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: $\tau_c$ 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

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!

Studied in paper at ICASSP 2016
Proposed Frame Structure

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

90% of contentions resolved at this point!
System Model

- Preliminaries
  - $K$ UEs want to connect
  - Selects one of $\tau_p$ 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
  \[ \Pr\{|\mathcal{S}| \geq 2\} = 1 - \left( 1 - \frac{P_a}{\tau_p} \right)^K - K \frac{P_a}{\tau_p} \left( 1 - \frac{P_a}{\tau_p} \right)^{K-1} \]
Distributed Method to Detect Collisions (1/3)

Step 1:

- BS receives uplink pilot signal:
  \[ y = \sum_{i \in S} \sqrt{\rho} h_i + n \]
  \[ n \sim CN(0, \sigma^2 I_M) \]

- Compute least-square channel estimate of \( \sum_{i \in S} h_i \):
  \[ \hat{h}_{LS} = y / \sqrt{\rho} \]

- Form a precoding vector with fixed power \( q \):
  \[ w = \sqrt{q} \frac{\hat{h}_{LS}}{\|\hat{h}_{LS}\|} \]
Distributed Method to Detect Collisions (2/3)

Step 2:
- BS sends downlink pilot using $w$
- Received signal at UE $k \in S$:
  \[ z_k = h_k^H w + \eta_k \]
  \[ \mathbb{E} \left\{ \frac{z_k}{\sqrt{M}} \right\} = \frac{\rho q \beta_k^2}{\rho \alpha_S + \sigma^2} \frac{\Gamma \left( M + \frac{1}{2} \right)}{\sqrt{M} \Gamma(M)} \rightarrow \frac{\rho q \beta_k^2}{\rho \alpha_S + \sigma^2} \quad \text{as} \quad M \rightarrow \infty \]
  \[ \text{Var} \left\{ \frac{z_k}{\sqrt{M}} \right\} = \frac{\rho q \beta_k^2}{\rho \alpha_S + \sigma^2} \left( 1 - \left( \frac{\Gamma \left( M + \frac{1}{2} \right)}{\sqrt{M} \Gamma(M)} \right)^2 \right) + \frac{\sigma^2 + q \beta_k - \frac{\rho q \beta_k^2}{\rho \alpha_S + \sigma^2}}{M} \rightarrow 0 \quad \text{as} \quad M \rightarrow \infty \]
- Define sum channel gain: $\alpha_S = \sum_{i \in S} \beta_i$

\( \eta_k \sim \mathcal{CN}(0, \sigma^2) \)
Distributed Method to Detect Collisions (3/3)

**Step 2 (cont.):**

- In Massive MIMO we have:

\[
\begin{align*}
\frac{z_k}{\sqrt{M}} &\approx \mathbb{E} \left\{ \frac{z_k}{\sqrt{M}} \right\} = \sqrt{\frac{\rho q \beta_k^2}{\rho \alpha_s + \sigma^2}} \frac{\Gamma \left( M + \frac{1}{2} \right)}{\sqrt{M} \Gamma(M)} \\
\end{align*}
\]

- UE \( k \) estimates \( \alpha_s \) as

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

**Detect collision at UE \( k \):**

- Compute \( \hat{\alpha}_{S,k} \)
- Compare with \( \hat{\alpha}_{S,k} - \beta_k \) with a threshold

*ML estimator is also be derived in the paper*
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 \( \frac{\beta_k}{\hat{\alpha}_{S,k}} \)

• Assumption: The contention winner is the UE \( k \in S \) with largest \( \beta_k \)

  "Strongest-User Collision Resolution (SUCR)"

**Activation decision rule at UE \( k \):**

**Active:** \( \beta_k > \frac{\hat{\alpha}_{S,k}}{2} \)

**Inactive:** \( \beta_k \leq \frac{\hat{\alpha}_{S,k}}{2} \)

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

\[ S_{\text{retrans}} = \{ k \in S : \beta_k > \frac{\hat{\alpha}_{S,k}}{2} \} \]
Allocate Protected Pilot Signals

Step 4:

Only UEs in $S_{\text{retrans}}$ retransmitted the pilot

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

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**LTE**

1. Random Preamble
2. Random Access Response
3. RRC Connection Request
4. Centralized Contention Resolution

**Proposed: SUCR**

1. Random Pilot Sequence
2. Precoded Random Access Response
3. Distributed Contention Resolution and Pilot Retransmission
4. Allocation of Dedicated Data Pilots
Basic Test: Resolving a Two-UE Collisions

Assumptions

- Pilot SNR of UE k is $\beta_k$ \hspace{0.5cm} ($p = q = \sigma^2 = 1$), $\epsilon_k = 0$,
- First UE: $\beta_1 = 10$ dB
- Second UE: $\beta_2 = 4$ 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:

\[ \Pr\{|S_{\text{retrans}}| = 1\} \]
Simulation: Cellular Scenario (2/2)

$M = 50$ is sufficient for convergence

$P_a$ 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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