Adaptive Modulation and Combining for Bandwidth and Power Efficient Communication over Fading Channels

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Outline

• Background, Motivation, and Goals

• Brief Review of Switched Combining
  – System & Channel Model
  – Mode of Operation

• Adaptive Combining for Diversity Rich Environments
  – Generalized Selection Combining (GSC)
  – Minimum Selection GSC
  – Minimum Estimation & Combining GSC

• Adaptive Modulation and Combining
  – Bandwidth Efficient Version
  – Power Efficient Version

• Conclusion
Diversity Techniques

• Effective fading mitigation technique.
• Create multiple faded replicas of the same signal.

• Traditional combining schemes
  – Maximum ratio combining.
  – Equal gain combining.
  – Selection combining.
  – Switched combining.

[Trade-off between performance and complexity!]

Transmitter

Diversity Combiner

Receiver
Selection Combining

• Also known as ideal switched combining.
• Always uses the best available branch for reception.

Complexity issues
  – Simultaneously monitor all antenna branches.
  – Compare estimated random quantities.
  – Frequently execute branch switching.

Complexity is reduced with non-ideal switched combining!
Switched Combining

• Use current branch and switch when it becomes unacceptable.

• Check branch quality by comparing with a fixed threshold.

• Complexity savings with respect to SC
  – Only one branch needs to be monitored.
  – Comparison with a fixed threshold.
  – Reduced frequency of branch switching.

• Two variants: switch and stay combining (SSC) and switch and examine combining (SEC).
Discrete-Time Implementation

- Branch switching is only executed during guard periods.
- In each guard period, the receiver
  - Estimate the channel
  - Perform a comparison to a fixed threshold.
  - Switch or not depending on the comparison result.
- Two important assumptions:
  - Block fading channel model.
  - Fading independence between successive guard periods.
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Combining in Diversity Rich Environments

- Performance of diversity combining schemes improve with additional combined branches.

- Many emerging and proposed wireless communication systems will operate in diversity rich environments (Examples: Ultra-wideband, millimeter-wave, and MIMO systems).

- For best performance: MRC
  - Requires one RF chain for each combined branch.
  - Mandates complete knowledge of channel conditions.
  - Sensitive to channel estimation errors.

- To reduce complexity and be less sensitive to channel estimation errors ⇒ Only good branches are MRC combined.
Reduced-Complexity Combining Schemes

• Apply MRC to a properly-selected subset of available paths.

• Generalized selection combining (GSC) [Eng *et. al.*’96, Win and Winter’99, Alouini and Simon’00, Ma and Chai’00]
  – Apply MRC to a fixed-size subset of best paths.

• Generalized switch and examine combining (GSEC) [Yang and Alouini’03]
  – Apply MRC to a fixed-size subset of acceptable (and unacce
table if necessary) paths.

MRC combine less branches than the available paths!
**L/Lc Generalized Selection Combining (GSC)**

- **L**: number of available diversity paths.
- **Lc**: number of MRC combined branches. \((L_c < L)\)
- Operations before combining
  - Estimate channel quality of all \(L\) diversity paths.
  - Rank them according to SNR (for example)
  - Select and combine only the \(L_c\) strongest branches.
- Require \(L\) estimations and \(\approx L_c \times L\) comparisons.
- Performance analysis of GSC received a great deal of attention over the last decade.
Adaptive Combiners

• Conventional combiners are designed for worst-case channel conditions.

• Adaptive combiners:
  – Do not run a computationally complex and power greedy full-MRC combining for all channels conditions.
  – Choose most appropriate combining scheme and acceptable branches to be combined in response to channel variations and given a desired QoS performance.

• Goal: Minimize the average receiver complexity and average power consumption for a target QoS performance.
Power-Saving GSC Schemes

• Output-oriented combining
  – Target a particular output SNR threshold.
  – Adaptively combine paths to increase the combined SNR above the output threshold.

• Switch-based combining
  – Do not necessarily go after the “best” paths but rather for “acceptable” paths.
  – Example: Generalized SEC: [Yang and Alouini, T-COM’04]
Minimum Selection GSC (MS-GSC)

- Introduce a threshold check at the output of traditional GSC.
- Raise combined SNR $\Gamma = \gamma_c$ above the threshold $\gamma_T$ by gradually increasing the number of combined best paths.
Alternative View of MS-GSC

• Mode of operation
  – Start from $L/1$-GSC (L-branch SC) scheme.
  – Switches to higher order GSC by combining more paths.

