Resource Management for Relay-Enhanced WiMax: OFDM and OFDMA

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• Wireless downlink data transmission...

\[ R \leq W \log_2 (1 + SNR) = W \log_2 \left( 1 + \frac{P_T |h|^2}{N_o W} \right) \]

[Shannon-54]
... always affected by the propagation channel

\[ P_{\text{loss}} = \beta d^\rho \]
Estimated system requirements for wireless systems beyond 3G

**Peak user data rates:** 50 to 100 Mbps

**Average user data rate:** 0,1 to 1 Mbps

**Aggregate cell capacity (r=0,5 Km):** 25 to 50 Mbps (payload)

**Traffic demand per area:** ~1 to 500 Mbps/ km²

Coverage area fitting the peak aggregate data rates is very reduced, so the AP deployment needs to be dense and the capacity offered per area turns to be around 3 Gbps/km², which is uneconomical!

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Base station deployment is expensive...
• **One solution:** use multiple antennas at the transmitter and the receiver (MIMO systems)

\[
H = \begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix}
\]

\[
R \leq W \log_2 \det \left( I + \frac{P_T}{N_o W} HH^H \right)
\]

\[
\approx W \cdot \min(M, N) \cdot \log_2 \left( 1 + \frac{P_T}{N_o WM} \right)
\]

[Telatar-95]

The capacity scales with the \( \min(M, N) \), robust to fast fading, but requires increased hardware complexity and is not robust to shadowing.
• **Alternate solution:** use other terminals acting as relays

\[ R_{SH} \leq W \log_2 \left( 1 + \frac{P_T d^{-\rho}}{N_o W} \right) \]

\[ R_{MH} = \min\left( R_1, \ldots, R_{N_{hops}} \right) \leq \frac{1}{N_{hops}} W \log_2 \left( 1 + \frac{P_T (d / N_{hops})^{-\rho}}{N_o W} \right) \]
• **Deal:**  - Capacity gains at the cell edges
  - For a given peak rate, enlargement of cell radius and reduced density of BS deployment

\[
C_{1hop} \leq \frac{\rho \log_2 N_{hops}}{N_{hops} - 1}
\]

Capacity gain @ low SNR

\[
G \approx N_{hops}^{\rho^{-1}}
\]
• **Improved solution:** the receiver combines the signal through the direct transmission and the relayed path

Very active area in SP and IT, and under study in IEEE 802.16m, 802.11s, 802.15.3
Summary

- Capacity of a cooperative system
- Enhancing WiMAX with relay transmissions
- Radio resource management techniques
- System level simulations
- Outlook
Summary

• **Capacity of a cooperative system**
• **Enhancing WiMAX with relay transmissions**
• **Radio resource management techniques**
• **System level simulations**
• **Outlook**
Half-duplex cooperation (I)

Terminals cannot receive and transmit simultaneously on the same band

**Forwarding transmission**

The third protocol achieves the highest transmission rate, but the others are relevant...
Half-duplex cooperation (II)

A lot of issues are open:

- The best retransmission strategy at the relay is unknown

- Capacity is unknown, only for some particular cases

- Capacity of vector channels with channel knowledge in transmission

- Multiuser cooperation

- Resource allocation

- New protocols...
Three possible operations at the relay...

**Amplify and forward**
- The relay amplifies the received signal and noise, without regenerating the received message

**Decode and forward**
- The relay demodulates the message and transmits a codeword from a different codebook

**Compress and forward**
- The relay encodes the received analog signal and retransmits it digitally, knowing that the destination will have side information (Wyner-Ziv coding)
Examples of achievable rates (I)

... no channel state information in transmission is assumed

**Amplify and forward**

\[
C^{AF} = \frac{1}{2} \log_2 \left| I_2 + P_S H_{AF}^H H_{AF} R_n^{-1} \right|
\]

\[
H_{AF} = \begin{bmatrix} h_0 \\ gh_2 h_1 \end{bmatrix}, \quad R_n = \begin{bmatrix} \sigma^2 & 0 \\ 0 & \sigma^2 \left(1 + |g|^2 h_2 h_2^H \right) \end{bmatrix}
\]

