THE UNIVERSITY OF EDINBURGH

Spatial Modulation

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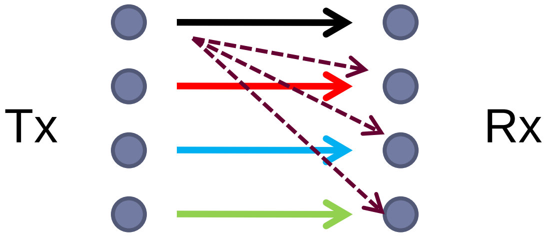
MIMO systems

- MIMO technology constructively exploits multipath propagation to provide higher data throughput for the same given bandwidth.

- There are three main categories of MIMO techniques:
  - The first improves power efficiency by **maximizing spatial diversity** (e.g., Alamouti STC).
  - The second improves throughput by **increasing the SINR** at the receiver (e.g., antenna "beamforming").
  - The third improves throughput through **spatial multiplexing** with and without channel knowledge at the transmitter (e.g., "V-BLAST" algorithm).

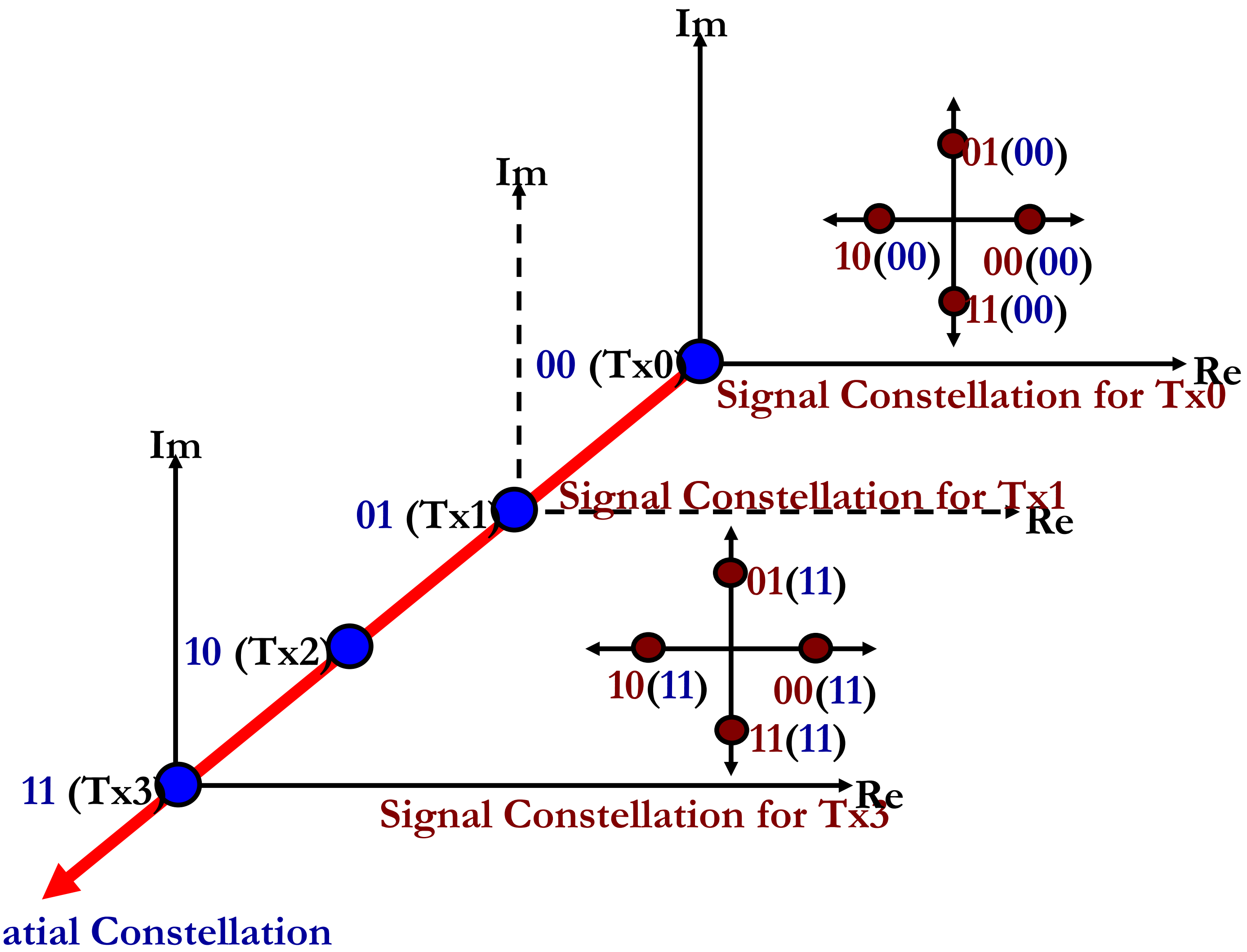
Classical Spatial Multiplexing MIMO



Significantly improve spectral efficiency (~min(N_t,N_r)), **but**:

- Suffer from inter-channel interference (ICI) resulting in high computational complex algorithms (e.g., V-BLAST)
- Suffer from antenna antennae correlation as a result of:
  - Spatial correlation
  - Mutual coupling
  - Line-of-sight conditions
- Require inter-antenna synchronisation (IAS)
- Require multiple RF-chains (→ expensive)

