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

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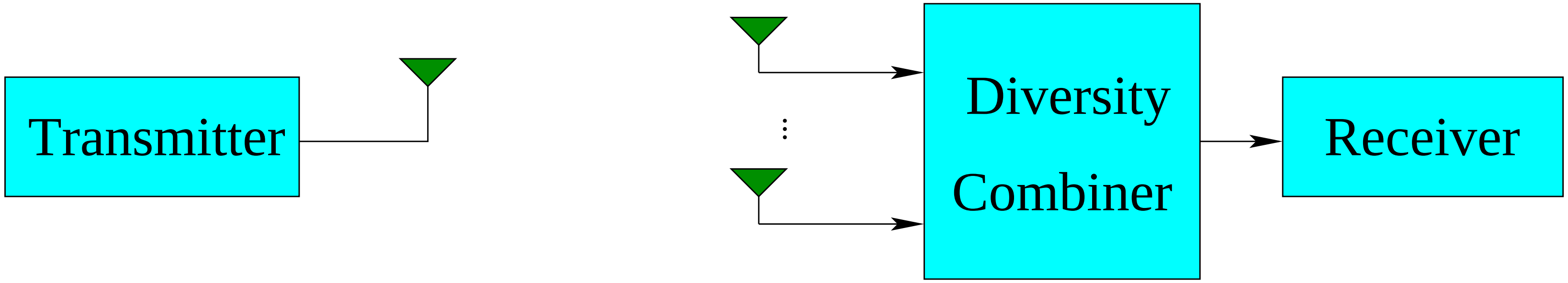
Outline

- 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.

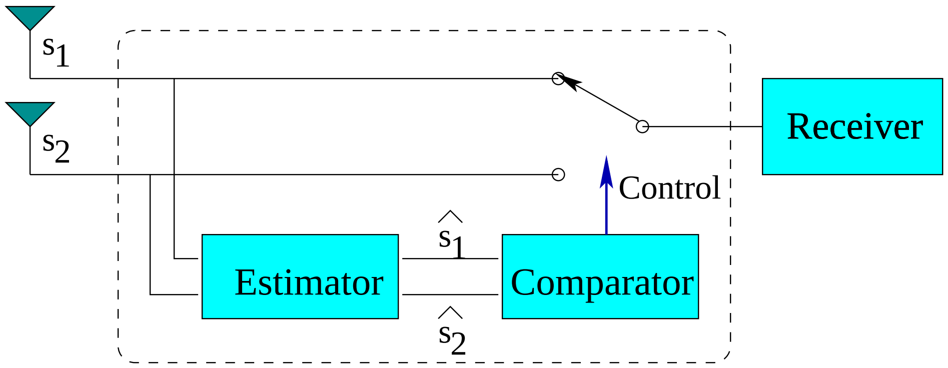


- Traditional combining schemes
  - Maximum ratio combining.
  - Equal gain combining.
  - Selection combining.
  - Switched combining.

Trade-off between performance and complexity!

Selection Combining

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

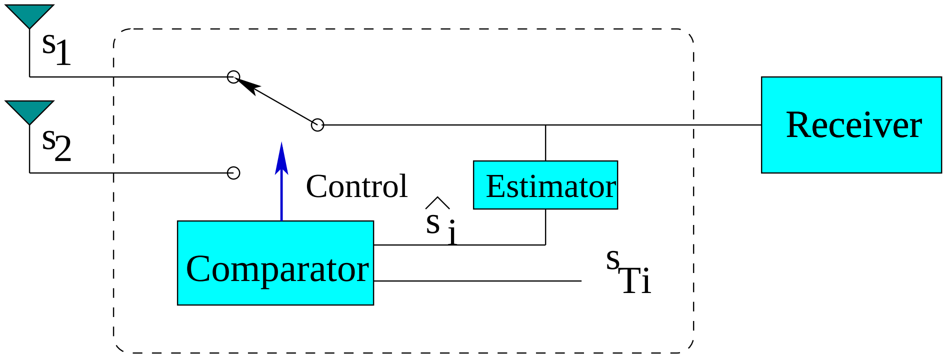


- Complexity issues
  - Simultaneously monitor all antenna branches.
  - Compare estimated random quantities.
  - Frequently execute branch switching.

Complexity is reduced with non-ideal switched combining!

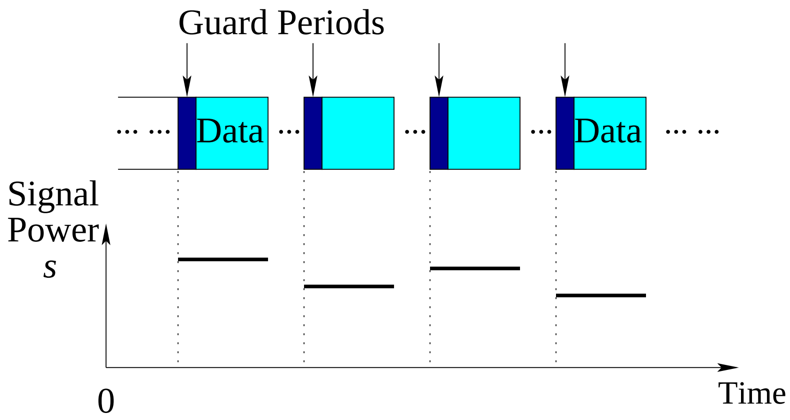
Switched Combining

- 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

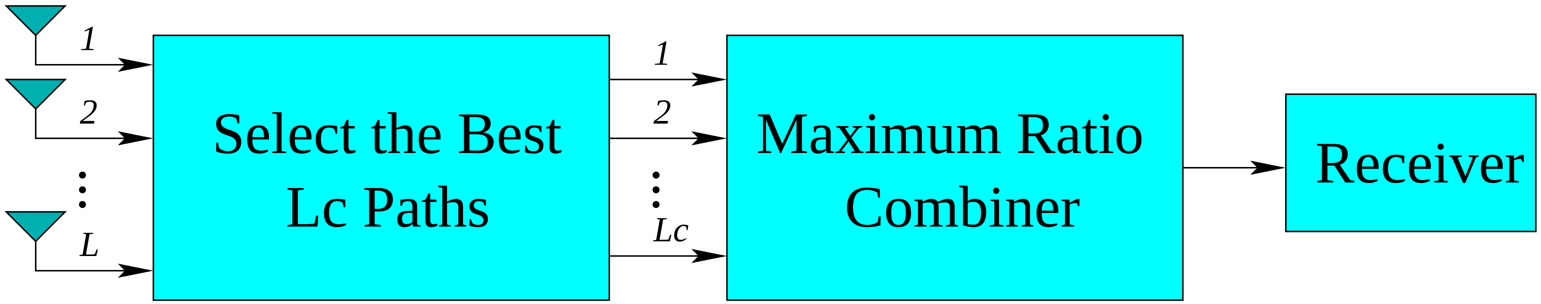
- Performance of diversity combining schemes improve with additional combined branches.
- Many emerging and proposed wireless communication systems will operate in diversity rich environments (Examples: Ultra-wideband, millimeter-wave, and MIMO systems).
- For best performance: MRC
  - Requires one RF 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 $\Rightarrow$ 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 unacceptable if necessary) paths.

MRC combine less branches than the available paths!

L/L_c Generalized Selection Combining (GSC)



- L: number of available diversity paths.
- L_c: 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.

