Link Adaptation Techniques for Future Terrestrial and Satellite Communications

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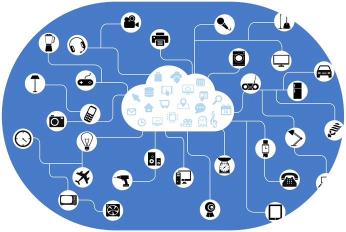
Outline

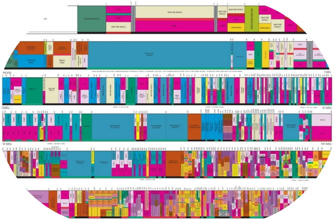
Motivation

Data traffic



M2M and IoT connections

Carbon emissions



Spectrum saturation

Motivation

Mobile Satellite Systems

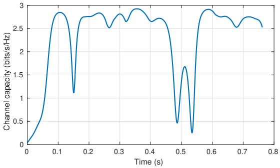
Fixed Satellite Systems

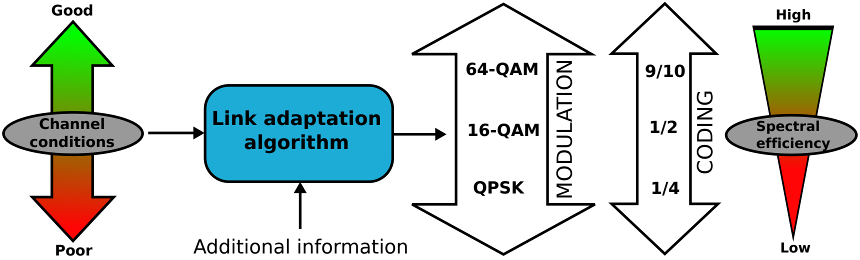
Future terrestrial and satellite communication systems

5G

Motivation

Time variant channels





Good

Channel conditions

Poor

Link adaptation algorithm

Additional information from the receiver (ACK/NAK)

64-QAM

16-QAM

QPSK

MODULATION

9/10

1/2

1/4

CODING

Modulation and Coding Scheme (MCS)

High

Spectral efficiency

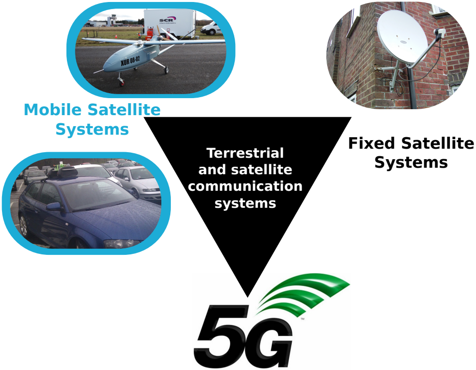
Low

Outline

1. 1. Motivation
2. 2. Mobile Satellite System: Field Trial Results
3. 3. Multibeam Satellite Systems with Linear Precoding
4. 4. Spatial Modulation Transmission Capacity
5. 5. Mobile Satellite Systems with Dual Polarization
6. 6. Spatial Modulation Systems
7. 7. Conclusions

Chapter 2

Link Adaptation in Mobile Satellite Links: Field Trials Results



Mobile Satellite Systems

Terrestrial and satellite communication systems

Fixed Satellite Systems

Publications

ASMS2016 SPSC2016

Motivation

- **Experimental validation of the link adaptation algorithms**
  - Deployment of a Mobile SatCom link
  - Implementation of S-UMTS standard (family SL)
  - Using SDR technology
  - With a real S-band MEO satellite
- **Partners**

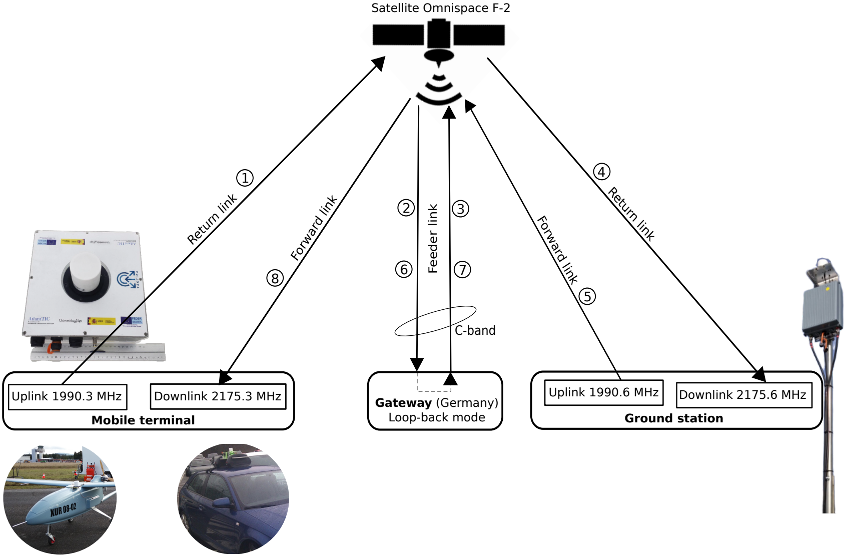
Gradiant

OMNISPACE

Aeroespacial y Defensa everis

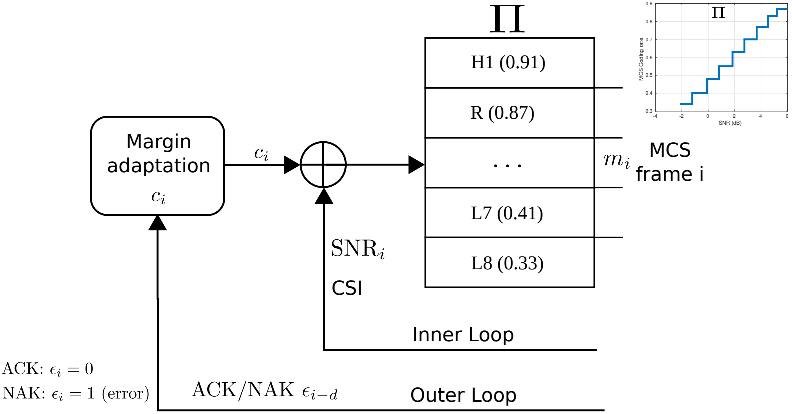
SCR SISTEMAS DE CONTROL REMOTO S.L.

The whole system



Outer Loop Link Adaptation (OLLA)

$$m_i = \Pi(\mathrm{SNR}_i + c_i)$$



Π

H1 (0.91)

R (0.87)

$\cdots$

L7 (0.41)

L8 (0.33)

Margin adaptation c_i

c_i

SNR_i

CSI

m_i MCS frame i

Inner Loop

ACK: $\epsilon_i = 0$

NAK: $\epsilon_i = 1$ (error)

ACK/NAK ϵ_{i-d}

Outer Loop

Balancing Closed and Open Loop CSI

- **Closed loop CSI** $(\mathrm{SNR}_i^{\mathrm{cl}})$
  - Measured by the Ground Station (GS) and fed back
  - ✔ Accurate
  - ✘ After a potentially large delay
- **Open loop CSI** $(\mathrm{SNR}_i^{\mathrm{ol}})$
  - Measured directly by the Mobile Terminal (MT)
  - ✔ Small delay
  - ✘ Less accurate

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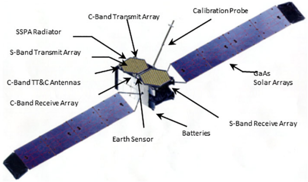
- **Open loop CSI** $(\mathrm{SNR}_i^{\mathrm{ol}})$
  - Measured directly by the Mobile Terminal (MT)
  - ✔ Small delay
  - ✘ Less accurate
- **Balanced convex algorithm**

$$m_i = \Pi\left((1-\xi_i)\,\mathrm{SNR}_i^{\mathrm{ol}} + \xi_i \mathrm{SNR}_i^{\mathrm{cl}} + c_i\right) \tag{1}$$

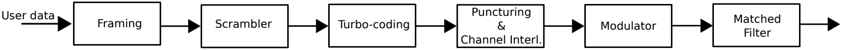
Satellite Component



Characteristic	**Value**
Satellite	Omnispace F-2 (former ICO F-2)
Operator	Omnispace LLC
Orbit	MEO (10,500 km) 45^o inclination
Leased bandwidth	200 kHz in each direction
Maximum EIRP (MT and GS)	43 dBm
Minimum Delay (RTT)	140 ms (280 ms)

Table 1: Main parameters of the satellite link.