SM Principle

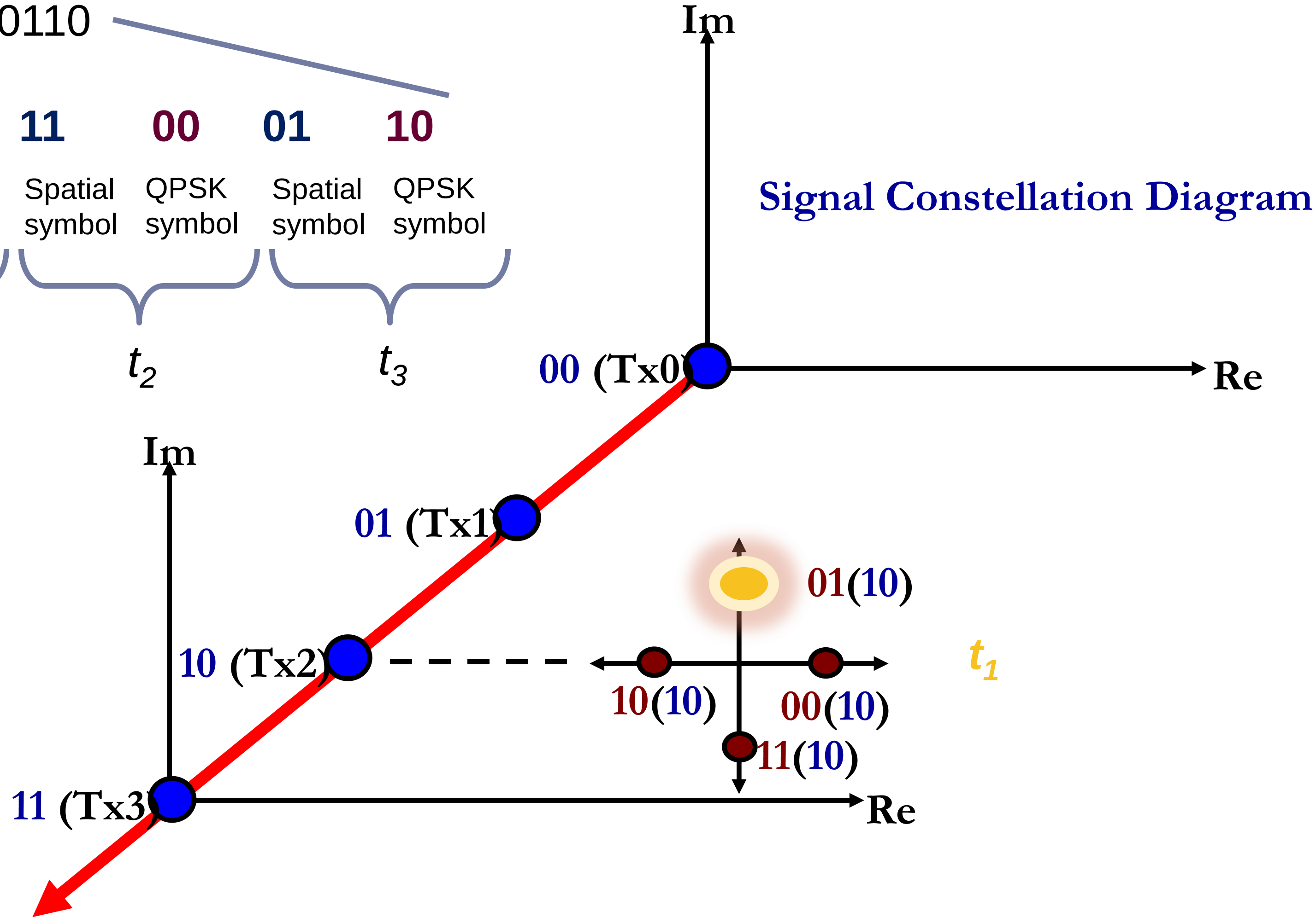


SM Principle

100111000110

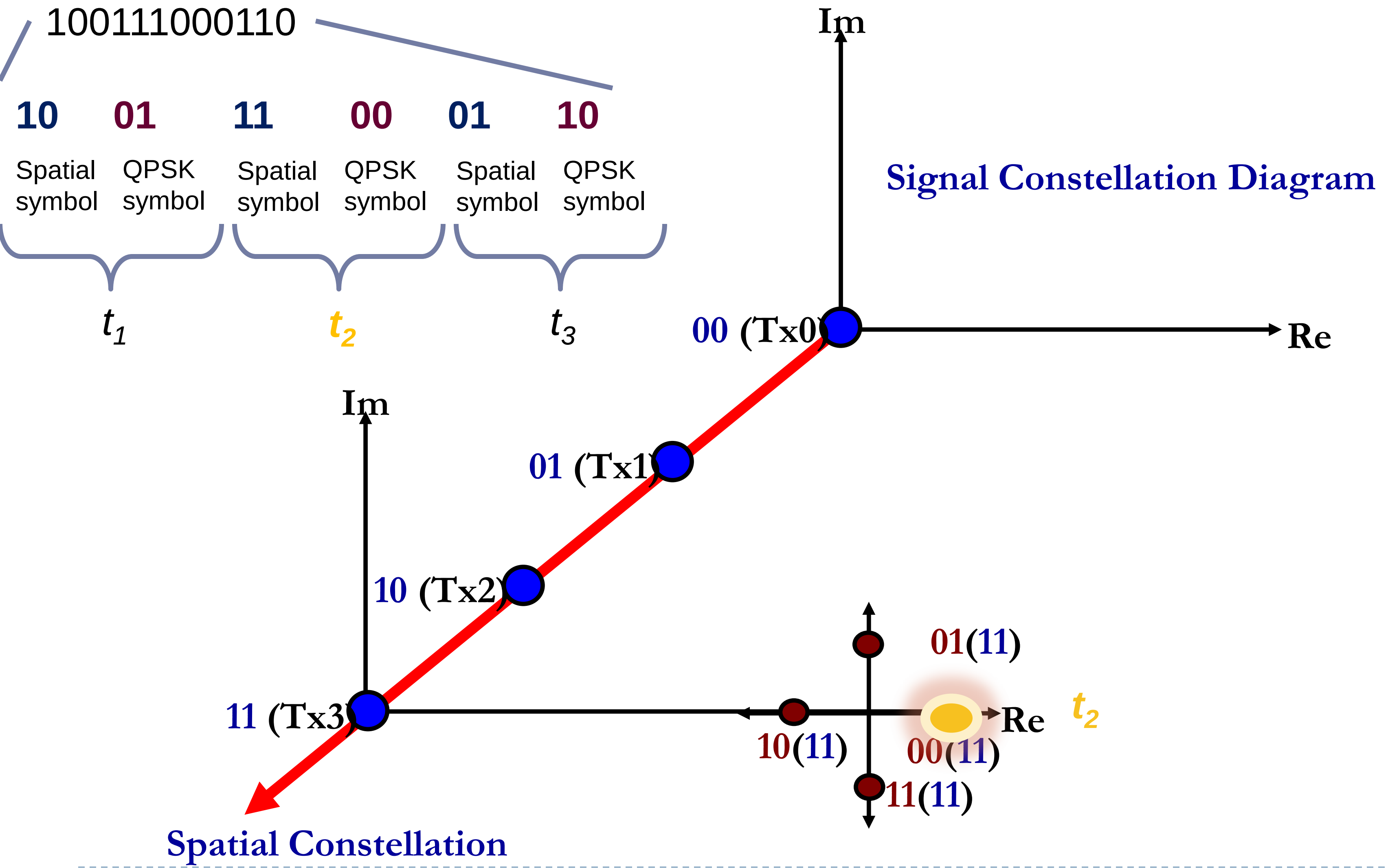
10	**01**	**11**	**00**	**01**	**10**
Spatial symbol	QPSK symbol	Spatial symbol	QPSK symbol	Spatial symbol	QPSK symbol

t_1	t_2	t_3



Spatial Constellation

SM Principle



100111000110

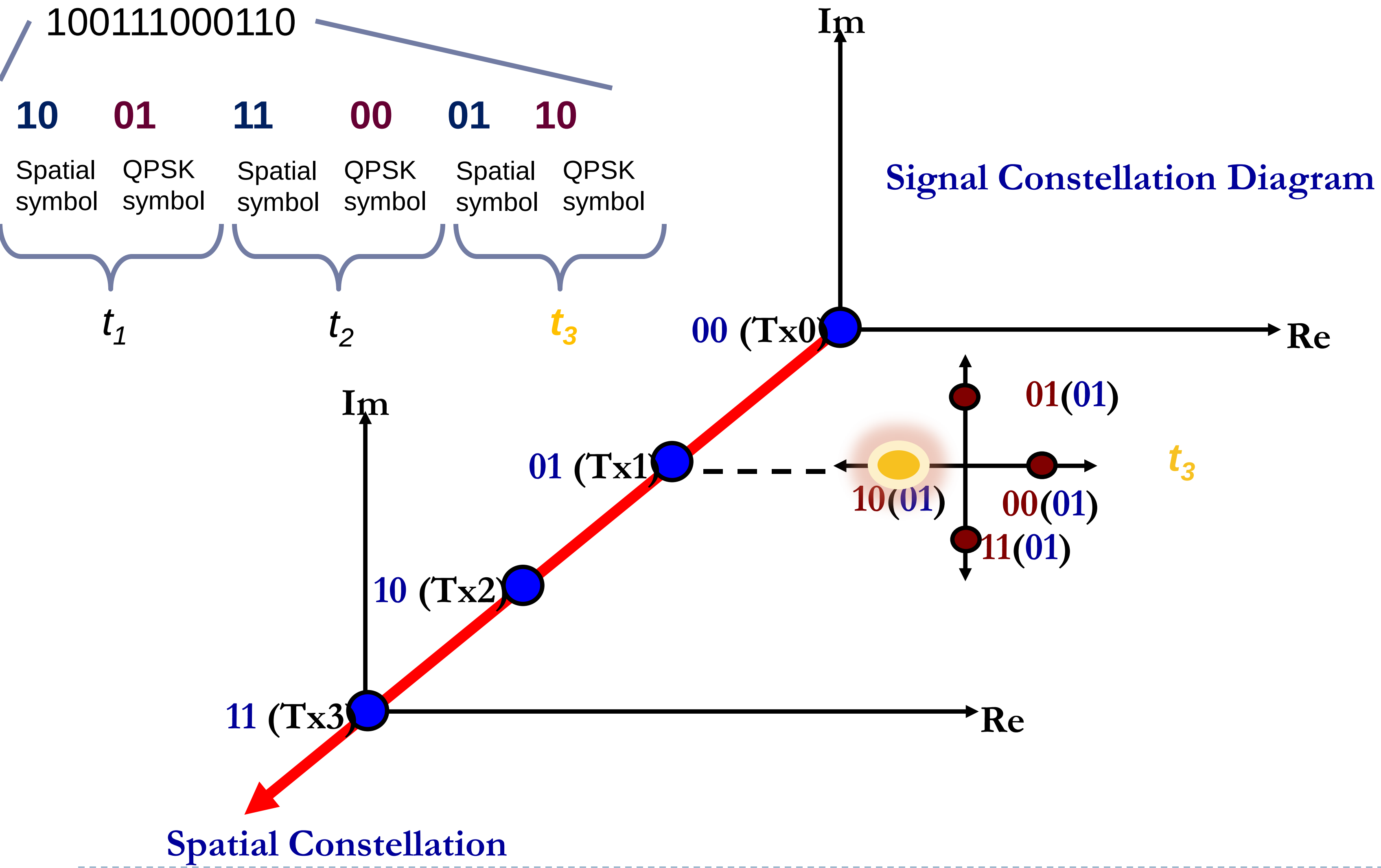
10	**01**	**11**	**00**	**01**	**10**
Spatial symbol	QPSK symbol	Spatial symbol	QPSK symbol	Spatial symbol	QPSK symbol