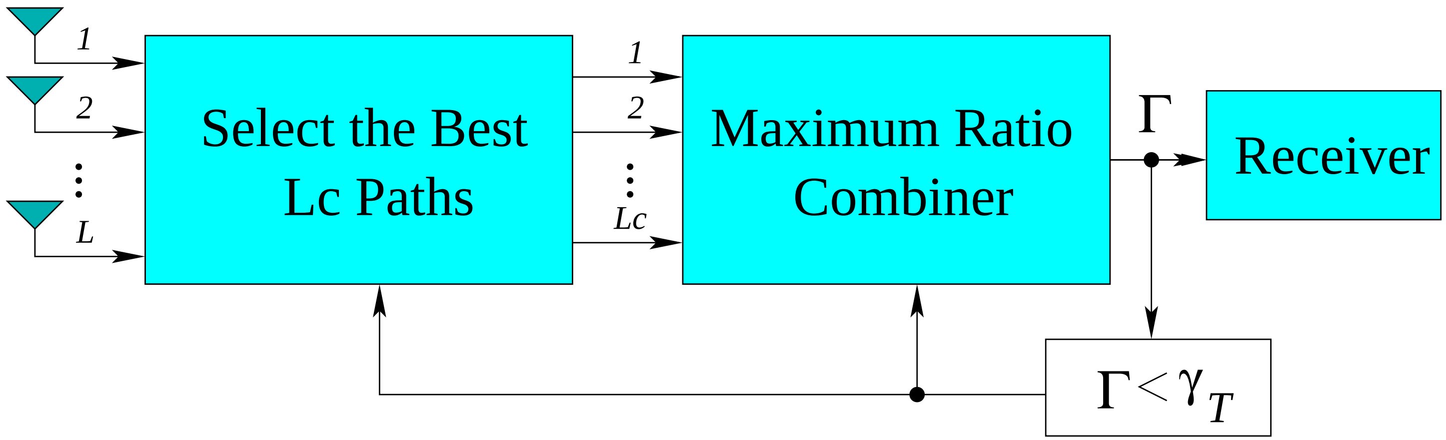
Adaptive Combiners

- 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

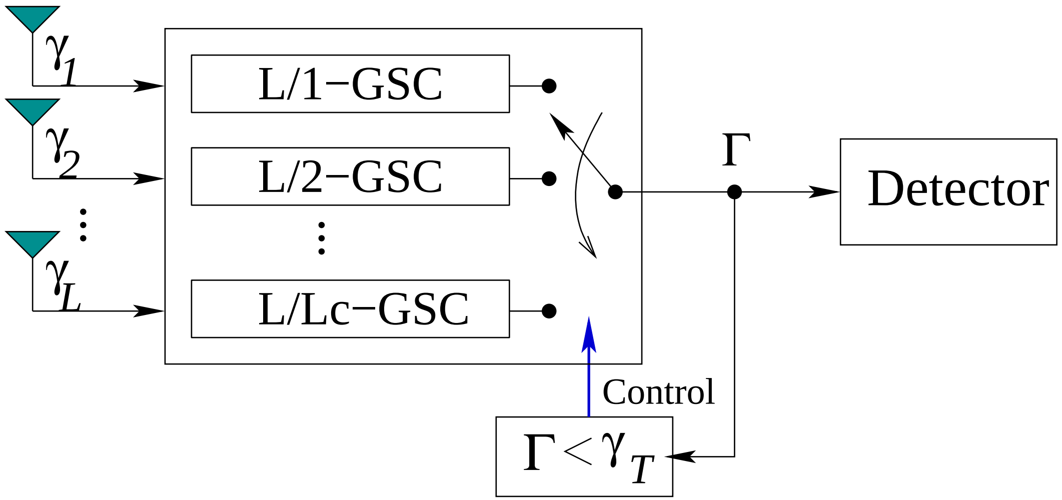
- Output-oriented combining
  - Target a particular output SNR threshold.
  - Adaptively combine paths to increase the combined SNR above the output threshold.
  - Examples: Minimum selection GSC (MS-GSC): [Kim *et al.* ISCAS'03, Gupta *et al.* ICC'04, and Yang ICC'05]], Output-Threshold MRC (OT-MRC): [Yang and Alouini, ICC'04], and Output-Threshold GSC (OT-GSC): [Yang and Alouini, Globecom'04]
- 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 γ_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

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

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]

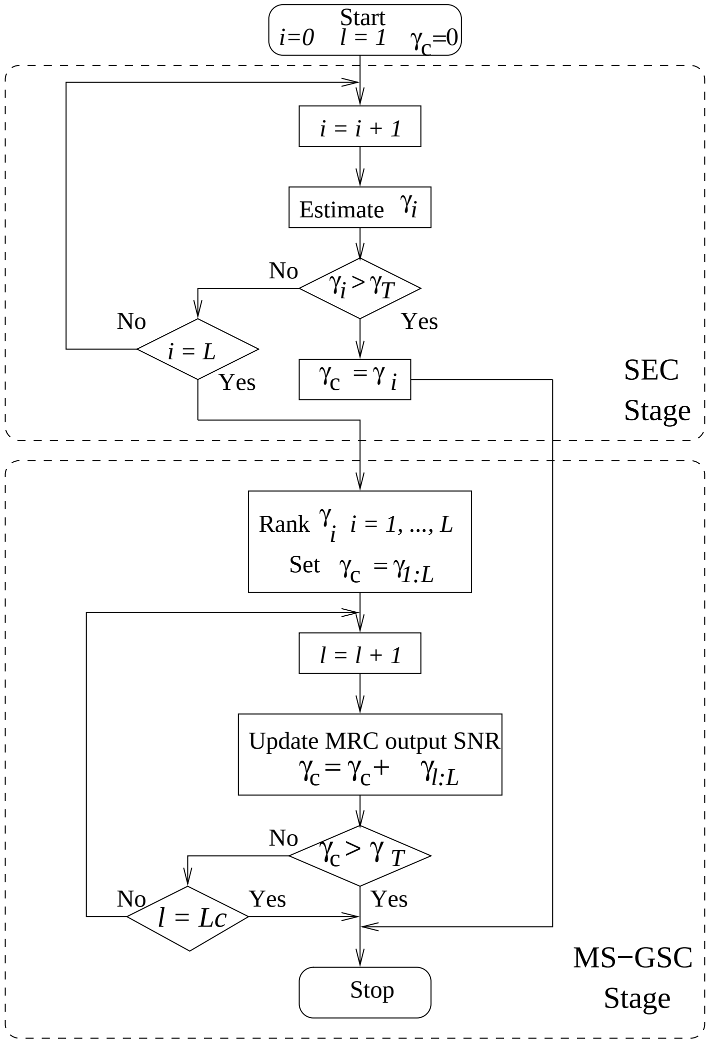
$$P\left[N_c = l\right] = \begin{cases} 1 - P_{\Gamma_1}(\gamma_T), & l = 1; \\ P_{\Gamma_{l-1}}(\gamma_T) - P_{\Gamma_l}(\gamma_T), & 1 < l < L_c; \\ P_{\Gamma_{L_c-1}}(\gamma_T), & l = L_c, \end{cases}$$

where $P_{\Gamma_l}(\cdot)$ is the CDF of Γ_l.