Physical Layer Specification

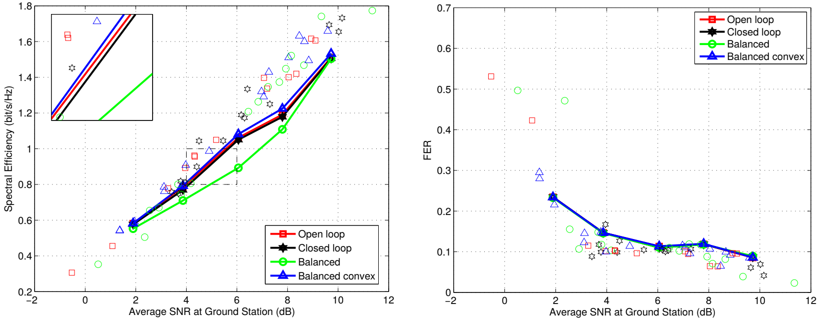


Characteristic	Value
Standard	ETSI TS 102 704 (S-UMTS family SL)
Frame length	20 ms
Modulation	$\pi/4$-QPSK
Sybmol rate	67.2 ksymb/s
Channel bandwidth	84 kHz
Polarization	RHCP
Channel coding	Turbocodes (10 coding rates)

Table 2: Physical layer parameters.

Spectral efficiency and FER

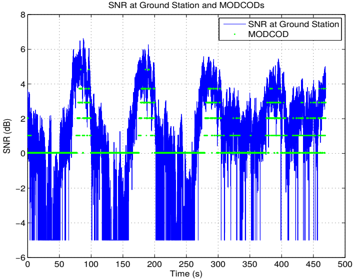
- Three trial environments: highway, semi-rural and aeronautical
- Tests of 5 minutes
- Target FER of 10 %

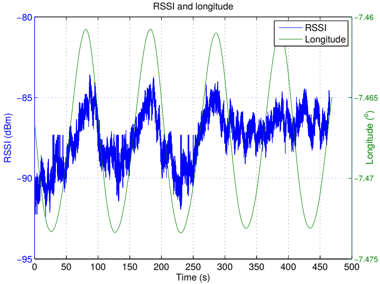


- **Markers:** trials
- **Lines:** simulations with data from the trials

Link adaptation in action

Algorithms can follow the channel variations due to decrement of the antenna gain in the direction of the satellite when the UAV turns.





Conclusions

- All algorithms satisfy the objective FER of 10 %
- All algorithms behave similarly in terms of spectral efficiency
- Adaptation schemes were able to track the fluctuations of the SNR
- The open loop SNR seems useful in the link adaptation
- Later on Chapter 5: Dual Polarization (DP) Mobile Satellite Systems

Outline

Chapter 3

Link Adaptation and SINR Errors in Practical Multicast Multibeam Satellite Systems with Linear Precoding

Mobile Satellite Systems

Future terrestrial and satellite communication systems

5G

Fixed Satellite Systems

Publications

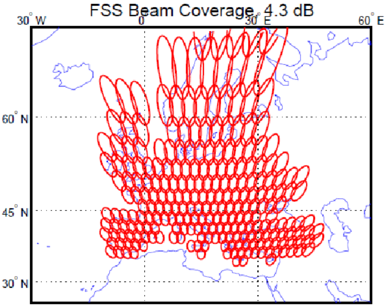
ASMS2018 SPSC 2018

international journal of satellite communications and networking

(under revision)

Introduction

- High Throughput Satellite (HTS) at Ka-band
  - Multibeam satellite + Linear Precoding + Link Adaptation



Full Frequency reuse, 245 beams

- Imperfect Channel State Information at the Transmitter (CSIT)

System Model

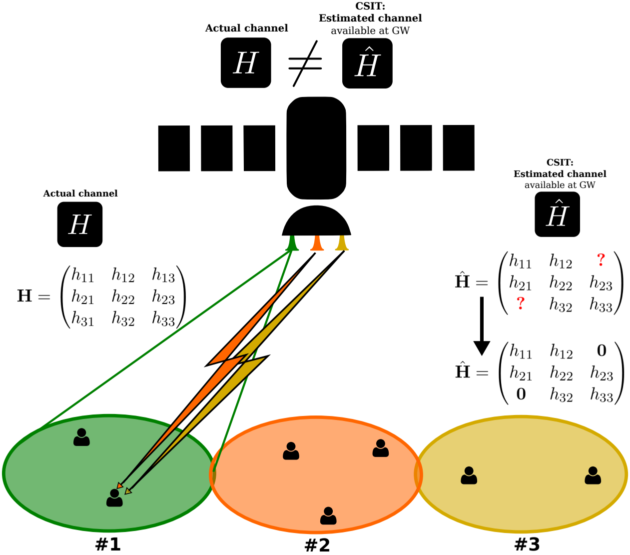
- Signal model:

$$\mathbf{y}^{[i]} = \mathbf{H}^{[i]}\mathbf{x} + \mathbf{n}^{[i]} = \mathbf{H}^{[i]}\mathbf{W}\mathbf{s} + \mathbf{n}^{[i]}, \quad i = 1,\ 2, \ldots, M, \qquad (2)$$

- Channel model:
  ESA's 245 beams radiation pattern
- $\hat{\mathbf{H}}$: Imperfect CSIT due to...
  - Nullification
  - Gaussian estimation errors
- Linear Precoding: MMSE with Sum Power Constraint (SPC)

$$\mathbf{W} = \eta \cdot \hat{\mathbf{H}}^H \left(\hat{\mathbf{H}}\hat{\mathbf{H}}^H + \frac{1}{\mathsf{snr}}\mathbf{I}_N \right)^{-1} \qquad (3)$$

Nullification effect



Actual channel

$$H \neq \hat{H}$$

CSIT:
Estimated channel
available at GW

Actual channel

H

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix}$$

CSIT:
Estimated channel
available at GW

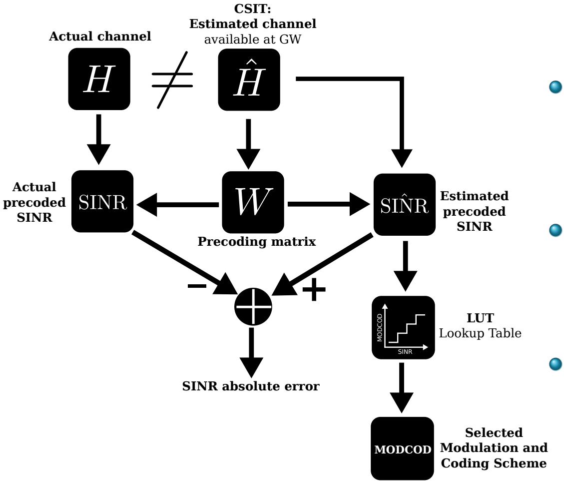
$\hat{H}$

$$\hat{\mathbf{H}} = \begin{pmatrix} h_{11} & h_{12} & ? \\ h_{21} & h_{22} & h_{23} \\ ? & h_{32} & h_{33} \end{pmatrix}$$

$$\downarrow$$

$$\hat{\mathbf{H}} = \begin{pmatrix} h_{11} & h_{12} & \mathbf{0} \\ h_{21} & h_{22} & h_{23} \\ \mathbf{0} & h_{32} & h_{33} \end{pmatrix}$$

SINR Absolute Error due to Nullification



- **SINR calculated by the GW**

$$\widehat{\text{sinr}}_k = \frac{|\hat{\mathbf{h}}_k^{\perp}\mathbf{w}_k|^2}{\sum_{j\neq k}|\hat{\mathbf{h}}_k^{\perp}\mathbf{w}_j|^2 + N_0}$$

- **Actual user SINR**

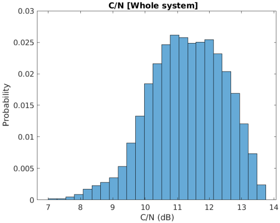
$$\text{sinr}_k = \frac{|\mathbf{h}_k^{\perp}\mathbf{w}_k|^2}{\sum_{j\neq k}|\mathbf{h}_k^{\perp}\mathbf{w}_j|^2 + N_0}$$