t_1 t_2 t_3

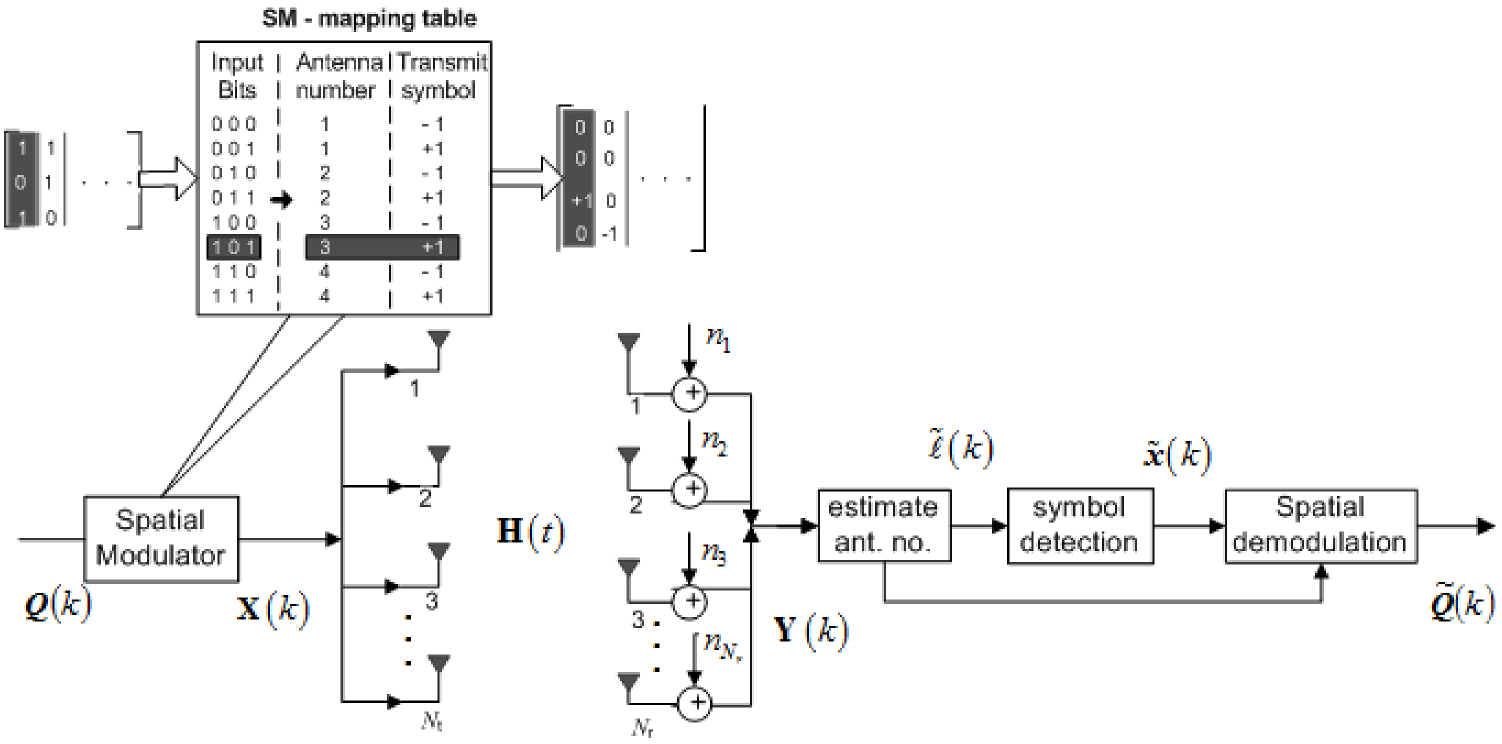
Signal Constellation Diagram

Spatial Constellation

SM Principle



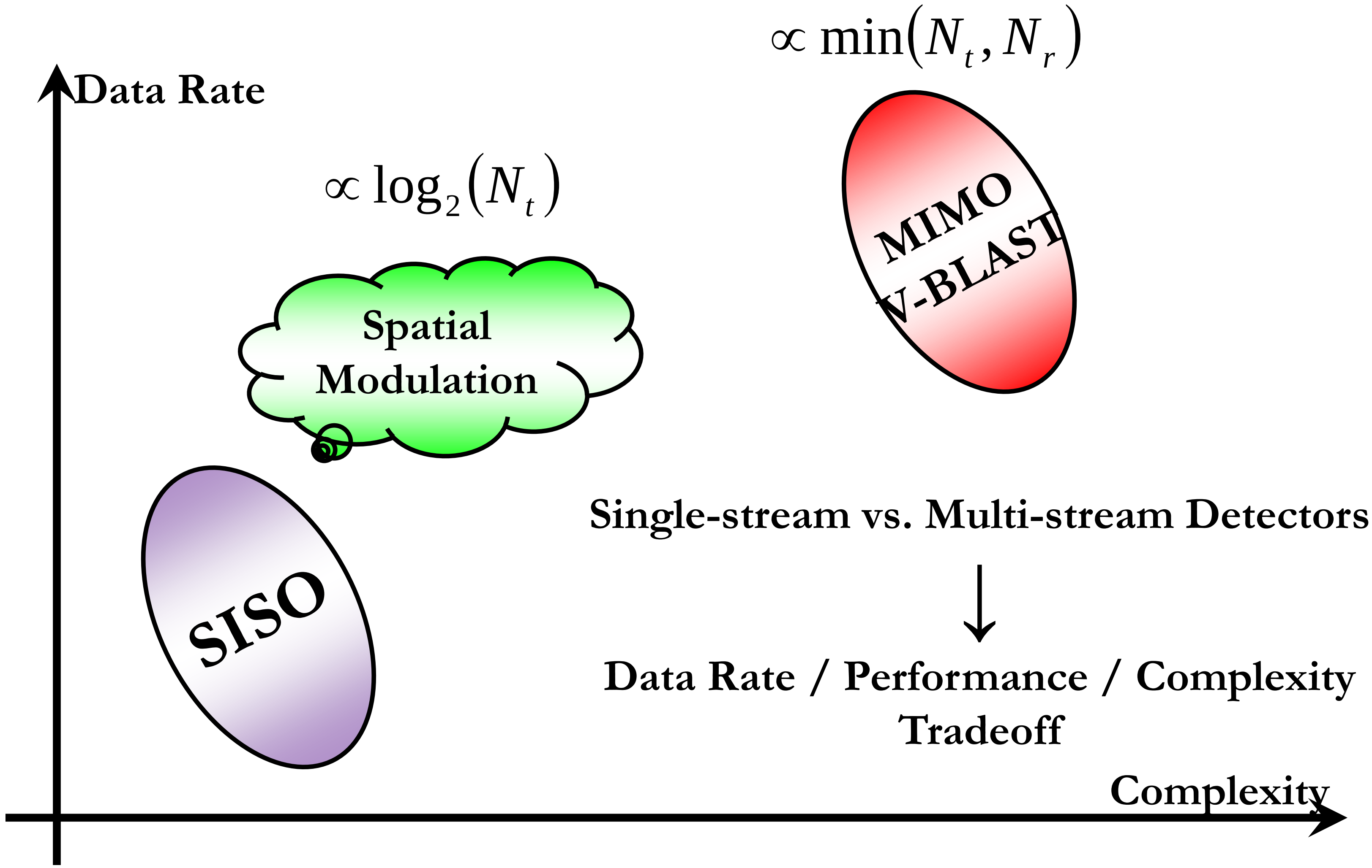
SM Essential Building Blocks



SM - mapping table

Input Bits	Antenna number	Transmit symbol
0 0 0	1	- 1
0 0 1	1	+1
0 1 0	2	- 1
0 1 1	2	+1
1 0 0	3	- 1
1 0 1	3	+1
1 1 0	4	- 1
1 1 1	4	+1

SM Complexity vs. Performance



Single-stream vs. Multi-stream Detectors

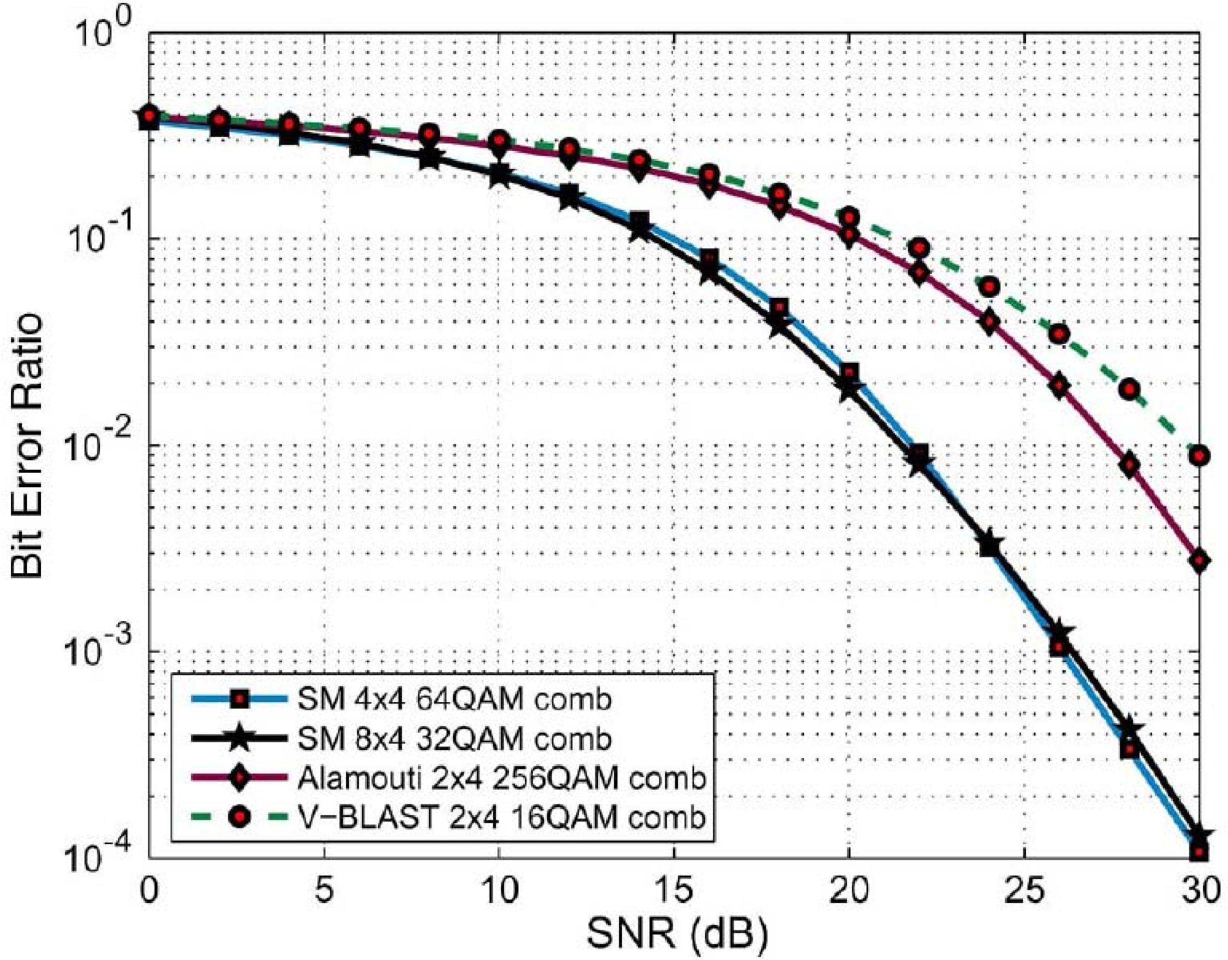
↓

Data Rate / Performance / Complexity Tradeoff

Spatial Modulation

- SM is a radically different and relatively new MIMO approach [Mesleh, *et al.*, "Spatial Modulation", Trans. Veh. Technol., July 2008]
- In SM, antenna indexes are considered as spatial constellation points
- Incoming data bits are mapped to **signal constellation** point and to **spatial constellation point**
- The receiver estimates both, the transmitted symbol and the transmit antenna index.

SM vs. V-BLAST and Alamouti



R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial Modulation", IEEE Transactions on Vehicular Technology, vol. 57, no. 4, pp. 2228-2241, July 2008.