- Average number of combined paths

$$\overline{N}_c = \sum_{l=1}^{L_c} l \ \Pr\left[N_c = l\right] = 1 + \sum_{l=1}^{L_c-1} P_{\Gamma_l}(\gamma_T),$$

Minimum-Estimation-Combining (MEC)-GSC

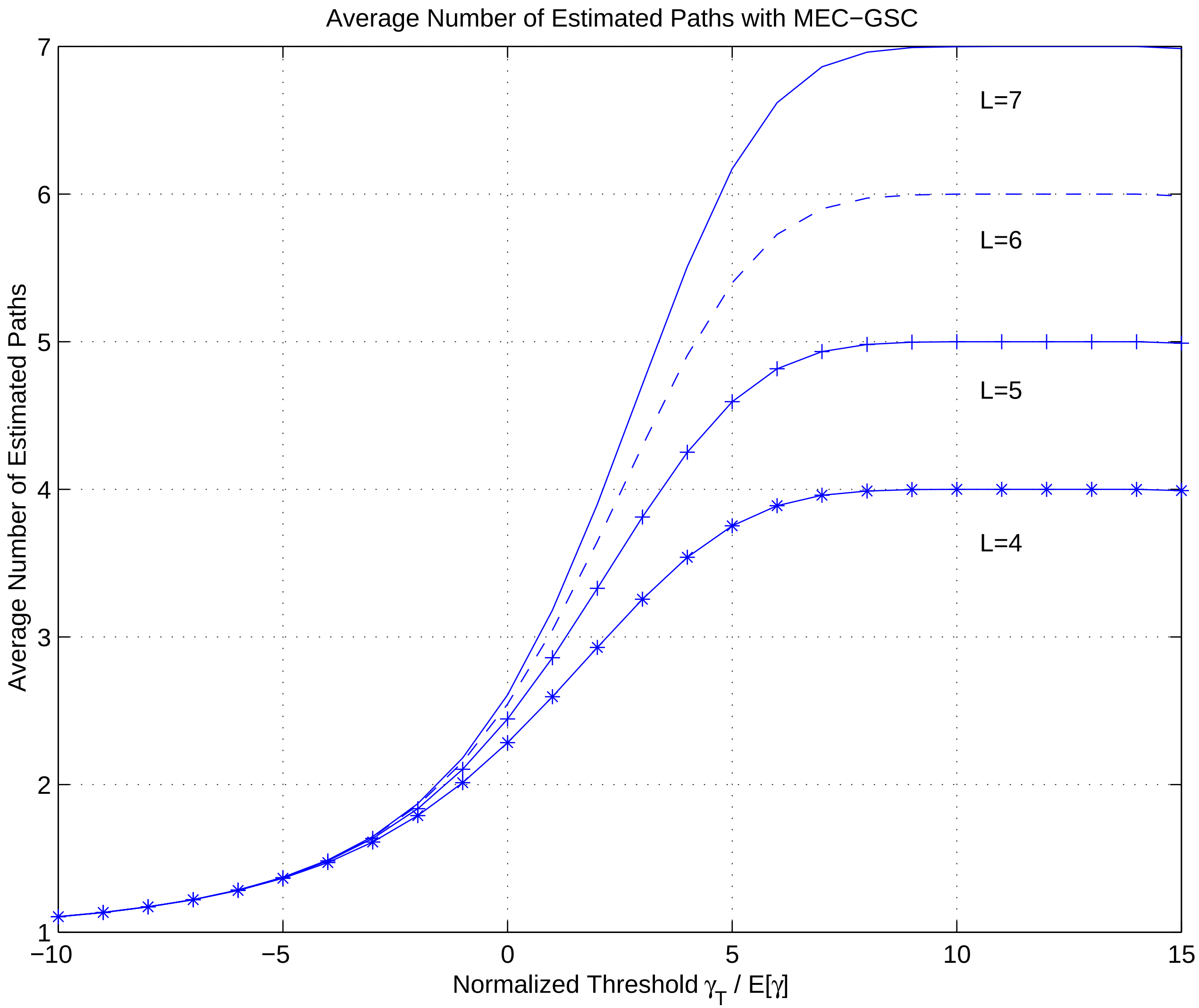


Savings on the Estimated Branches

- 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 γ and γ_T is the switching threshold.
- Average number of estimated branches

$$
\begin{aligned}
\overline{N}_E &= 1(1-p) + 2p(1-p) + \cdots + (L-1)p^{L-2}(1-p) + L\,p^{L-1} \\
&= 1 - p + 2p - 2p^2 + \cdots + (L-1)p^{L-2} - (L-1)p^{L-1} + Lp^{L-1} \\
&= 1 + p + p^2 + \cdots + p^{L-1} = \frac{1-p^L}{1-p}
\end{aligned}
$$

Average Number of Channel Estimates



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 γ_c denote the L_c-branch MEC-GSC output SNR.
- CDF of γ_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 $\gamma_T \leq \gamma$

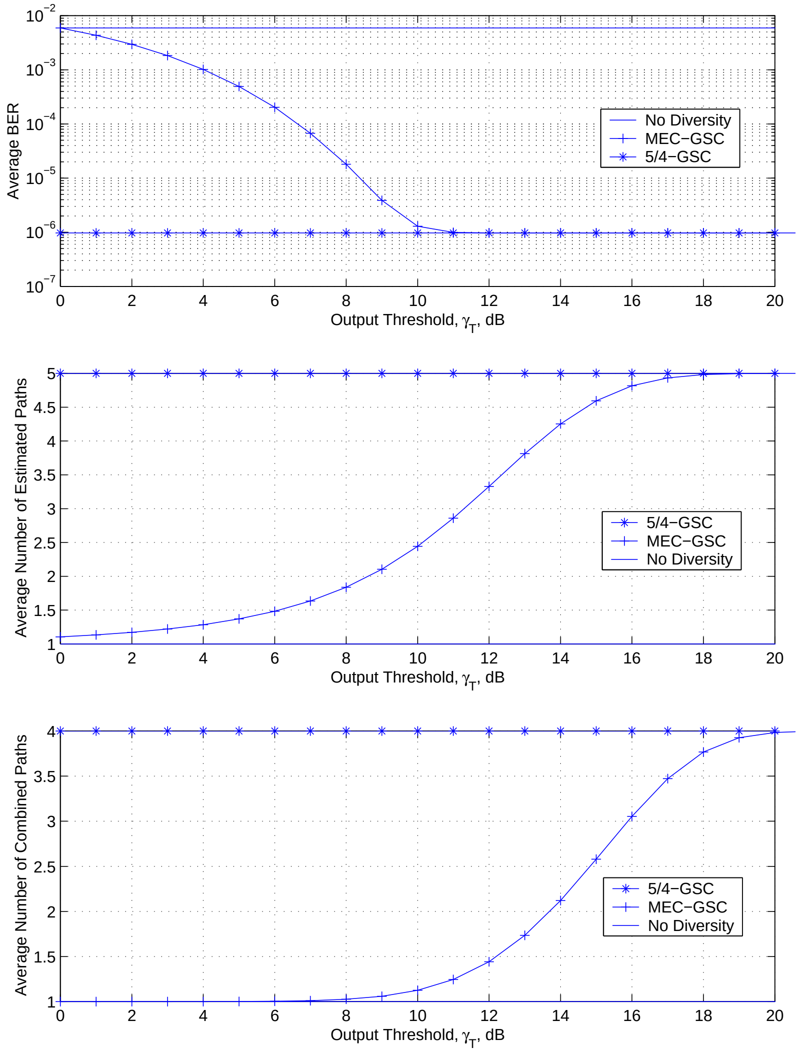
$$\begin{aligned} P_{\gamma_c}(\gamma) &= p^0 P[\gamma_T \leq \gamma_1 \leq \gamma] + p^1 P[\gamma_T \leq \gamma_2 \leq \gamma] + \cdots \\ &\quad + p^{L-1} P[\gamma_T \leq \gamma_L \leq \gamma] + \sum_{l=2}^{L_c} P_{\gamma_c}^{(l)}(\gamma) + P_{\Gamma_{L_c}}(\gamma_T) \\ &= \frac{1-p^L}{1-p}(P_\gamma(\gamma) - p) + \sum_{l=2}^{L_c} P_{\gamma_c}^{(l)}(\gamma) + P_{\Gamma_{L_c}}(\gamma_T), \end{aligned}$$

where

$$P_{\gamma_c}^{(l)}(\gamma) = P\left[\sum_{j=1}^{l-1}\gamma_{j:L} < \gamma_T \;\&\; \gamma_T < \sum_{j=1}^{l}\gamma_{j:L} < \gamma\right].$$

Estimation-Combining-Performance Tradeoff

$L = 5$, $L_c = 4$, and $\overline{\gamma} = 10$ dB.



