Towards Optimized Planning, Operation, and Utilization of Heterogeneous Wireless Networks

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Wireless technologies are evolving
LTE cellular technology is evolving

Wireless networking: Research project I

- Multimedia apps require the wireless interfaces of APs/BSs and MTs to be active for long periods
- Mobile-to-mobile cooperation can provide gains in wireless networks
- Smartphones are equipped with multiple wireless interfaces with different designs, bit rates, ranges, etc.

NPRP 09 – 180 – 2 – 078: Optimized Energy Efficient Video Streaming for Wireless Networks with Cooperation among Mobile Devices [joint work with QMIC and LAU]
Wireless networking: Research project I

![Wireless networking diagram](image)

Number of MTs
Locations of MTs
Topology dynamics

Energy-centric objective

Optimized models
Algorithm design
Lab testbed

Content distribution strategy

Content QoS constraints

Clustering of MTs

\[
\min_{\nu, x, q} E_{T,U} = S_T E_{Rx,L} \sum_{k=1}^{K} \frac{x_k}{R_{L,k}} + S_T (E_{Tx,S} + E_{Rx,S}) \sum_{k=1}^{K} \sum_{j=1, j \neq k}^{K} \frac{q_{kj}}{R_{S,kj}}
\]
Research project I: Design parameters...

- Video codec
- Layered coding vs. MDC
- With/without network coding

- WiFi AP vs. cellular BS (3G, LTE)

- Energy measurements

- Long-Range Link

- Bluetooth vs. WiFi Direct vs. LTE Direct

Research project I: Design parameters...

- One Grand Group
  - Server
  - Wired LAN
  - Mobile Phone
  - PDA
  - Laptop

- Disjoint Clustering
  - Server
  - Wired LAN
  - Mobile Phone
  - PDA
  - Laptop
Research project I: Design parameters...

Unicasting/Unicasting

Unicasting/Multicasting

Multicasting/Unicasting

Multicasting/Multicasting

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Research project I: Design parameters...

Single hop cooperation

Multihop cooperation
Research project I: Design parameters...

The optimal unicast/unicasting problem is similar to the complete uncapacitated facility location (CUFL) problem which is NP-hard [1].

Sample formulation I: Results

No cooperation  
One cluster  
Disjoint clustering: unicasting/unicasting  
Disjoint clustering: unicasting/multicasting

The optimal multicasting/multicasting problem with multihop connections is a mixed integer non-linear programming problem (MINLP)
Sample formulation II: Results

(a) Optimal uni./uni.  
(b) Optimal multi./multi.  
(c) SA multi./multi.  
(d) SA multi./multi. with interference avoidance for $f_r = 2$

Experimental results: WiFi + Bluetooth

<table>
<thead>
<tr>
<th>Devices</th>
<th>LR only</th>
<th>master Rx and Tx</th>
<th>master Tx</th>
<th>peer Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 device</td>
<td>27.5 J</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2 devices</td>
<td>32.0 J</td>
<td>63.7 J</td>
<td>36.2 J</td>
<td>31.5 J</td>
</tr>
<tr>
<td>3 devices</td>
<td>43.9 J</td>
<td>69.4 J</td>
<td>41.9 J</td>
<td>NA</td>
</tr>
<tr>
<td>4 devices</td>
<td>54.1 J</td>
<td>71.9 J</td>
<td>44.4 J</td>
<td>37.0 J</td>
</tr>
</tbody>
</table>

**TABLE II**

Experimental results for a given scenario with WiFi on the LR interface and Bluetooth on the SR D2D links.

- Energy consumption does not increase linearly with the number of devices that the master device relays the content to on the SR links:
  - Relaying to one device consumes 36.2 J
  - Relaying to three devices consumes 44.4 J
- This favors forming larger cooperation clusters
- Demonstrates potential gains of D2D offloading
Wireless networking: Research project II

- Resource allocation [slots, sub-channels, power, antennas] in cellular networks is performed independently between uplink and downlink.
- Many emerging multimedia services require symmetrical uplink and downlink resources for adequate quality of experience.
- **Aim**: develop and optimize joint uplink/downlink resource allocation algorithms for 4G cellular networks.