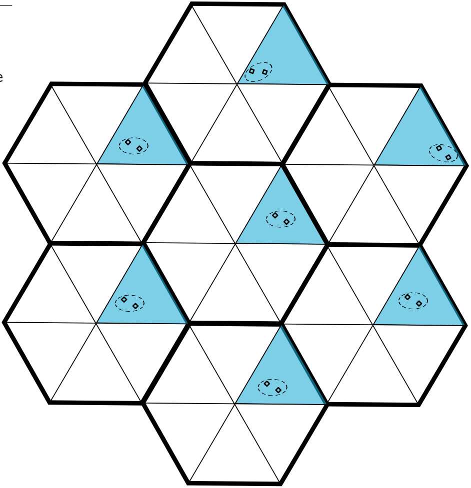
- **SINR absolute error in dB**

$$\boxed{e_k = 10\log_{10}\widehat{\text{sinr}}_k - 10\log_{10}\text{sinr}_k}$$

Simulated System Parameters

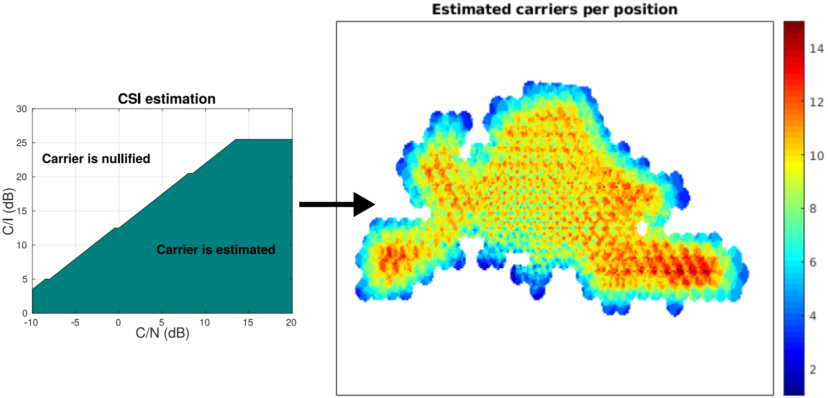
Parameter	Value
Satellite orbit	GEO
Downlink frequency	Ka-band (20 GHz)
Number of beams	245
Color scheme	Full frequency reuse
Fading	No fading / Rice
Multicast groups size	2
Sectors per beam S	1, 4 or 6



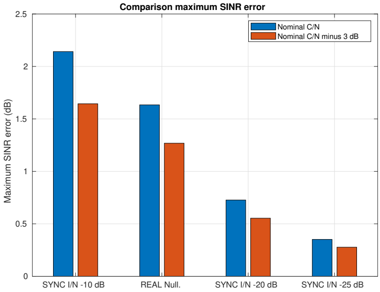


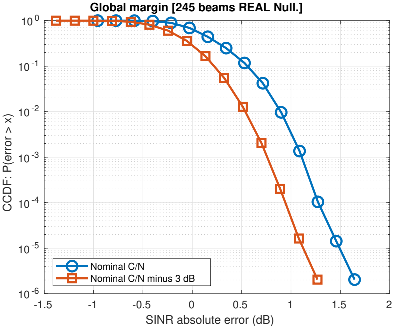
Number of Estimated Channel Coefficients

- Total number of coefficients per channel vector = **245**
- DVB-S2X standard allows to report up to **32** coefficients
- Number of estimated coefficients with nullification: **1-15**



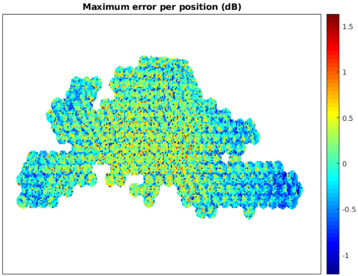
SINR Absolute Error (Aggregated Results)

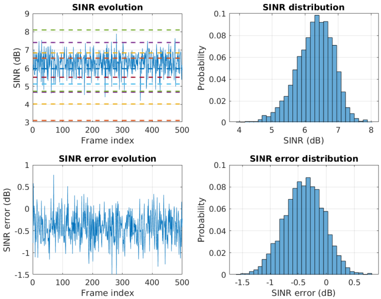




- Averaging more pilots reduces the nullification threshold and the errors
- CCDF allows to obtain the margin for a given target FER

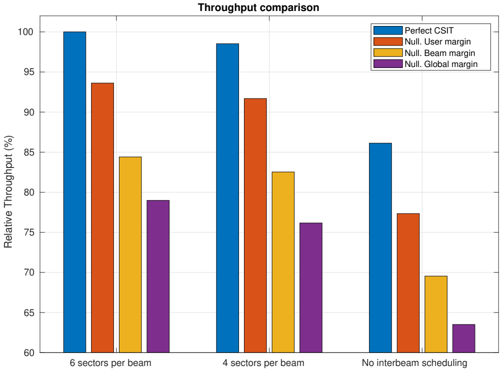
SINR Absolute Error at a Fixed Position





- Error much lower than the maximum in the vast majority of the positions
- Stationary behavior of SINR and SINR error

System Throughput and Back-off Margin

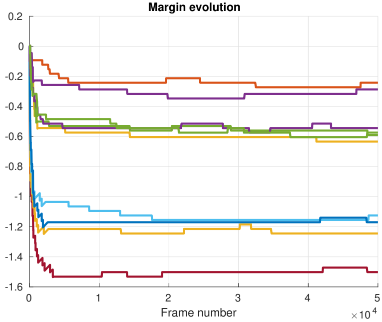


- **Global margin**: 79 % throughput
- **Margin per beam**: 84 % throughput
- **Margin per user**: 94 % throughput

Nullification Countermeasure: Adaptive Margin per User

[1] R. A. Delgado, K. Lau, R. Middleton, R. S. Karlsson, T. Wigren, and Y. Sun. *Fast convergence outer loop link adaptation with infrequent updates in steady state*. In 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall).

- **Simulations**
  - Without fading
  - Rice fading $K = 25$ dB (terrestrial)
  - Rice fading $K = 34$ dB (aeronautical)
- **Experimental FER**
  - 80-120 % of the target FER



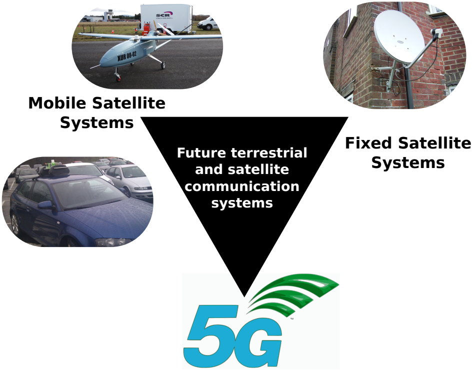
Conclusions

- The practical problem of the nullification in multibeam precoded systems was analyzed
- A solution based on a link adaptation algorithm was proposed
- The adaptive margin per user allows to meet the FER constraint with a small impact on the throughput of the system

Outline

Chapter 4

Evaluation of the Spatial Modulation Transmission Capacity



Mobile Satellite Systems

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Future terrestrial and satellite communication systems

Publications

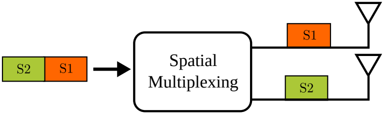
27th EUSIPCO 2019 European Signal Processing Conference A Coruña, Spain, September 2-6, 2019

IEEE TRANSACTIONS ON COMMUNICATIONS

(submitted, under revision)

What is Spatial Modulation?

Spatial Multiplexing (SMux)



- N_t Radio Frequency (RF) chains
- Max. spectral efficiency:

$$\eta = N_t \log_2 M$$

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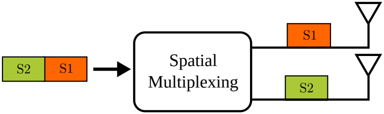

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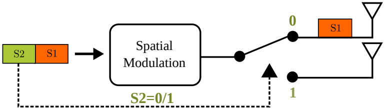

- One RF chain
- Max. spectral efficiency:

$$\eta = \log_2 N_t + \log_2 M$$

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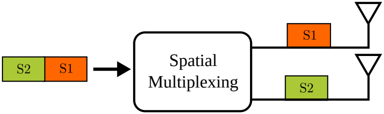

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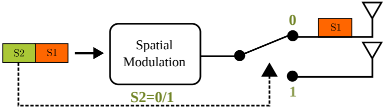
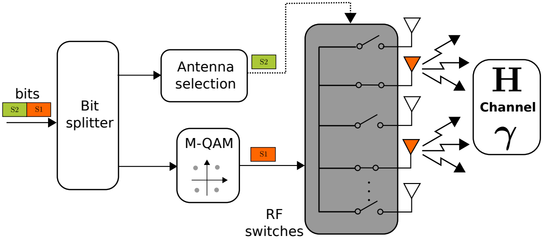


