# Spatial Modulation for Multiple-Antenna Wireless Systems: A Survey

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# Outline

- Introduction
- Working Principle of Spatial Modulation
- Advantages & Disadvantages
- Research Issues
- Conclusion

# Introduction

- Multiple-antenna techniques trade-off superior error performance and higher data rates for increased system complexity and cost.
- The major drawback of any MIMO scheme (i.e., an increase in complexity and cost) is primarily due to three main reasons:
  1) Inter-Channel Interference (ICI)
  2) Inter-Antenna Synchronization (IAS)
  3) Multiple Radio Frequency (RF) chains
- Several transceiver designs require a number of receive-antenna greater than the number of transmit-antenna.
  - Practical limitation due to economical reasons on mobile handsets

# Introduction

- Spatial Modulation (SM) can offer
  - ✓ improved data rates with a very low system complexity (Compared to SISO systems)
  - ✓ robust error performance even in correlated channel environments

- SM exploits the uniqueness and randomness properties of the wireless channel for communication by adopting a simple but effective coding mechanism.

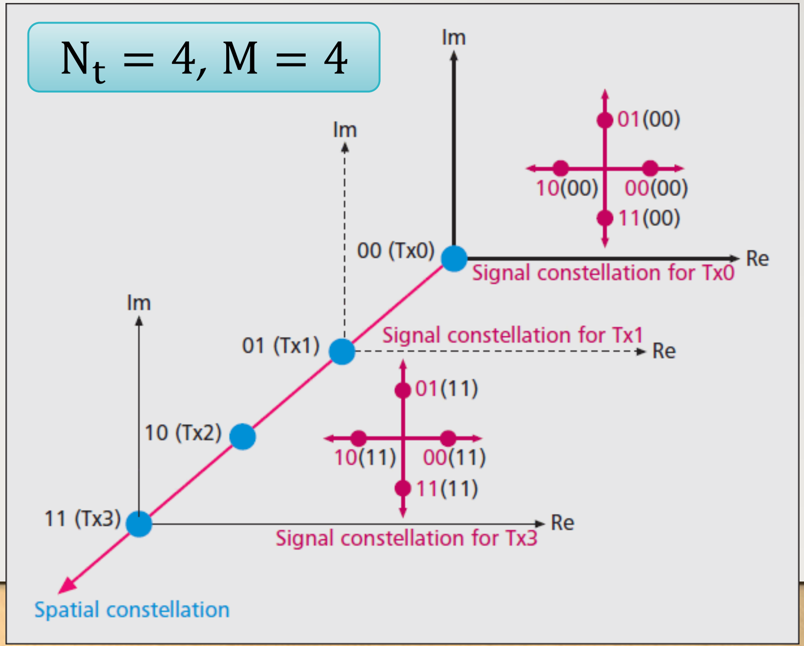
# Spatial Modulation: Features

1. Just one transmit-antenna is activated for data transmission at any signaling time instance.
   - SM entirely avoids ICI and IAS, and only requires a single RF chain at the transmitter.
   - This allows SM to exploit a low-complexity single-stream receiver design for optimal Maximum-Likelihood (ML) decoding.
2. The spatial position of each transmit-antenna in the antenna-array is used as a source of information.
   - This is obtained by establishing a one-to-one mapping between blocks of information bits to be transmitted and the spatial positions of the transmit-antenna in the antenna-array
     - transmit-antenna index coded modulation

# The Basic Idea of Spatial Modulation

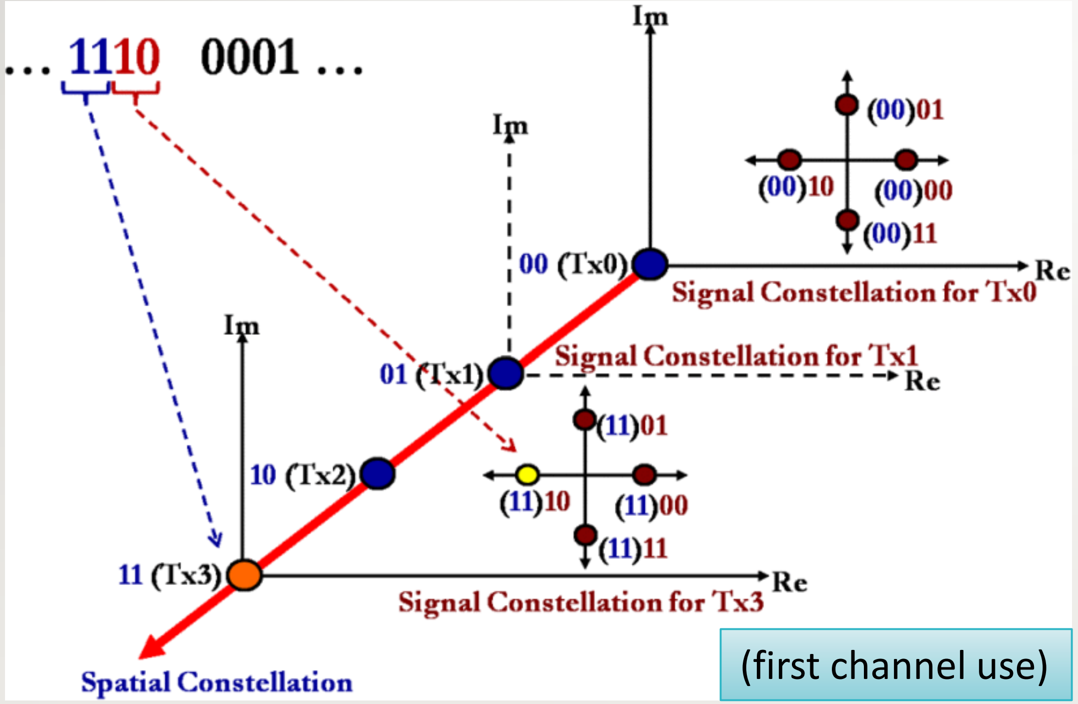
- Map a block of information bits into two information carrying units:
  - ✓ A symbol that is chosen from a complex signal-constellation diagram.
  - ✓ A unique transmit-antenna index that is chosen from the set of transmit-antenna in the antenna-array (i.e., spatial constellation-diagram).

