect
  - Selects one of τ_p pilots at random ($\tau_p \leq \tau_c/2$)
  - P_a is probability of sending a pilot



- $\mathcal{S}$: Set of UEs picking an arbitrary pilot sequence:

$$|\mathcal{S}| \sim \text{Binomial}\left(K, \frac{P_a}{\tau_p}\right)$$

  - Probability of pilot collision

$$\Pr\{|\mathcal{S}| \geq 2\} = 1 - \left(1 - \frac{P_a}{\tau_p}\right)^K - K\frac{P_a}{\tau_p}\left(1 - \frac{P_a}{\tau_p}\right)^{K-1}$$

How to detect collisions?

Distributed Method to Detect Collisions (1/3)

Step 1:

Uplink pilot power

- BS receives uplink pilot signal:

$$\boldsymbol{y} = \sum_{i \in \mathcal{S}} \sqrt{\rho}\boldsymbol{h}_i + \boldsymbol{n}$$

Noise:
$\boldsymbol{n} \sim CN(0, \sigma^2 \mathbf{I}_M)$

- Compute least-square channel estimate of $\sum_{i \in \mathcal{S}} \boldsymbol{h}_i$:

$$\widehat{\boldsymbol{h}}_{LS} = \boldsymbol{y}/\sqrt{\rho}$$

- Form a precoding vector with fixed power q:

$$\boldsymbol{w} = \sqrt{q}\frac{\widehat{\boldsymbol{h}}_{LS}}{\left\|\widehat{\boldsymbol{h}}_{LS}\right\|}$$

Distributed Method to Detect Collisions (2/3)

Step 2:

- BS sends downlink pilot using $\boldsymbol{w}$
- Received signal at UE $k \in \mathcal{S}$:

$$z_k = \boldsymbol{h}_k^H \boldsymbol{w} + \eta_k$$

Noise:
$\eta_k \sim \mathcal{CN}(0, \sigma^2)$

- **Define sum channel gain**: $\alpha_{\mathcal{S}} = \sum_{i \in \mathcal{S}} \beta_i$

Channel Hardening Properties

$$\mathbb{E}\left\{\frac{z_k}{\sqrt{M}}\right\} = \sqrt{\frac{\rho q \beta_k^2}{\rho \alpha_{\mathcal{S}} + \sigma^2}} \frac{\Gamma\left(M + \frac{1}{2}\right)}{\sqrt{M}\Gamma(M)} \rightarrow \sqrt{\frac{\rho q \beta_k^2}{\rho \alpha_{\mathcal{S}} + \sigma^2}} \quad \text{as} \quad M \rightarrow \infty$$

$$\mathbb{V}\left\{\frac{z_k}{\sqrt{M}}\right\} = \frac{\rho q \beta_k^2}{\rho \alpha_{\mathcal{S}} + \sigma^2}\left(1 - \left(\frac{\Gamma\left(M + \frac{1}{2}\right)}{\sqrt{M}\Gamma(M)}\right)^2\right) + \frac{\sigma^2 + q\beta_k - \frac{\rho q \beta_k^2}{\rho \alpha_{\mathcal{S}} + \sigma^2}}{M} \rightarrow 0 \quad \text{as} \quad M \rightarrow \infty$$

Distributed Method to Detect Collisions (3/3)

Step 2 (cont.):

- In Massive MIMO we have:

$$\frac{z_k}{\sqrt{M}} \approx \mathbb{E}\left\{\frac{z_k}{\sqrt{M}}\right\} = \sqrt{\frac{\rho q \beta_k^2}{\rho \alpha_{\mathcal{S}} + \sigma^2}} \frac{\Gamma\left(M + \frac{1}{2}\right)}{\sqrt{M}\Gamma(M)}$$

- UE k estimates $\alpha_{\mathcal{S}}$ as

$$\hat{\alpha}_{\mathcal{S},k} \approx \frac{q \beta_k^2}{z_k^2} \left(\frac{\Gamma\left(M + \frac{1}{2}\right)}{\Gamma(M)}\right)^2 - \frac{\sigma^2}{\rho}$$

ML estimator is also be derived in the paper

***Detect collision** at UE k:*

Compute $\hat{\alpha}_{\mathcal{S},k}$

Compare with $\hat{\alpha}_{\mathcal{S},k} - \beta_k$ with a threshold

Distributed Contention Resolution

Step 3:

- Each user can infer 1) if a collision has occurred
  2) how strong the own channel gain is relative to the contenders $\beta_k / \hat{\alpha}_{\mathcal{S},k}$

- **Assumption**: The contention winner is the UE $k \in \mathcal{S}$ with largest β_k

"Strongest-User Collision Resolution (SUCR)"