- One RF chain
- Max. spectral efficiency:

$$\eta = \log_2 N_t + \log_2 M$$

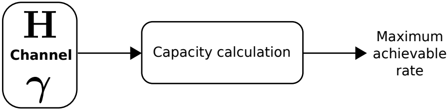


Generalized Spatial Modulation (GSM)

- $R < N_t$ RF chains
- Max. spectral efficiency:

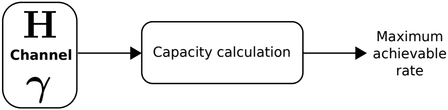
$$\eta = \left\lfloor \log_2 \binom{N_t}{R} \right\rfloor + \log_2 M$$

Problem Formulation



- **Applications:**
  - Adaptation of transmission bit rate in adaptive (G)SM systems
  - Theoretical performance evaluation of (G)SM systems

Problem Formulation



- **Applications:**
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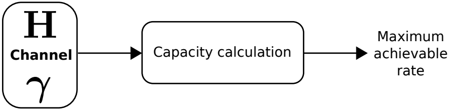
- **Solutions in the literature:**
  - Expressions for obtaining the capacity with numerical integration
  - Two analytical approximations of the SM capacity
- **Comparison:**
  - **Numerical integration:** accurate but very time consuming
  - **Approximations:** reduce notably the time calculation but less accurate

Problem Formulation



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- **Comparison:**
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- **Our proposal:**

Machine Learning (ML) based capacity calculation

System Model

- **SM:**

$$\mathbf{y} = \sqrt{\gamma} \cdot \mathbf{H} \cdot \mathbf{x} + \mathbf{w} \ = \ \sqrt{\gamma} \cdot \mathbf{h}_l \cdot s + \mathbf{w}$$

$\mathbf{h}_l$: Column of the channel matrix $\mathbf{H}$, $l = 1,\ 2, \ldots, N_t$

System Model

- **SM:**

$$\mathbf{y} = \sqrt{\gamma} \cdot \mathbf{H} \cdot \mathbf{x} + \mathbf{w} \;=\; \sqrt{\gamma} \cdot \mathbf{h}_l \cdot s + \mathbf{w}$$

$\mathbf{h}_l$: Column of the channel matrix $\mathbf{H}$, $l = 1,\ 2, \ldots, N_t$

- **GSM:**

$$\mathbf{y} = \sqrt{\gamma/R} \cdot \mathbf{H} \cdot \mathbf{x} + \mathbf{w} \;=\; \sqrt{\gamma/R} \cdot \mathbf{H} \cdot \mathbf{A}_l \cdot \mathbf{1} \cdot s + \mathbf{w}$$

$\mathbf{A}_l$: Antenna activation pattern matrix from the set $\mathcal{A}$

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}^T$$

Set of $L = |\mathcal{A}| = 2^{\lfloor \log_2 \binom{N_t}{R} \rfloor}$ matrices

Sum of R columns of $\mathbf{H}$: $\mathbf{c}_l = \sqrt{\gamma/R} \cdot \mathbf{H} \cdot \mathbf{A}_l \cdot \mathbf{1}$

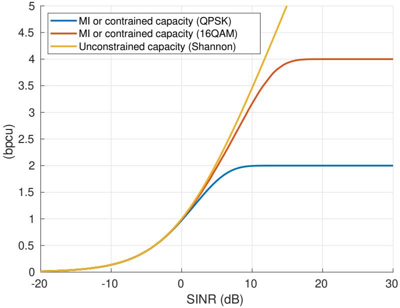
Mutual Information and Capacity Expressions

- **Mutual Information (MI) or constrained capacity of SM:**

$$I_T = \log_2(2M) - \frac{1}{2M}\sum_{s\in\mathcal{S}}\sum_{l=1}^{2}\mathbb{E}_{\mathbf{w}}\left\{\log_2\left(\sum_{s'\in\mathcal{S}}\sum_{l'=1}^{2} e^{-\gamma\left\|\mathbf{h}_l s - \mathbf{h}_{l'} s' + \frac{\mathbf{w}}{\sqrt{\gamma}}\right\|^2 + \|\mathbf{w}\|^2}\right)\right\}$$

- **Capacity of GSM:**

$$C_{\mathrm{GSM}} = -\frac{1}{L}\sum_{i=1}^{L}\int_{\mathbf{y}}\mathcal{CN}(\mathbf{0},\mathbf{\Phi}_i)\log_2\left(\frac{1}{L}\sum_{j=1}^{L}\mathcal{CN}(\mathbf{0},\mathbf{\Phi}_j)\right)d\mathbf{y} - \log_2\det(\pi e I_{N_r})$$

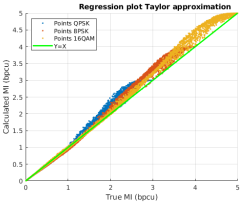


Analytical Approximations to the SM MI

- **Taylor approximation**

  Henarejos et al.

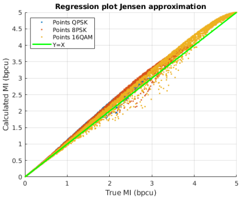
$$I_{T_{\text{Taylor}}} = \log_2\left(\frac{2M}{\mathfrak{G}(\mathcal{D}_{sl})}\right) + \\ + \mathfrak{A}\left(\frac{\log_2\left(\mathfrak{G}_{sl}\left({D_{s,l,s',l'}}^{D_{s,l,s',l'}}\right)\right)}{\mathfrak{A}_{sl}\left(D_{s,l,s',l'}\right)} + \frac{\gamma}{\log(2)\mathcal{D}_{sl}^2}\sum_{m=1}^{2}\left(\mathcal{D}^2_{m,sl,\Re} + \mathcal{D}^2_{m,sl,\Im}\right)\right)$$



- **Jensen approximation**

  Guo et al.

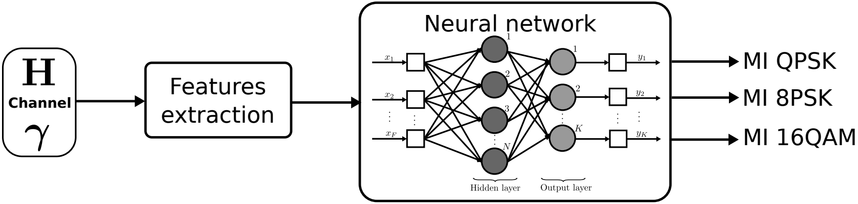
$$I_{T_{\text{Jensen}}} = -\log_2\left(\frac{\sum_{\Delta_x \in \mathcal{D}} e^{-\frac{1}{2}\Delta_x^H \mathbf{H}^H \mathbf{H} \Delta_x}}{(2M)^2}\right)$$



- **Drawbacks of these approximations:**
  - Biased and limited accuracy
  - Complexity scales with the square of the constellation size M and the number of antennas N_t
  - Calculation for a single constellation