- Each block contains $\log_2(N_t) + \log_2(M)$ bits.
  - $N_t$ (the number of transmit-antenna)
  - $M$ (the size of the complex signal-constellation diagram)




**Tridimensional** constellation diagram of SM

# The Basic Idea of Spatial Modulation



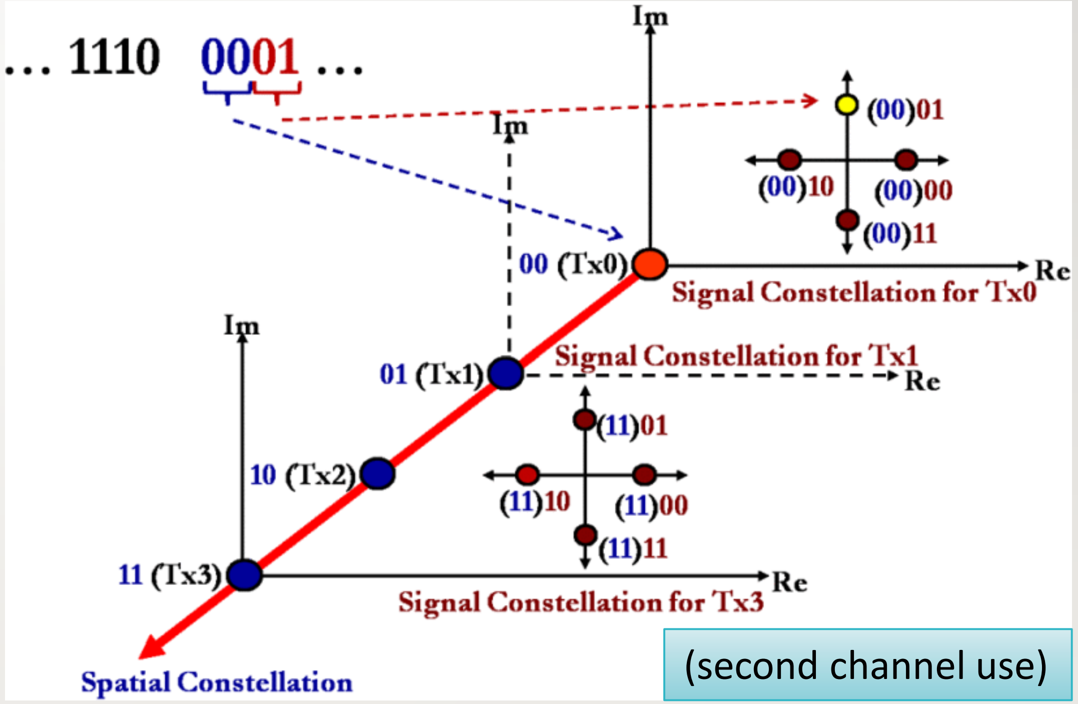
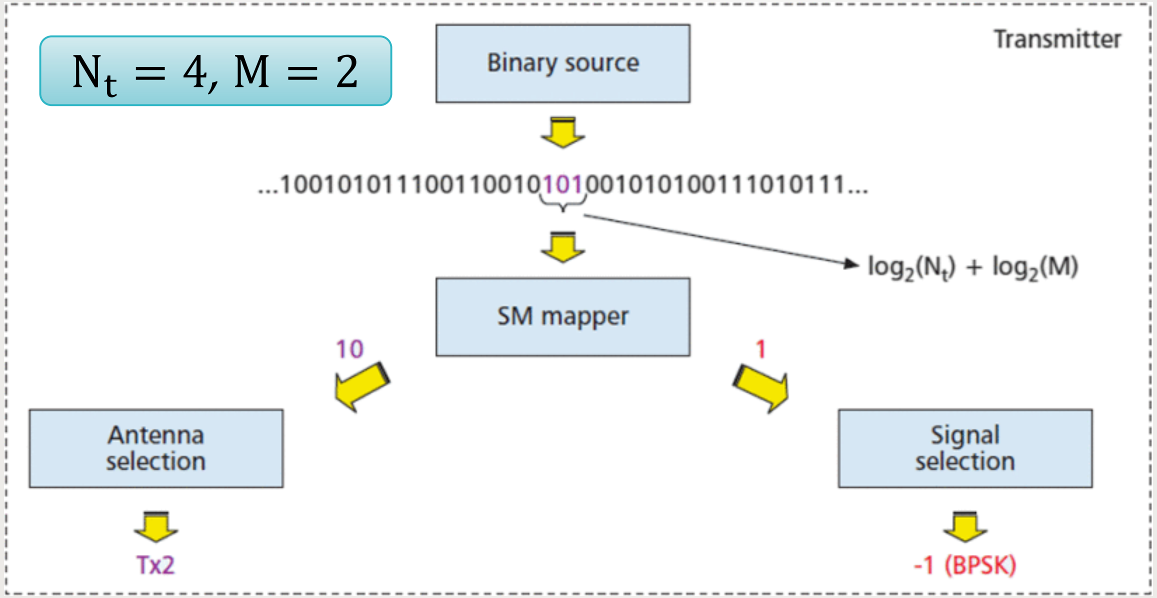




Illustration of the 3-D constellation diagram of SM (Cited from [1])

[1] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura and L. Hanzo, "Spatial Modulation for Generalized MIMO: Challenges, Opportunities, and Implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

