Non-orthogonal Access with Successive Interference Cancellation for Future Radio Access

Kenichi Higuchi
Tokyo University of Science
Evolution of Radio Access

Radio access scheme beyond 4G?

We think that the non-orthogonal access with more advanced transceiver can be the next radio access.

- In theory, non-orthogonal access with SIC/DPC achieves the multiuser capacity region both in uplink and downlink.
  - Especially important for improving the performance of cell-edge users with small system efficiency loss
- OFDM signaling with superposition coding is a promising transmission scheme.

3G
- Non-orthogonal access

3.9G and 4G
- Orthogonal access

Beyond 4G
- Non-orthogonal access with advanced transceiver?
Orthogonal vs. Non-orthogonal Access

◆ Orthogonal access

- Narrow transmission bandwidth per user
- No inter-user (intra-cell) interference

User A’s signal, $x_A$

User B’s signal, $x_B$

Frequency

◆ Non-orthogonal access with SIC

- Wide transmission bandwidth per user
- With inter-user (intra-cell) interference
- No inter-user (intra-cell) interference

SIC (successive interference cancellation) at the receiver

$\hat{x}_A + x_B + \text{noise}$

$\hat{x}_B + \text{noise}$

Decoding of $x_A$

Decoding of $x_B$

$\hat{x}_A$

$\hat{x}_B$

$\text{noise}$
Comparison with Orth. Access in Uplink

Throughput pair with orthogonal access

\[
R_1 = \alpha \log_2 \left( 1 + \frac{P|h_1|^2}{\alpha N_0} \right), \quad R_2 = (1 - \alpha) \log_2 \left( 1 + \frac{P|h_2|^2}{(1 - \alpha)N_0} \right)
\]

Symmetric channel

\[P|h_1|^2/N_0 = 10 \text{ dB}\]
\[P|h_2|^2/N_0 = 10 \text{ dB}\]

Both access schemes are optimal.

Asymmetric channel

\[P|h_1|^2/N_0 = 20 \text{ dB}\]
\[P|h_2|^2/N_0 = 0 \text{ dB}\]

\(\checkmark\) Maximum total throughput is achieved by both access schemes.
\(\checkmark\) However, if we want to increase \(R_2\), the non-orthogonal access with SIC is much more effective than the orthogonal access.
Summary in Uplink

◆ In cellular uplink, the channel conditions vary significantly among users due to the near-far effect.

◆ When we want to improve the throughput of weak user ... 
  – Orthogonal access
    • Needs to allocate wide bandwidth to weak user
      Reduced bandwidth allocation to strong user
  – Non-orthogonal access with SIC
    • Best decoding order is in decreasing channel gain.
      Wide transmission bandwidth for all users
      No inter-user interference for weak user
      Small inter-user interference to strong user
Comparison with Orth. Access in Downlink

Throughput pair with orthogonal access

\[ R_1 = \alpha \log_2 \left( 1 + \frac{P_1 |h_1|^2}{\alpha N_{0,1}} \right), \quad R_2 = (1 - \alpha) \log_2 \left( 1 + \frac{P_2 |h_2|^2}{(1 - \alpha) N_{0,2}} \right) \]

Symmetric channel

\[ P|h_1|^2/N_{0,1} = 10 \text{ dB} \]
\[ P|h_2|^2/N_{0,2} = 10 \text{ dB} \]

Asymmetric channel

\[ P|h_1|^2/N_{0,1} = 20 \text{ dB} \]
\[ P|h_2|^2/N_{0,2} = 0 \text{ dB} \]

✓ Maximum total throughput is achieved by both access schemes.
✓ However, if we want to increase \( R_2 \), the non-orthogonal access with SIC is much more effective than the orthogonal access.

Throughput regions of two access schemes are identical.
Summary in Downlink

◆ In cellular downlink, the channel conditions vary significantly among users due to the near-far effect.