Proposed Solution

- **Spatial Modulation**



$\mathbf{H}$
Channel
γ

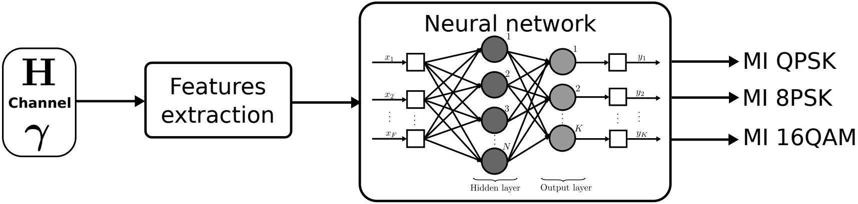
Features extraction

Neural network

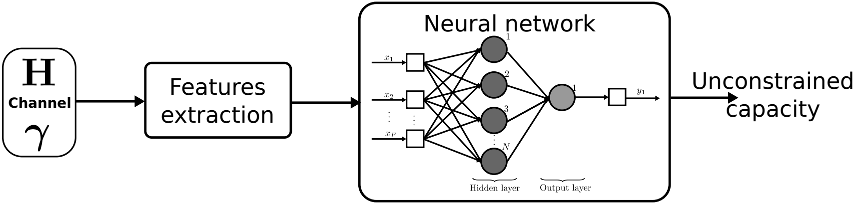
MI QPSK
MI 8PSK
MI 16QAM

Proposed Solution

- **Spatial Modulation**

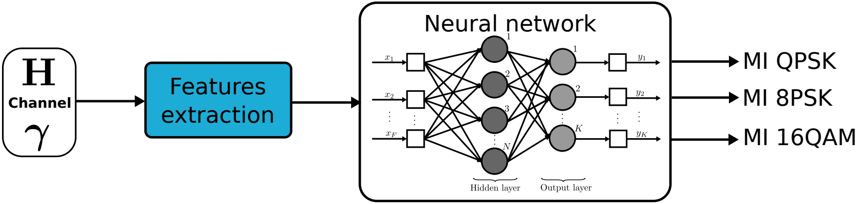


- **Generalized Spatial Modulation**



Proposed Solution

- **Spatial Modulation**



$\mathbf{H}$ **Channel** γ

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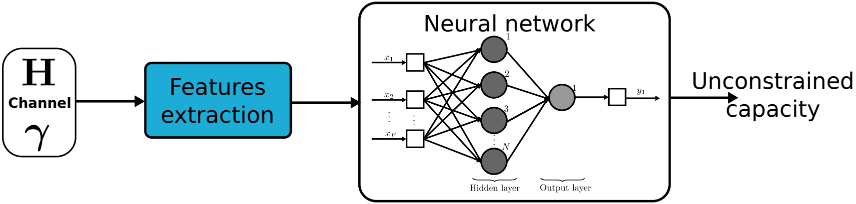


$\mathbf{H}$ **Channel** γ

Features extraction

Neural network

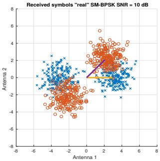
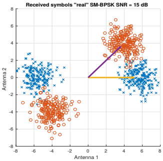
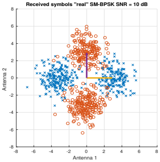
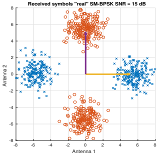
Unconstrained capacity

Features selection for 2 × 2 SM

$$\mathcal{X} = \{\mathbf{h}_l \cdot s_k\} \longrightarrow \mathbf{D} = \{\|\mathbf{h}_l s_k - \mathbf{h}_{l'} s_{k'}\|^2\} = \begin{pmatrix} \|\mathbf{h}_1\|^2 \mathbf{D}_S & \mathbf{D}_L \\ \mathbf{D}_L^t & \|\mathbf{h}_2\|^2 \mathbf{D}_S \end{pmatrix}$$

$\mathbf{D}_L$ can be characterized with four real values: $\|\mathbf{h}_1\|^2$, $\|\mathbf{h}_2\|^2$ and $\mathbf{h}_1^H \mathbf{h}_2$

$$\mathbf{h}_1^H \mathbf{h}_2 = \|\mathbf{h}_1\| \cdot \|\mathbf{h}_2\| \cdot \cos\Theta_H \cdot e^{i\varphi}, \quad \begin{cases} \Theta_H \in [0, \pi/2] \longrightarrow \text{Hermitian angle} \\ \varphi \in [-\pi, \pi] \rightarrow \text{Kasner's pseudoangle} \end{cases}$$

	Moderate SNR	**High SNR**
Non orthogonal	 Received symbols "real" SM-BPSK SNR = 10 dB	 Received symbols "real" SM-BPSK SNR = 15 dB
Orthogonal	 Received symbols "real" SM-BPSK SNR = 10 dB	 Received symbols "real" SM-BPSK SNR = 15 dB

Generalization for More Antennas and GSM

- **Features for GSM**

$$\mathcal{X} = \{\mathbf{H} \cdot A_l \cdot \mathbf{1} \cdot s_k\}$$

$$\mathbf{h}_l \longrightarrow \mathbf{c}_l = \sqrt{\gamma/R} \cdot \mathbf{H} \cdot \mathbf{A}_l \cdot \mathbf{1}$$

- **Number of features**

	# norms	**# pairs of angles**
SM	N_t	$\binom{N_t}{2}$
GSM	$L = 2^{\lfloor \log_2 \binom{N_t}{R} \rfloor}$	$L_2 = \binom{L}{2}$

	# norms	**# pairs of angles**
SM 8×8	8	28
GSM 8×8, $R = 2$	16	$L_2 = 120$

- **Features reduction**
  - Characterize norms and angles distribution with Q quantiles, equispaced in [0,1]
  - Example Q=5:
    - Minimum, 25th percentile, median, 75th percentile, maximum

Simulations setup

- **Supervised learning**
- **ML dataset**
  - $50,000$ Rayleigh distributed random matrices $h_{ij} \sim \mathcal{CN}(0,1)$
  - SNR γ ∼U($-20, 20$) dB
  - 70 % training, 15 % validation, 15 % testing
- **Calculation reference values of MI and capacity**
  - Monte Carlo simulation with $5,000$ realizations of the noise $\mathbf{w}$
  - Variance in the estimation $\sim 10^{-5}$
- **Learning algorithm**
  - Levenberg-Marquardt (LM) backpropagation algorithm
  - MSE as cost function
  - Random initialization of weights and margins
- **Architecture**
  - One hidden layer of 10 or 20 neurons with sigmoid activation function
  - Linear output

Simulation Results: MI of 2 × 2 SM

- **Impact of different input features**

Option	**# Features**	**Global MSE**
i) Column norms and scalar product	4	$6.98 \cdot 10^{-4}$
ii) Column norms and angles	4	$3.36 \cdot 10^{-4}$
iii) Column norms and distances	6	$5.21 \cdot 10^{-5}$
iv) Column norms, distances and scalar product	8	$4.96 \cdot 10^{-5}$
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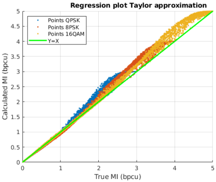

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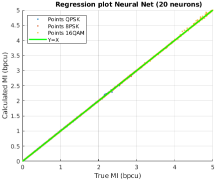

	Global MSE	QPSK	
		3σ	Max. error
Taylor approximation	$1.87 \cdot 10^{-2}$	0.330	0.523
Jensen based approximation	$1.21 \cdot 10^{-2}$	0.229	0.300
Neural network	$\mathbf{2.97 \cdot 10^{-5}}$	**0.016**	**0.067**

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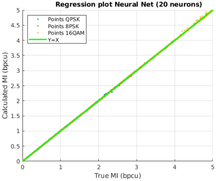

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- **Computational complexity**

	Taylor approx.	Jensen approx.	Neural network
Real products	$7,168$	$32,800$	**368**
Non linear operations	784	$1,347$	**20**

Generalization

- **MI of SM with 4 and 8 antennas**

	# features	**Global MSE**
SM 2×2 option (ii)	4	$3.36 \cdot 10^{-4}$
SM 4×4	16	$2.40 \cdot 10^{-4}$
SM 8×8 (Q $=$ 5)	18	$5.06 \cdot 10^{-5}$

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  - Global MSE $7.40 \cdot 10^{-5}$

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- **Dual Polarization Mobile Satellite Channel: PMod**
  - Global MSE $7.40 \cdot 10^{-5}$
- **Correlated channels**
  - Performance degrades with increasing correlation
- **Capacity of GSM**
  - **Studied scenarios**
    - SM with 2, 4 and 8 antennas
    - GSM with 6 and 8 antennas and 2 or 3 RF chains
  - **Results**
    - **MSE** $\sim 10^{-4}$
    - **3σ** ~ 0.05
    - **Number of neural network inputs:** 4 - 27

Conclusions

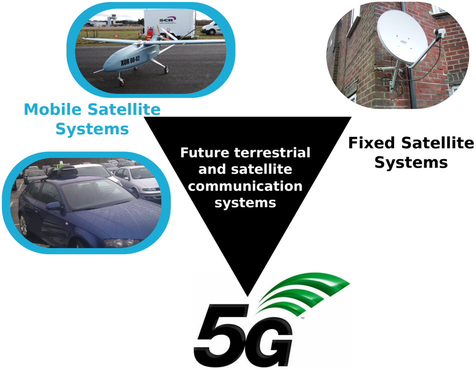
- A Machine Learning-based solution was proposed for obtaining the capacity of SM and GSM systems
- Simple neural networks outperform approximations of the literature both in terms of accuracy and complexity
- The fast and accurate calculation can find applications in adaptive SM systems

Outline

1. Motivation
2. Mobile Satellite System: Field Trial Results
3. Multibeam Satellite Systems with Linear Precoding
4. Spatial Modulation Transmission Capacity
5. Mobile Satellite Systems with Dual Polarization
6. Spatial Modulation Systems
7. Conclusions

