Switched Diversity Systems: Design, Performance, and Optimization

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Outline

- Background and Motivation
- Switching strategies
  - Markov chain-based analysis
  - Comparison of switching strategies
- Post-detection switched diversity
  - Mode of operation
  - Performance analysis
  - Comparison between pre-detection and post-detection
- Multi-branch switched diversity
  - Switch and examine versus switch and stay
  - Generalized switch and examine
- Concluding remarks and on-going efforts
Transmit Diversity

• Improve the performance of downlink.
• Limited resource at the mobile ⇒ Transmit diversity.
• Space-time transmit diversity.
• Time domain transmit diversity
  – Attractive for receiver simplicity.
  – Time switched transmit diversity ⇒ No feedback
  – Selection transmit diversity ⇒ Feedback
• Selection transmit diversity can outperform space-time diversity when both are used in conjunction with adaptive modulation [Kim et al., VTC-Spring’02].
Selection Diversity

• Ideal switch diversity
  – Always uses the best available antenna for transmission.
  – Simultaneously monitor all antenna branches.
  – Compare estimated random quantities.
  – Frequent branch switching.
Switched Diversity

- “Practical” implementation of selection diversity
- Low/cheap complexity solution for fading mitigation.
- Mode of operation
  - Use current antenna as long as it is acceptable.
  - Switch if signal quality falls below predetermined threshold.
  - Check branch quality by comparing with a fixed threshold.
  - Switch and stay combining (SSC) vs switch and examine combining (SEC).
- Complexity savings with respect to selection diversity
  - Only current antenna needs to be monitored.
  - Comparison with a fixed threshold.
  - Reduced frequency of branch switching.
Dual-Branch SSC

- Use current branch and switch when it becomes unacceptable.
- Stay on the switch-to branch regardless of its quality.
- Introduces switching transient into signal.
Discrete-Time Implementation

- Branch switching is only executed during guard periods.
- In each guard period, the receiver
  - Estimate the channel and perform comparison.
  - Reach switching decision based on comparison results.
  - Switch or not depending on the switching decision.
- Two important assumptions
  - Data signal experiences roughly the same fading as its preceding guard period.
  - Fading conditions during successive guard periods are nearly independent.
Previous Work on Switched Combining

- Jakes summarized early contributions on switched diversity.
- Blanco and Zdunek, [T-COM ’79] proposed and analyzed a first discrete-time switching strategy of SSC over i.i.d. Rayleigh fading.
- Blanco [SECON ’83] extended the analysis to i.i.d. Nakagami fading.
- Abu-Dayya and Beaulieu, [T-COM ’94,T-VT ’94] introduced a second switching strategy of SSC and analyzed its performance over i.i.d. and correlated Nakagami and Rician fading.
- Ko et. al., [T-VT ’00] and [Tellambura et. al., T-COM ’01], independently and simultaneously extended their analysis to more modulation formats and non i.i.d. fading cases.
Interesting Questions on Switch Diversity

• What is the difference between Abu-Dayya and Beaulieu (SSC-A) and Blanco and Zdunek (SSC-B) SSC strategies?
• How much performance improvement will post-detection switched diversity provide over its pre-detection counterpart?
• Can we generalize switched diversity to multiple branch scenario and benefit from it?
• What is effect of time delay, imperfect channel estimates, and interference on the performance of switch diversity?
• What is the average outage duration of switched diversity systems?
• How can we use switched diversity in MIMO systems?
• What is the performance of switched diversity when used in conjunction with variable-rate variable-power transmission schemes?
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System and Fading Models

- Assuming slow fading and perfect channel estimation

- PDF, CDF, and MGF of $s_i(n)$ are denoted by $p_i(\cdot)$, $P_i(\cdot)$, and $M_i(\cdot)$, respectively.

- Joint CDF of $s_1(n)$ and $s_2(n)$ is denoted by $P_{s_1,s_2}(\cdot, \cdot)$. 
Type 1 SSC: SSC-A

- Branch switches occur if and only if current channel estimate is less than the switching threshold.

