Cooperation in UMTS Cellular Networks: A Practical Perspective

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Outline

• Introduction and system description
• Outage probability:
  • Non-cooperative transmission
  • Amplify&Forward
  • Decode&Forward
• Coverage Range
• Design directions and discussion
System description

- Receiver gain $C_g$
- HATA path-loss, with parameters $\alpha, A$
- Rayleigh fading (correlation factor $\rho$)
- Maximum power $P_m$
- Maximum ratio combining of the received signals referring to the same packet
- Threshold model for the outage event
  \[ \zeta = \mathcal{P} [\Gamma < \eta] \]
- Maximum outage probability (coverage range) equal to $\zeta$

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum TX power $P_m$</td>
<td>0.125 W</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Receiver noise figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>Receiver noise power $N_0$</td>
<td>-103.2 dBm</td>
</tr>
<tr>
<td>Required SNR $\eta$</td>
<td>5 dB</td>
</tr>
<tr>
<td>Processing gain $C_g$</td>
<td>25 dB</td>
</tr>
<tr>
<td>Base Station antenna gain $B_g$</td>
<td>18 dB</td>
</tr>
<tr>
<td>Rate $R$</td>
<td>12.2 kbps</td>
</tr>
<tr>
<td>Correlation factor $\rho$</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Direct transmission:

\[ \Gamma_{sd} = \frac{P_t}{GN_0} d_{sd}^{-\alpha} |\delta_{sd}|^2 \] 

with \[ G = \frac{A}{B g C_g} \]

Fading term
Gain term
Path-loss term

Outage probability
\[ \zeta = \mathcal{P} \left( \frac{P_t}{GN_0} d_{sd}^{-\alpha} |\delta_{sd}|^2 < \eta \right) = 1 - e^{-\frac{\eta G N_0}{P_t} d_{sd}^\alpha} \]

Double direct transmission:
The source performs a further transmission in the subsequent slot t+1 if the first one (slot t) fails

\[ \zeta_{DT} = \mathcal{P} \left[ \left| \delta_{sd}^{(t)} \right|^2 + \left| \delta_{sd}^{(t+1)} \right|^2 < \frac{\eta G N_0}{P_m} d_{sd}^\alpha \right] \]

where

\[ l = \frac{\eta G N_0 d_{sd}^\alpha}{P_m} \]

\[ f_{XY}(x, y) = \frac{1}{1 - \rho^2} e^{-\frac{x+y}{1-\rho^2}} I_0 \left( \frac{2\rho}{1 - \rho^2} \sqrt{xy} \right) \]

\[ Y = \left| \delta_{sd}^{(t)} \right|^2 \quad X = \left| \delta_{sd}^{(t+1)} \right|^2 \]

\[ X = \rho Y + \sqrt{1 - \rho^2} \phi \]
\( \zeta_{AF} = \mathcal{P} [\Gamma_{sd} + \Gamma_{cd} < \eta] \)  
\text{outage probability}

- **Direct transmission term**
  \[ r_c = \frac{P_s M_g}{A} d_{sc}^{-\alpha} |\delta_{sc}|^2 \]
  \text{power of the signal received by the RS}

- **Relay station transmission term**
  \[ r_d = \frac{P_s M_g \beta}{AG} d_{sc}^{-\alpha} d_{cd}^{-\alpha} |\delta_{sc}|^2 |\delta_{cd}|^2 \]
  \text{power of the signal received by the BS station due to RS transmission}

\[ \Gamma_{cd} = \frac{P_c M_g \beta d_{sc}^{-\alpha} d_{cd}^{-\alpha}}{AG N_0 \left( 1 + \frac{\beta B_g}{A} d_{cd}^{-\alpha} |\delta_{cd}|^2 \right)} |\delta_{sc}|^2 |\delta_{cd}|^2 \]

\[ r_n = N_0 \left( 1 + \frac{\beta B_g}{A} d_{cd}^{-\alpha} |\delta_{cd}|^2 \right) \]  
\text{noise term of RS transmission}

**OP: A&F**

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\[ \zeta_{AF} = \mathcal{P} \left[ \frac{\psi_{sd} \delta_{sd}}{1 + \psi_{sc} \delta_{sc}^2 + \psi_{cd} \delta_{cd}^2} < \frac{\eta}{C_g} \right] \]

where

\[ \psi_{sd} = \frac{P_s B_g d_{sd}^{-\alpha}}{A N_0} \]
\[ \psi_{sc} = \frac{P_s M_g d_{sc}^{-\alpha}}{A N_0} \]
\[ \psi_{cd} = \frac{P_c B_g d_{cd}^{-\alpha}}{A N_0} \]

\[ Q = \frac{YZ}{1 + aY + bZ} \]