Computational Complexity

TABLE III
RECEIVER COMPLEXITY COMPARISON FOR 6 B/S/HZ TRANSMISSION

V-BLAST				SM		Alamouti
MMSE		QR		MRRC		ML
2x4 8QAM	3x4 4QAM	2x4 8QAM	3x4 4QAM	4x4 16QAM	2x4 32QAM	2x4 64QAM
110	560	85	140	28	14	15

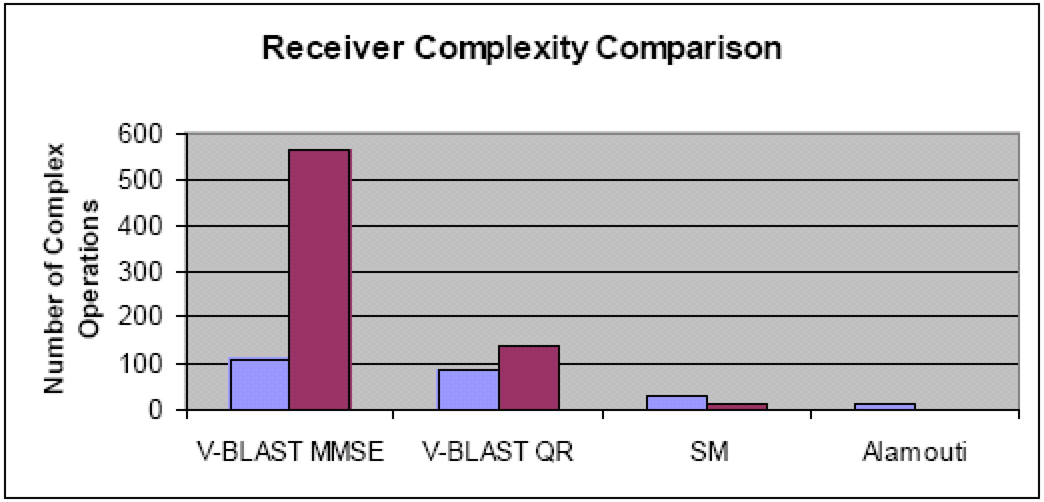
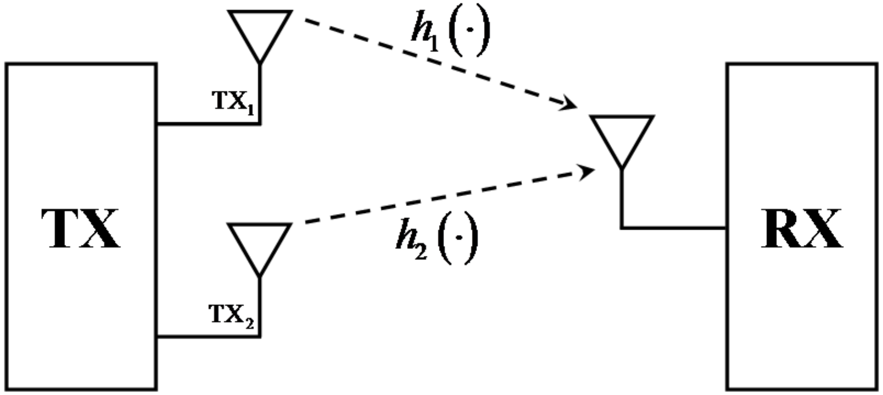


Fig. 14. Receiver complexity comparison for 6 b/s/Hz transmission using MMSE V-BLAST, V-BLAST based QR decomposition, SM and Alamouti algorithms.

SSK Analysis

Under Nakagami-m Fading



$$\begin{cases}\tilde{s}_l(t)=\sqrt{E_u}\,\beta_l\exp(j\varphi_l)\,w(t)\\ r(t)=\tilde{s}_l(t)+n(t)\end{cases}$$

$$\begin{cases}\hat{u}=\underset{\{u_i\}_{i=1}^{N_t}}{\arg\max}\{D_i\}\\ D_i=\mathrm{Re}\left\{\int_{T_u} r(t)\,\tilde{s}_i^*(t)\,dt\right\}-\frac{1}{2}\int_{T_u}\tilde{s}_i(t)\,\tilde{s}_i^*(t)\,dt\end{cases}$$

$$\boxed{\mathrm{ABEP}=\mathrm{E}_{h_1,h_2}\left\{\mathrm{P_E}(h_1,h_2)\right\}=\frac{1}{\pi}\int_0^{\pi/2}M_\gamma\left(\frac{E_u/4N_0}{2\sin^2(\theta)}\right)d\theta}$$

$$\begin{cases}\mathrm{P_E}(h_1,h_2)=Q\left(\sqrt{\frac{E_u}{4N_0}\left|\beta_2\exp(j\varphi_2)-\beta_1\exp(j\varphi_1)\right|^2}\right)\\ M_\gamma(s)=\int_0^{+\infty}\int_0^{+\infty}\underbrace{\left[\exp\left(-s\xi_1^2\right)\exp\left(-s\xi_2^2\right)I_0\left(2s\xi_1\xi_2\right)\right]}_{M_\gamma(s;\xi_1,\xi_2)}f_{\beta_1,\beta_2}(\xi_1,\xi_2)\,d\xi_1 d\xi_2\end{cases}$$

Independent Nakagami-*m* Fading

$$\begin{cases} \left\{ f_{\beta_i}\left(\xi_i\right) \right\}_{i=1}^{2} = \tilde{A}_i \xi_i^{\tilde{C}_i} \exp\left(-\tilde{B}_i \xi_i^2\right) \\ \tilde{A}_i = \dfrac{2}{\Gamma\left(m_i\right)} \left(\dfrac{m_i}{\Omega_i}\right)^{m_i} ; \tilde{B}_i = \dfrac{m_i}{\Omega_i} ; \tilde{C}_i = 2m_i - 1 \end{cases}$$