Chapter 5

Link Adaptation in Mobile Satellite Systems with Dual Polarization



Mobile Satellite Systems

Future terrestrial and satellite communication systems

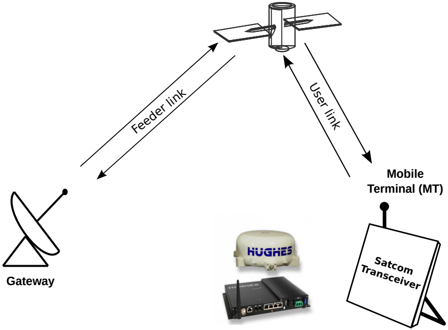
Fixed Satellite Systems

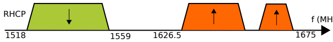
Publications

WiSATS2017
Wireless and SATellite Systems

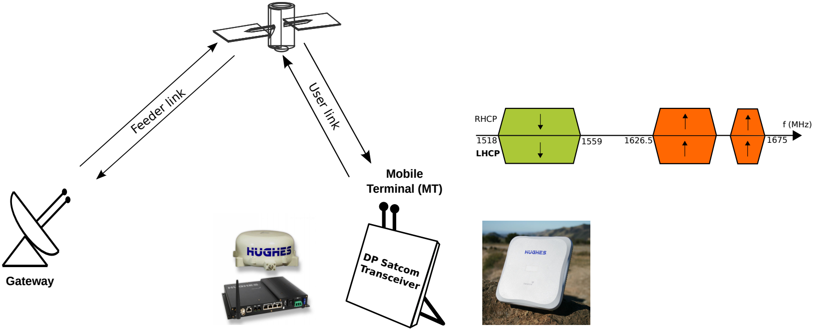
Biennial since 1998
CSNDSP
2018
11th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing
18–20 July 2018 | Budapest, Hungary

Introduction





Introduction



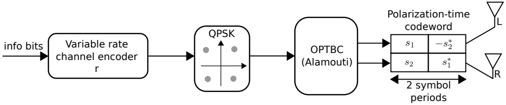
- Link adaptation in...
- Mobile Satellite Communications with Dual Polarization (DP)
  - L-band (1-2 GHz) and S-band (2-4 GHz)
  - RHCP and LHCP as a 2 × 2 MIMO
  - Several MIMO modes and MCS available

Four Available MIMO Modes

- **SISO**

Four Available MIMO Modes

- **SISO**
- **Orthogonal Polarization-Time Block Code (OPTBC)** ∼ Alamouti



Four Available MIMO Modes

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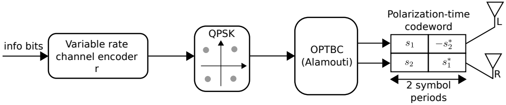
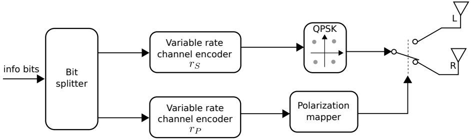


- **Polarized Modulation (PMod)** $\sim$ Spatial Modulation (SM)



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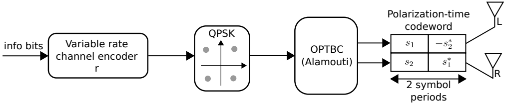

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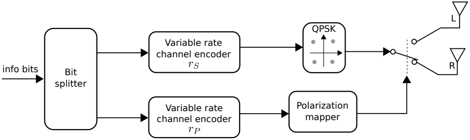
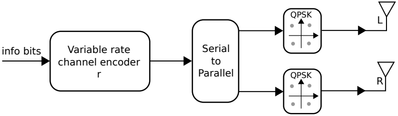
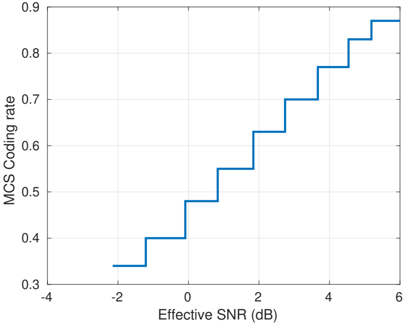


- **Vertical-Bell Lab. Layered Space-Time (V-BLAST)** ∼ Spatial Multiplexing



Modulation and Coding Schemes (MCS)

- QPSK constellation
- 9 coding rates for symbols bits (SISO, OPTBC, PMod, V-BLAST)



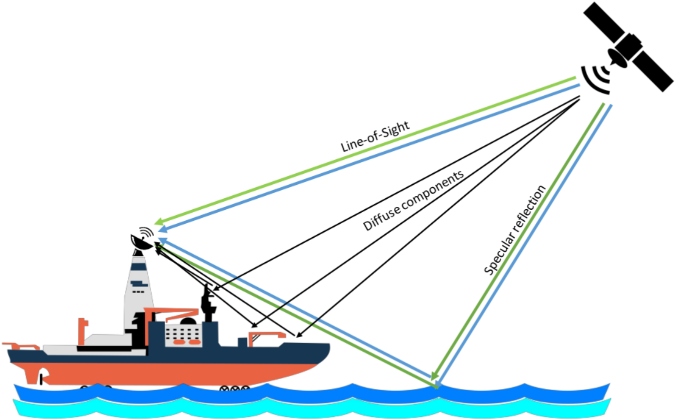
- 9 coding rates for polarization bits of PMod

Coding rate	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

Channel Generation

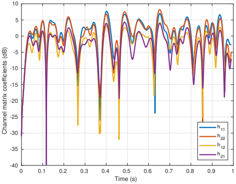
- M. Sellathurai et al., "Space-time coding in mobile satellite communications using dual-polarized channels", IEEE Transactions on Vehicular Technology, Jan 2006

$$\mathbf{H} = \beta e^{j\phi}\mathbf{K}_L + \xi e^{j\phi}\mathbf{K}_S + \mathbf{D}\mathbf{K}_D$$

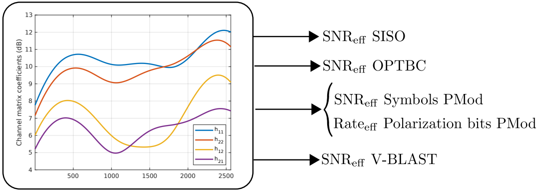


Physical Layer Abstraction

1. **Channel generator:** $\{\mathbf{H}_n,\ n = 1, 2, \ldots, N\}$



2. **SINR calculation per received symbols**
   - Different equation for each MIMO mode
3. **SINR compression**



SNR_{eff} SISO

SNR_{eff} OPTBC

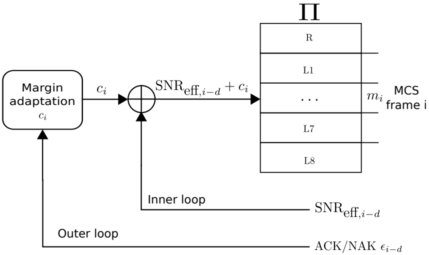
SNR_{eff} Symbols PMod

Rate_{eff} Polarization bits PMod

SNR_{eff} V-BLAST

Link Adaptation Algorithms

- **MIMO mode selection**
    - Mode which maximizes spectral efficiency
    - By the receiver
- **MCS selection**
    - Using LUT with adaptive margins
    - By the transmitter
    - **PMod**: two LUTs (independent coding rates for symbols and polarization)



SISO, OPTBC, V-BLAST. PMod (symbols bits)

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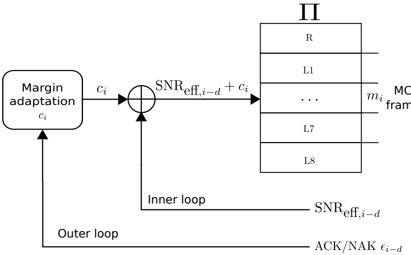
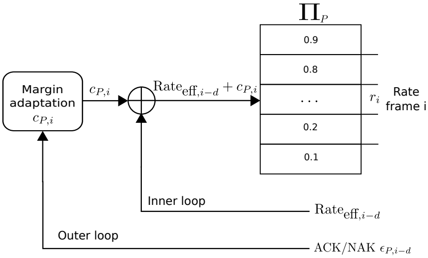