# Spatial Modulation: How It Works

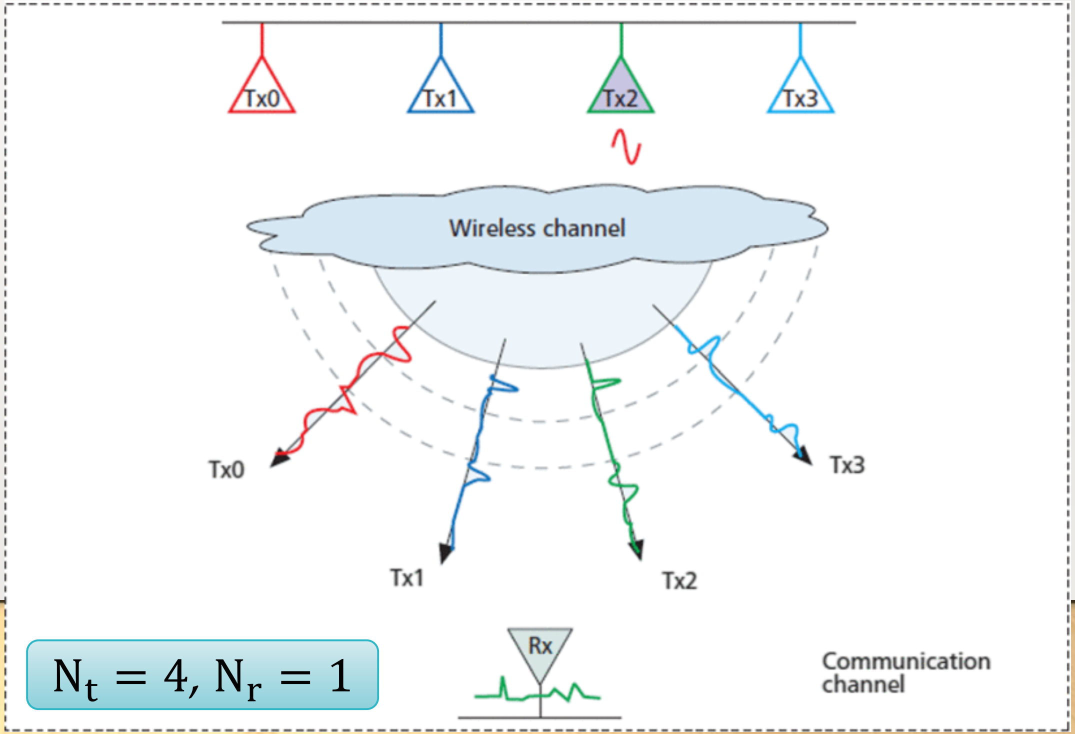



- Space Shift Keying (SSK) modulation
  - The information carrying unit is only the transmit-antenna index (i.e., M = 1).
  - Each transmit-antenna, when switched on, will send exactly the same signal out.

# Spatial Modulation: How It Works

- The wireless channel plays the role of a "modulation unit."
  - ➢ The signal transmitted by each antenna will experience distinct propagation conditions.

    (Different interacting environmental objects along any transmit-to-receive wireless link)

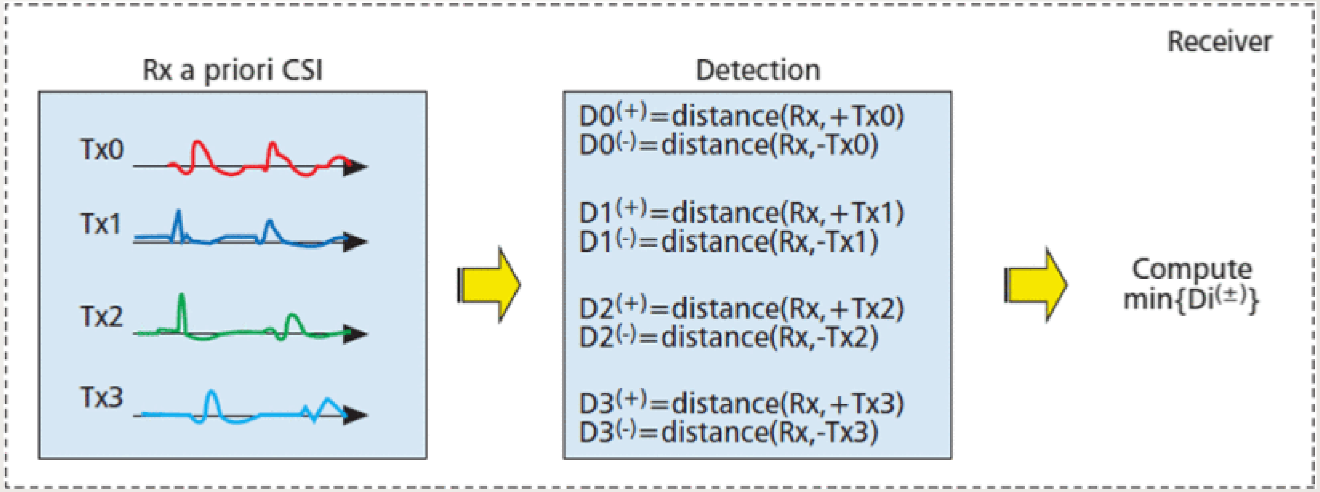



$N_t = 4, N_r = 1$

- $N_r$ (the number of receive-antenna)

# Spatial Modulation: How It Works

- The receiver must know a priori (in practice this is obtained via channel estimation) the channel impulse response of all the transmit-to-receive wireless links.
  - ➢ ML detector with perfect Channel State Information (CSI)




- Rx (the received signal)
- distance(x, y) = Euclidean distance between signals x and y

# Spatial Modulation: How It Works

- In summary, the working principle of SM is based on the following facts:
  - ✓ The wireless environment *naturally* modulates the transmitted signal.
  - ✓ Each transmit-to-receive wireless link has a *different* channel.
  - ✓ The receiver employs the *a priori* channel knowledge to detect the transmitted signal.

- SM exploits the location-specific property of the wireless channel (i.e., the uniqueness of each transmit-to-receive wireless link) for communication.

# Advantages

- The 3-D constellation diagram of SM increases the spectral efficiency by a factor of $\log_2(N_t)$ without any bandwidth expansion.
- The receiver design is inherently simpler than conventional MIMO schemes.
  - SM can attain ML decoding via a simple single-stream receiver.
- SM can efficiently work if $N_t < N_r$
  - SM is suitable for downlink settings with low-complexity mobile units.

# Advantages

ABEP (Average Bit Error Probability)

$E_m$ (the energy radiated by each transmit-antenna)

$N_0$ (the noise power at the receiver input)

- SM is inherently able to work in multiple-access scenarios:
  - Different pairs of transmitters and receivers usually occupy different spatial positions.
- SSK modulation can reduce the receiver complexity.
  - ➢ A loss in the achievable data rate

Multi-user Setup:

① 2 transmitters and 1 receiver

② Each transmitter has $N_t = 2$ and the receiver has $N_r = 1$

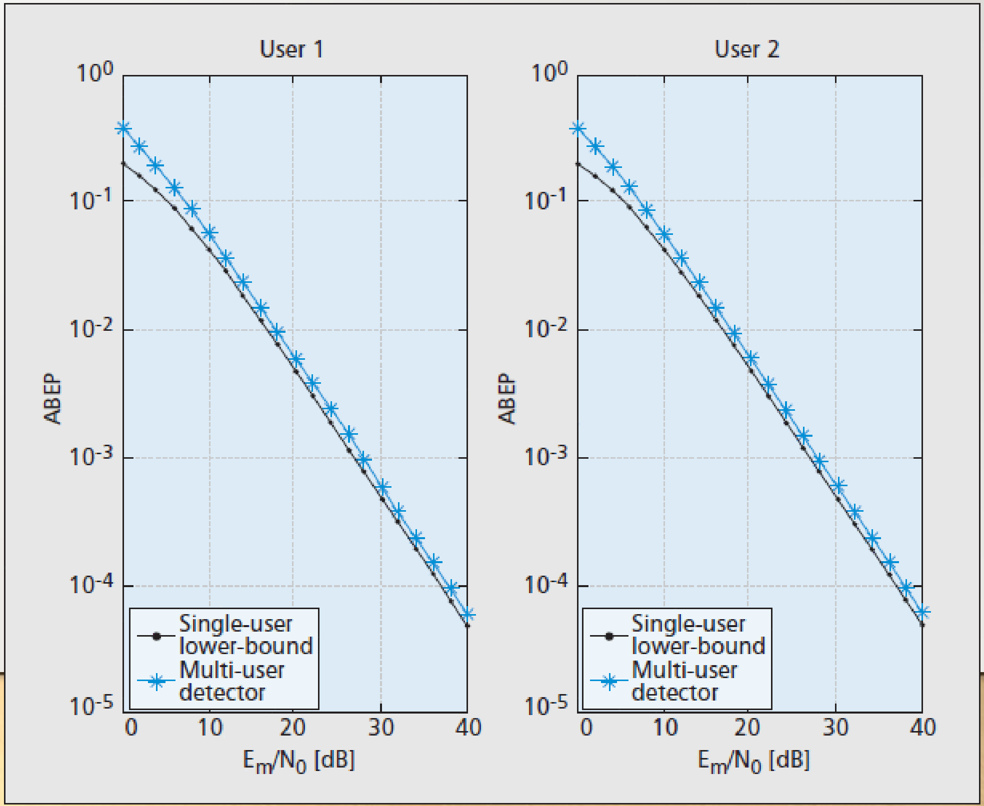
The channel of both users:

➢ uncorrelated and identically distributed Nakagami-*m* fading

① $m_1 = m_2 = 1$ (fading parameter)

② $\Omega_1 = \Omega_2 = 1$ (average power gain)

$$f(x; m, \Omega) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{m}{\Omega}x^2\right)$$



# Disadvantages

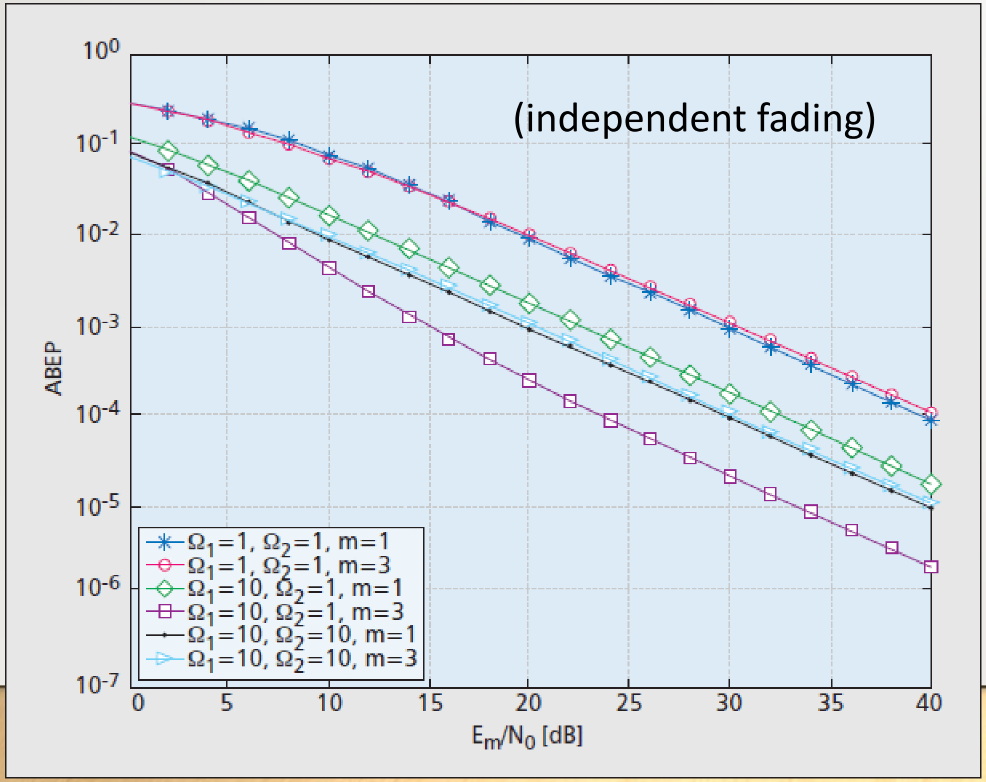
1. At least two transmit-antenna are required to exploit the SM concept.
2. If the transmit-to-receive wireless links are not sufficiently different, the SM paradigm might not be used or might not yield adequate performance.
3. The receiver requires perfect channel knowledge for data detection.
   - Pose complexity constraints on the channel estimation unit
4. When compared to conventional MIMO solutions, SM can offer only a logarithmic (instead of linear) increase of the data rate with the number of transmit-antenna.