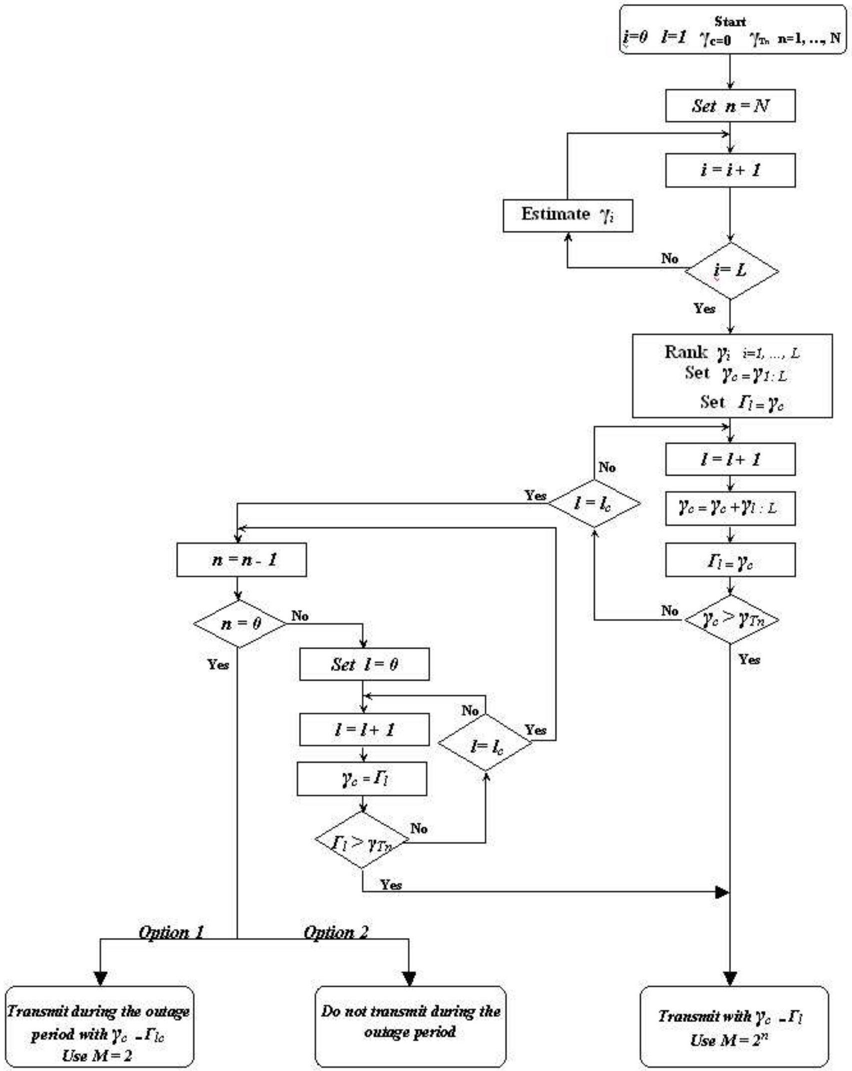
Summary and Perspectives

- 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 transeivers
    $\Rightarrow$ Adaptive modulation and combining

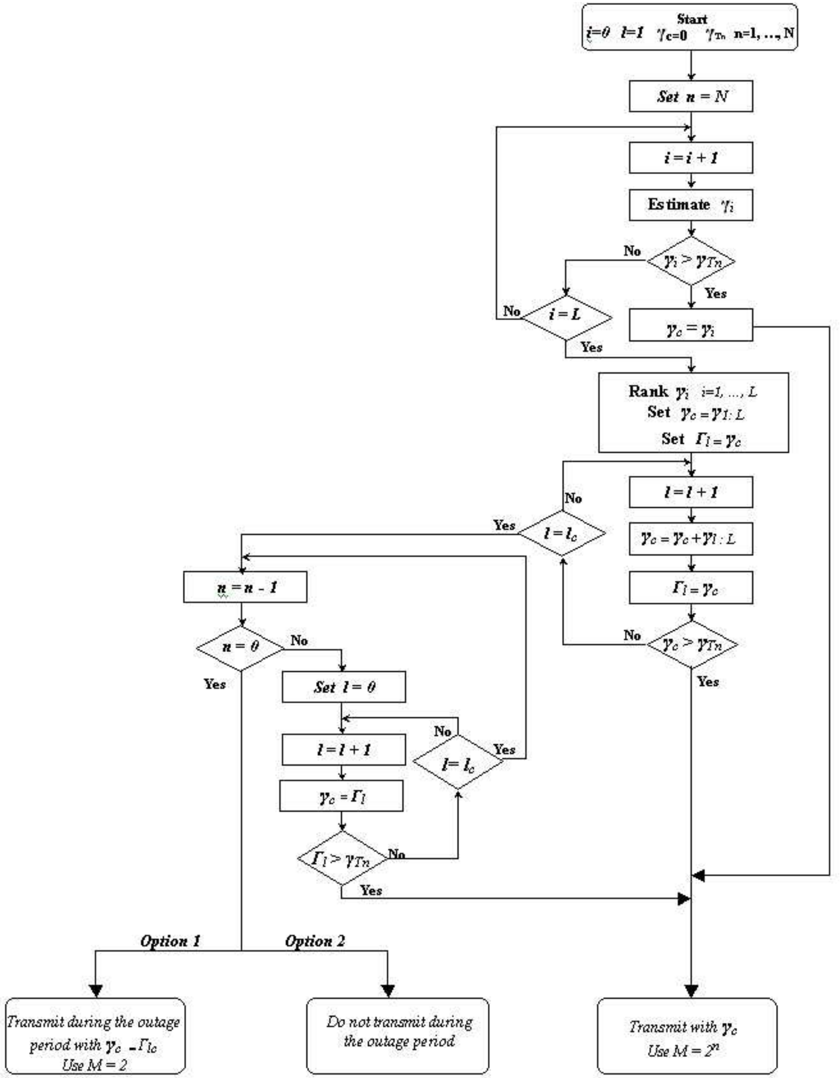
Bandwidth Efficiency Considerations

- 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).

