D2D and Relay Assisted Cellular Architecture
• CWC Sponsors
  – Ericsson
  – Huawei

• Faculty Participants
  – Pam Cosman
  – Tara Javidi
  – Young-Han Kim
  – Larry Milstein
  – Bhaskar Rao

• Calit2
  – Zhongren Cao
  – Curt Schurgers

• Supports
  – Testbed
  – Three PhD students (Approx)
D2D Communications

Direct device to device communication between cellular UE based on proximity
Benefits of D2D

- Proximity leads to lower power and potentially higher rates
- Hop Gain
- Radio resource reuse
Multi-link D2D Sharing
Challenges and Issues

• Peer Discovery
  – Network Assisted

• Mode Selection

• Interference management/coordination
D2D Interference

Uplink Frequency Reuse

Downlink Frequency Reuse
Research Topics

• **System issues**
  – Synchronization and Reference Signal Design
  – Testbed to debug and learn

• **Theory**
  – Channel Modeling
  – Mode Selection and Resource allocation for system optimization
Test-Bed Background

- Industry – University collaboration
  - Ericsson Research, Wireless Access Group, Stockholm
  - Calit2-UCSD, Communications System Group, UCSD

- Push test-beds into early stage research
  - Make innovation process faster
  - Shorten "research to development"

- Large test-beds lack flexibility
  - Small scale test-beds
Testbed

- WARP-board based platform
- UCSD:
  - HW design
  - PHY
- Ericsson:
  - SW design
  - MAC, protocols, IP
- Full access to entire protocol stack
NA-D2D implementation

- 3-nodes setup: Radio network node + 2 devices
- 10-slot TDMA system: devices synchronize to beacon broadcasted by network node – over the air
  ![image]
- Devices attach to network via control-channel signaling
- Real-time IP-traffic transmitted between devices
- Centralized GUI to illustrate device and network behavior
NA-D2D Demonstration Setup

• Emulated scenario: BS and two devices
• Devices communicate in “classical” topology
• Network discovers their close proximity, instructs direct communication
• Radio resources saved
• Demonstrated outside!
D2D Resource Sharing

• Consider a simple network of two links as depicted in the diagram. The D2D link $\text{UE}_2 \leftrightarrow \text{UE}_3$ uses the same resource as the cellular user $\text{UE}_1$.

• Our objective is to achieve fairness between the cellular and D2D links.

• We then extend the framework to multiple D2D links sharing a single cellular resource.
Motivation for Relays

• **Increased Coverage**: With multi-hop relays the macro cell coverage can be expanded to the places where the base station cannot reach.

• **Lower Power Consumption and lower Interference**

• **Lower cost of deployment**

• **Multiple Relays**
  – Spatial Diversity
  – More Advanced Cooperative Techniques
Relays to Enhance Cellular Coverage

OFDMA: N resource blocks

resource block 1,6
Multimedia
News
Pictures
…..

resource block 2,3,5

resource block 4

Web surfing
Email
Download
Youtube
…..

Relay node

Voice
SMS
…..
Research Topics

• Relay Enhanced to Cellular Systems
  — Opportunistic Fair Scheduling and Resource Allocation Algorithms

• Relay Enhanced Layered Video Communication

• Networking and Information theory to understand the fundamental theoretical benefits of Relay/D2D communications
Multiuser OFDM systems in LTE have

- Many users with different resource requirements
  - Different applications: web, mail, multimedia,...
  - Relay nodes serve demands from large subsets of users
- These users need to be served differently.
  - CDF based scheduling
- Limited feedback
  - Using best M feedback

Sum Rate Analysis of a Weighted CDF-based Scheduling in an OFDMA Relay Downlink with Partial Feedback
Performance tradeoff in an OFDMA system with $N = 10$, $M = 5$, $K1 = 10$, $K2 = 5$ due to the biased treatment
60 GHz Wireless Relay network

Fig. 1: Relay network model: a) when direct-link is not broken, the direct-link is used; b) when the direct-link is broken, a non-broken relay-link is selected. If all links are broken, the system is in outage due to strong attenuation.
Throughput of a Gaussian source

• We assume a Gaussian source is transmitted at the source, and an information-theoretic approach is used to evaluate the system performance.

• In the protocol, each link between the source, the relays, and the destination are orthogonal in the time domain, and optimal beamforming vectors are used.

• We evaluate the system throughput and expected distortion by assuming that anytime the instantaneous mutual information (MI) exceeds the rate (R), the message gets through perfectly [2].

• The results show that the performance of the system with the relays is significantly improved when the link break-probability, \( p_0 \), is between roughly 10% to 60%.

Numerical Results

Fig. 2: Average throughput: single relay (solid curves) versus no relay (dashed curves).