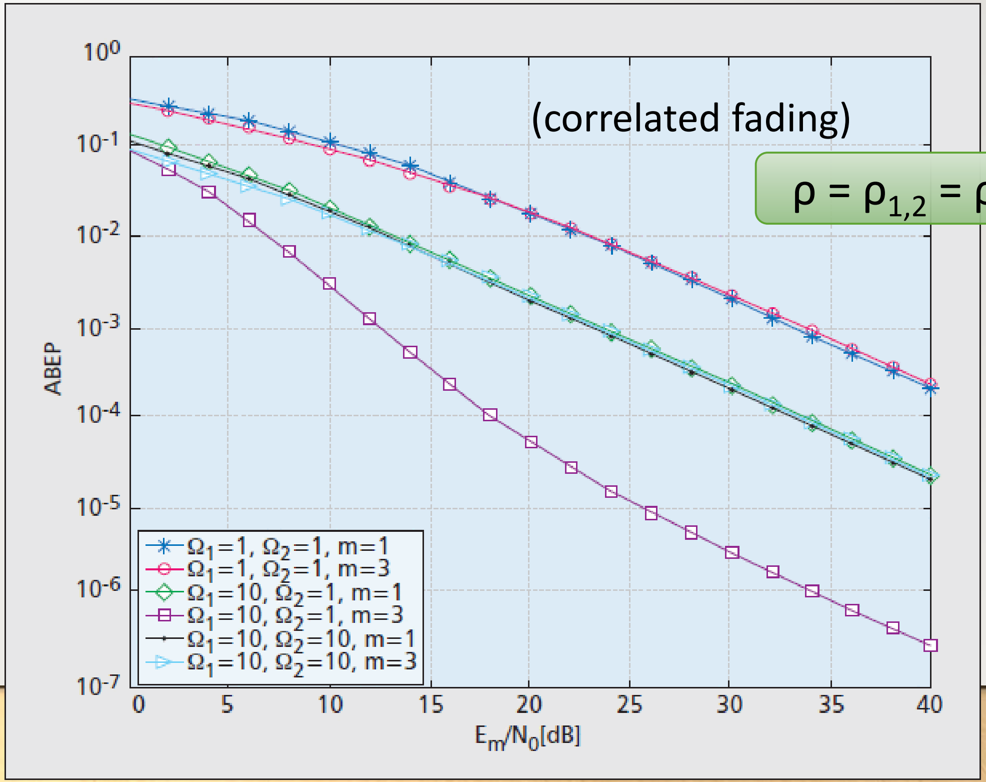
# Development of Flexible SM Schemes

- SM requires that the number of transmit-antennas is a power of two.
  - Only 2, 4, 8, 16, etc. antennas at the transmitter
  - Practical limits on the bit rates achievable by small-size portable devices
- Design of a flexible SM schemes for an arbitrary number of transmit-antennas
  - Trade-off achievable performance and rates for system complexity and cost

# Importance of the Wireless Channel

- The performance of SM is significantly affected by different fading conditions.
- SM offers better ABEP in the presence of power imbalance between the wireless links.