\[ \max_{\text{ PU, PD, WD}} \sum_{i=1}^{M} Q_i^U(t) R_i^U(t) + \sum_{i=1}^{M} Q_i^D(t) R_i^D(t) - \alpha \left\| R^D(t) - R^U(t) \right\|_1 \]

Wireless networking: Research project II

**Exploring Social Ties for Enhanced Device-to-Device Communications in Wireless Networks**

Wireless networking: Research project III

Network selection and traffic splitting in WiFi/cellular heterogeneous networks

On network selection in hetnets
Hetnets testbed: Design components

Hetnets testbed: Sample results

\[ E = \frac{C}{R + D} + (M - 1000) \]
Hetnets testbed: HetApp

- Energy using Wi-Fi in the three slots = 12.42 Joules
- Energy using 3G in the three slots = 14.67 Joules
- Energy using HetApp = 10.23 Joules
  - 18% energy saved with respect to Wi-Fi
  - 30% energy saved with respect to 3G

Wireless networking: Research project IV

- Existing planning approaches for 2G/3G networks based on static link budget analysis with Monte-Carlo simulations
- LTE/LTE-A: dynamic adaptive operation in multi-RAT multi-tier heterogeneous environment with advanced features
- Opportunity to develop a new radio planning framework to capture dynamic operation and advanced features of LTE-A
Wireless networking: Research project IV

- How to statistically model interference in LTE-A networks?
- How to capture dynamic cellular network variation as part of the planning process?
  - Users’ number and locations are time varying
  - Users’ wireless channel conditions are time varying
- How to capture emerging LTE-A features as part of the planning process?
  - How to perform optimized radio network planning if cellular operator supports WiFi offloading, femtocells, D2D connections, green BS on/off switching, etc.?
- How to implement the developed framework and algorithms in a prototype planning tool with real maps and traffic conditions?

Interference modeling: Approach

- Derive the distribution of the distance of the allocated user from its serving BS in a cell considering various scheduling scheme, i.e., $f_{d_{sel}}(r)$.
- Derive the distribution of the distance between the allocated users in the neighbor interfering cells and the BS of the cell of interest, i.e., $f_{d_{sel}}(\tilde{r})$.
- Derive the distribution and MGF of the interference $X_l = \tilde{r}_{sel}^{-\beta} \zeta$ considering a single interfering cell $l$.
- Derive the MGF of the cumulative interference $Y = \sum_{l=1}^{L} X_l$ caused by the users in all interfering cells.
Interference modeling: Approach

<table>
<thead>
<tr>
<th>Pr(r_{sel} = r_k)</th>
<th>Modified Fast PC</th>
<th>Modified Slow PC</th>
<th>Conventional Fast PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sum_{j=1}^{K} \prod_{i=1}^{J} \frac{1 - (p - \tilde{p})^{j}}{1 - (p - \tilde{p})^{j}} \prod_{j=1}^{K} (1 - (p - \tilde{p})^{j}) \prod_{j=1}^{K} (1 - (p - \tilde{p})^{j})$</td>
<td>$\sum_{j=1}^{K} \prod_{i=1}^{J} \frac{1 - (p - \tilde{p})^{j}}{1 - (p - \tilde{p})^{j}} \prod_{j=1}^{K} (1 - (p - \tilde{p})^{j}) \prod_{j=1}^{K} (1 - (p - \tilde{p})^{j})$</td>
<td>$\frac{1}{K}$</td>
</tr>
</tbody>
</table>

$f_S(s)$

<table>
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<tr>
<th>Modified Fast PC</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\delta(s - P_0) \sum_{k=1}^{K} \Pr(r_{sel} = r_k) + \delta(s) \Pr(A)$</td>
<td>$\sum_{k=1}^{K} \frac{1}{T_{max}} f_0 \left( \frac{T_{max}}{T_{max}} \right) + \delta(s - P_0) \left( 1 - F_c \left( \frac{P_0}{F_{max}} \right) \right)$</td>
<td>$\Pr(r_{sel} = r_k)$</td>
</tr>
</tbody>
</table>