- One channel estimate and one comparison per guard period.
Type 2 SSC: SSC-B

- Switching decision based on the channel estimates of the current branch in two consecutive guard periods.
- Switch is initiated whenever a downwards crossing of the preselected threshold occurs.

Depending on whether branch switch occurs or not, one or two channel estimates and comparisons in each guard period.
Type 3 SSC: SSC-C

• Simplified version of SSC-B.

• Switch is initiated whenever a downwards crossing of the preselected threshold occurs.

• No switch if no enough information ⇒ no consecutive switches.

• One channel estimate and one comparison per guard period.
SSC is Markovian

• Future branch switching depends only on the fading condition of currently used branch.

• All SSC strategies satisfy Markovian property if fading conditions during successive guard periods are independent.

• Some facts on Markov chains
  – Markovian property: given the present, the future does not depend on the past.
  – State space and transition probability matrix define a Markov chain.
  – For certain Markov chain, stationary probabilities exist and can always be obtained in terms of transition probabilities.
Markov Chains for SSC-A

• Two-state Markov chain [Tellambura et. al. TCOM-01].
  – State $i \Leftrightarrow$ Branch $i$ used during the guard period.
  – Transition probability matrix
    $$P^a = \begin{bmatrix} 1 - q_1 & q_1 \\ q_2 & 1 - q_2 \end{bmatrix}_{2 \times 2}.$$
    $$q_i = \Pr[s_i(n) < s_{T_i}] = P_i(s_{T_i}), \ i = 1, 2.$$

• Subdivide states according to comparison results
  $\Rightarrow$ Four-state Markov chain.
  – State space
    State 1 $\Leftrightarrow$ $s_1(n) < s_{T_1}$;  State 2 $\Leftrightarrow$ $s_1(n) \geq s_{T_1}$;
    State 3 $\Leftrightarrow$ $s_2(n) < s_{T_2}$;  State 4 $\Leftrightarrow$ $s_2(n) \geq s_{T_2}$.
  – Transition probability matrix $P^a_{4 \times 4}$. 
Transition Probability Matrix for SSC-A

\[ P^a = \begin{bmatrix} 0 & 0 & q_2 & 1 - q_2 \\ q_1 & 1 - q_1 & 0 & 0 \\ q_1 & 1 - q_1 & 0 & 0 \\ 0 & 0 & q_2 & 1 - q_2 \end{bmatrix} \]

\[ 4 \times 4 \]
Markov Chain for SSC-B

- Switching decision based on two comparison results
  \(\Rightarrow\) state definition using two comparison results.

- Six-state Markov chain
  
  - State space
    
    \[
    \begin{align*}
    \text{State 1} & \iff s_1(n - 1) \geq s_{T_1} \text{ and } s_1(n) < s_{T_1}; \\
    \text{State 2} & \iff s_1(n - 1) < s_{T_1}; \\
    \text{State 3} & \iff s_1(n - 1) \geq s_{T_1} \text{ and } s_1(n) \geq s_{T_1}; \\
    \text{State 4} & \iff s_2(n - 1) \geq s_{T_2} \text{ and } s_2(n) < s_{T_2}; \\
    \text{State 5} & \iff s_2(n - 1) < s_{T_2}; \\
    \text{State 6} & \iff s_2(n - 1) \geq s_{T_2} \text{ and } s_2(n) \geq s_{T_2}.
    \end{align*}
    \]

  - Transition probability matrix \(P_{6\times6}^b\)
Transition Probability Matrix for SSC-B

\[ P^b = \begin{bmatrix}
0 & 0 & 0 & (1 - \frac{q_{12}}{q_1})q_2 & \frac{q_{12}}{q_1} & (1 - \frac{q_{12}}{q_1})(1 - q_2) \\
(1 - q_1)q_1 & q_1 & (1 - q_1)^2 & 0 & 0 & 0 \\
q_1 & 0 & 1 - q_1 & 0 & 0 & 0 \\
(1 - \frac{q_{12}}{q_2})q_1 & \frac{q_{12}}{q_2} & (1 - \frac{q_{12}}{q_2})(1 - q_1) & 0 & 0 & 0 \\
0 & 0 & 0 & (1 - q_2)q_2 & q_2 & (1 - q_2)^2 \\
0 & 0 & 0 & q_2 & 0 & 1 - q_2 \\
\end{bmatrix} \]

where \( q_{12} = \Pr[s_1(n) < s_{T1} \text{ and } s_2(n) < s_{T2}] = P_{s_1,s_2}(s_{T1}, s_{T2}) = q_1q_2, \) if branches are independent.
Markov Chain for SSC-C