• MS-GSC requires the estimation and ranking of all paths (like GSC).

• MS-GSC combines less paths on average than GSC.
Quantification of Power Savings

- Quantified in terms of the average number of combined paths.
- The probability mass function (PMF) of the number of combined paths $N_c$ is

$$
P [N_c = l] = \begin{cases} 
P[\gamma_{1:L} > \gamma_T], & l = 1; \\
P[\Gamma_{l-1} < \gamma_T & \Gamma_l \geq \gamma_T], & 1 < l < L_c; \\
P[\Gamma_{Lc-1} < \gamma_T], & l = L_c,
\end{cases}
$$

where $\Gamma_l = \sum_{i=1}^{l} \gamma_{i:L}$ and $\gamma_{1:L} \geq \gamma_{2:L} \geq \cdots \geq \gamma_{L:L}$.
- Can be shown to be given by [Yang, ICC’05]

$$
P [N_c = l] = \begin{cases} 
1 - P_{\Gamma_1}(\gamma_T), & l = 1; \\
P_{\Gamma_{l-1}}(\gamma_T) - P_{\Gamma_l}(\gamma_T), & 1 < l < L_c; \\
P_{\Gamma_{Lc-1}}(\gamma_T), & l = L_c,
\end{cases}
$$

where $P_{\Gamma_l}(\cdot)$ is the CDF of $\Gamma_l$.
- Average number of combined paths

$$
\overline{N}_c = \sum_{l=1}^{L_c} l \ Pr [N_c = l] = 1 + \sum_{l=1}^{L_c-1} P_{\Gamma_l}(\gamma_T),
$$
Minimum-Estimation-Combining (MEC)-GSC

1. Start with $i = 0$, $l = 1$, $\gamma_c = 0$.
2. Increment $i$ by 1.
3. Estimate $\gamma_i$.
4. If $\gamma_i > \gamma_T$, then set $\gamma_c = \gamma_i$.
5. If $i = L_c$, stop.
6. Rank $\gamma_i$ for $i = 1, ..., L$.
    - Set $\gamma_c = \gamma_L$.
7. Update MRC output SNR: $\gamma_c = \gamma_c + \gamma_L$.
8. If $\gamma_c > \gamma_T$, then set $l = l + 1$.
9. If $l = L_c$, stop.
10. Increment $l$ by 1.
Savings on the Estimated Branches

- Consider an i.i.d. scenario and let $p = P[\gamma < \gamma_T] = P_\gamma(\gamma_T)$, where $P_\gamma(\cdot)$ is the CDF of the SNR per branch $\gamma$ and $\gamma_T$ is the switching threshold.

- Average number of estimated branches

$$N_E = 1 - p + 2p - 2p^2 + \cdots + (L - 1)p^{L-2}(1 - p) + L p^{L-1} = 1 - p + 2p - 2p^2 + \cdots + (L - 1)p^{L-2} - (L - 1)p^{L-1} + Lp^{L-1} = 1 + p + p^2 + \cdots + p^{L-1} = \frac{1 - p^L}{1 - p}$$
Average Number of Channel Estimates

![Graph showing average number of estimated paths with MEC-GSC]

- Average Number of Estimated Paths with MEC-GSC
- Normalized Threshold $\gamma_T / E[\gamma]$
- Average Number of Estimated Paths
  - $L=4$
  - $L=5$
  - $L=6$
  - $L=7$

Student Version of MATLAB

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Characteristics of MEC-GSC

- MEC-GSC has exactly the same $\overline{N}_e$ as SECps
  - Slightly higher than conventional SEC
  - Lower than the deterministic $N_e = L$ of SC, GSC and MS-GSC

- MEC-GSC has exactly the same $\overline{N}_c$ as MS-GSC
  - Higher than $N_c = 1$ of conventional SEC, SECps, and SC
  - Lower than $N_c = L_c$ of GSC.