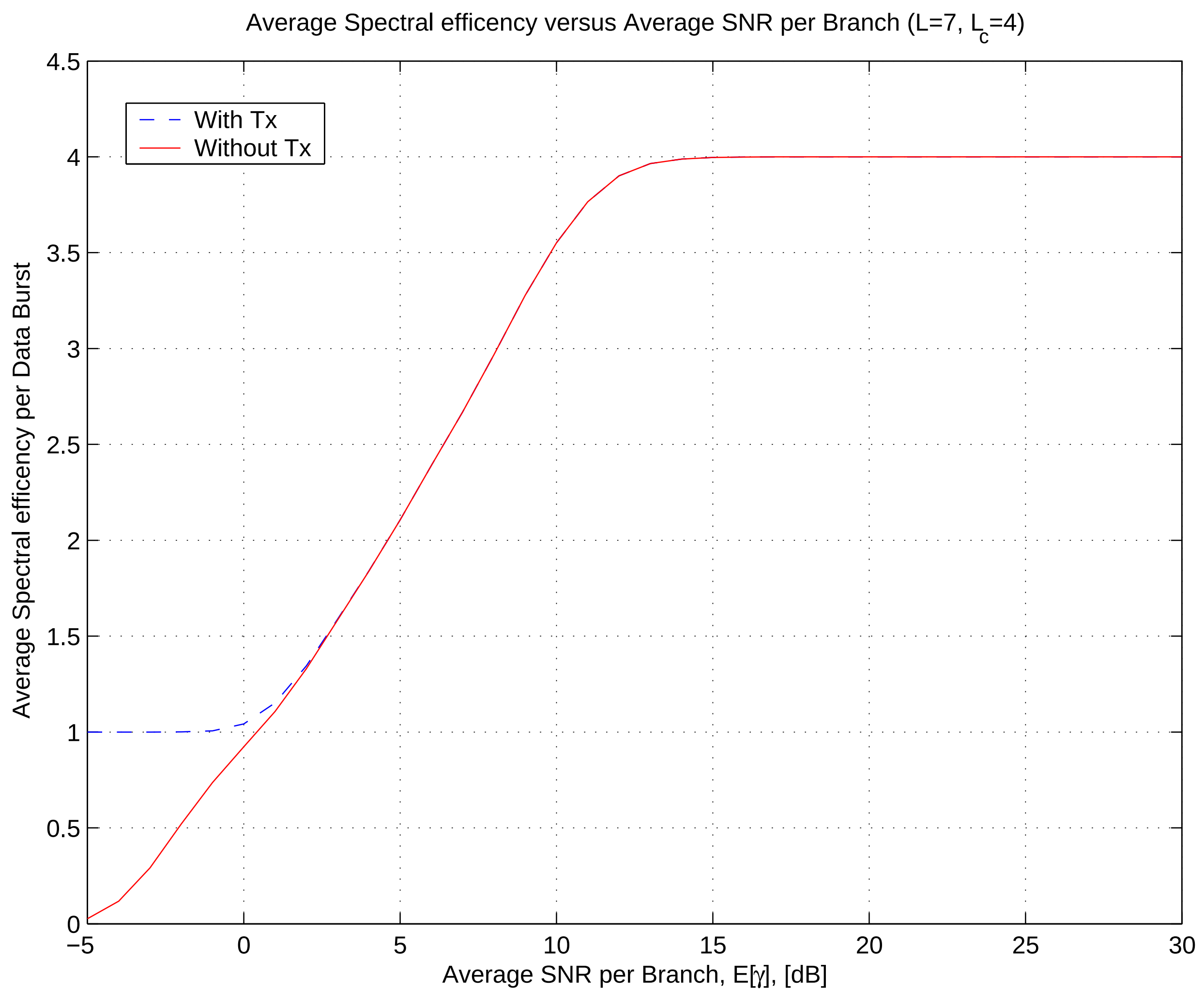
Adaptive Multiple Threshold MSC



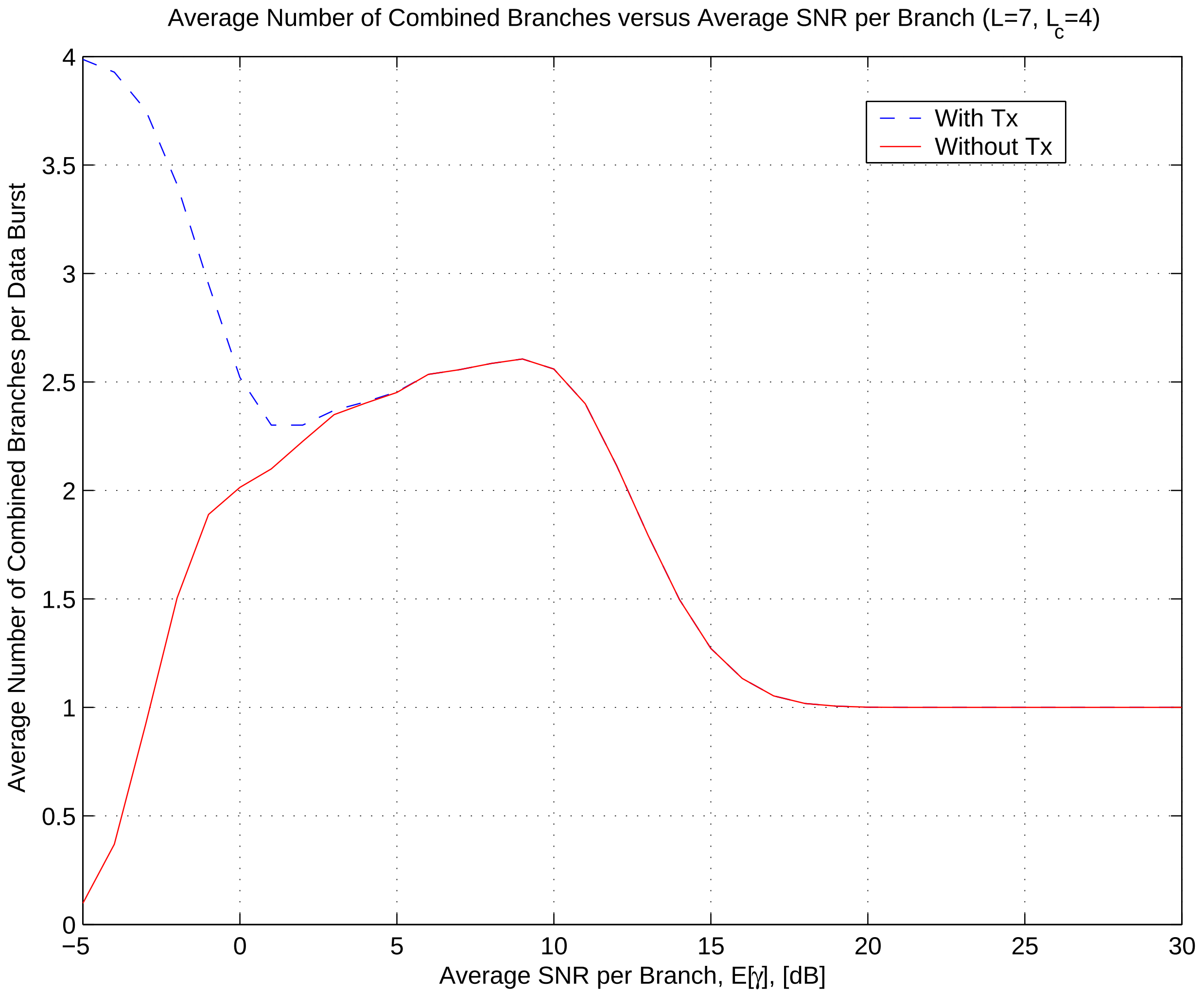
Adaptive Multiple Threshold MEC



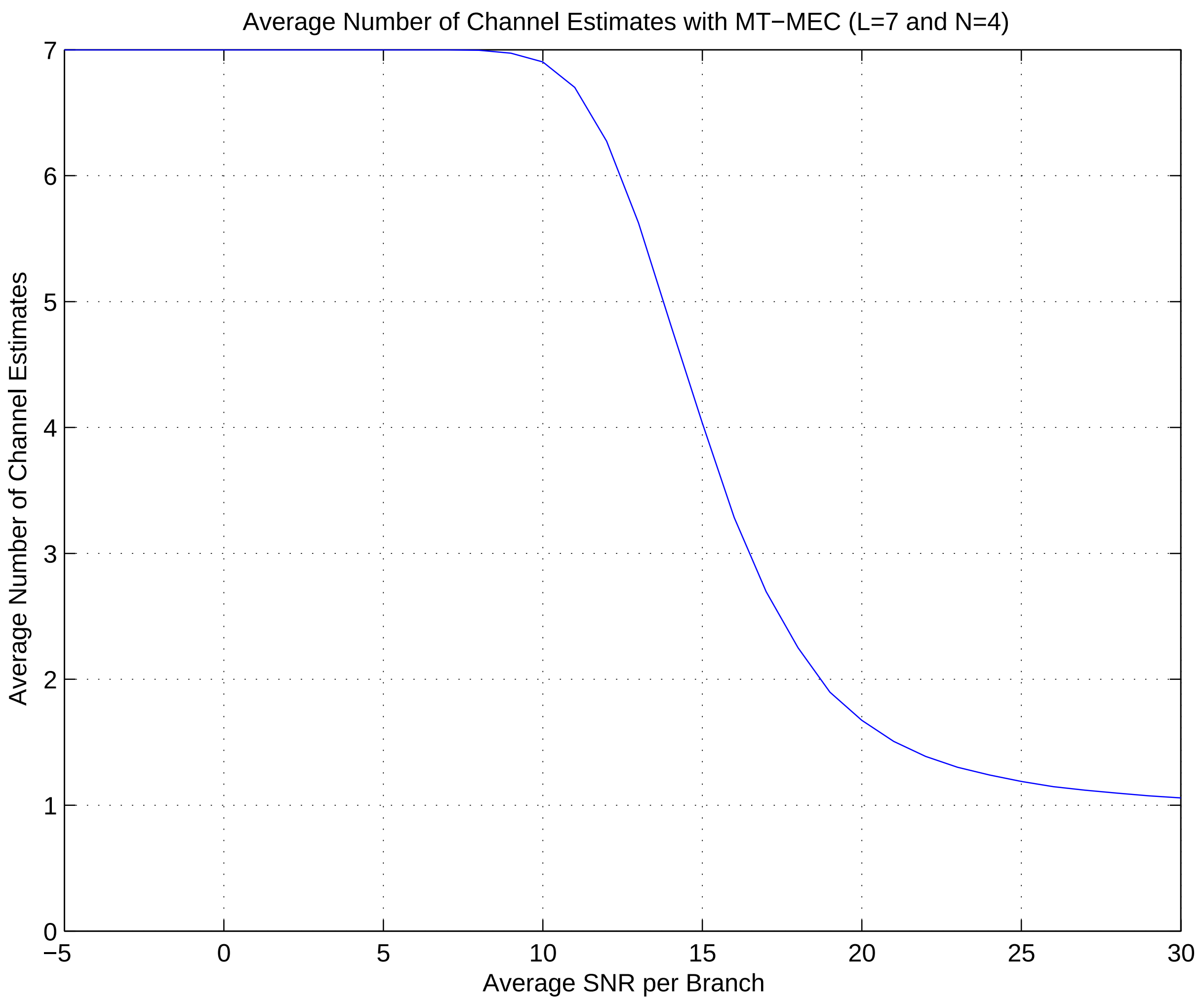
Average Spectral Efficiency



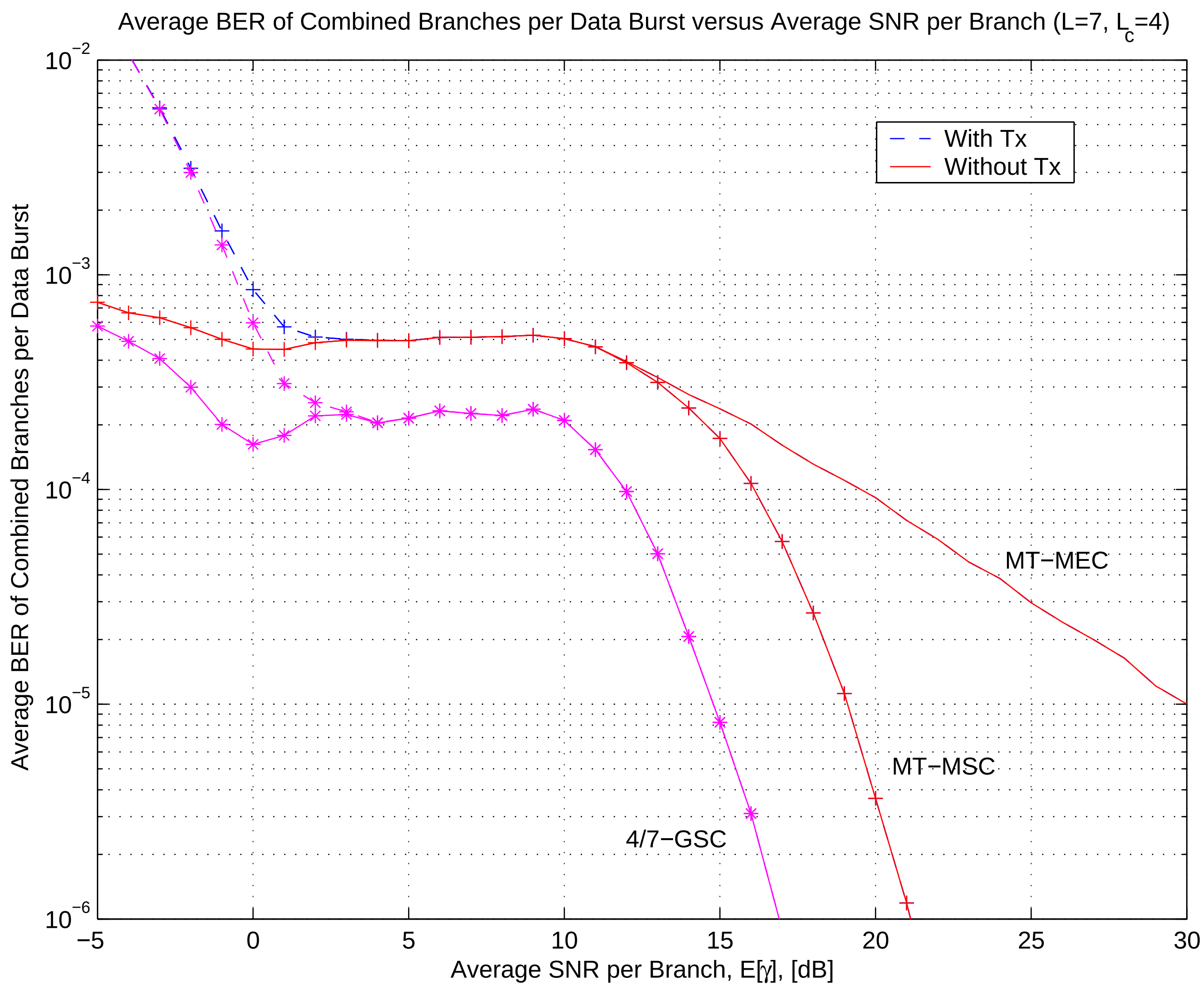
Average Number of Combined Branches



Average Number of Estimated Branches



Average BER


Average BER of Combined Branches per Data Burst versus Average SNR per Branch (L=7, Lc=4)
Average BER of Combined Branches per Data Burst
Average SNR per Branch, E[γ], [dB]
With Tx
Without Tx
MT−MEC
MT−MSC
4/7−GSC
10−2
10−3
10−4
10−5
10−6
−5
0
5
10
15
20
25
30