- Similar to that for SSC-B.
- Additional pair of states for no enough information case.
- Eight-state Markov chain
  - State space definition

  
  State 1 ⇔ \( s_1(n - 1) \geq s_{T1} \) and \( s_1(n) < s_{T1} \);
  State 2 ⇔ \( s_1(n - 1) < s_{T1} \);
  State 3 ⇔ \( s_1(n - 1) \geq s_{T1} \) and \( s_1(n) \geq s_{T1} \);
  State 4 ⇔ \( s_1(n - 1) \) unknown;
  State 5 ⇔ \( s_2(n - 1) \geq s_{T2} \) and \( s_2(n) < s_{T2} \);
  State 6 ⇔ \( s_2(n - 1) < s_{T2} \);
  State 7 ⇔ \( s_2(n - 1) \geq s_{T2} \) and \( s_2(n) \geq s_{T2} \);
  State 8 ⇔ \( s_2(n - 1) \) unknown.

  - Transition probability matrix \( P_{8 \times 8}^c \).
### Transition Probability Matrix for SSC-C

\[
P^c = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(1 - q_1)q_1 & q_1 & (1 - q_1)^2 & 0 & 0 & 0 & 0 & 0 \\
q_1 & 0 & 1 - q_1 & 0 & 0 & 0 & 0 & 0 \\
(1 - q_1)q_1 & q_1 & (1 - q_1)^2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & (1 - q_2)q_2 & q_2 & (1 - q_2)^2 & 0 \\
0 & 0 & 0 & 0 & q_2 & 0 & 1 - q_2 & 0 \\
0 & 0 & 0 & 0 & 0 & (1 - q_2)q_2 & q_2 & (1 - q_2)^2 & 0 \\
\end{bmatrix}_{8 \times 8}
\]
Statistical Description of Combiner Output

• CDF of the SSC combiner output $S(n)$

$$P_{ssc}(x) = \sum_{i=1}^{M} \pi_{i} P^{(i)}(x),$$

- $M$: Size of the state space.
- $\pi_{i}$: Stationary probability of the $i$th state.
- $P^{(i)}(\cdot)$: State-dependent CDF.

• PDF of $S(n)$

$$p_{ssc}(x) = \sum_{i=1}^{M} \pi_{i} p^{(i)}(x) = \sum_{i=1}^{M} \pi_{i} \frac{dP^{(i)}(x)}{dx}.$$  

• MGF of $S(n)$

$$M_{ssc}(t) = \sum_{i=1}^{M} \pi_{i} M^{(i)}(t) = \sum_{i=1}^{M} \pi_{i} \int_{0}^{\infty} p^{(i)}(x)e^{xt} dx.$$
Stationary Probabilities

- Solution of the system of linear equations

\[
\begin{align*}
\vec{\pi} P &= \vec{\pi}; \\
\sum_{i=1}^{M} \pi_i &= 1,
\end{align*}
\]

- \(P\): transition probability matrix.
- \(\vec{\pi}\) = \([\pi_1, \pi_2, \cdots, \pi_M]\).