Mean of the terms
Exponential random variables

\[ \zeta_{AF} = 1 - e^{-\frac{n}{m}} - e^{-\frac{n}{m}(t+s)} \int_0^{\frac{n}{m}} e^{(t+s-1)h} g(h) K_1(g(h)) dh \]

where

\[ g(h) = 2\sqrt{n - mh + st \left( \frac{n}{m} - h \right)^2} \]

\[ n = \frac{\eta}{C_g \psi_{sc} \psi_{cd}} \]
\[ m = \frac{1}{\psi_{sc}} \left( \frac{d_{cd}}{d_{sd}} \right)^\alpha \]
\[ s = \left( \frac{d_{cd}}{d_{sd}} \right)^\alpha \]
\[ t = \frac{B_g}{M_g} \left( \frac{d_{sc}}{d_{sd}} \right)^\alpha \]

\[ F_Q(t) = 1 - e^{-(a+b)t} 2\sqrt{t + abt^2} K_1 \left( 2\sqrt{t + abt^2} \right) \]
The total received SNR at the BS is conditioned on the correct/erroneous reception of the RS (we assume the relay station decodes the packet and checks the CRC)

\[ \zeta_{DF} = \mathbb{P} \left[ \psi_{sd} | \delta_{sd} |^2 < \frac{\eta}{C_g} \right] \mathbb{P} \left[ \psi_{sc} | \delta_{sc} |^2 < \frac{\eta}{C_g} \right] + \mathbb{P} \left[ \psi_{sd} | \delta_{sd} |^2 + \psi_{cd} | \delta_{cd} |^2 < \frac{\eta}{C_g} \right] \mathbb{P} \left[ \psi_{sc} | \delta_{sc} |^2 \geq \frac{\eta}{C_g} \right] \]

\[ P \left[ \psi | \delta |^2 < \frac{\eta}{C_g} \right] = 1 - e^{-\frac{\eta}{C_g} \frac{1}{\psi}} \]

\[ \mathbb{P}[\psi_{sd} X + \psi_{cd} Y < l] = 1 - \frac{\psi_{cd} e^{-\frac{l}{\psi_{cd}}} - \psi_{sd} e^{-\frac{l}{\psi_{sd}}}}{\psi_{cd} - \psi_{sd}} \]

\[ \zeta_{DF} = 1 - e^{-\frac{1}{\psi_{sd}}} \left( 1 - e^{-\frac{1}{\psi_{sc}}} \right) - e^{-\frac{1}{\psi_{sc}}} \left( \frac{\psi_{cd} e^{-\frac{1}{\psi_{cd}}} - \psi_{sd} e^{-\frac{1}{\psi_{sd}}}}{\psi_{cd} - \psi_{sd}} \right) \]
**OP: results**

- The greater the antenna gain of the RS, the greater the success probability.
- If the antenna gain is equal to Bg, the distance between the source and the RS and the RS and the BS can be exchanged.
- RS close to the source, unless the RS has an antenna gain comparable to that of the BS.

**A&F**

- Optimal position close to the middle for antenna gain values approaching Bg.
- If Mg<<Bg, then the low probability the RS decodes the packet hampers performance as the RS gets closer to the BS.

**D&F**
OP: results

\[ \bar{r}_c = \frac{P_m M_g d_{sc}}{A} \]
\[ \bar{r}_{tot} = \bar{r}_c + N_0 \]
\[ \lambda_s = P_m \frac{\bar{r}_c}{\bar{r}_{tot}} \]
\[ \lambda_n = P_m \frac{N_0}{\bar{r}_{tot}} \]
\[ \lambda_s^d = \lambda_s \frac{B_g C_g}{d_{cd}^{\alpha}} \]
\[ \lambda_n^{d_1} = \lambda_n \frac{B_g}{d_{cd}^{\alpha}} \]
\[ \lambda_n^{d_2} = N_0. \]

- Cooperator in the best position
- The gap between the plots for Mg=Bg and Mg=1 is greater if D&F is used instead of A&F
Coverage range

\[ \Omega_T = \left( -\frac{\ln (1 - \bar{\zeta}) P_m}{\eta G N_0} \right)^{\frac{1}{\alpha}} \]

Maximum distance between the source and the BS

N=3 relay stations at the same distance from the BS and uniform angle

- The farther the RS, the greater the ratio
- D&F achieves better coverage when the RSs are placed on the border of the cell, since the minimum outage probability, achieved when the RS is in the middle between the MT and the BS, is sufficient to guarantee the target error probability
- A&F geometric consideration: close to the BS is better than close to the border of the cell (even if we have another minimum of the outage probability close to the source)
Coverage range

As RSs get closer to the border, the coverage region becomes a trilobed area, due to the geometry of the three-node topology.

Higher number of RSs can partially remove this effect.
Conclusions & Future Work

• We investigated the impact of cooperation in cellular UMTS-like networks;
• Two different cooperative techniques (A&F and D&F) were compared;
• Particular attention was put on the effects of channel asymmetry due to different terminal capabilities;
• Cooperation grants an improvement in terms of outage probability and coverage range;
• The performance depends on the location of the cooperator, whose position should be properly designed;
• We suggested the use of fixed Relay Stations deployed around the Base Station, acting as cooperators.

• Power control algorithms, properly designed for cooperative transmissions, are needed in order to counteract the effects of multipath fading;
• Effects of interference, when multiple Mobile Terminals exploiting cooperation are deployed in the cell, must be studied too;
• A channel allocation algorithm is needed to set up a cooperative transmission, and to assign the best cooperator to each Mobile Terminal.

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