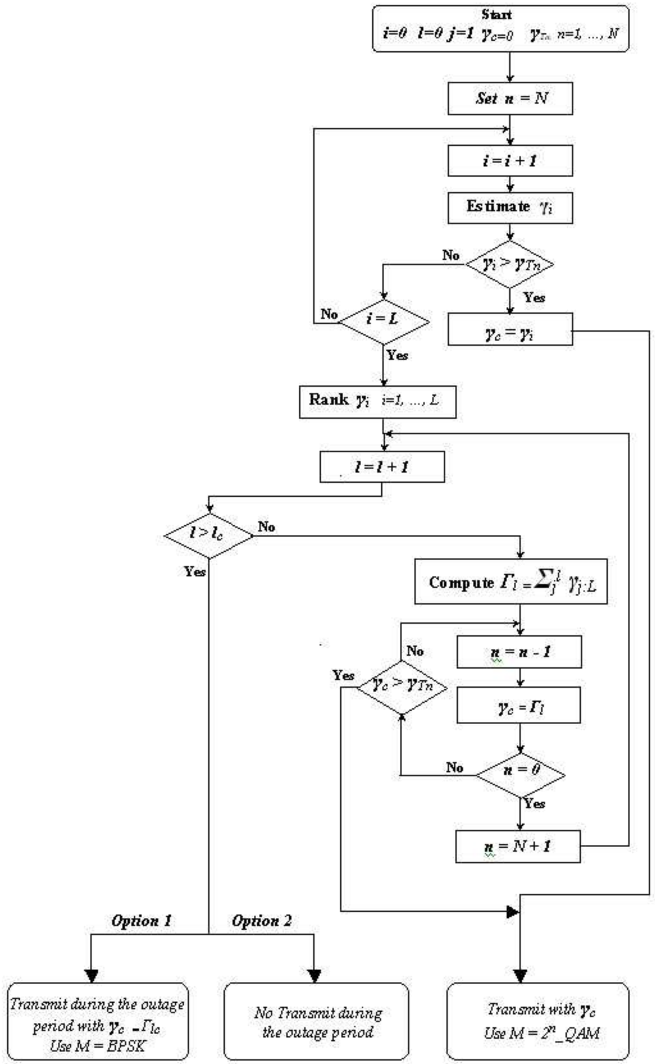
Summary on Bandwidth Efficient Version

- 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 $\text{BER}_0 = 10^{-3}$ (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.

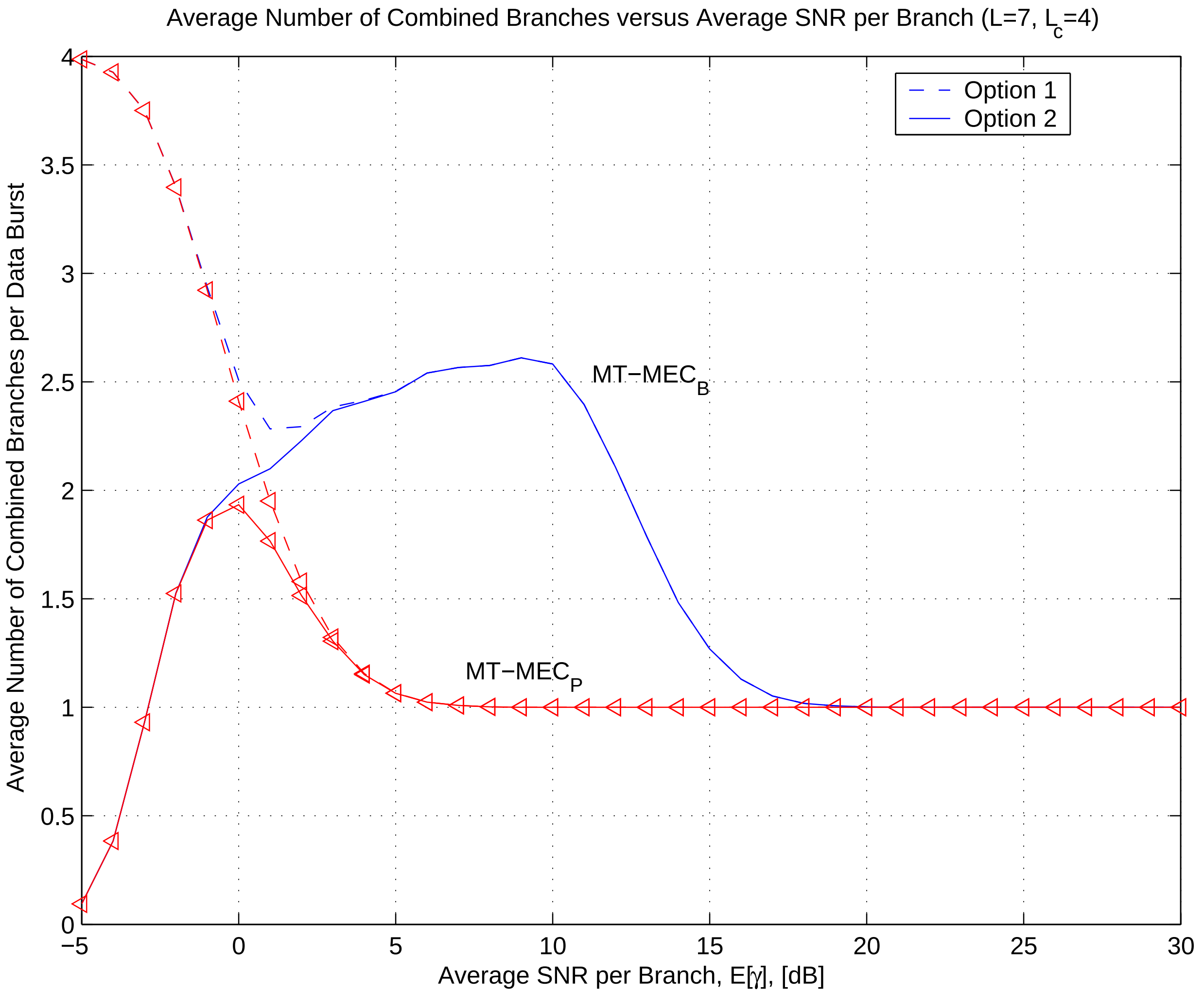
Power Efficient Versions

- 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.

