Uplink User-Assisted Distributed Relaying for Cellular Communications

Ahmad Abu Al Haija, Hussain Elkotby, Mai Vu

Electrical and Computer Engineering
Tufts University

18 August 2014
Presentation DMIMO Summit, WPI
Research areas

• Research areas
  – Wireless communications, network communications
  – Signal processing, applied optimization

• Recent topics
  – MIMO precoding and capacity
  – Cognitive radio and cognitive networks
  – Cooperative communications

• Current directions
  – Future cellular systems (4G, 5G)
  – Ad hoc network communications
Students whose work is in this talk

Ahmad Abu Al Haija  Hussain ElKotby

Uplink User-Assisted Cooperative Relaying in Cellular Networks
Context

• 2G/3G cellular systems
  – Resource partitioning – connections are single-user links
  – Spectral efficiency per link approaches the theoretical limit

• Future high data rate demands

• 4G solutions
  – Small (femto) cells
  – Multi-cell processing
  – D2D communication

• 5G ideas
  – More small cells (HetNets)
  – mmWave
  – Massive MIMO
  – Smarter devices
Multi-cell Processing / Cooperation

- The BSs are connected via Backhaul networks.

- CoMP:
  - BSs share channel state information (CSI)
  - Perform beamforming and power control
  - Downlink cooperation among BSs

- What about uplink cooperation among UEs?
Hybrid D2D-infrastructure cooperation

- Uplink communications
  - Two close UEs (mobiles) can “hear” each other
  - They can communicate directly (D2D)
  or
  - Exchange their information and perform uplink beamforming (hybrid)
Hybrid D2D-infrastructure cooperation

- Uplink communications
  - Two close UEs (mobiles) can “hear” each other
  - They can communicate directly (D2D)
  - Exchange their information and perform uplink beamforming (hybrid)

Can be applied in small cells / HetNets as well
Comparison among 3 transmission modes

- Half-duplex transmissions
- Consider transmissions on the same frequency band

Resource partitioning (LTE and LTE-A)
- Each UE transmits on a different time slot

Concurrent trans. with SIC
- Both UEs transmit at the same time
- BS performs SIC

Cooperative trans. (TD and D2D)
- Two UEs cooperate to transmit to the BS.
- 3 phase transmission
- Virtual beamforming
- Advance processing
3 transmission modes over a frame

Resource partitioning (LTE and LTE-A)  
Concurrent trans. with SIC

Cooperative transmission (TD and D2D)

Phase 1  |  Phase 2  |  Whole time
Outline for the rest of the talk

• User-assisted cooperative transmission
  – Transmit signal design
  – Decoding techniques
  – Achievable rate region

• Deployment in cellular networks

• Reliability/Outage performance
Channel Model

\[
\begin{align*}
Y_{12} &= h_{12}X_{10} + Z_1 \\
Y_1 &= h_{10}X_{10} + Z_{31} \\
Y_{21} &= h_{21}X_{20} + Z_2 \\
Y_2 &= h_{20}X_{20} + Z_{32} \\
Y_3 &= h_{10}X_{11} + h_{20}X_{22} + Z_{33}
\end{align*}
\]

Rayleigh block fading
\[h_{ij} = g_{ij}e^{\kappa\theta_{ij}}\]

Complex Gaussian noise
\[Z \sim \mathcal{CN}(0, 1)\]
Transmission Scheme  
\[ w_1 \rightarrow (w_{10}, w_{11}) \quad w_2 \rightarrow (w_{20}, w_{22}) \]
Transmit signal design

Transmit signals

\[ X_{10} = \sqrt{\rho_{10}} U_{10}(w_{10}) \quad X_{20} = \sqrt{\rho_{20}} U_{20}(w_{20}) \]

\[ X_{11} = \sqrt{\rho_{11}} V_{11}(w_{11}) + \sqrt{\rho_1} S(w_{10}, w_{20}) \]

\[ X_{22} = \sqrt{\rho_{22}} V_{22}(w_{22}) + \sqrt{\rho_2} S(w_{10}, w_{20}) \]