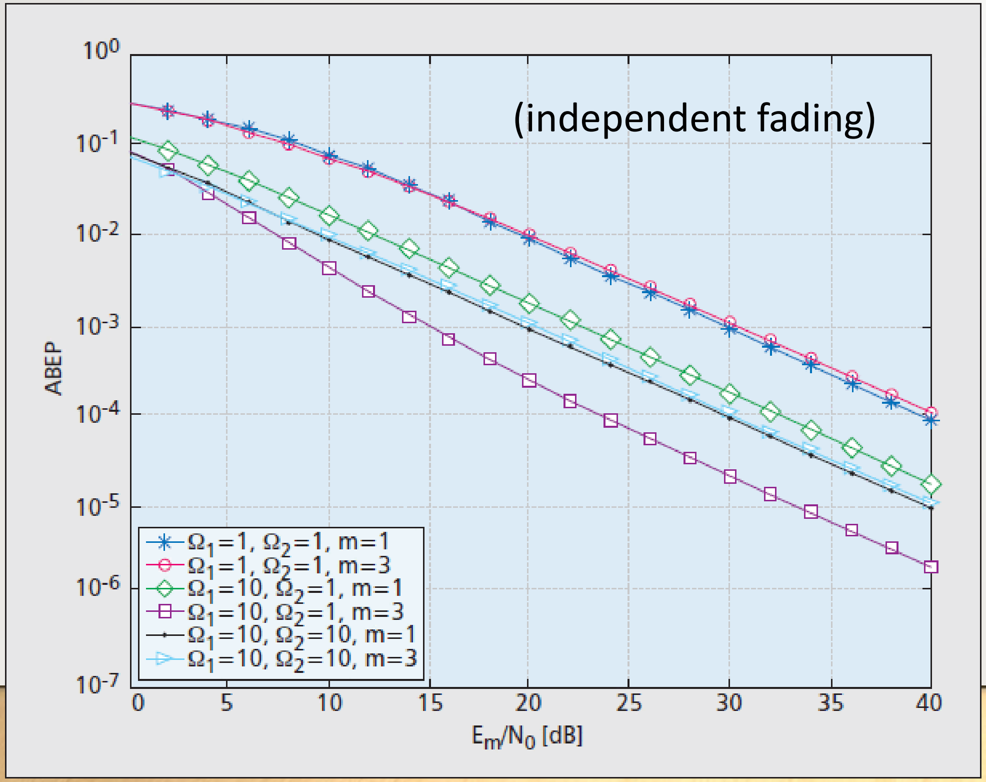



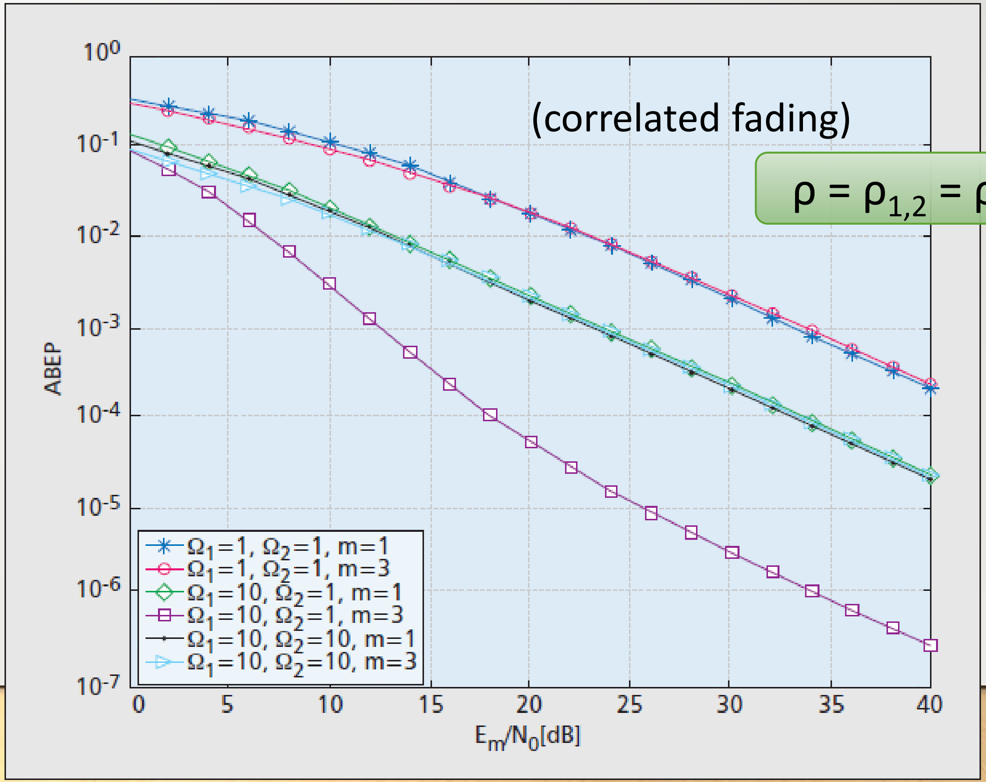

$\rho = \rho_{1,2} = \rho_{2,1} = 0.75$

$N_t = 2$
$N_r = 1$
$m = m_1 = m_2$

# Importance of the Wireless Channel

- Different values of the fading parameter m can yield a different ABEP in the presence of power imbalance (i.e., the channel power gains $\Omega_1$, $\Omega_2$ are different).




$\rho = \rho_{1,2} = \rho_{2,1} = 0.75$

$N_t = 2$
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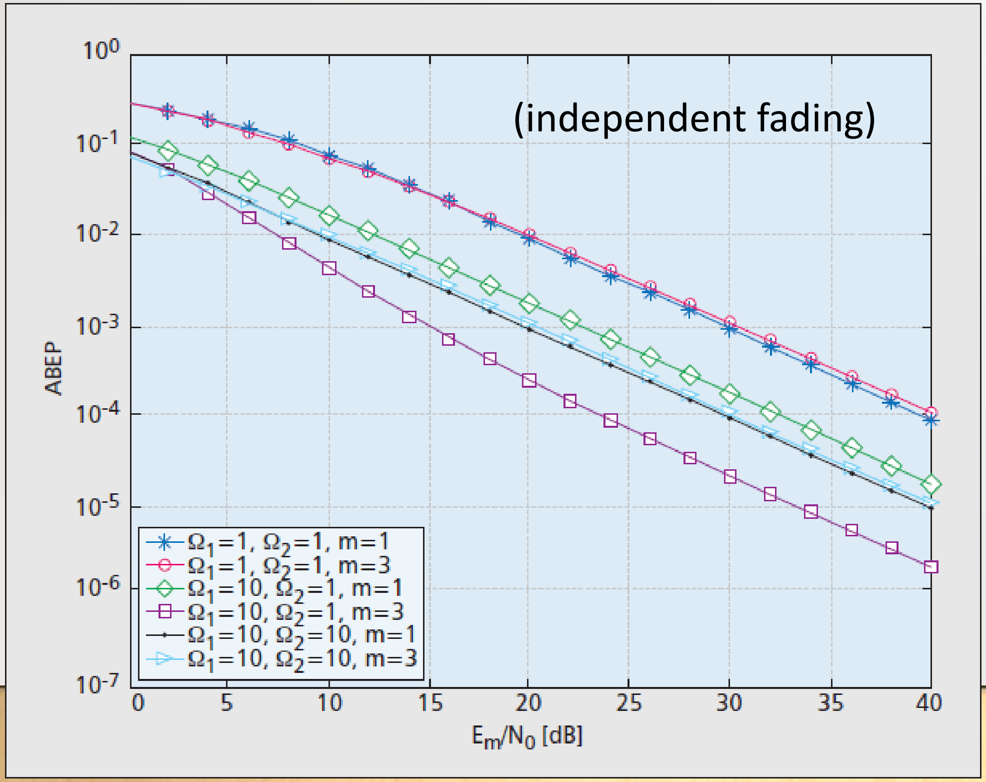
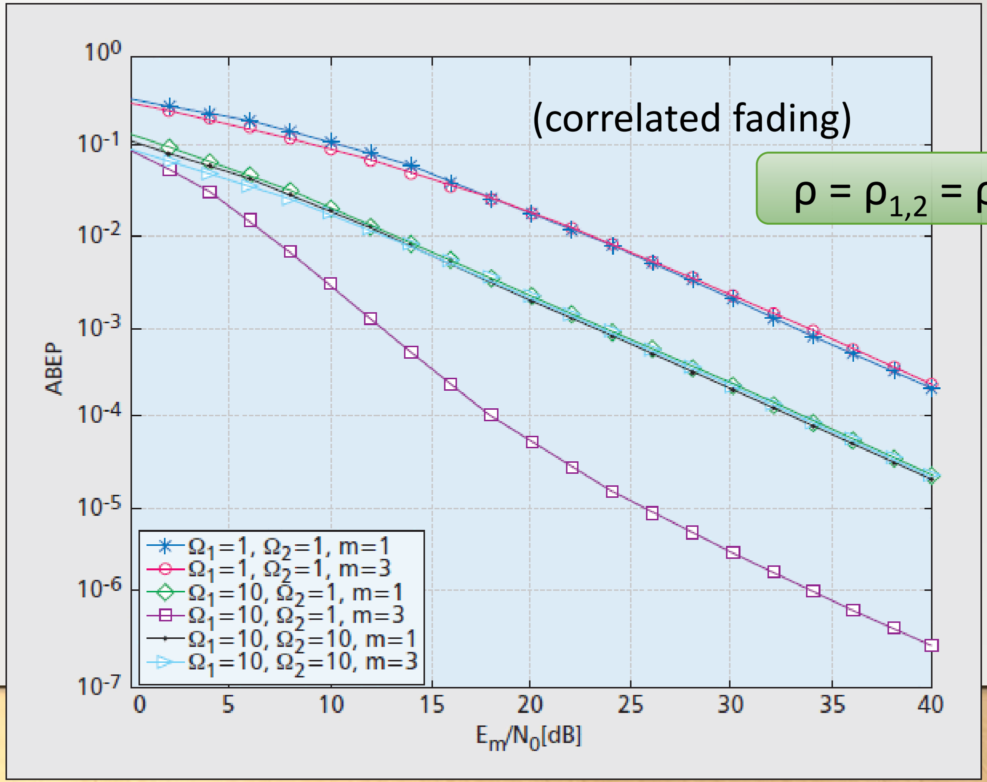
# Importance of the Wireless Channel

- If the wireless links are balanced, the performance of SM degrades for increasing values of the correlation coefficient $\rho$.