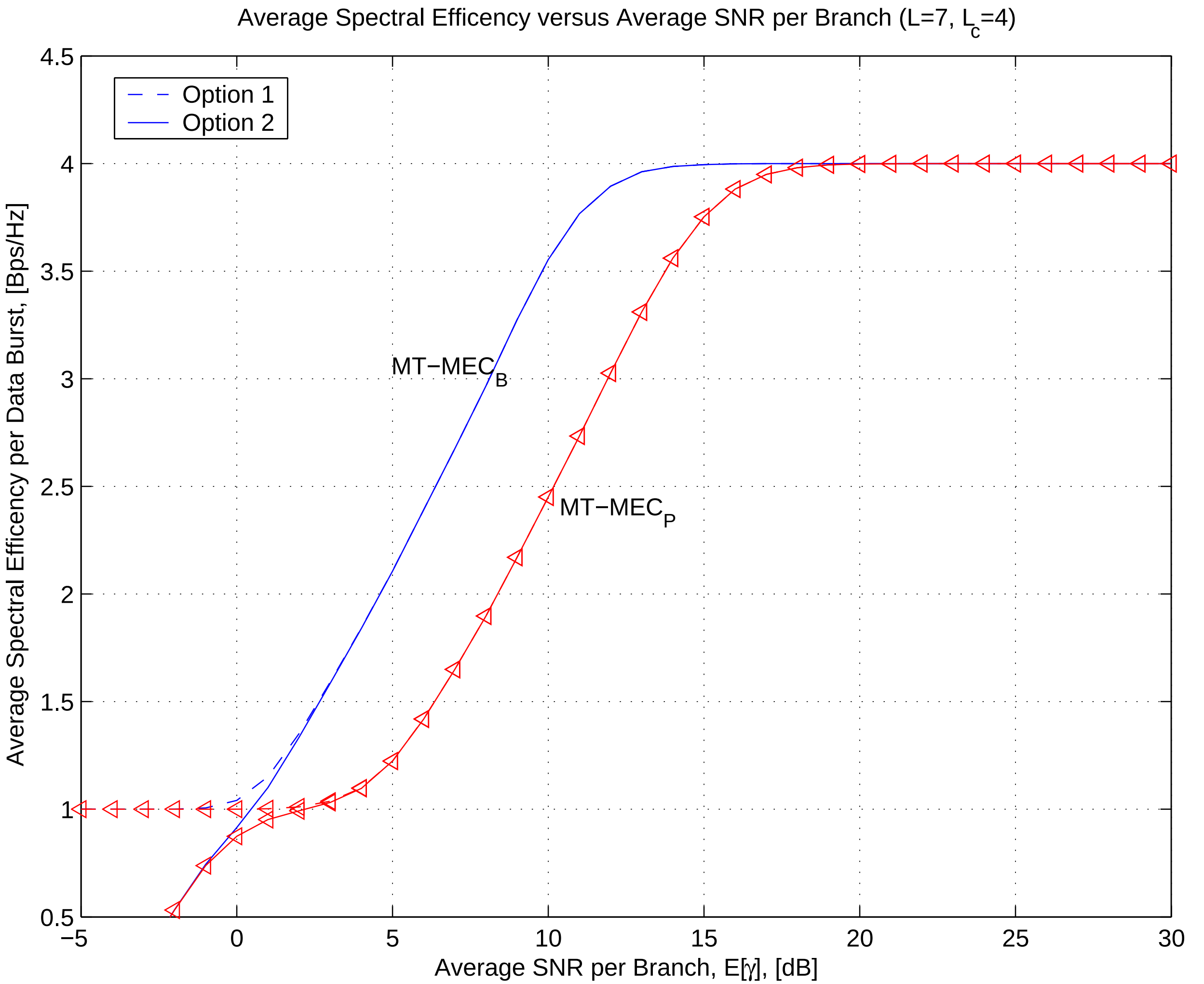
Adaptive Multiple Threshold MEC



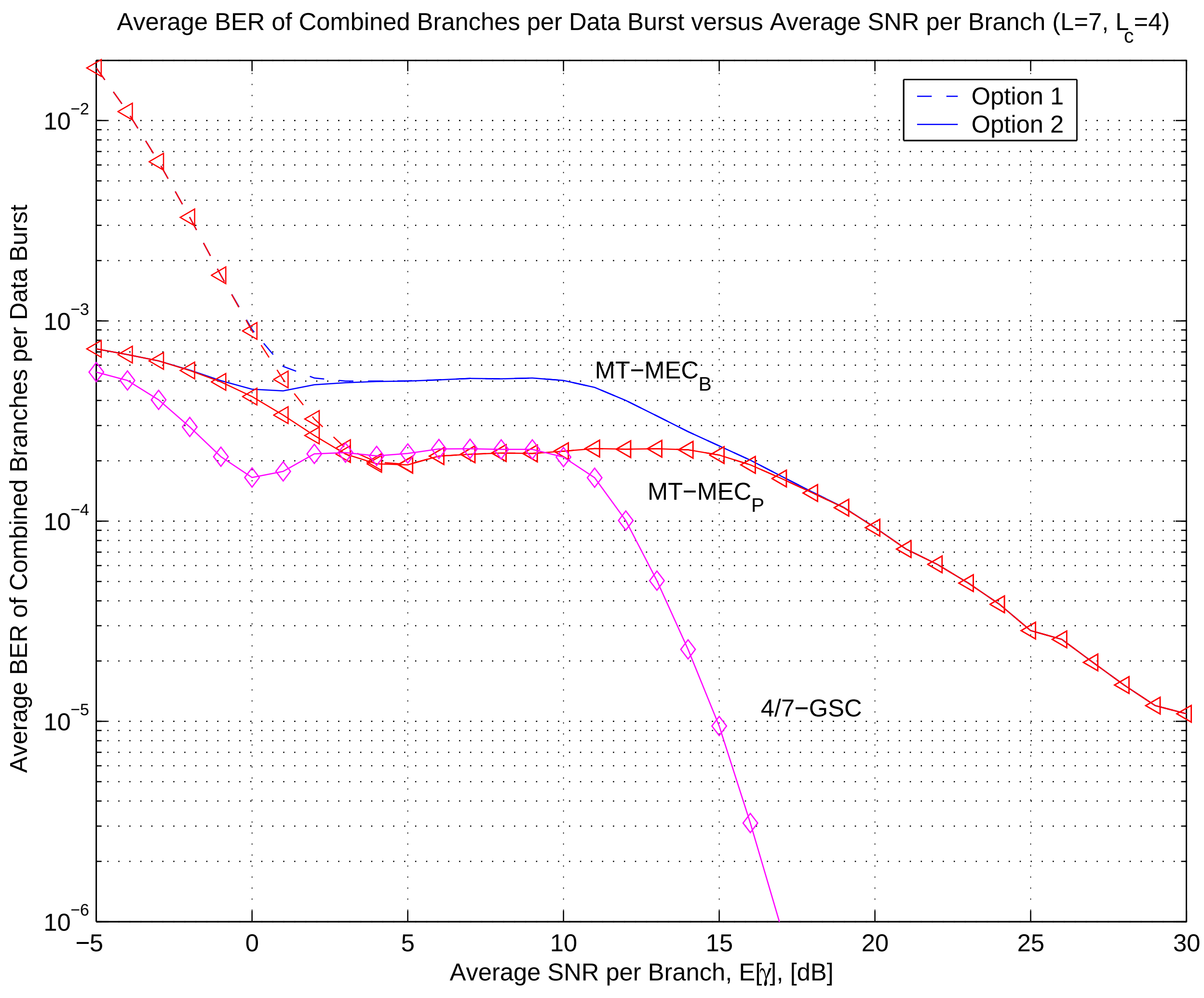
Average Number of Combined Branches



Average Spectral Efficiency



Average BER


Average BER of Combined Branches per Data Burst versus Average SNR per Branch (L=7, L_c=4)
Option 1
Option 2
MT−MEC_B
MT−MEC_P
4/7−GSC
Average BER of Combined Branches per Data Burst
Average SNR per Branch, E[γ], [dB]
10^−2
10^−3
10^−4
10^−5
10^−6
−5
0
5
10
15
20
25
30

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.