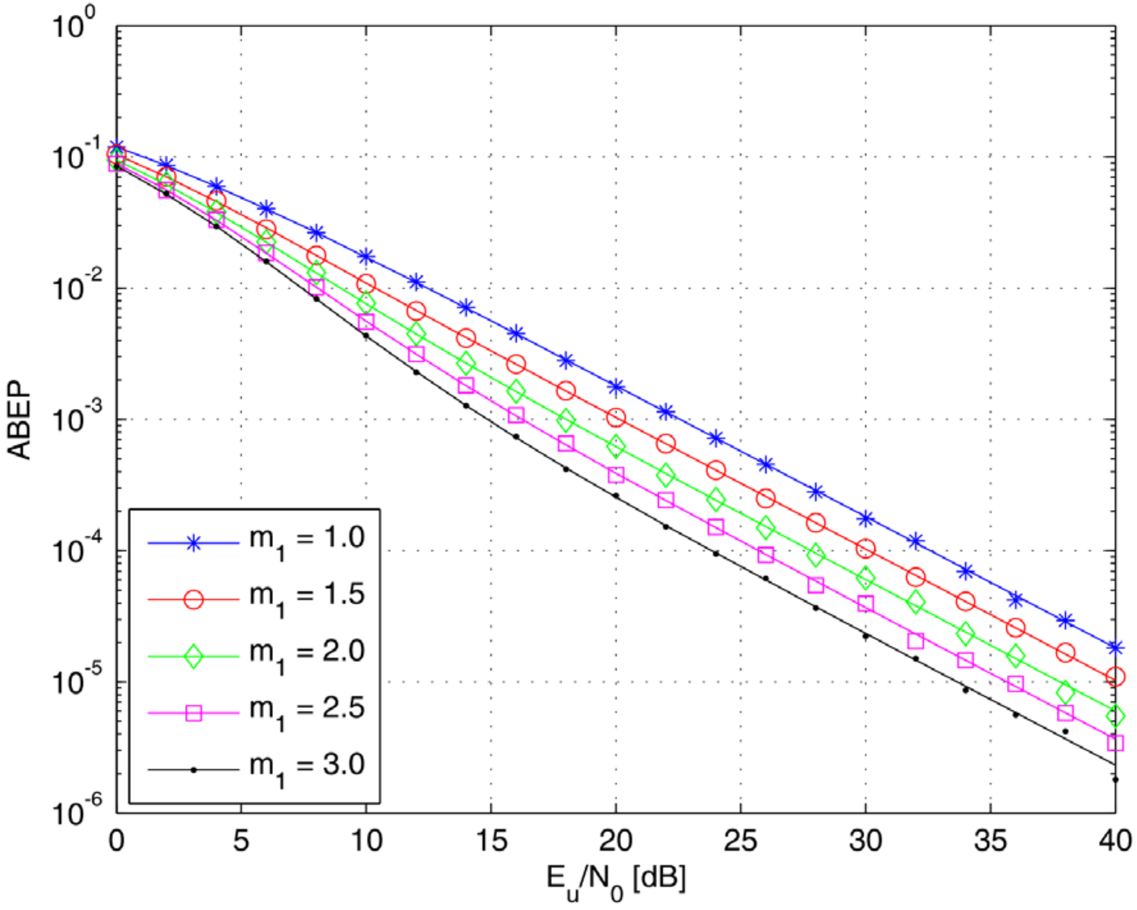
$$\Downarrow$$

$$M_\gamma\left(s\right) = \frac{\tilde{A}_1 \tilde{A}_2}{4} \left(s + \tilde{B}_1\right)^{-\left(\frac{1}{2} + \frac{\tilde{C}_1}{2}\right)} \left(s + \tilde{B}_2\right)^{-\left(\frac{1}{2} + \frac{\tilde{C}_2}{2}\right)} G_{2,2}^{1,2}\left(-\frac{s^2}{\left(s + \tilde{B}_1\right)\left(s + \tilde{B}_2\right)} \middle| \begin{matrix} \frac{1}{2} - \frac{\tilde{C}_2}{2} & \frac{1}{2} - \frac{\tilde{C}_1}{2} \\ 0 & 0 \end{matrix} \right)$$

M. Di Renzo and H. Haas, "A General Framework for Performance Analysis of Space Shift Keying (SSK) Modulation for MISO Systems over Correlated Nakagami-*m* Fading Channels", IEEE Transactions on Communications, (accepted, to appear).

Results

2x1 MIMO, Independent Nakagami-*m* Fading



Setup:

→ $m_1 = 1 – 3$

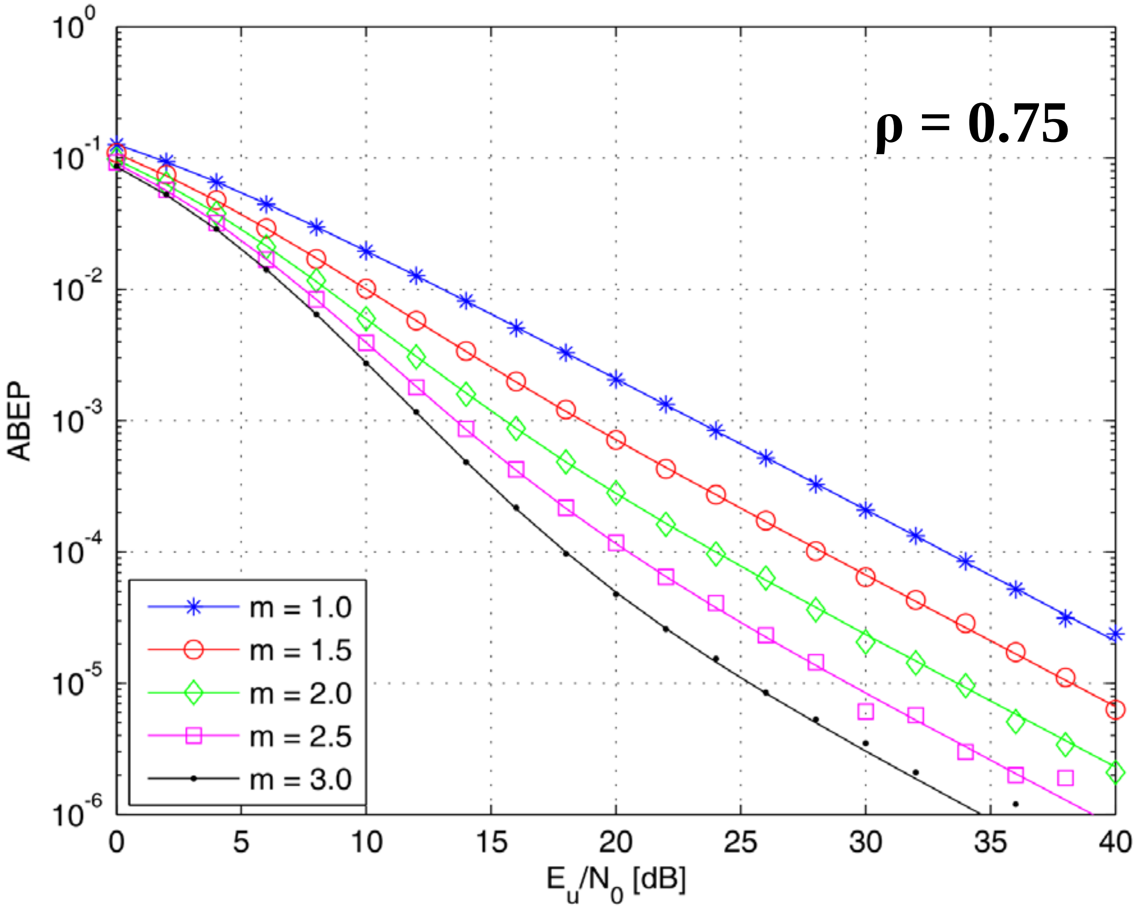
→ $m_2 = 2$

→ $\Omega_1 = 10$

→ $\Omega_2 = 1$

Results

2x1 MIMO, Correlated Nakagami-*m* Fading



Setup:

→ $m_1 = 1 - 3$

→ $m_2 = 2$

→ $\Omega_1 = 10$

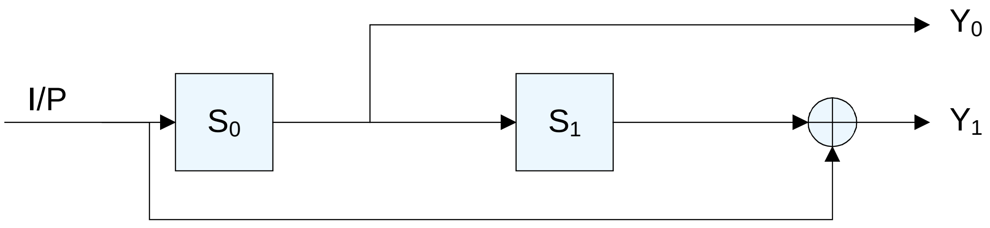
→ $\Omega_2 = 1$

Trellis Coded Spatial Modulation

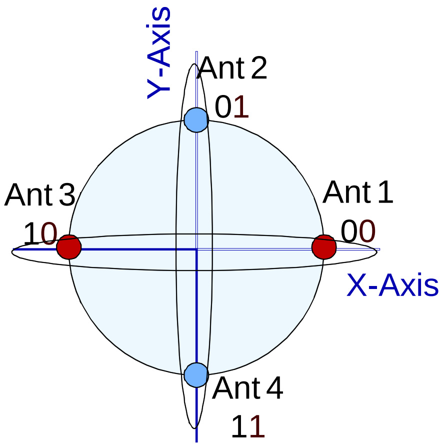
Under Spatial Correlation and LoS Conditions

Trellis coded SM (TCSM)