- Outage probability and average error rate of MEC-GSC is better than the performance of SEC, SECps, and SC but slightly worse than the performance of MS-GSC and GSC.
MEC-GSC Output SNR Statistics

• Let $\gamma_c$ denote the $L_c$-branch MEC-GSC output SNR.

• CDF of $\gamma_c$, $P_{\gamma_c}(\cdot)$, in i.i.d. fading scenario
  
  - For $0 \leq \gamma < \gamma_T$
    \[
P_{\gamma_c}(\gamma) = P \left[ \sum_{l=1}^{L_c} \gamma_l : L \leq \gamma \right] = P_{\Gamma_{L_c}}(\gamma).
    \]
  
  - For $\gamma_T \leq \gamma$
    \[
P_{\gamma_c}(\gamma) = p_0 P[\gamma_T \leq \gamma_1 \leq \gamma] + p_1 P[\gamma_T \leq \gamma_2 \leq \gamma] + \cdots
    \]
    \[
    + p^{L-1} L \sum_{l=2}^{L_c} P^{(l)}_{\gamma_c}(\gamma) + P_{\Gamma_{L_c}}(\gamma_T)
    \]
    \[
    = \frac{1 - p}{1 - p} (P_{\gamma}(\gamma) - p) + \sum_{l=2}^{L_c} P^{(l)}_{\gamma_c}(\gamma) + P_{\Gamma_{L_c}}(\gamma_T),
    \]
where
\[ P_{\gamma}^{(l)}(\gamma) = P \left[ \sum_{j=1}^{l-1} \gamma_j : L < \gamma_T \& \gamma_T < \sum_{j=1}^{l} \gamma_j : L < \gamma \right] . \]
**Estimation-Combining-Performance Tradeoff**

\[ L = 5, \; L_c = 4, \text{ and } \bar{\gamma} = 10 \text{ dB}. \]

![Graphs showing performance tradeoff comparisons](image-url)
Summary and Perspectives

- Switched-based combining schemes offer a low-complexity low-power solution for fading mitigation.
- MEC-GSC offers a good tradeoff of performance versus complexity and power consumption.
- Further investigations:
  - Effect of power delay profile and fading correlation on switched-based combining schemes.
  - Fully adaptive switched-based transceivers
    ⇒ Adaptive modulation and combining
Bandwidth Efficiency Considerations

- The spectral efficiency aspect is ignored in the design of MS-GSC and MEC-GSC.

- We generalize both of these adaptive combining schemes to a *multiple-threshold* mode and use them in conjunction with adaptive modulation.

- Resulting *adaptive modulation and combining* schemes:
  - Multiple threshold minimum-selection combining (MT-MSC).
  - Multiple threshold-minimum estimation and combining (MT-MEC)

- **Goal:** Attempt to maximize the link spectral efficiency with the minimum number of combined diversity branches (i.e. with a minimum amount of processing power).
Adaptive Multiple Threshold MSC

Start

\[ i = 0 \]

\[ k = 0 \]

\[ n = 1 \ldots N \]

Set \( n = N \)

\[ i = i + 1 \]

Estimate \( \gamma_i \)

Yes

\[ n = L \]

No

Rank \( \gamma_i = \ldots \ldots L \)

Set \( \gamma_i = \gamma_i \)

Set \( F_i = F_i \)

\[ i = i + 1 \]

\[ L = L \]

\[ \gamma_i = \gamma_i + \gamma_i \]

\[ F_i = F_i \]

Yes

\[ i = L \]

No

\[ n = n - 1 \]

\[ n = 0 \]

Yes

Set \( i = 0 \)

\[ i = i + 1 \]

\[ F_i = F_i \]

\[ \gamma_i = \gamma_i \]

Yes

\[ \gamma_i < \gamma_i \]

No

Option 1

Transmit during the outage period with \( \gamma_i - F_i \)

Use \( M = 2 \)

Option 2

Do not transmit during the outage period

Transmit with \( \gamma_i \cdot F_i \)

Use \( M = 2 \)
Adaptive Multiple Threshold MEC

Diagram:

1. Start
2. Set $n = N$
3. $i = 0$
4. Estimate $\gamma_i$
5. If $\gamma_i > \gamma_i^p$, then $y_i = Y_i$; otherwise, $y_i = \phi$.
6. $i = i + 1$
7. If $i > L$, then stop; otherwise, go to step 3.
8. $n = n - 1$
9. If $n = 0$, then stop; otherwise, go to step 4.
10. Transmit during the outage period with $y_i = T_i$, use $M = \phi$.