Power constraints

\[ \alpha_1 \rho_{10} + \alpha_3 (\rho_{11} + \rho_1) \leq P_1, \quad \alpha_2 \rho_{20} + \alpha_3 (\rho_{22} + \rho_2) \leq P_2 \]
Decoding and Rate region

At UE$_2$: $Y_{12} \rightarrow \hat{w}_{10}$

At UE$_2$: $Y_{21} \rightarrow \hat{w}_{20}$

At BS: $(Y_1, Y_2, Y_3) \rightarrow (\hat{w}_1, \hat{w}_2)$

\[
R_{12} \leq \alpha_1 C \left( g_{12}^2 \rho_{10} \right) = J_1
\]

\[
R_{21} \leq \alpha_1 C \left( g_{21}^2 \rho_{20} \right) = J_2
\]

\[
R_{11} \leq \alpha_3 C \left( g_{10}^2 \rho_{11} \right) = J_3,
\]

\[
R_{22} \leq \alpha_3 C \left( g_{20}^2 \rho_{22} \right) = J_4,
\]

\[
R_{11} + R_{22} \leq \alpha_3 C \left( R_1 + R_2 \leq J_1 + J_3, \right) \quad R_2 \leq J_2 + J_4
\]

\[
R_1 + R_{22} \leq \alpha_1 C \left( R_1 + R_2 \leq J_1 + J_2 + J_5, \quad R_1 + R_2 \leq J_8 \right)
\]

\[
R_1 + R_2 \leq \alpha_1 C \left( g_{10}^2 \rho_{11} \right) + \alpha_2 C \left( g_{20}^2 \rho_{20} \right) + \alpha_3 \zeta = J_8, \quad \zeta = C \left( g_{10}^2 \rho_{11} + g_{20}^2 \rho_{22} + (g_{10} \sqrt{\rho_1} + g_{20} \sqrt{\rho_2})^2 \right).
\]
Achievable Rate Region

\[ \mu_{10} = 4, \mu_{20} = 1, \mu_{12} = \mu_{21} = 16 \]

Proposed TD Coop. Trans.
- Concurrent trans. with SIC
- RP with Orthogonal Trans. (LTE)
- Outer bound

\[ \mu_{ij} = E[g_{ij}^2] \]

Talk Outline

• User-assisted cooperative transmission

• Deployment in cellular networks
  – Deployment policy
  – Out-of-cell interference
  – Throughput performance gain

• Reliability/Outage performance
Deployment in Cellular Networks

- Deployment of user-assisted relaying
  - An idle user helps relay data of an active user
- Study **network-wide impact** of user-assisted relaying
  - On throughput, outage, coverage

![Diagram of cellular network with relaying links](image-url)
Stochastic Geometry Model

- Factors to consider:
  - When should a user cooperate?
  - What is the effect on network interference and overall performance?
- Performance evaluation:
  - Analysis using stochastic geometry tools
  - Verify analysis with simulation
Consider a multi-cell system

- Each cell has a single base station
- Reuse factor 1 in the whole network
- An active user can relay through the closest idle user
Channel Model & Relaying Scheme

$T$: Transmission Time

$\alpha_1, \alpha_2 \in [0, 1], \alpha_1 + \alpha_2 = 1$

- User-assisted relaying:
  - Two phase transmission scheme
  - Flat fading over the two phase period
- **Active user (source S):** uses superposition coding
- **Relay user (relay R):** transmit coherently with the source in 2$^{nd}$ phase
- **Base station (destination D):** utilizes received signals in both phases to decode the message
Network Geometric Model

- We use stochastic geometry to model the network
- Active UEs as a PPP with density $\lambda_1$
- Idle UEs as a PPP with density $\lambda_2$
Cooperation Policies

• Ideal policy ($E_1$):
  • Perfect knowledge of source channel state information
  • Perfect knowledge of the interference

$$E_1 \simeq \left\{ \frac{g_{sr} r_2^{-\alpha}}{T_r^2} \geq \frac{g_{sd} r_1^{-\alpha}}{T_d^2} \right\}.$$ 