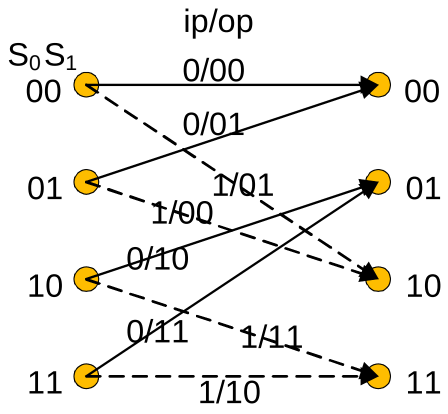
- Apply TCM to the spatial constellation points in SM
- Aim: partition the transmit antennas into sets, with each set having maximum spatial separation distance between the selected antennas
- Correlation between antennas is significantly reduced



a) TCM Convolutional Encoder



b) TCM encoded bits and their mapping to spatial constellation points

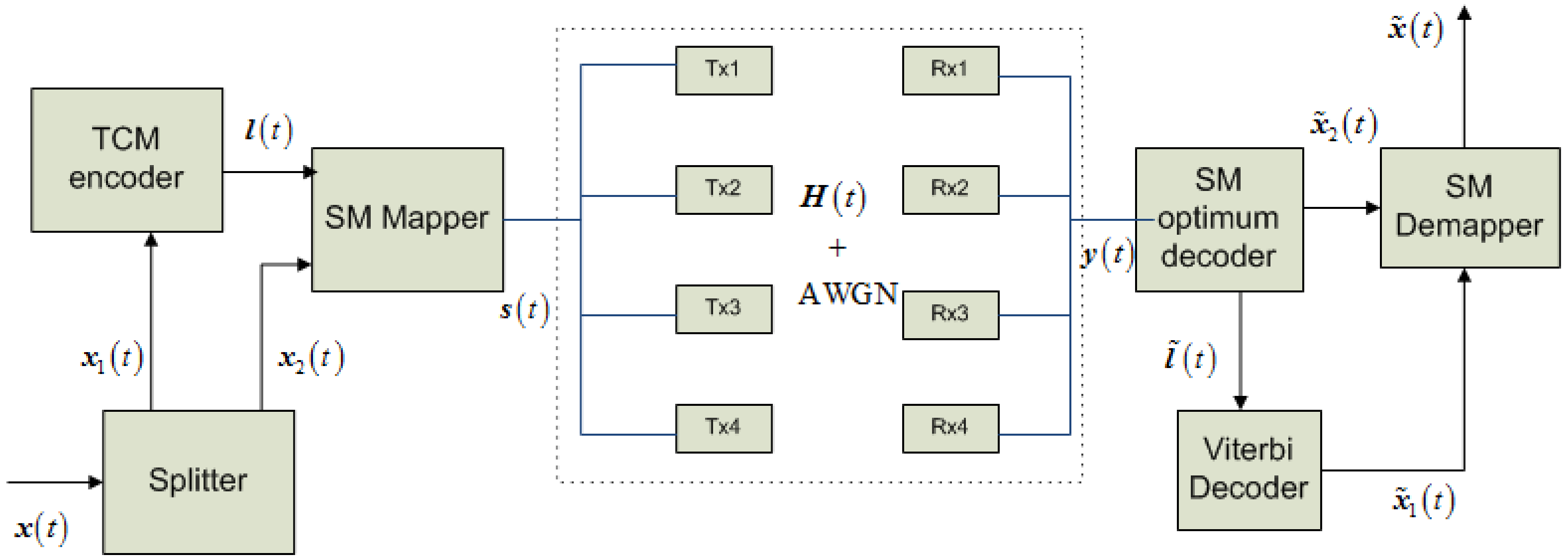


c) ⟶ State transition when input is 0

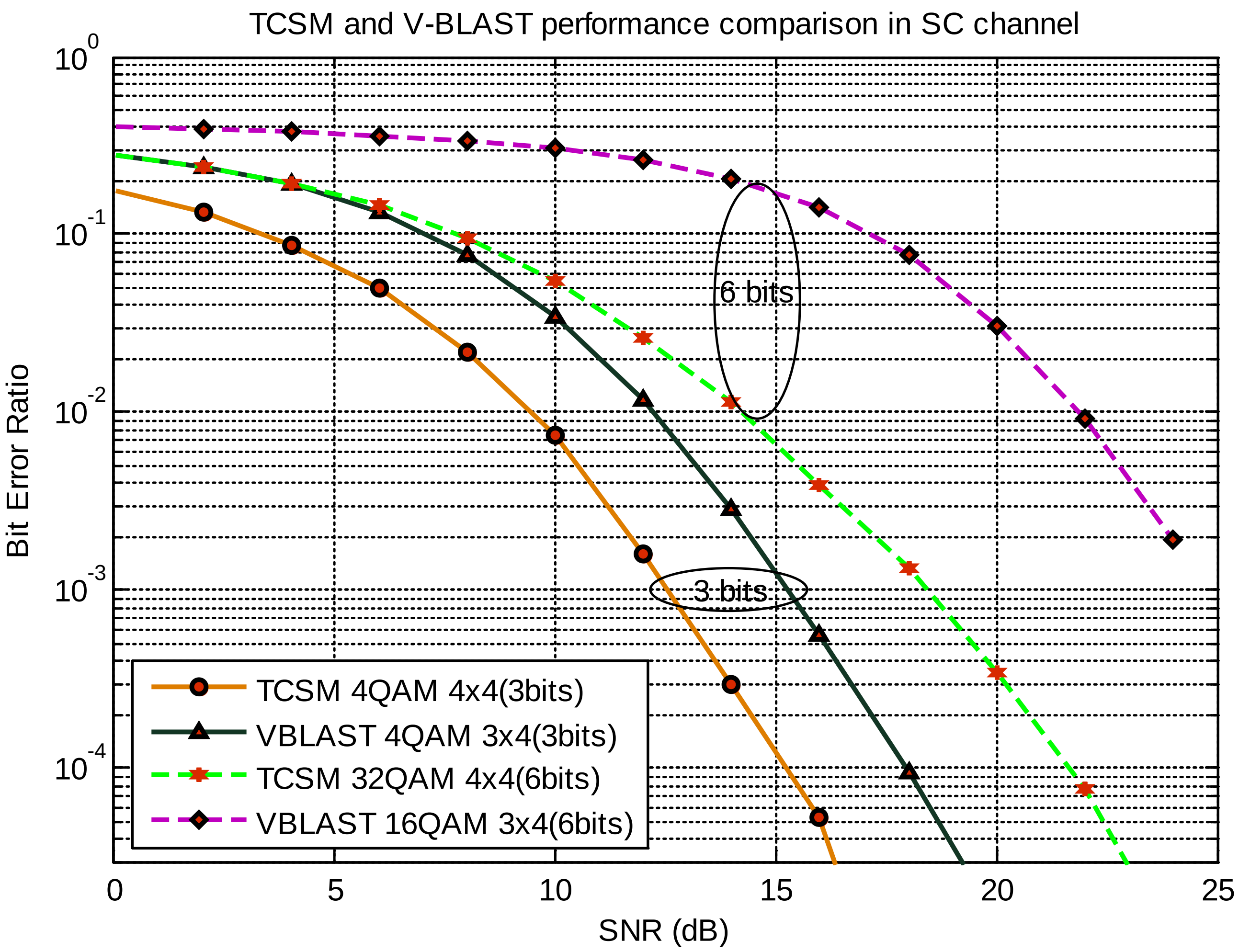
- - → State transition when input is 1

TCSM system model

- The bits to be mapped to spatial points are encoded by a TCM encoder.
- TCM partitions the entire set of transmit antennas into sub-sets maximising the spacing between antennas in a sub-set.
- At the receiver, optimum SM decoder is applied to estimate the transmit antenna index and the transmitted symbol.