◆ When we want to improve the throughput of weak user …
  – In orthogonal access, bandwidth allocation to strong user is severely limited.
  – Non-orthogonal access with SIC
    • Best decoding order is in increasing channel gain.
      – Wide transmission bandwidth for all users
      – Allocates large power to weak user
        » Small impact of interference to weak user without SIC
      – Strong user uses SIC to cancel out the interference from weak user and therefore small power allocation is enough.
Non-orthogonal Access with Random Beamforming and Intra-beam SIC for Cellular MIMO Downlink
Purpose of This Study

Non-orthogonal access with SIC appropriate for MIMO downlink

◆ Key issues in mind
  – Use of SIC instead of DPC
    • DPC is difficult to implement and sensitive to the error in channel state information feedback.
  – Avoidance of increase in reference signaling overhead
    • Non-orthogonal access is assumed that the number of users multiplexed within a same frequency is beyond the number of BS antennas.
    • If we assume the user-specific beamforming, the number of reference signals in non-orthogonal access exceeds the number of BS antennas.
Proposed Method

Intra-beam superposition coding and SIC

◆ BS transmitter: Intra-beam superposition coding
  – The number of beams is equal to that of BS antennas.
  – Within a beam, multiple-user signals are non-orthogonally multiplexed based on superposition coding.
    • The number of reference signals is the same as in the orthogonal access irrespective of # of non-orthogonally multiplexed users.

◆ UE receiver: Intra-beam SIC
  – Inter-beam interference is suppressed by the linear spatial filtering.
  – Then, intra-beam interference due to superposition coding is removed by SIC.
    • Effective use of SIC as in the SISO or SIMO downlink
Signal Representation (1)

◆ Transmit signal vector

Number of beams is limited to number of BS antennas. Intra-beam superposition coding for non-orthogonal user multiplexing

\[ x = \sum_{b=1}^{B} m_b \sum_{u=1}^{K} \sqrt{P_{b,i(b,u)}} s_{b,i(b,u)} \]

\( b \)-th beam vector \( \rightarrow \) Signal to user \( i(b,u) \)

◆ Received signal vector at user \( i(b,u) \)

\[ y_{i(b,u)} = H_{i(b,u)} x + w_{i(b,u)} = H_{i(b,u)} \left( \sum_{b'=1}^{B} m_{b'} \sum_{u'=1}^{K} \sqrt{P_{b',i(b',u')}} s_{b',i(b',u')} \right) + w_{i(b,u)} \]
**Signal Representation (2)**

- **Spatial filtering for inter-beam interference suppression**

$$
Z_{b,i(b,u)} = \mathbf{v}_{b,i(b,u)}^H \mathbf{y}_{i(b,u)} \\
= \mathbf{v}_{b,i(b,u)}^H \mathbf{H}_{i(b,u)} \mathbf{m}_b \sum_{u'=1}^{K} \sqrt{P_{b,i(b,u')}} S_{b,i(b,u')} \\
+ \mathbf{v}_{b,i(b,u)}^H \mathbf{H}_{i(b,u)} \sum_{b'=1}^{B} \mathbf{m}_{b'} \sum_{u'=1}^{K} \sqrt{P_{b',i(b',u')}} S_{b',i(b',u')} + \mathbf{v}_{b,i(b,u)}^H \mathbf{w}_{i(b,u)} \\
= \sqrt{g_{b,i(b,u)}} \sum_{u'=1}^{K} \sqrt{P_{b,i(b,u')}} S_{b,i(b,u')} + q_{b,i(b,u)} \\
\Rightarrow \text{SISO channel after spatial filtering}$$

- **Followed by intra-beam SIC, throughput of user } i(b,u) \text{ with beam } b \text{ becomes**}

$$
R_{b,i(b,u)} = \log_2 \left( 1 + \frac{g_{b,i(b,u)} P_{b,i(b,u)}}{\sum_{u'=1}^{K} g_{b,i(b,u')} P_{b,i(b,u')} + 1} \right)
$$
Pictorial Example

orem equivalent channel gain, $g$

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In general, any kind of beamforming control can be applied to the proposed method.

- We assumed open-loop random beamforming in this work.