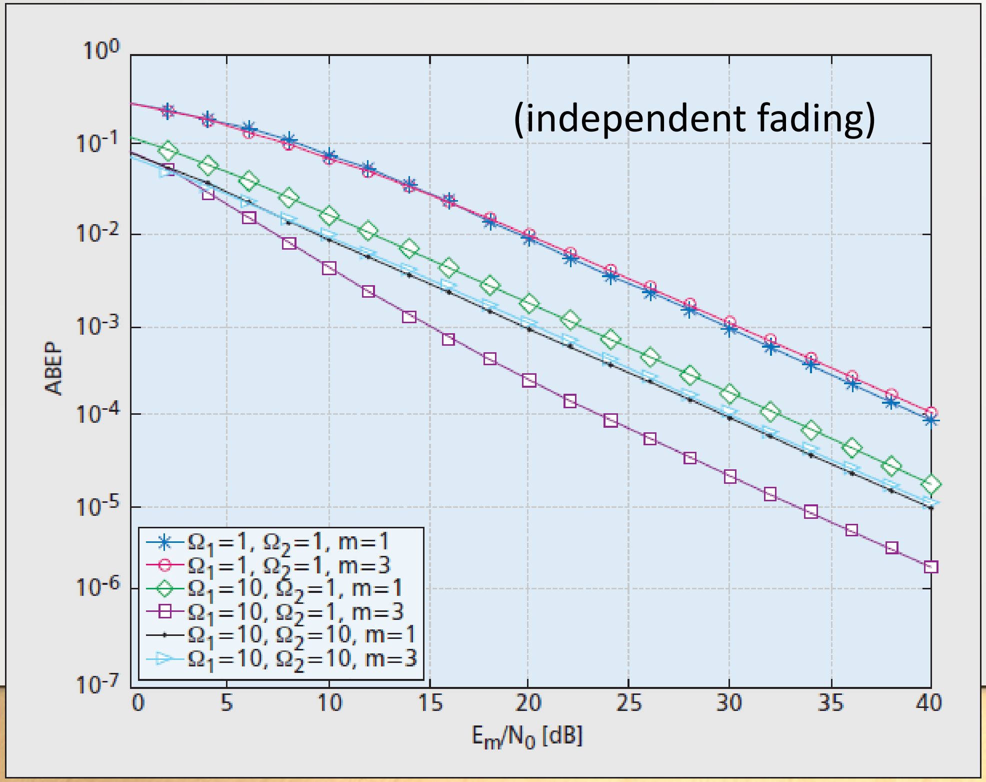



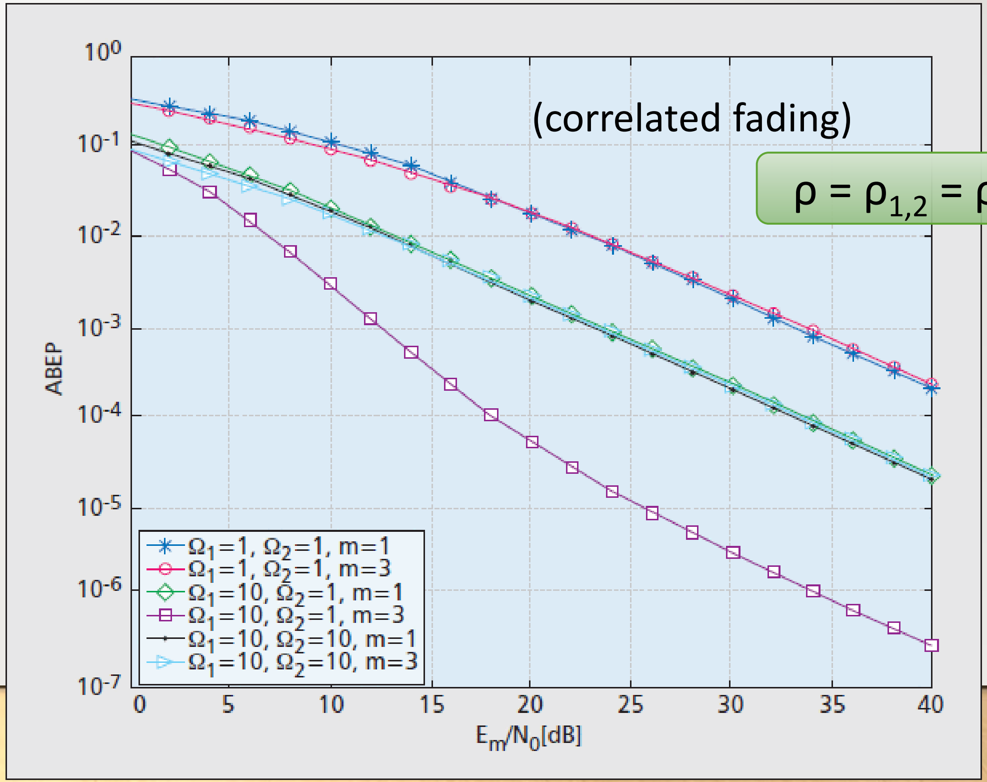

$\rho = \rho_{1,2} = \rho_{2,1} = 0.75$

$N_t = 2$
$N_r = 1$
$m = m_1 = m_2$

# Importance of the Wireless Channel

- Channel correlation can improve the ABEP by keeping the average power gap between the wireless links (i.e., $\Omega_1 - \Omega_2$) almost constant regardless of the fading fluctuations.