$M_S(t)$

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>$\sum_{k=1}^{K} \left( e^{-t_{0}} - F_c \left( \frac{P_0}{F_{max}} \right) \right) + \frac{r_0}{P_{max}} \int_{0}^{t_{0}} e^{-t_{0}} f_c \left( \frac{r_0}{P_{max}} \right) ds \Pr(r_{sel} = r_k)$</td>
<td>$\sum_{k=1}^{K} \left( e^{-t_{0}} - F_c \left( \frac{P_0}{F_{max}} \right) \right) + \frac{r_0}{P_{max}} \int_{0}^{t_{0}} e^{-t_{0}} f_c \left( \frac{r_0}{P_{max}} \right) ds \Pr(r_{sel} = r_k)$</td>
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</tr>
</tbody>
</table>

$E_I(t)$

<table>
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<tr>
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<th>Conventional Fast PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum_{k=1}^{K} \sum_{i=1}^{I} A_W(A) \Pr(r_{sel} = r_{i,k}) + \Pr(A) \delta(t)$</td>
<td>$\sum_{k=1}^{K} \sum_{i=1}^{I} A_W(A) \Pr(r_{sel} = r_{i,k}) + \Pr(A) \delta(t)$</td>
<td>$\sum_{k=1}^{K} \sum_{i=1}^{I} A_W(A) \Pr(r_{sel} = r_{i,k}) + \Pr(A) \delta(t)$</td>
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$M_E(t)$

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<td>$\sum_{k=1}^{K} \sum_{i=1}^{I} A_W(A) \Pr(r_{sel} = r_{i,k}) + \Pr(A)$</td>
</tr>
</tbody>
</table>

Interference modeling: Scenarios

- Interference distributions (PDFs, CDFs, and MGFs):
  - Resource allocation (RR, PF, greedy)
  - Uplink and downlink
  - Generic fading channel models
  - With/without power control [slow and fast power control]
- Single carrier and multicarrier systems
- With/without interference coordination schemes
- Universal and fractional frequency reuse
- With femtocell deployments
- With heterogeneous network deployments
Interference modeling: Sample results

Figure 5: PMF of the distance of the allocated users in a given cell (i.e., PMF of $r_{seq}$) for proportional fair, greedy and round robin scheduling schemes with path loss exponent $\beta = 2.6$, $U = 50$, Number of Monte-Carlo simulations = 100,000, $C = 60$ dB, $P_{\text{max}} = 1$W, $\sigma^2 = -174$ dBm/Hz.

Interference modeling: Sample results
From interference modeling to planning...

• In a given geographical area:
  – Number of users vary
  – Locations of users vary
  – Distribution of users vary

• How to capture this variation as part of the planning problem?
• Approach:
  – Optimization problem formulation
  – Solution: robust optimization and stochastic optimization
  – Solution: sub-optimal search-based algorithms

Robust cellular planning under uncertainty

➢ A chance-constraint approach:

\[
\min_{s,c} \alpha \sum_{i=1}^{N_0} c_i - (1-\alpha) \sum_{t=1}^{T} p(t) \sum_{k=1}^{K_t} \sum_{i=1}^{N_0} s_{k,i,t} P_{k,i,t} \tag{1}
\]

subject to

\[
Pr\{\Gamma_{p} \geq \Gamma_{thr}\} \geq (1-\epsilon) \tag{2}
\]

\[
c_i \in \{0,1\} \tag{3}
\]

➢ SNR PDF [6]:

\[
f_1(\gamma|x_k,y_k) = \int_{0}^{\infty} f_{A} \left( \frac{(\sigma^2 + \eta)\gamma}{P_{k,i}} \right) f_{I_{total}}(\eta) d\eta
\]

interfering power
noise
received power
fading PDF
interference PDF
Robust cellular planning: Sample results

Figure 5: The optimal subset of eNodeBs and allocation of users (i) when the scenarios occur with equal probability and (ii) when the scenario at the center occurs with a higher probability.