**Decode and forward**

Transmission time in each phase is optimally allocated through \(\alpha\)

\[
C = \max_{0 < \alpha < 1} \left( \min \left( \alpha C_{S-R}, (1-\alpha) C_{R-D} + \alpha C_{S-D} \right) \right)
\]

where \(C_{i-j} = \log_2 \left(1 + \frac{P_i}{\sigma^2} |h_{i-j}|^2 \right)\)

In all cases, the presence of two orthogonal phases induces spectral efficiency loss
Examples of achievable rates (II)

Best known inner bound for decode and forward

Transmission time in each phase is optimally allocated through $\alpha$

$$C = \max_{0 < \alpha < 1} \left( \min \left( \alpha C_{S-R} + (1 - \alpha) C_{S-D}, \alpha C_{S-D} + (1 - \alpha) C_{SR-D} \right) \right)$$

where $C_{i-j} = \log_2 \left( 1 + \frac{P_i}{\sigma^2} |h_{i-j}|^2 \right)$

Phase I. S transmits message $m_1$ through $X_1$
Phase II. R transmits message $m_1$ through $X_2$, and S transmits message $m_2$ through $X'_1$

The destination decodes with a successive cancellation receiver
Performance of protocols is different depending on the relative position of the relay.
Achievable rates for non-cooperative multihop

Achievable rates for DF cooperation in DL

Gains of DF cooperation with respect to best non-cooperative strategy
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The full DL subframe is split for transmissions in the first and second phases. Duration of each phase is variable.
A phase for direct transmission is inserted between phases to allow processing at the relay terminals.
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RRM for multiuser OFDMA multihop (I)

Problem statement

- TDD relays
- Users are orthogonal in frequency
- FUSC/PUSC transmission mode
- RRM for 802.16e
- Downlink or uplink

- Resources:
  - Power at BS ($\gamma$)
  - Bandwidth ($\beta$)
  - Time ($\alpha$)
  on each hop
RRM for multiuser OFDMA multihop (II)

Maximise the weighted sum rate at mobile stations:

$$\max_{\alpha, \beta^{(1)}_i, \beta^{(2)}_i, \gamma_i} \sum_{i=1}^{K} \mu_i R_i$$

$\alpha$: Fraction of time associated to the first phase

$\beta^{(1)}_i$: Fraction of bandwidth associated to the first hop for user $i$

$\gamma_i$: Fraction of power at the BS associated to user $i$

The problem is not convex, but can be formulated as concave-over-convex optimisation: simple iterative solutions providing optimum solution.
RRM for multiuser OFDMA multihop (III)

General case: all cooperative protocols can be seen under the same framework

PROTOCOL III

\[ P_s = 0 \text{ in phase II} \]

\[ \alpha \neq 0 \]

\[ \alpha = 1 \text{ or } \beta_2 = 0 \text{ or } \alpha = 0 \text{ or } \beta_1 = 0 \]

\[ \alpha = 0 \text{ or } \beta_1 = 0 \]

PROTOCOL II

\[ \alpha = 0 \text{ or } \beta_1 = 0 \]

PROTOCOL III

\[ \alpha = 1 \text{ or } \beta_2 = 0 \text{ or } \alpha = 0 \text{ or } \beta_1 = 0 \]

\[ \alpha = 1 \text{ or } \beta_2 = 0 \]

PROTOCOL I

\[ P_s = 0 \text{ in phase II} \]

\[ \alpha \neq 1 \]

\[ \alpha = 1 \text{ or } \beta_2 = 0 \text{ or } \alpha = 0 \text{ or } \beta_1 = 0 \]
RRM for multiuser TDMA multihop

It is not the case for TDMA

\[ \alpha = 1 \text{ or } \alpha = 0 \]

\[ \alpha \neq 1 \]

\[ \alpha = 0 \]
RRM for multiuser OFDMA multihop (IV)

... for cooperation:

- Protocols arise naturally as a result of the decisions taken by the RRM

- Optimise resource allocation based on protocol III (the one achieving the highest capacity): protocol I and direct transmission as particular cases, and will depend on the propagating conditions of other users

- Force protocol II for legacy users (those that cannot receive over two time slots): forwarding and direct transmission as particular cases
Network Settings Under Test

Network Setting 1

Network Setting 2
Experimental settings

- **LOS path-loss constant**: 2.6
- **NLOS path-loss**: 4.05

- BS-RS links in LOS (240 m)
- RS-MS and BS-MS links in NLOS (160 m and 400 m)