- Can be solved in closed-form
  - For SSC-C

\[
\vec{\pi}^c = \left[ \frac{(1 - q_1)q_1(1 - q_2)q_2}{(1 - q_1)q_1 + (1 - q_2)q_2}, \frac{q_1^2(1 - q_2)q_2}{(1 - q_1)q_1 + (1 - q_2)q_2}, \frac{(1 - q_1)^2(1 - q_2)q_2}{(1 - q_1)q_1 + (1 - q_2)q_2}, \frac{(1 - q_1)q_1q_2^2}{(1 - q_1)q_1 + (1 - q_2)q_2} \right].
\]
State-Dependent CDF

• Take three general simple forms
  – For State 1 of SSC-A, SSC-B and SSC-C
    \[
    P^{(1)}(x) = \begin{cases} 
    \frac{P_{1,2}(sT_1,x)}{P_1(sT_1)}, & \text{in general;} \\
    P_2(x), & \text{if branches are independent.}
    \end{cases}
    \]
  – For State 2 of SSC-B and State 2 and 4 of SSC-C
    \[
    P^{(2)}(x) = P_1(x).
    \]
  – For State 3 of SSC-B and SSC-C and State 2 of SSC-A
    \[
    P^{(3)}(x) = \begin{cases} 
    \frac{P_1(x)-P_1(sT_1)}{1-P_1(sT_1)}, & x \geq sT_1; \\
    0, & x < sT_1.
    \end{cases}
    \]

Unify and add to previous analysis on SSC-A, SSC-B and newly proposed SSC-C.
CDF of SSC-A

- Assuming $sT_1 < sT_2$

\[
P^a_{ssc}(x) = \sum_{i=1}^{4} \pi^a_i P^{(i)}(x)
\]

\[
= \begin{cases} 
A, & x < sT_2; \\
A + \frac{(1-q_2)q_1 P_2(x)-q_2}{q_1+q_2} \frac{1-q_2}{1-q_1}, & sT_2 \leq x < sT_1; \\
A + \frac{(1-q_1)q_2 P_1(x)-q_1}{q_1+q_2} + \frac{(1-q_2)q_1 P_2(x)-q_2}{q_1+q_2} \frac{1-q_2}{1-q_1}, & sT_1 \leq x,
\end{cases}
\]

where

\[
A = \frac{q_1 q_2}{q_1 + q_2} \left( \frac{P_{s_1,s_2}(sT_1, x)}{q_1} + \frac{P_{s_1,s_2}(x, sT_2)}{q_2} \right).
\]

- $sT_1 = sT_2 \Rightarrow$ Eq. 4 of Tellambura et. al. [T-COM ’01].

- $sT_1 = sT_2$ and $q_1 = q_2 \Rightarrow$ Eq. 6 of Abu-Dayya and Beaulieu [T-COM’94].

- $sT_1 = sT_2$ and independent branches

$\Rightarrow$ Eq. 62 of Ko et. al. [T-VT’00].
Outage Probability Comparison

SSC-A gives the smallest outage probability!
Error Probability Analysis

- Average BER

\[ P_b(E) = \sum_{i=1}^{M} \pi_i \, P_b^{(i)}(E). \]

- Average BER of BPSK with SSC-A

\[
P_b^a(E) = \frac{\pi_1^a}{2} \left(1 - \sqrt{\frac{\bar{\gamma}_2}{1 + \bar{\gamma}_2}}\right) + \frac{\pi_3^a}{2} \left(1 - \sqrt{\frac{\bar{\gamma}_1}{1 + \bar{\gamma}_1}}\right) \\
+ \frac{\pi_2^a}{1 - q_1} \left[ \exp \left(-\frac{\gamma T_1}{\bar{\gamma}_1}\right) Q(\sqrt{2\gamma T_1}) - \sqrt{\frac{\bar{\gamma}_1}{1 + \bar{\gamma}_1}} Q\left(\frac{2\gamma T_1 (1 + \bar{\gamma}_1)}{\bar{\gamma}_1}\right) \right] \\
+ \frac{\pi_4^a}{1 - q_2} \left[ \exp \left(-\frac{\gamma T_2}{\bar{\gamma}_2}\right) Q(\sqrt{2\gamma T_2}) - \sqrt{\frac{\bar{\gamma}_2}{1 + \bar{\gamma}_2}} Q\left(\frac{2\gamma T_2 (1 + \bar{\gamma}_2)}{\bar{\gamma}_2}\right) \right].
\]

where \( Q(\cdot) \) is the Gaussian \( Q \)-function.
Error Probability Comparison

Optimal switching thresholds exist!
Error Probability Comparison with Optimal Switching Thresholds

SSC-A offers the best performance!
Switching Rate Analysis

- Power consumption due to switching.