Robust cellular planning: Sample results

- Initial set of base stations:
- 8 different traffic states:

---

90 users
75 users
90 users
50 users
40 users
40 users
40 users
40 users
Robust cellular planning: Sample results

<table>
<thead>
<tr>
<th>Case</th>
<th>Conventional approach</th>
<th>Stochastic approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0.33 bps/Hz</td>
<td>0.34 bps/Hz</td>
</tr>
<tr>
<td>19</td>
<td>0.32 bps/Hz</td>
<td>0.41 bps/Hz</td>
</tr>
<tr>
<td>20</td>
<td>0.33 bps/Hz</td>
<td>0.41 bps/Hz</td>
</tr>
</tbody>
</table>
Green cellular planning: Motivation

![Graph showing cellular planning]

Green cellular planning: BS On/Off switching

**Proactive Approach**
- Start Planning at the: 
  - Lowest traffic state ($s=1$)
  - $s=2$
  - $s=3$

**Reactive Approach**
- Start Planning at the: 
  - Highest traffic state ($S$)
  - $s=2$
  - Lowest traffic state ($s=1$)
Algorithm 1 LTE RNP Solution

Input: $N_0: K; \{x_i, y_i, i = 1, \ldots, N_0\}; \{u_k, v_k, k = 1, \ldots, K\}; \mathcal{F} = \emptyset, \mathcal{I} = \emptyset$

while true do
  for $i = 1: N_0$ [Try eliminating base station $i$] do
    $x_{\text{temp}} = \{x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{N_0}\}$
    $y_{\text{temp}} = \{y_1, \ldots, y_{i-1}, y_{i+1}, \ldots, y_{N_0}\}$
    Step 1. Construct the new Voronoi tessellation corresponding to the base station locations and find the distance between each (BS, MS) pair
    Step 2. Calculate the SINR expressions based on the estimated pathloss for each (BS, MS) pair as given in (3)
    Step 3. if SINR $< \text{SINR}_{th}$ [If eliminating the base station causes outage] then
      $i \in \mathcal{I}$ [Place BS $i$ in the infeasible set]
    else
      $i \in \mathcal{F}$ [Place BS $i$ in the feasible set]
      Calculate the total SINR which is the sum of the users’ SINR for the given BS configuration.
    end if
  end for
  if $\mathcal{F} = \emptyset$ [If some base station can be eliminated and e represents the BS $i$ that when eliminated led to the highest total SINR that was calculated in Step 3] then
    $x = \{x_1, \ldots, x_{e-1}, x_{e+1}, \ldots, x_{N_0}\}$
    $y = \{y_1, \ldots, y_{e-1}, y_{e+1}, \ldots, y_{N_0}\}$
    $N_0 = N_0 - 1$
  else
    break [Converged: No BS can be eliminated without causing outage]
  end if
end while

Output: $N$

\[
\begin{align*}
\min & \sum_{i=1}^{N_0} c_i \\
\text{s.t.} & \sum_{k=1}^{T'} \alpha k^{(k)} \cdot P_{k,k}^d + \alpha \sum_{k=1}^{T'} \alpha k^{(k)} \cdot (P_k^e - P_{\text{max}})^r
\end{align*}
\]
Green cellular planning: Sample results

<table>
<thead>
<tr>
<th>Traffic states</th>
<th>Number of BSs</th>
<th>Coverage percentage</th>
<th>CO₂ emissions in KgCO₂/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>s=3</td>
<td>40</td>
<td>90%</td>
<td>1.996</td>
</tr>
<tr>
<td>s=2</td>
<td>33</td>
<td>91%</td>
<td>0.818</td>
</tr>
<tr>
<td>s=1</td>
<td>23</td>
<td>90%</td>
<td>1.488</td>
</tr>
</tbody>
</table>

As for the traditional planning, where all the 40 BSs are always on 5.952 Kg CO₂ /day are emitted.

Using green planning, CO₂ emissions are decreased by 28% compared to traditional planning.

From wireless network planning/operation to wireless network utilization...
“machines” are becoming connected

Most global challenges are in cities...
Silent data acquisition
On-device processing
Storage and upload

Big data analytics
Map visualization
Mobile services

Privacy
Incentives
Semantic web

WiFi signal strength
Cellular signal strength
Humidity
Temperature

Sound level
Magnetic field
Light
Pressure
Cross-platform web and mobile solutions...
Addressing the challenges…
@ device level
Addressing the challenges…
@ network level

Towards Optimized Planning, Operation, and Utilization of Heterogeneous Wireless Networks

Thank You