• Pure geometric policy ($E_2$):
  • Only knows the distances
  • Practical for fast fading channels

$$E_2 = \{ r_1 \geq r_2, D \leq r_1 \}.$$ 

• Hybrid fading and geometric policy ($E_3$):
  • Knows both small and large scale fading but not the interference
  • Applicable for slow fading channels

$$E_3 = \{ g_{sd} r_1^{-\alpha} \leq g_{sr} r_2^{-\alpha}, D \leq r_1 \}.$$
Cooperation Probability

![Graph showing Cooperation Probability vs \( \frac{\lambda_2}{\lambda_1} \)]
Interference Model

• We need to characterize the interference at
  – Relay user during 1\(^{st}\) phase
  – Base station during 1\(^{st}\) phase
  – Base station during 2\(^{nd}\) phase
• Stochastic geometry and PPP
  – Can provide analytic expression for moments
  – Fails to provide the exact distribution
• Consider a Gamma distribution model
  – Fit the first two moments of interference distribution
  – Approximately fit empirical data
Fit of Gamma Distribution
Interference Model: Effect of Gamma Distribution

![Graph showing the effect of transmission power on average rate for different distances and models.](image)
Throughput vs. Distance to Relay

![Graph showing throughput vs. distance to relay](image-url)
Data rate gain vs. active user location
Average data rate gain vs. idle to active ratio

Talk Outline

- User-assisted cooperative transmission
- Deployment in cellular networks
- Reliability/Outage performance
  - Outage at the UEs and BS
  - Common outage
  - Individual outage
Outage Probabilities

- Full CSI at Rx and limited at Tx.

- Consider both individual and common outage probabilities
  - Common outage: either one or both UEs information is in outage.
  - Individual outage: one UE information is in outage regardless of the other UE information.

- The outage probabilities in Rayleigh fading channels

\[ \text{Rates: } R_1 \leq A_1, \quad R_2 \leq A_2, \]

\[ \begin{align*}
\text{Individual Outage (UE_1)} & \quad \text{Individual Outage (UE_2)} \\
R_2 & \quad R_2 \\
A_2 & \quad A_2 \\
B & \quad B \\
C & \quad C \\
& \quad A
\end{align*} \]

\[ \begin{align*}
\text{Common Outage} & \quad \text{Common Outage} \\
R_2 & \quad R_2 \\
A_2 & \quad A_2 \\
B & \quad B \\
C & \quad C \\
& \quad A
\end{align*} \]

Concurrent trans. with SIC

\[ \text{Rates: } R_1 \leq B_1, \quad R_2 \leq B_2, \quad R_1 + R_2 \leq B_3 \]

\[ \begin{align*}
\text{Individual Outage (UE_1)} & \quad \text{Individual Outage (UE_2)} \\
R_2 & \quad R_2 \\
B & \quad B \\
C & \quad C \\
& \quad A
\end{align*} \]

\[ \begin{align*}
\text{Common Outage} & \quad \text{Common Outage} \\
R_2 & \quad R_2 \\
B & \quad B \\
C & \quad C \\
& \quad A
\end{align*} \]
Cooperative Transmission Outages

Outage at UE2

No Outage at UE2 but at outage UE1

No Outage at both UEs but outage at the BS

Coop. and/or private part

Phase 1

Phase 1

Phase 1

Phase 2

Phase 2

Phase 3

Mai Vu
Outage Analysis for Cooperative Transmission

Outage can occur at UEs in addition to the BS
- But cooperative links are stronger than direct links
- Hence outage at UEs is small (insignificant)
- Cooperation reduces outage probability

Superposition coding
- Outage for **cooperative and private** parts
Outage at the BS (if no outage at UEs)

\[ R_{10} \leq J_4 - R_p, \quad R_{20} \leq J_5 - R_p, \quad R_{10} + R_{20} \leq J_6 - R_p, \]

where \( R_p = R_{11} + R_{22} \)

\[ R_{12} \leq J_1, \quad R_{22} \leq J_2, \quad R_{12} + R_{22} \leq J_3, \]

Cooperative rates const.

Private rates const.