- Switching probabilities
  - For SSC-A
    \[ P_s^a = \pi_1^a + \pi_3^a = \frac{2q_1q_2}{q_1 + q_2}. \]
  - For SSC-B
    \[ P_s^b = \pi_1^b + \pi_4^b = \frac{2q_1(1 - q_1)q_2(1 - q_2)}{(q_1 + q_2)(1 + q_1q_2 + q_1q_2) - (q_1 + q_2)^2 - 2q_1q_2q_1q_2}. \]
  - For SSC-C
    \[ P_s^c = \pi_1^c + \pi_5^c = \frac{2q_1(1 - q_1)q_2(1 - q_2)}{q_1(1 - q_1) + q_2(1 - q_2)}. \]

- Switching probability for SC over independent branches
  \[ P_s^{sc} = \frac{2\Omega_1\Omega_2}{(\Omega_1 + \Omega_2)^2} \] for Rayleigh.
Switching Rate Comparison

SSC-C offers the lowest switching rate!
Summary of Results

• A unified Markov chain-based analytical framework for the performance analysis of various SSC strategies.

• Applicable to dual-branch switched diversity systems over a variety of fading scenarios.

• Tradeoff between switching rate and performance
  – SSC-A offers the best performance but exhibits the highest switching rate.
  – SSC-C has lower switching rate at the expense of certain performance loss.
  – SSC-B falls between SSC-A and SSC-C from both perspectives.
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Post-Detection Selection Combining

• For SC two basic types have been considered:
  – Pre-detection SC [e.g. Stuber textbook]
  – Post-detection SC [Montgomery, Proc. IRE’54], [Chyi and Proakis, T-COM’89], and [Neasmith and Beaulieu, T-COM’98].

• Post-detection SC
  – Does not require monitoring of the instantaneous SNR
  – Provides a performance gain over pre-detection SC.

• Only pre-detection SSC has thus far been considered [Blanco and Zdunek, T-COM ’79], [Abu-Dayya and Beaulieu, T-COM’94], [Ko et al., T-VT’00], [Tellambura et al., T-COM’01].

• Goal: Investigate the performance of post-detection SSC.
System and Channel Models

- Noncoherent binary frequency shift keying (BFSK) over a slowly-varying flat fading channel.
- Dual-branch switched diversity receiver.
- \( \{\alpha_l\}_{l=1}^2 \) denote the random channel amplitudes for antenna 1 and 2.
- \( \alpha_1 \) and \( \alpha_2 \) are independent.
- Average fading powers \( \Omega_l = \alpha_l^2 \) \( (l = 1, 2) \) are not necessarily equal.
Figure 1: Block diagram of noncoherent BFSK with post-detection SSC.
Switching Strategy and Mechanism

• Switching is based on the magnitude of the decision variables $W_1$ or $W_2$.

• Let $W(n)$ denote the sequence variables from which decisions on the data are being made. Then

$$W(n) = W_1(n) \text{ if } \begin{cases} W(n - 1) = W_1(n - 1) \text{ and } |W_1(n)| \geq w_{T_1} \\ W(n - 1) = W_2(n - 1) \text{ and } |W_2(n)| < w_{T_2}, \end{cases}$$

and

$$W(n) = W_2(n) \text{ if } \begin{cases} W(n - 1) = W_2(n - 1) \text{ and } |W_2(n)| \geq w_{T_2} \\ W(n - 1) = W_1(n - 1) \text{ and } |W_1(n)| < w_{T_1}. \end{cases}$$
Switching Threshold

• Setting of the predetermined switching threshold is an additional important system design issue for SSC schemes.

• Switching threshold should be high enough to prevent the antenna switching unit from almost being locked to one of the diversity branches.

• Switching threshold should also be low enough to avoid the continuous switching between antennas.

• Analysis will show that there is an optimal threshold (in the minimum average BER sense).