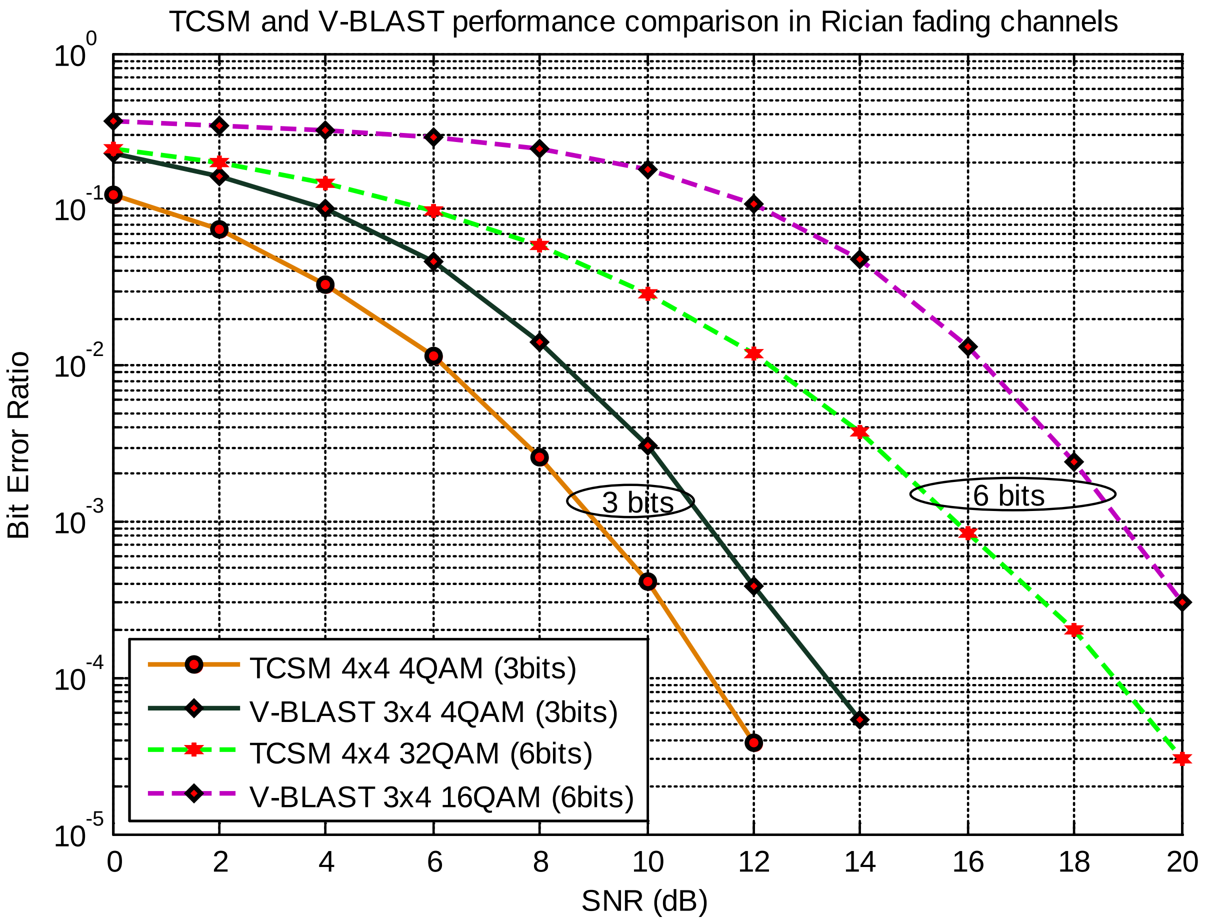


Results – Spatial Correlation (SC)



- TCSM outperforms V-BLAST by 3dB for 3bps/Hz and by 6dB for 6bps/Hz
- SC significantly degrades the performance of V-BLAST

Results – Rician Fading (LoS)



- Rician fading degrades the performance of V-BLAST by 2~3dB, compared to ideal channel.
- LoS enhances the SNR at the receiver, but increases the correlation between transmit antennas
- TCSM mitigates correlation between transmit antennas and benefits from the higher SNR obtained from Rician channel.

Summary and Conclusions

- SM is a new MIMO transmission technique offering:
  - Low implementation complexity while retaining multiplexing gain $\sim(\log_2(N_T))$ instead of $\sim\min(N_T, N_R)$ in V-BLAST
  - Fully avoids inter-channel interference
  - No constraint on the minimum number of receive antennas
  - Only one Tx-Chain and no inter-antenna synchronisation required
  - Channel correlation can be beneficial when average magnitude of the channel transfer factors is sufficiently different
  - Trellis coding in spatial domain further enhance robustness to channel correlation

Related Papers

- Mesleh, R., Haas, H., Sinanović, S., Ahn, C. W. and Yun, S., "Spatial Modulation," *IEEE Transactions on Vehicular Technology,* vol. 57, no. 4, pp. 2228 – 2241, July 2008.
- M. Di Renzo, H. Haas, "A General Framework for Performance Analysis of Space Shift Keying (SSK) Modulation for MISO Systems over Correlated Nakagami-m Fading Channels", *IEEE Trans. Commun. (to appear).*
- R. Y. Mesleh, M. Di Renzo, H. Haas, P. M. Grant, "Trellis Coded Spatial Modulation", IEEE Trans. Wireless Commun. July 2010
- M. Di Renzo, H. Haas, "Space Shift Keying (SSK) Modulation with Partial Channel State Information at the Receiver: Optimal Detector and Performance Analysis over Correlated Fading Channels", *IEEE Trans. Commun. (to appear).*
- M. Di Renzo, H. Haas, "Improving the Performance of Space Shift Keying (SSK) Modulation via Opportunistic Power Allocation", *IEEE Commun. Lett. (to appear).*
- N. Serafimovski, M. Di Renzo, S. Sinanovic, H. Haas, R. Y. Mesleh, "Fractional Bit Encoded Spatial Modulation (FBE-SM*)", IEEE Commun. Lett.* (*to appear*).
- M. Di Renzo, H. Haas, P. M. Grant, "Spatial Modulation for MIMO Systems: State of the Art and Challenges Ahead", *IEEE Commun. Mag.* (submitted).
- M. Di Renzo, H. Haas, "SSK-MIMO over Correlated Rician Fading Channels: Performance Analysis and a New Method to Achieve Transmit-Diversity Gains", *IEEE Trans. Commun. (submitted).*
- A. Younis, H.Haas, and P. Grant, "Reduced Complexity Sphere Decoder for Spatial Modulation Detection Receivers", IEEE Globecom (2010), (Miami, Florida, USA), 2010 (to appear)
- M. Di Renzo, H. Haas, "Performance Analysis of Spatial Modulation (SM) over Nakagami–m Fading Channels" *IEEE Conference on Communications and Networking in China (ChinaCom 2010),* (**invited**)

We gratefully acknowledge support from the Engineering and Physical Sciences Research Council (EPSRC). Grant number EP/G011788/1

Simulation parameters

- A static fading Rayleigh channel matrix that is flat for all frequency components is modeled.
- Rician fading channel with Rician K-factor of 3 is implemented as follows:

$$\mathbf{H}_{\mathrm{Ricean}}(t) = \sqrt{\frac{K}{1+K}}\bar{\mathbf{H}}(t) + \sqrt{\frac{1}{1+K}}\mathbf{H}(t),$$

where $\bar{\mathbf{H}}$ is a channel matrix with all elements being one

- For SC channel, a "*Kronecker*" channel is modeled.
- Transmit antennas and receive antennas are 0.1λ and 0.5λ separated, respectively.
- The SC channel is modeled as follows:

$$\mathbf{H}^{\mathrm{corr}}(t) = \mathbf{R}_{\mathrm{rx}}^{1/2}\mathbf{H}(t)\mathbf{R}_{\mathrm{tx}}^{1/2}$$

V-BLAST system model

- The performance of TCSM in ideal, Rician, and SC channels is compared to V-BLAST system with a sphere decoder (SD).
- SCBLAST is considered.
- SD algorithm employs integer lattice theory.