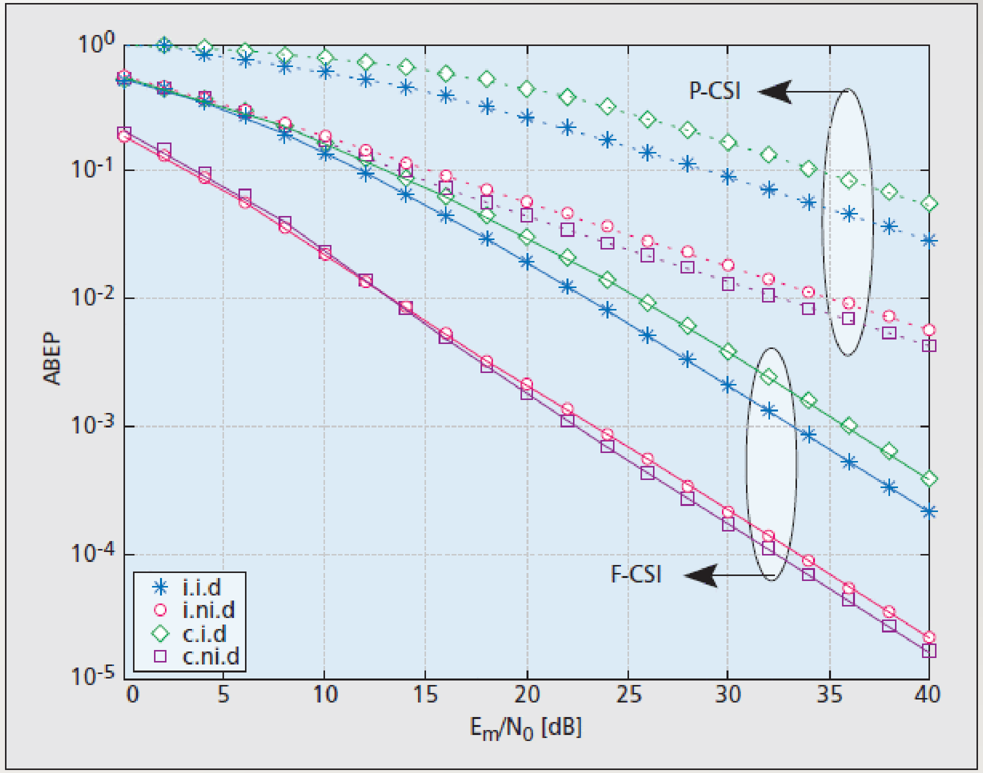




$\rho = \rho_{1,2} = \rho_{2,1} = 0.75$

$N_t = 2$
$N_r = 1$
$m = m_1 = m_2$

# Performance of SM with Partial CSI (P-CSI)

- The perfect estimation of CSI might be impractical.
  - ✓ Complexity of the channel estimator
  - ✓ Required overhead for channel estimation
- In the case of SM with P-CSI, the receiver is blind to the channel phase.
  - ➢ An unexpectedly high performance loss




(F-CSI = Full CSI, P-CSI = Partial CSI)

Scenario:

① $N_t = 4, N_r = 1$

② $\{\rho_{i,j}\}_{i,j=1}^{4} = \exp(-0.22[i-j])$ (if c.i.d and c.ni.d)

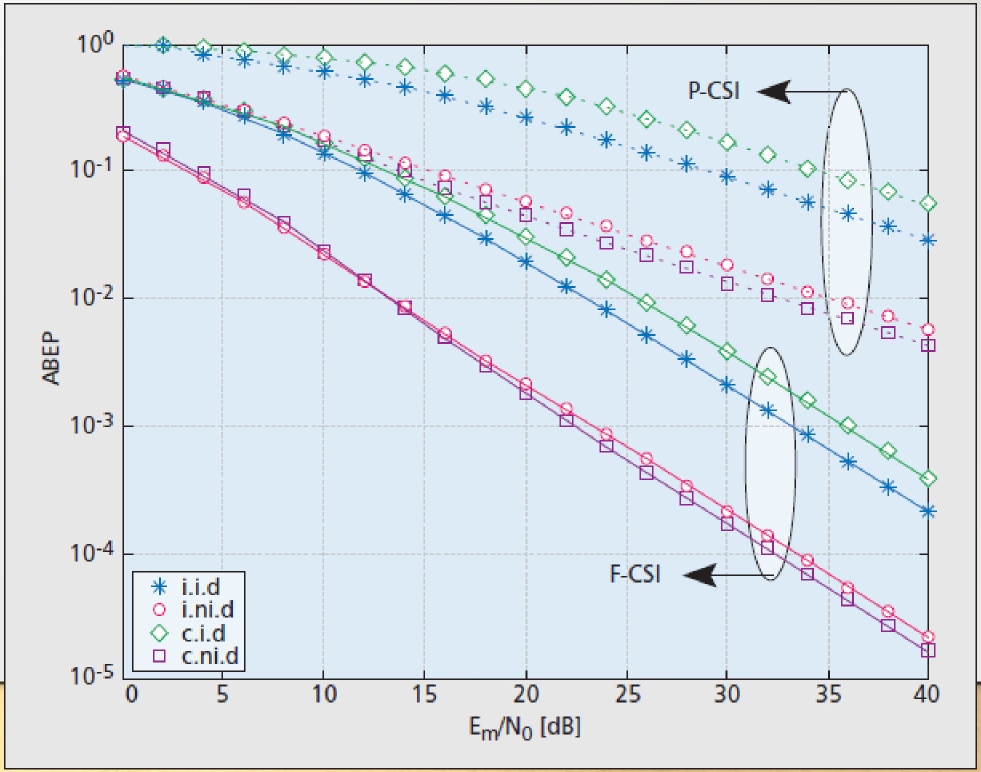
③ $\{m_i\}_{i=1}^{4} = 2.5$ and $\{\Omega_i\}_{i=1}^{4} = 1$ (if i.i.d and c.i.d)

④ $\{m_i\}_{i=1}^{4} = 2.5$ and $\Omega_1 = 1, \{\Omega_i\}_{i=2}^{4} = 4(i-1)$ (if i.ni.d and c.ni.d)

# Intriguing Results

- The best propagation scenario for SM is given by c.ni.d wireless links, while the worst one arises when the wireless links are c.i.d.

① i.i.d = independent and identically distributed
② i.ni.d = independent and non-identically distributed
③ c.i.d = correlated and identically distributed
④ c.ni.d = correlated and non-identically distributed



# Intriguing Results

- Power imbalance can be artificially created by allowing the transmit-antenna to emit a different power while still transmitting the same signal according to the SM principle.

- This way, a wireless environment with identically distributed fading could be made equivalent to a non-identically distributed fading scenario at the receiver.

- This approach requires a feedback channel to make available the required CSI at the transmitter.

# Conclusion

- SM is an entirely new physical layer transmission technique:
  - Combine digital modulation, coding, and multiple-antenna transmission in a unique fashion
  - Exploit the location-specific property of the wireless channel for communication
    - This enables the position of each transmit-antenna in the antenna-array to be used as an additional dimension for conveying information.

- SM can be a promising candidate for low-complexity MIMO implementations.

*Thank you for listening.*