BS determines the beamforming (precoding) matrix for the next transmission

Transmission of reference signals for respective beams

Feedback of SINR of each beam measured by using the reference signal from UE to BS

User scheduling for each beam based on the reported SINR

Transmission of data channel
**Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell layout</td>
<td>Hexagonal 19-cell model</td>
</tr>
<tr>
<td>Frequency reuse</td>
<td>Universal frequency reuse</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>0.5 km</td>
</tr>
<tr>
<td>Overall transmission bandwidth</td>
<td>4.32 MHz</td>
</tr>
<tr>
<td>Resource block bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Number of resource blocks</td>
<td>24</td>
</tr>
<tr>
<td>BS transmitter antenna</td>
<td>Number of antennas: 1, 2, Antenna gain: 14 dBi</td>
</tr>
<tr>
<td>UE receiver antenna</td>
<td>Number of antennas: 2, Antenna gain: 0 dBi</td>
</tr>
<tr>
<td>Beamforming matrix</td>
<td>Random unitary matrix</td>
</tr>
<tr>
<td>Receiver linear filtering</td>
<td>MMSE-based</td>
</tr>
<tr>
<td>BS transmission power</td>
<td>40 dBm</td>
</tr>
<tr>
<td>Distance-dependent pathloss</td>
<td>$128.1 + 37.6 \log_{10}(r)$ dB, $r$: kilometers</td>
</tr>
<tr>
<td>Log-normal shadowing</td>
<td>$\delta = 8$ dB, Correlation among cells = 0.5</td>
</tr>
<tr>
<td>Instantaneous fading</td>
<td>Six-path Rayleigh, rms delay spread = 1 $\mu$s, $f_D = 55.5$ Hz</td>
</tr>
<tr>
<td>Receiver noise density</td>
<td>-169 dBm/Hz</td>
</tr>
<tr>
<td>Scheduling and power allocation policy</td>
<td>Proportional fair</td>
</tr>
<tr>
<td>Number of non-orthogonally multiplexed users</td>
<td>2 per beam</td>
</tr>
<tr>
<td>Scheduling interval</td>
<td>1 ms</td>
</tr>
<tr>
<td>Throughput calculation</td>
<td>Based on Shannon formula</td>
</tr>
<tr>
<td>Averaging interval of user throughput</td>
<td>100 ms</td>
</tr>
</tbody>
</table>
$R_{\text{sum}}, R_{\text{edge}}$ vs Number of Users Per Cell

- **Sum throughput, $R_{\text{sum}}$ (Mb/s)**
  - Orthogonal access
  - Non-orthogonal access
  - Num. of BS antennas = 1
  - Num. of BS antennas = 2

- **Cell-edge user throughput, $R_{\text{edge}}$ (Kb/s)**
  - Orthogonal access
  - Non-orthogonal access
  - Num. of BS antennas = 1
  - Num. of BS antennas = 2

1.5 times

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User Throughput Gain

Number of BS antennas = 2
Number of users per cell = 30

When higher priority to cell-edge users is assumed for non-orthogonal access
Conclusion

Non-orthogonal access using intra-beam superposition coding and SIC was proposed for MIMO cellular downlink.

- BS transmitter
  - The number of beams is equal to that of BS antennas.
    - The number of reference signals is the same as in the orthogonal access irrespective of # of non-orthogonally multiplexed users.
  - Superposition coding-based non-orthogonal multi-user signal multiplexing within a beam

- UE receiver
  - Inter-beam interference is not SIC processed (only receiver linear filtering if UE has multiple receiver antennas).
    - User scheduling based on CQI reports can mitigate the impact of inter-beam interference.
  - Intra-beam interference among superposition coded users is effectively mitigated by SIC.
At each beam, proportional fair resource allocation at time $t$ is achieved by selecting optimal scheduled user set $S^*$ and allocation power set $P^*$ as:

$$(S^*, P^*; t) = \arg\max_{S, P} \prod_{k \in S} \left( 1 + \frac{R(k \mid S, P; t)}{(t_c - 1)T(k; t)} \right) \approx \arg\max_{S, P} \sum_{k \in S} \frac{R(k \mid S, P; t)}{T(k; t)}$$

Averaging interval of user throughput. $t_c$ is set to 100.

Since $R(k \mid S, P; t)$ is a weighted sum rate, optimal $P^*(S)$ for each of given $S$ can be calculated by the iterative waterfilling algorithm.

CDF of User Throughput

$N_{\text{max}} = 1$
(Orthogonal access)

$N_{\text{max}} = 2$

$N_{\text{max}} = 4$

$N_{\text{max}}$: Number of multiplexed users per beam

Cumulative probability

User throughput (Kb/s)

Number of BS antennas = 2
Number of users per cell = 30