- **Bandwidth**: 20 MHz
- **Subcarriers**: 256
- **Data subcarriers**: 192 (25% BW overhead considered)

- **One-sided noise PSD**: -113.9 dBm/MHz
- **Total source power**: 40 dBmW
- **Relay’s power**: 36 dBmW
Achievable rate regions and power consumption

\((\mu_1, \mu_2)\)
Achievable rate regions and power consumption

Network excess power consumption for network setting 1

\[ \Delta(P) [\text{dB}] \]

\[ \mu \]

Legend:
- fwd
- II-A
- II-B
- III-A
- III-C
Sum-rate scaling and power consumption

Achievable sum-rate network setting 1

- direct
- fwd
- II-A
- II-B
- III-A
- III-C

fwd - TDMA

achievable sum-rate [Mbps]

users

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Sum-rate scaling and power consumption

Network excess power consumption for sum-capacity maximization in network setting 1
Network Settings Under Test

Network Setting 1

Network Setting 2
Achievable rate regions and power consumption

Achievable rate region for network setting 3

- direct
- fwd
- II-A
- II-B
- III-A
- III-C

R₂ [Mbps] vs. R₁ [Mbps]
Achievable rate regions and power consumption
Sum-rate scaling and power consumption
Sum-rate scaling and power consumption

Network excess power consumption for sum-capacity maximization in network setting 3
QoS provision in OFDMA multihop

QoS criteria may be adopted to select the weights in

$$\max_{\alpha, \beta_{1..K}, \gamma_{1..K}} \sum_{i=1}^{K} \mu_i R_i$$
QoS provision in OFDMA multihop

QoS criteria may be adopted to select the weights in

\[
\max_{\alpha, \beta^{(1)}_i, \beta^{(2)}_i, \gamma_{1..K}} \sum_{i=1}^{K} \mu_i R_i
\]

**Delay sensitive traffic**

\[
K^* = \arg \max_k \sum_{i \in K} \frac{U_i' \left( D_{i \text{Hol}} \right)}{\bar{T}_i} R_i
\]

\(D_{i \text{Hol}}\) is the waiting time of the head-of-line packet for user \(i\)

\(\bar{T}_i\) is the average given throughput

**Rate sensitive traffic**

\[
K^* = \arg \max_k \sum_{i \in K} \phi_i D_{i \text{LW}} \frac{R_i}{\bar{T}_i}
\]

\(D_{i \text{LW}}\) is the waiting time of the longest-waiting packet for user \(i\)

2\(^{K-1}\) multiuser RRM optimisation procedures are required to provide \(K^*\), the best set of users among the \(K\) ones having non-empty queues.
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Simulation setup

- Cell radius of 1500 m, non-sectorised
- BS with M=2 omni-directional antennas
- Bandwidth: 5 MHz @ 3.55 GHz
- Frame length: 5 ms
- $P_{BS}=40$ dBm, $P_{RS}=26$ dBm
- Number of active users: 30
- Channel model: Type E, LOS in BS-SS link
  Type H, NLOS in BS-RS and RS-SS link
- Traffic: fixed packet size with exponential dist. Arrivals
- Access: OFDM-TDMA
- Scheduler: Exhaustive round-robin
- 10 independent drops, 20 sec per drop
**Throughput**

Total traffic: 2.5 Mbps

1x1x1 antennas

2x2x1 antennas

Enhanced throughput as compared to direct transmission at any load
Unprivileged users benefit from the presence of relays: the worst 30% of users increase its throughput from <30 Mbps to <78 Mbps
CDF of maximum delay per flow

Total traffic: 2.5 Mbps

CDF max delay per flow, 2.5 mbps, 13 RS, 2x2x1, 5 ms

Total traffic: 5 Mbps

CDF max delay per flow, 5 mbps, 13 RS, 2x2x1, 5 ms

Improved connections provide also better packet delays

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Outlook

• Derive achievable rate regions for multiuser cases

• Define practical coding/decoding schemes approaching the multiuser capacity bounds

• Obtain stability regions in queue servicing

• Devise and evaluate protocols involving simultaneous UL and DL transmissions

• Activities to be continued in the 7th FP project