Fig. 3: Expected distortion for the system with multiple relays (N), and $p_0=0.2$. 
Information Flooding

- Common message broadcast over a network via D2D communication
- Control signal broadcast, multimedia streaming, etc.
- Goal: Provide a general framework for optimal communication
Network Information Theory Approach

• What is the fundamental limit on communication (capacity)?
• Which coding scheme, protocol, or architecture achieves that limit?
• Broadcast is easier than unicast or multicast
Main Result 1

Decode–forward is optimal for
- Simple relay channel
- Diamond network
- Layered network
Main Result 2

- **Decode–forward** is **not** optimal in general.
- **Partial decode–forward** and **compress–forward** can outperform decode–forward for networks with cycles.

More generally, **interactive relaying** can outperform *--forward.
Demos and Poster

• Demo: EXCITE: Experimental Software Radio Testbed for Device-to-Device (D2D) Communication (with Ericsson)

• Phuong Bang C. Nguyen, Resource Sharing Considerations for Device-to-Device Communications

• Anh Nguyen, Weighted CDF-based Scheduling for an OFDMA Relay Downlink with Limited Feedback

• Tu Nguyen, 60 GHz Wireless Relay Network

• Yu Xiang, Information Flooding
Complete Set of Slides Provided by the Students/Faculty*

*Time did not permit a discussion of all of them and are included here for anyone interested in more details
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Network Assisted D2D Motivation

- Exponential growth in wireless devices
- Constraints on available radio spectrum
- Close proximity devices exploit broadcast nature of radio by direct communications
- Offload burden on radio networks while still operating within licensed spectrum
NA-D2D implementation

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Fairness Objective: Max-min Rate

\[ (P_{c}^{\text{opt}}, P_{d}^{\text{opt}}) = \arg \max \left\{ \min \left\{ R_{c,d}(P_{c}, P_{d}) \right\} \right\} \]

Subject to: \( 0 \leq P_{c}, P_{d} \leq P_{\text{max}} \)

Where:

\[ R_{c}(P_{c}, P_{d}) = \log_{2}(1 + \Gamma_{c}(P_{c}, P_{d})) \]

\[ R_{d}(P_{c}, P_{d}) = \log_{2}(1 + \Gamma_{d}(P_{c}, P_{d})) \]

• Depending on channel conditions, it can be shown that the optimal solution is one of the following two cases:
  
  – Case 1: \((P_{c}, P_{d}) = (P_{c}^{\text{opt}}, P_{\text{max}})\)
  
  – Case 2: \((P_{c}, P_{d}) = (P_{\text{max}}, P_{d}^{\text{opt}})\)
Max-min Rate Power Allocation

- The power allocation can be shown to be:

\[
\begin{align*}
\chi_{\text{opt}} &= \frac{P_{c}^{\text{opt}}}{P_{\text{max}}} = \frac{-\alpha_d + \sqrt{\alpha_d^2 + 4 \frac{\gamma_d}{\gamma_c} (1 + \alpha_c)}}{2} \\
(x) &= \text{opt} \\
\gamma_d &= \frac{g_{1}}{g_{dc}}, \quad \gamma_c &= \frac{g_{23}}{g_{cd}}, \quad \alpha_c = \frac{N_c}{g_{dc} P_{\text{max}}}, \quad \alpha_d = \frac{N_d}{g_{cd} P_{\text{max}}} \\
\end{align*}
\]
Max Min Rate versus Max Sum Rate

• Consider the scenario where \( k = \frac{g_{23}}{g_1} > 1 \), which is true when the D2D link gain is higher than the cellular link gain, it can be shown that:

\[
\Gamma_{\text{min, max-min rate}} = \frac{\gamma}{1 + \alpha} \times (ky_{opt}) > \frac{\gamma}{1 + \alpha} = \Gamma_{\text{min, max-sum rate}}
\]

Where \( ky_{opt} > 1 \) and \( y_{opt} = \frac{P_d^{opt}}{P_{max}} < 1 \)

• The minimum rate obtained by max-min objective in this case is strictly higher than that obtained by max sum rate objective.

• Furthermore, the max-min rate is achieved at a lower transmit power (\( P_d^{opt} = y_{opt} \times P_{max} < P_{max} \)).
Multi-user Max-min Objective

• We can generalize the max-min problem to one with one cellular link and N D2D links as long as the achievable min rate is acceptable.

\[
(P_c^*, P_{di}^*) = \arg \max_{(P_c, P_{di}) \in \Omega_1} \left\{ \min \left\{ \Gamma_{c,di} (P_c, P_{di}) \right\} \right\}
\]

\[
\Gamma_{c} (P_c, P_d) = g_c P_c / \left( \sum_{i=1}^{n} g_{dic} P_{di} + N_c \right)
\]

\[
\Gamma_{di} (P_c, P_d) = g_{di} P_{di} / \left( g_{cdi} P_c + \sum_{j=1, j \neq i}^{n} g_{dji} P_{dj} + N_{di} \right)
\]