• These optimal thresholds \( w_{T_1}^* \) and \( w_{T_2}^* \) depend on the average fading power \( \Omega_1 \) and \( \Omega_2 \).
Average BER Analysis

- For antenna 1 (assuming +1 transmitted) an erroneous decision occurs
  - If the magnitude of $W_1$ exceeds the threshold $w_{T_1}$ but $W_1 < 0$
  - If the magnitude of $W_1$ falls below the threshold $w_{T_1}$ but $W_2 < 0$.

- Under the equiprobable bits and independent fading assumptions

$$P_b(E) = p_1 \left[ F_{W_1}(-w_{T_1}) + \left( F_{W_1}(w_{T_1}) - F_{W_1}(-w_{T_1}) \right) F_{W_2}(0) \right]$$
$$+ p_2 \left[ F_{W_2}(-w_{T_2}) + \left( F_{W_2}(w_{T_2}) - F_{W_2}(-w_{T_2}) \right) F_{W_1}(0) \right].$$

where $F_{W_1}(\cdot)$ and $F_{W_2}(\cdot)$ are the cumulative distribution functions (CDFs) of the decision variables $W_1$ and $W_2$ and $p_1$ and $p_2$ are the probability that antenna 1 and 2 are connected, respectively.
Identically and Nonidentically Distributed Branches

- Identically distributed branches:
  
  $- F_{W_1} (\cdot) = F_{W_2} (\cdot) \triangleq F_W (\cdot)$.
  
  $- w_{T_1} = w_{T_2} \triangleq w_T$.
  
  $- p_1 = p_2 = 1/2$.
  
  As a result, the average BER reduces in this case to:
  
  $P_b (E) = F_W (- w_T) + [F_W (w_T) - F_W (- w_T)] \cdot F_W (0)$.

- Non identically distributed branches:

  \[
  p_1 = \frac{F_{W_2} (w_{T_2}) - F_{W_2} (- w_{T_2})}{F_{W_1} (w_{T_1}) + F_{W_2} (w_{T_2}) - F_{W_1} (- w_{T_1}) - F_{W_2} (- w_{T_2})} \]

  \[
  p_2 = \frac{F_{W_1} (w_{T_1}) - F_{W_1} (- w_{T_1})}{F_{W_1} (w_{T_1}) + F_{W_2} (w_{T_2}) - F_{W_1} (- w_{T_1}) - F_{W_2} (- w_{T_2})}.
  \]
Average BER in Rayleigh Fading

• For the special i.i.d. Rayleigh branches cases with $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}$ and $w_{T_1} = w_{T_2} = w_T$, we obtain:

$$P_b(E) = \frac{1}{2 + \bar{\gamma}} \left[ 1 + \frac{1 + \bar{\gamma}}{2 + \bar{\gamma}} \left[ \exp \left( -\frac{\eta_T \bar{\gamma}}{4} \right) - \exp \left( -\frac{\eta_T \bar{\gamma}}{4(1 + \bar{\gamma})} \right) \right] \right],$$

where $\eta_T = w_T / (\Omega E_b^2)$ is the normalized switching threshold.

• Optimal threshold given by

$$\eta_T^* = \frac{4(1 + \bar{\gamma})}{\bar{\gamma}^2} \ln(1 + \bar{\gamma}),$$

• Resulting minimum average BER

$$P_b^*(E) = \frac{1}{2 + \bar{\gamma}} \left[ 1 - \frac{\bar{\gamma}}{2 + \bar{\gamma}}(1 + \bar{\gamma})^{-1/\bar{\gamma}} \right].$$
Figure 2: Average BER of noncoherent BFSK with post-detection SSC versus normalized switching threshold over i.i.d. Rayleigh channels.
Comparison with No Diversity Case

- BER of a single-branch (no diversity) noncoherent BFSK receiver is given by
  \[ P_b^-(E) = \frac{1}{2 + \bar{\gamma}}. \]

- Let
  \[ f(x) = (1 + x)^{-1/x}. \]

- \( f(x) \) is bounded between \( e^{-1} \approx 0.36 \) and 1.