***Activation decision rule** at UE k:*

Active: $\beta_k > \hat{\alpha}_{\mathcal{S},k}/2$

Inactive: $\beta_k \leq \hat{\alpha}_{\mathcal{S},k}/2$

Only active UEs retransmit pilot in Step 3 (and sends UE ID):

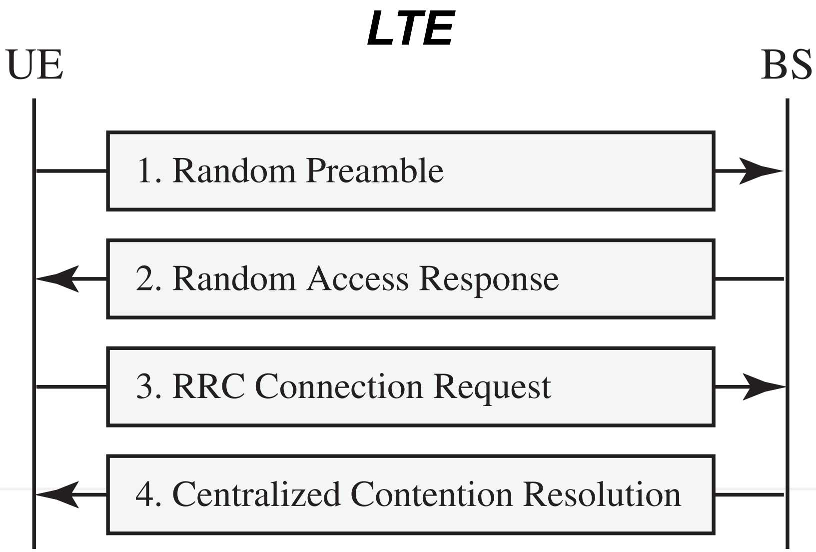
$$\mathcal{S}_{\mathrm{retrans}} = \left\{k \in \mathcal{S}:\ \beta_k > \hat{\alpha}_{\mathcal{S},k}/2\right\}$$

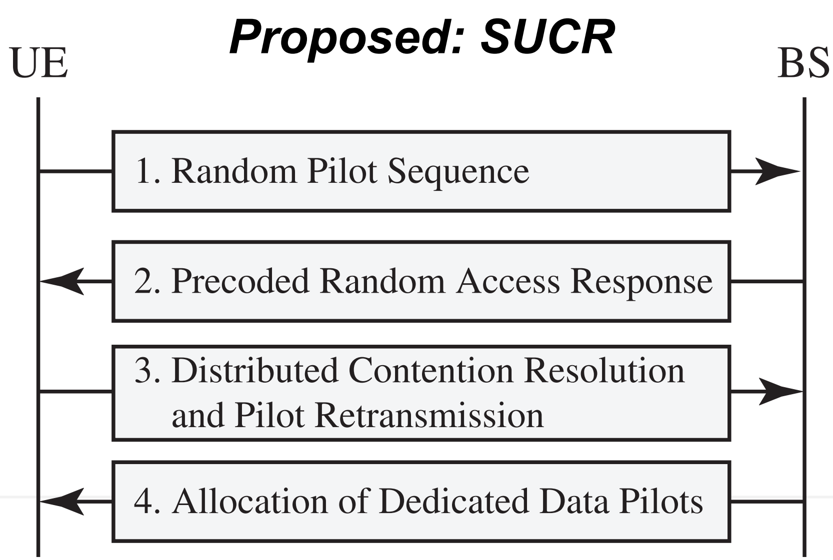
Allocate Protected Pilot Signals

Step 4:

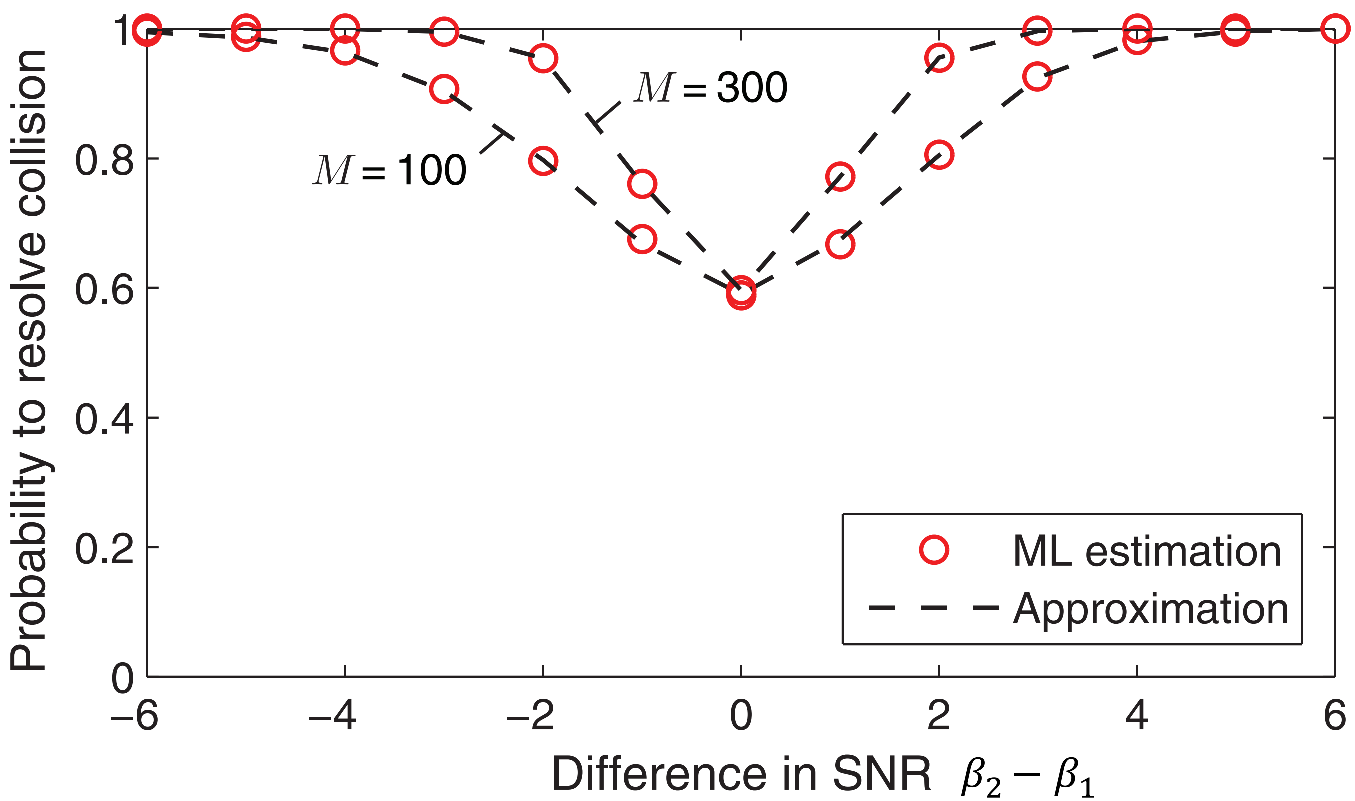
Only UEs in $\mathcal{S}_{\text{retrans}}$ retransmitted the pilot

- If $|\mathcal{S}_{\text{retrans}}| = 1$: Successful admission of one UE to the data blocks (allocate protected pilot)
- If $|\mathcal{S}_{\text{retrans}}| = 0$: Missed opportunity (false negative)
- If $|\mathcal{S}_{\text{retrans}}| \geq 2$: Contention not fully resolved (false positive)





Basic Test: Resolving a Two-UE Collisions



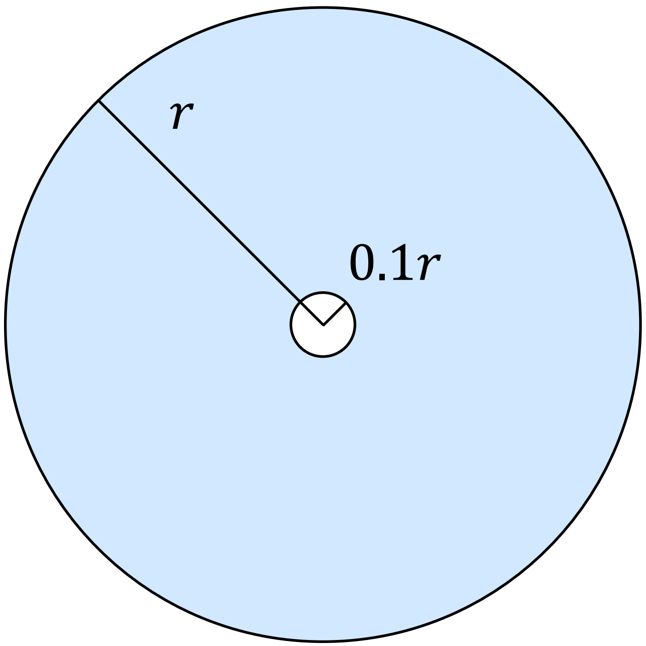
Assumptions

- Pilot SNR of UE k is β_k $(p = q = \sigma^2 = 1)$, $\epsilon_k = 0$,
- First UE: $\beta_1 = 10$ dB
- Second UE: $\beta_2 = 4 \text{ to } 16$ dB

Simulation: Cellular Scenario (1/2)