• This is a quasi-concave maximization problem, which can be solved by solving a series of feasibility problems.
References

Weighted CDF-based Scheduling for an OFDMA Relay Downlink with Partial Feedback

Anh Nguyen, Yichao Huang
Advisor: Prof. Bhaskar Rao
University of California, San Diego
Multiuser OFDM systems in LTE have

- Many users with different resource requirements
  - Different applications: web, mail, multimedia, ...
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- These users need to be served differently.
  - CDF based scheduling
- Limited feedback
  - Using best M feedback
Scheduling - competition among users

- There are $N$ resource blocks in OFDM signal
- The BS transmit to $L$ groups of users
  - Each group $i$ has priority $w_i$
  - Each user feeds back only $N_{FB}$ best among its $N$ resource blocks
- On each resource blocks $i$
  - The BS receives $n_i$ feedback from users in group $i$; with $i = 1, \ldots, L$
  - The BS selects the best user based on weighted cdf of the gain of these users.
The system sum rate

\[ R = \frac{1}{N} \sum_{r=1}^{N} E \log(1 + X_r) = E \log(1 + X_r) \]

The steps are as follows

<table>
<thead>
<tr>
<th>Framework</th>
<th>CQI feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random variable</td>
<td>Output</td>
</tr>
<tr>
<td>Step 1</td>
<td>( Z_{k,r} ) CQI at a receiver</td>
</tr>
<tr>
<td>Step 2</td>
<td>( Y_{k,r} ) SNR seen at the transmitter</td>
</tr>
<tr>
<td>Step 3</td>
<td>( Z_{k,r} ) SNR of selected user receiver</td>
</tr>
<tr>
<td>Step 4</td>
<td>( E_{cond}E_{X_r} [\log(1 + X_r)</td>
</tr>
</tbody>
</table>

k: user index; r: block index
Performance tradeoff in an OFDMA system with $N = 10$, $M = 5$, $K_1 = 10$, $K_2 = 5$ due to the biased treatment
OFDMA systems with relays

Simulated CDF of throughput of an OFDMA system with: $N = 10$ resource blocks, 1 group of $K_1 = 10$ macro users using partial feedback $M = 5$, and 1 group of 5 users connected through a relay using full feedback on both hops
Conclusion and future works

The proposed limited feedback scheme for OFDMA systems can

• Conclusion
  – Control the long term probability users are allocated resource
  – Reduce feedback requirement
  – The analysis theoretically proves the performance of the system

• Future work
  – limited feedback for Relay OFDMA systems
60 GHz Wireless Relay Network

Authors: Tu Nguyen, Pamela Cosman, and Larry Milstein
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Outline

• Introduction
• 60 GHz system with multiple relays
  ✓ Relay network model
  ✓ Simple relay protocol
  ✓ Performance
• Future plans
Introduction

• The FCC has allocated a large bandwidth around 60GHz (from 57-64GHz) for unlicensed use, which can potentially support multi-gigabits per second system.

• Various measurement results show that the path loss due to blockage caused by human activity is non-negligible, especially in light-of-sight mode.

• We consider a 60 GHz wireless system with a source, a destination, and multiple relays.

• A protocol for relay selection is presented, and system performance in terms of throughput and distortion will be presented.

• The 60-GHz radio could potentially have numerous applications in residential areas, offices, conference rooms, corridors, and libraries. It is suitable for in home applications such as audio/video transmission, desktop connection, and support of portable devices.

• Our research will focus on the video streaming over 60 GHz wireless network for residential and office environments.
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Fig. 1: Relay network model: a) when direct-link is not broken, the direct-link is used; b) when the direct-link is broken, a non-broken relay-link is selected. If all links are broken, the system is in outage due to strong attenuation.
60 GHz system with multiple relays

• Consider an indoor wireless 60 GHz system with random link breaks due to human activity [1].
• Assume a single source, a single destination, and multiple relays which are half-duplex and use decode-and-forward protocol.
• Each terminal is equipped with multiple antennas, and beamforming is used on all links.
• Assume channel state information is available at the destination, and feedback channels exist from the destination to both the source and the relays.
• If the destination successfully receives signal from the source, the direct link is used and the relays keep silent.
• If not, a relay will be selected to decode the message from the source, and, if successful, will forward the decoded message to the destination.

Throughput of a Gaussian source

• We assume a Gaussian source is transmitted at the source, and an information-theoretic approach is used to evaluate the system performance.

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Future Plans

• Replace information-theoretic model based upon Gaussian source and outage probability with digital communication model based upon the bit error rate.

• Remove the assumption that $MI \geq R$ guarantees perfect communications.

• If time permits, replace Gaussian source with layered video source, and use video-layer priority in assigning individual layers to specific relays.