Option 1:
- Transmit during the outage period with $y_i = T_i$.

Option 2:
- Do not transmit during the outage period.

Transmit with $y_i$, use $M = \phi$. 

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Average Spectral Efficiency

Average Spectral efficacy versus Average SNR per Branch (L=7, L_c=4)

With Tx
Without Tx

Average Spectral efficacy per Data Burst

Average SNR per Branch, E[γ], [dB]
Average Number of Combined Branches versus Average SNR per Branch (L=7, L_c=4)

- With Tx
- Without Tx
Average Number of Estimated Branches

![Graph showing the average number of channel estimates with MT-MEC (L=7 and N=4) versus average SNR per branch. The graph indicates a decrease in the average number of channel estimates as the average SNR per branch increases.]
Average BER of Combined Branches per Data Burst versus Average SNR per Branch ($L=7$, $L_c=4$)

- **MT-MEC**
- **MT-MSC**
- **4/7-GSC**

With Tx

Without Tx

Average BER of Combined Branches per Data Burst versus Average SNR per Branch, $E[\gamma]$, [dB]
Summary on Bandwidth Efficient Version

• For an average SNR per branch above 15 dB, MT-MEC
  – Offers a full spectral efficiency of 4 Bps/Hz (like GSC and MT-MSC)
  – Meets the BER requirement $BER_0 = 10^{-3}$ (like GSC and MT-MSC)
  – Combines around 1.25 branches in average (like MT-MSC but in contrast to GSC which combines continuously 4 branches)
  – Estimates 4 branches in average (in contrast to GSC and MT-MSC which both need to estimate the 7 available diversity branches at the beginning of each time slot).

• Power consumption and estimation complexity advantage of MT-MEC comes at the expense of a slightly worse average BER performance in comparison to MT-MSC and GSC for high average SNR.
Power Efficient Versions

- Minimize the number of combined branches (i.e., the required processing power) at the expense of a certain spectral efficiency penalty in comparison with the schemes presented above.

- MT-MSC and MT-MEC versions.
Adaptive Multiple Threshold MEC

Start
Set $i = N$

$i = i + 1$

Examine $\gamma_i$

If $\gamma_i > \gamma_{i-1}$

Yes

No

$\gamma_i = \gamma_1$

Rank $\gamma_1, \ldots, \gamma_N$

$i = i + 1$

$\gamma_N > \gamma_i$

Yes

No

Compute $\Gamma_1 = \sum_{i=1}^{N} \gamma_i$

If $\gamma_N > \gamma_{i-1}$

Yes

No

$n = n - 1$

$n = 0$

Yes

No

Option 1

Option 2

Transmit during the outage period with $\gamma_i$, use $M = 2\text{PSK}$

Do Transmit during the outage period

Transmit with $\gamma_1$, use $M = 2\text{QAM}$
Average Number of Combined Branches versus Average SNR per Branch (L=7, L_c=4)
Average Spectral Efficiency

Average Spectral Efficiency versus Average SNR per Branch (L=7, L_c=4)

- Option 1
- Option 2

MT−MEC

Average SNR per Branch, E[γ], [dB]

Average Spectral Efficiency per Data Burst, [Bps/Hz]
Average BER of Combined Branches per Data Burst versus Average SNR per Branch \((L=7, L_c=4)\)

- Option 1
- Option 2

- MT-MEC
- MT-MEC\(_B\)
- MT-MEC\(_P\)
- 4/7-GSC
Conclusion

• Adaptive modulation and diversity combining techniques jointly select the most appropriate constellation size and the most suitable diversity branches in response to the channel variation and given a desired BER requirement.

• Bandwidth and power efficient versions were proposed and studied.

• Bandwidth efficient versions offer a higher spectral efficiency in the medium SNR region.

• Spectral efficiency advantage of the bandwidth efficient versions comes at the expense of a higher average processing power over the same medium SNR range.

• Power efficient version offers a lower average BER than the bandwidth efficient version in the medium SNR range but both versions yield the same average BER in the high SNR region.