Scenario

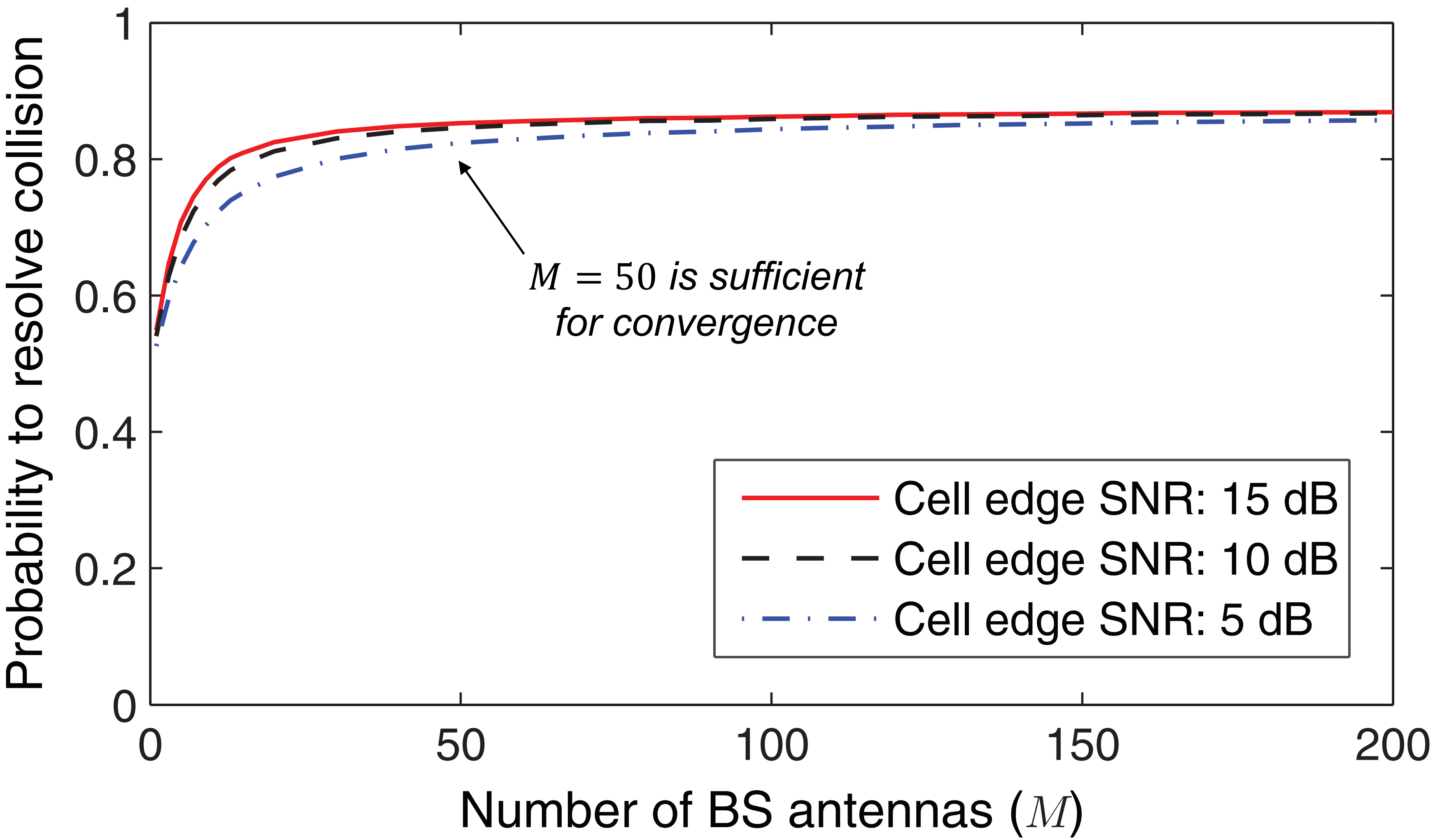
- $\tau_p = 10$ pilot sequences
- $K = 50$ UEs want to connect
- Uniformly distributed, except in cell center
- Pathloss exponent: 3.7
- Shadow fading: 8 dB standard deviation
- Cell edge SNR without shadowing is set



Performance Metric

- Probability to resolve conflicts: $\Pr\{|\mathcal{S}_{\text{retrans}}| = 1\}$

Simulation: Cellular Scenario (2/2)



P_a is optimized for maximal resolution

Summary

- Massive Number of UEs per Cell
  - Can only allocated dedicated pilots to active UEs
  - Request protected pilots by random access – leads to collisions

- Distributed "Strongest-User Collision Resolution (SUCR)"
  - Step 1: Send random uplink pilots, create joint precoding vector
  - Step 2: Send precoded downlink pilot, estimate sum channel gain of UEs
  - Step 3: Only UE with strongest channel gain retransmits pilot
  - Step 4: Allocate dedicated pilot or apply centralized contention resolution

Can resolve 80-90% of the collisions directly

Journal paper on arXiv: Any channel distribution, multi-cell setup, etc.

QUESTIONS?

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