- Hence:
  \[ \frac{P_b^*(E)}{P_b^-(E)} \Delta g(\bar{\gamma}) = 1 - \frac{\bar{\gamma}}{2 + \bar{\gamma}} f(\bar{\gamma}) \leq 1. \]
Comparison with Pre-Detection SSC

- Average BER of noncoherent BFSK over i.i.d. Rayleigh paths is given by [Abu-Dayya and Beaulieu, T-COM’94]

\[ P_b(E) = \frac{1}{2 + \bar{\gamma}} \left[ 1 - \exp \left( -\frac{\gamma_T}{\bar{\gamma}} \right) + \exp \left( -\gamma_T \left( \frac{1}{2} + \frac{1}{\bar{\gamma}} \right) \right) \right], \]

where \( \gamma_T \) is the SNR switching threshold.

- Optimal SNR switching threshold \( \gamma_T^+ \)

\[ \gamma_T^+ = 2 \ln \left( 1 + \frac{\bar{\gamma}}{2} \right). \]

- Resulting minimum average BER

\[ P_b^+(E) = \frac{1}{2 + \bar{\gamma}} \left[ 1 - \frac{\bar{\gamma}}{2 + \bar{\gamma}} f \left( \frac{\bar{\gamma}}{2} \right) \right]. \]

- Hence \( P_b(E)^* \leq P_b(E)^+ \).
Figure 3: Comparison of the average BER of noncoherent BFSK with no diversity and with pre-detection and post-detection SSC.
Unbalanced Rayleigh Paths

Figure 4: Average BER of noncoherent BFSK versus the normalized thresholds over unbalanced Rayleigh channels $\tilde{\gamma}_1 = 5$ dB and $\tilde{\gamma}_2 = 10$ dB.
Global vs. Individual Optimization

Figure 5: Comparison of the average BER of noncoherent BFSK over unbalanced Rayleigh channels with global and individual optimization.
Summary and Related Work

• Results extended to generalized Nakagami and Rician fading environments.

• The optimal switching threshold is a decreasing function of both the average SNR and the amount/severity of fading.

• Average BER gain over pre-detection SSC increases as the channel condition improves in terms of average SNR and/or severity of fading.

• Analysis extended to noncoherent MFSK and is readily extendible to other binary modulations and/or type of detection (such as coherent, differentially coherent, or non-coherent with envelope detection).
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  – Generalized switch and examine

• Concluding remarks and on-going efforts
Multi-Branch Switched Diversity

- L-branch SSC:
  - Cyclically switch between $L$ antenna.
  - Use current antenna and switch if it becomes unacceptable.
  - Stay on the switch-to antenna regardless of its quality.

- L-branch SEC:
  - Use current antenna and switch only when it becomes unacceptable.
  - Unlike SSC scheme, the combiner examines the channel for the switch-to antenna and switches again if unacceptable.
  - The combiner will repeat this process until either an acceptable antenna is found or no antenna is left to be examined.

- SSC does not while SEC benefits from more than two antennas.
Error Performance with SEC

SEC benefits from additional branches!
Summary

• Switched diversity offers a low complexity solution for fading mitigation.
  – Applicable to both transmitter and receiver.
  – Implementable in both pre- and post- detection fashion.
  – Abu-Dayya and Beaulieu switching strategy provides the best BER performance and (if switching threshold appropriately chosen) to acceptable switching rate.
  – $L$-branch SSC = 2-branch SSC if branches are equi-correlated and identically distributed.
  – Otherwise, it is better to use the best two branches for SSC i.e. least correlated and/or least faded in average.
  – Switch and examine combining benefits always from multi-branch diversity.
Conclusion and On-Going Efforts

- Markov chains can be used for the exact performance analysis of switched diversity systems.
  - Applicable to different switching strategies with appropriate chain definition.
  - Lead to closed-form results for very general fading scenarios.
- On going efforts are focused on diversity rich environments
  - Generalized selection combining (GSC) or hybrid SC/MRC
  - Generalized switch and examine combining (GSEC) [ICC’02]
  - Towards switched-based MIMO systems with adaptive modulation.
Related Publications (1)


Related Publications (2)