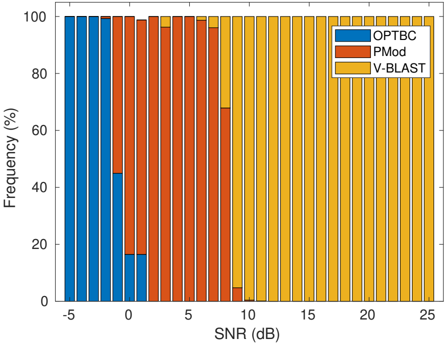
SISO, OPTBC, V-BLAST. PMod (symbols bits)



PMod (polarization bits)

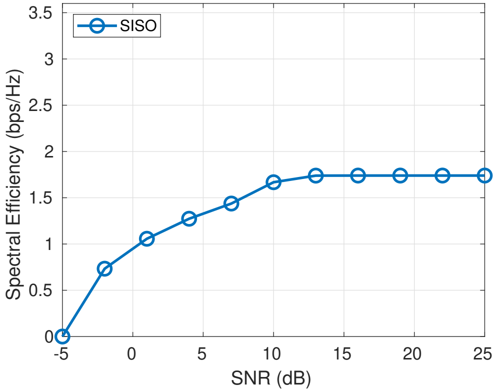
MIMO Mode

- **Selected mode**



- **Very low SNRs:** OPTBC ($\sim$ Transmit diversity)
- **Low SNRs:** PMod
- **Moderate and high SNRs:** V-BLAST ($\sim$ Spatial Multiplexing)

Spectral Efficiency



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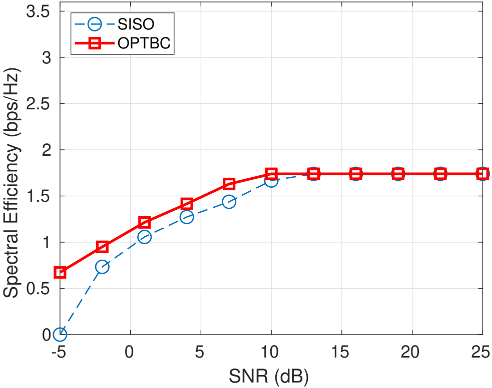
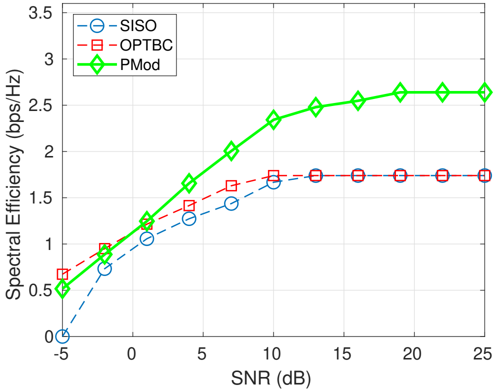


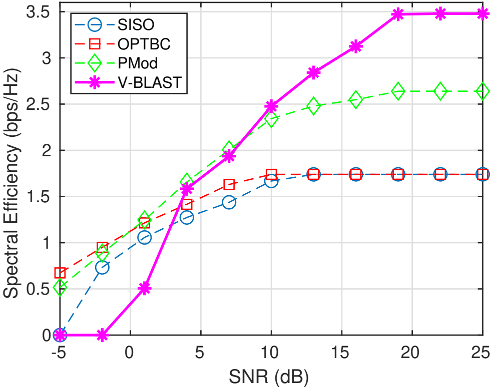
- Operation at lower SNRs and better spectral efficiency

Spectral Efficiency



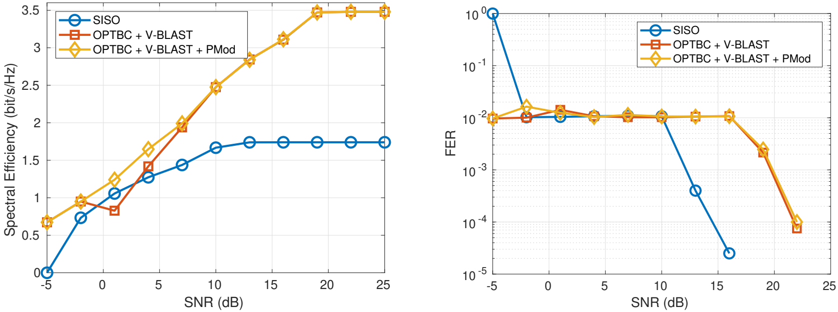
- + 50 % spectral efficiency

Spectral Efficiency



- + 100 % spectral efficiency

Spectral Efficiency and Frame Error Rate



- Inclusion of PMod improves efficiency at low SNRs
- Target FER is satisfied

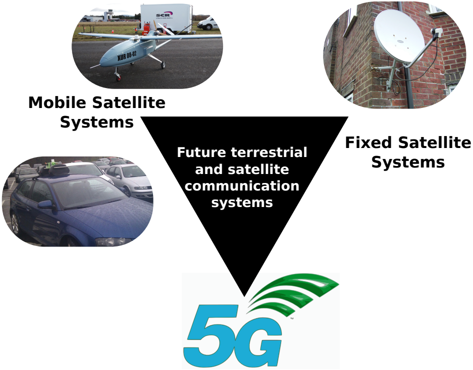
Conclusions

- Higher rates can be achieved by exploiting both polarizations
- MIMO mode and MCS can be adjusted
- Polarized Modulation increases spectral efficiency at low SNRs

Outline

Chapter 6

Deep Learning Assisted Rate Adaptation in Spatial Modulation Links



Publications

ISWCS 2019

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27-30 August 2019
Oulu, Finland

Introduction

- **Spatial Modulation**
  - New modulation scheme for 5G and beyond 5G
  - Multi-antenna: high spectral efficiency
  - Low complexity: single RF chain
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- **Coding rate selection mechanism for adaptive SM systems**
  - Supervised learning
  - Deep neural network
- **SM rate adaptation problem**

$$\begin{aligned} \underset{r}{\text{maximize}} \quad & r \log_2(N_t M) \\ \text{subject to} \quad & r \in \{r_1, r_2, \ldots, r_K\} \\ & \mathrm{BER}(\gamma; r, \mathbf{H}) \leq p_0. \end{aligned} \tag{4}$$

Block Diagram of an Adaptive SM System

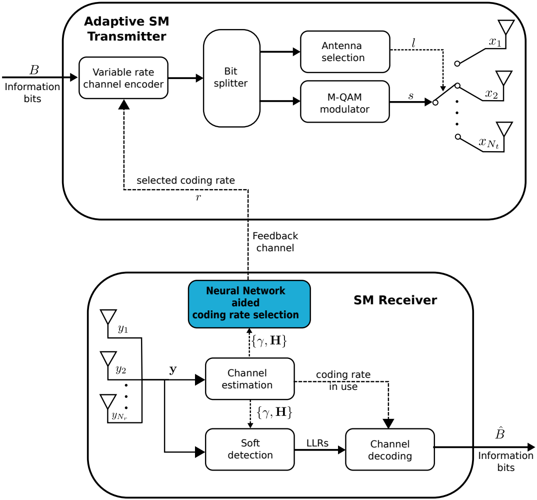

Figure 1: Block diagram of an adaptive SM system with variable coding rate.

DL-based Coding Rate Selection

1. **Evaluation of the performance of the channel codes**
   System level simulations

$$\mathrm{BER}(\gamma;\ r, \mathbf{H})$$

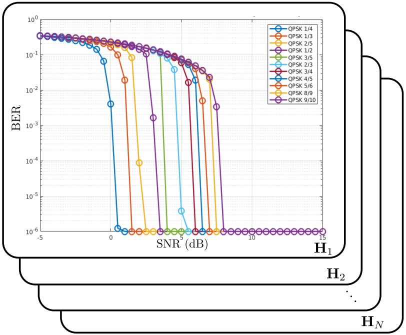

Figure 2: The different channel codes performance must be evaluated for a large number of channel matrices.

DL-based Coding Rate Selection

2. **Extraction of the SNR thresholds**

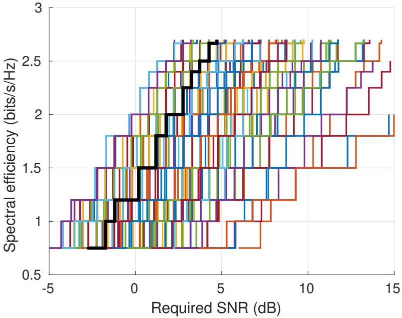

Figure 3: The minimum required SNR to guarantee a given BER p_0 with each coding rate for a set of 20 different channel matrices.