**Cooperative parts outage:** Outage of any cooperative part leads to an outage at both private parts because of superposition encoding

\[ (w_{20}, w_{11}, w_{22}) \times \]

\[ w_{10} \]

\[ (w_{10}, w_{20}, w_{11}, w_{22}) \times \]

\[ (w_{20}, w_{11}, w_{22}) \times \]

\[ w_{10} \]

**Common and individual Outages for private parts (no outage for the coop. parts)**

**Individual Outage (UE1)**

**Individual Outage (UE2)**

**Common Outage**
## Summary of the Outage Analyses

<table>
<thead>
<tr>
<th>*Resource Part. LTE &amp; LTE-A</th>
<th>*Concurrent Trans. with SIC</th>
<th>*Coop. Trans. using D2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No message splitting</td>
<td>• No message splitting</td>
<td>• Coop. &amp; private message splitting (outage for each part)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Additional outage at UEs</td>
</tr>
<tr>
<td>• Conventional coding</td>
<td>• Conventional coding</td>
<td>• Superposition Coding</td>
</tr>
<tr>
<td>• Outage at the BS only</td>
<td>• Outage at the BS only</td>
<td>• Outage at the UEs &amp; the BS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Rates at BS:</td>
<td>• Rates at BS:</td>
<td>• Outage at UE1 or UE2 leads to a common outage</td>
</tr>
<tr>
<td>$R_1 \leq A_1$, $R_2 \leq A_2$,</td>
<td>$R_1 \leq B_1$, $R_2 \leq B_2$,</td>
<td>• No outage at UEs but at BS</td>
</tr>
<tr>
<td>$R_1 + R_2 \leq B_3$</td>
<td>$R_1 + R_2 \leq B_3$</td>
<td>• Coop. Rates $R_{10} \leq J_4$, $R_{20} \leq J_5$, $R_{10} + R_{20} \leq J_6$,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Private Rates $R_{12} \leq J_1$, $R_{22} \leq J_2$, $R_{12} + R_{22} \leq J_3$,</td>
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</tr>
<tr>
<td><img src="image1" alt="Resource Part. LTE &amp; LTE-A" /></td>
<td><img src="image2" alt="Concurrent Trans. with SIC" /></td>
<td><img src="image3" alt="Coop. Trans. using D2D" /></td>
</tr>
</tbody>
</table>
Outage Probability of User-assisted Relaying

Outage Probabilities of Both Users Cooperating

\( R_1 = R_2 = 2 \text{ bps/Hz} \)

- Concurrent trans. with SIC
- Common outage in Resource part. (LTE-A)
- Proposed TD coop. Trans.

**Graph Details**
- **Outage Probability** vs. **SNR\(_1\) (dB)**
- **Common Outage (P\(_c\))**
- **UE\(_1\) Outage (P\(_1\))**
- **UE\(_2\) Outage (P\(_2\))**

**Diagram Notes**
- UE\(_1\) and UE\(_2\) are located at distances d=12 and d=30 from the BS.
- The diagram illustrates the outage probabilities for different SNR values.
Outage Rate Regions at 1% Outage Probability

\[ P_1 = P_2 = 0.01 \]

- **Common outage rate region**
- **Individual outage rate region**

**Proposed TD coop. trans., SNR_1 = 15 dB**

**Resource partitioning (LTE-A), SNR_1 = 20 dB**

**Concurrent trans. with SIC, SNR_1 = 20 dB**

Conclusion

• User-assisted cooperative relaying for uplink communication
  – Utilizes hybrid D2D-infrastructure cooperation
  – Has advanced signal design and decoding
  – Employs partial decode-forward relaying and joint decoding at BS

• Cooperation improves both the data rate and reliability
  – Compared to current LTE implementation

• Network deployment shows significant performance gain
  – Average rate gain up to 50%, max gain up to 200%
  – Suitable for crowded metropolitan areas and small cells
Relevant Publications


More information

- Research group: **Tufts LiNKS**

  Laboratory for communication in Networked Systems

  [http://links.ece.tufts.edu](http://links.ece.tufts.edu)

- My webpage [http://www.eecs.tufts.edu/~maivu/](http://www.eecs.tufts.edu/~maivu/)

- Email [maivu@ece.tufts.edu](mailto:maivu@ece.tufts.edu)