DL-based Coding Rate Selection

3. **Building the dataset for Machine Learning**
   - Dataset $\mathbb{X} = \{(\mathbf{x}_i, \mathrm{y}_i), i = 1, 2, \ldots, m\}$
   - Neural network input features:
     $$\mathbf{x} = g(\gamma, \mathbf{H}) = \left[\mathrm{sort}\left(\gamma\|\mathbf{h}_1\|^2,\ \gamma\|\mathbf{h}_2\|^2\right),\ \ \Theta_H,\ \ \varphi\right]^t$$
   - Neural network output variable: $\mathrm{y} = r_k$ (target coding rate)

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4. **Neural network training**
   - Training (70 %) and validation (15 %) datasets

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5. **Performance evaluation**
   - Testing dataset (15 %)
   - Confussion matrix: accuracy, rate of under-selection, outage probability

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   - Training (70 %) and validation (15 %) datasets
5. **Performance evaluation**
   - Testing dataset (15 %)
   - Confussion matrix: accuracy, rate of under-selection, outage probability
6. **Operation phase**
   - Coding rate selection with fixed neural network parameters $\boldsymbol{\theta}$

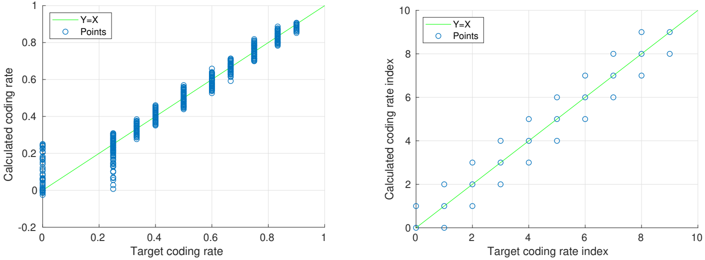
Simulated System Parameters

- SM 2 × 2 with QPSK constellation and 9 coding rate options

Paramter	**Value**
Transmit and receive antennas	$N_t = 2,\ N_r = 2$
Constellation	QPSK ($M = 4$)
Channel coding	DVB-S2 codes (BCH + LDPC)
Coding rate options	1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 5/6, 9/10
Target BER	$p_0 = 10^{-4}$
Channel matrices	1000 Rayleigh ditributed
SNR range	−5 to 15 dB (0.5 dB steps)

- Neural network configuration
  - Three hidden layers: 20+15+10 neurons
  - Activation function: tangent hyperbolic
  - Output layer: linear

Classification Performance



	Margin	
	$\Delta = 0$	**$\Delta = 0.03$**
Mean accuracy	96.2 %	80.0 %
Outage	2.0 %	0 %
Underselection	1.7 %	19.8 %

SM Link Adaptation

- **Fixed coding rate**

$$r = r_k, \quad \text{for some fixed } k. \tag{5}$$

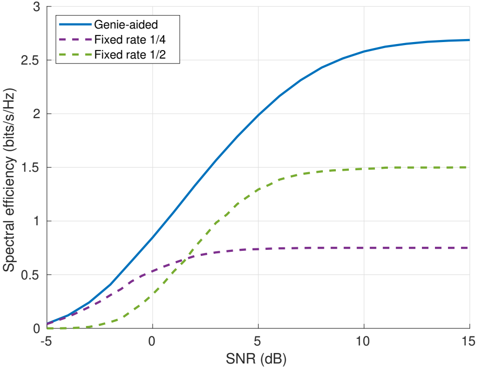
- **MI-based coding rate selection**

$$r = Q\left(\frac{I_T - \Delta}{3}\right) = \arg\min_{r_k} \left|\frac{I_T - \Delta}{3} - r_k\right|, \tag{6}$$

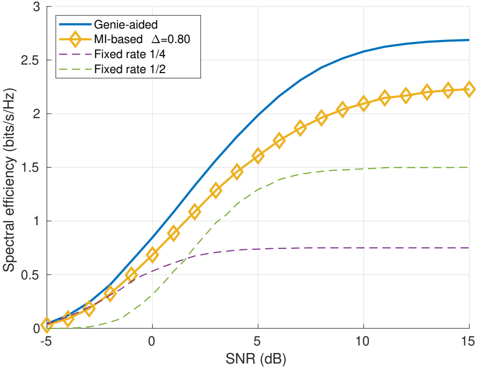
- **DL-based coding rate selection**

$$r = Q\left(\hat{\mathrm{y}} - \Delta\right) = \arg\min_{r_k} \left|\hat{\mathrm{y}} - \Delta - r_k\right|. \tag{7}$$

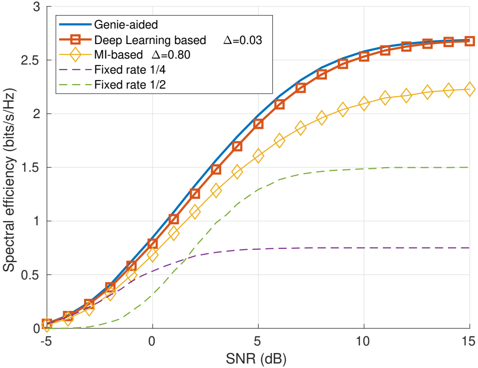
Spectral Efficiency



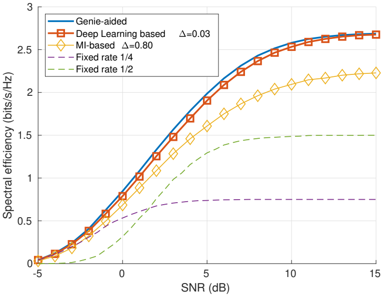
Spectral Efficiency

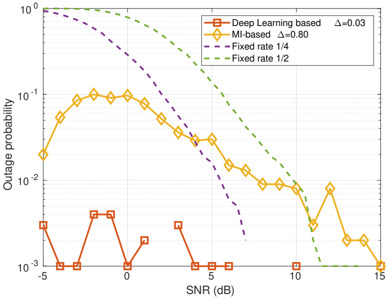


Spectral Efficiency



Spectral Efficiency and FER



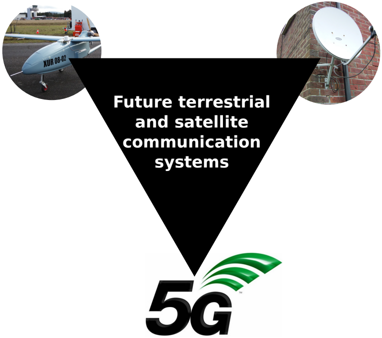


Conclusions and Future Work

- **Conclusions**
  - Neural networks can be used to select the coding rate in adaptive SM systems
  - The spectral efficiency is very close to the maximum achievable value
- **Future work**
  - Extension to more general scenarios: more antennas and several constellations
  - Online adaptation of the neural network during the operation

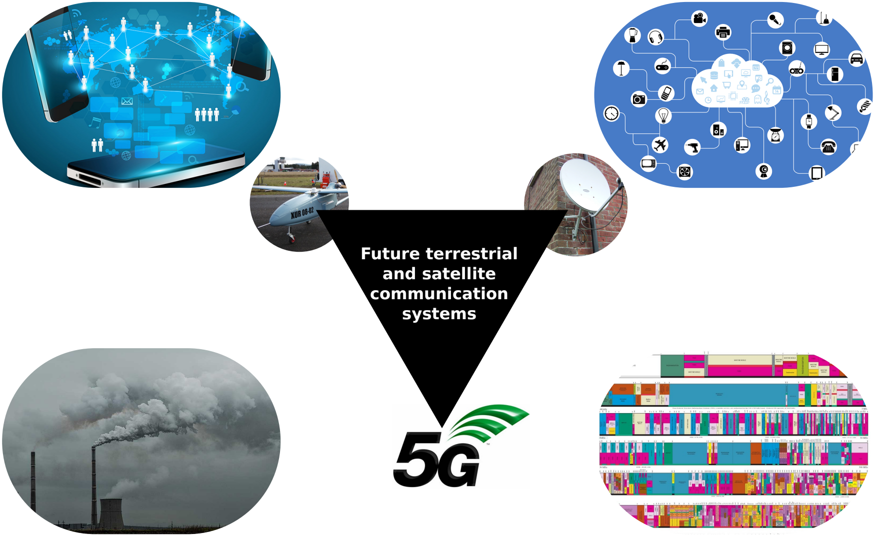
Outline

Conclusions



Future terrestrial and satellite communication systems

Conclusions



Future terrestrial and satellite communication systems

Thanks for your attention!

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Link Adaptation Techniques for Future Terrestrial and Satellite Communications