





Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation

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CTTC, Barcelona, Spain October 4, 2013

Outline

- 1. Introduction and Motivation behind SM-MIMO
- 2. History of SM Research and Research Groups Working on SM
- 3. Transmitter Design Encoding
- 4. Receiver Design Demodulation
- 5. Error Performance (Numerical Results and Main Trends)
- 6. Achievable Capacity
- 7. Channel State Information at the Transmitter
- 8. Imperfect Channel State Information at the Receiver
- 9. Multiple Access Interference
- 10. Energy Efficiency
- 11. Transmit-Diversity for SM
- 12. Spatially-Modulated Space-Time-Coded MIMO
- 13. Relay-Aided SM
- 14. SM in Heterogeneous Cellular Networks
- 15. SM for Visible Light Communications
- 16. Experimental Evaluation of SM
- 17. The Road Ahead Open Research Challenges/Opportunities
- 18. Implementation Challenges of SM-MIMO

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□ Array gain (beamforming), spatial division multiple access

□ Spatial multiplexing: Rate = $min(N_t, N_r)log_2(1+SNR)$

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\Box Reliability: BEP \sim SNR^{-(NtNr)}
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Very Good, But...



- Regardless of the use as diversity or spatial multiplexing system, the main drawback of conventional MIMO systems is the increased complexity, increased power/energy consumption, and high cost. Why?
 - Inter-channel interference (ICI): Introduced by coupling multiple symbols in time and space – signal processing complexity.
 - Inter-antenna synchronization (IAS): Detection algorithms require that all symbols are transmitted at the same time.
 - Multiple radio frequency (RF) chains: RF elements are expensive, bulky, no simple to implement, and do not follow Moore's law.
 - Energy consumption: The energy efficiency decreases linearly with the number of active antennas (RF chains) and it mostly depends on the Power Amplifiers (>60%) – EARTH model. 6

Conventional vs. Single-RF MIMO

Conventional MIMO



A. Mohammadi and F. M. Ghannouchi, "Single RF Front-End MIMO Transceivers", IEEE Commun. Mag., Vol. 49, No. 12, pp. 104-109, Dec. 2011. 7

The Energy Efficiency (EE) Challenge (1/3)





Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green Cellular Networks: A Survey, Some Research Issues and Challenges", IEEE Commun. Surveys & Tutorials, Vol. 13, No. 4, pp. 524-540, Nov. 2011. 8

The Energy Efficiency (EE) Challenge (2/3)



Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green Cellular Networks: A Survey, Some Research Issues and Challenges", IEEE Commun. Surveys & Tutorials, Vol. 13, No. 4, pp. 524-540, Nov. 2011. 9



S. D. Gray, "Theoretical and Practical Considerations for the Design of Green Radio Networks", IEEE VTC-2011 Spring, Budapest, Hungary, May 2011.

3GPP TSG-RAN WG2 #67, "eNB power saving by changing antenna number", R2-094677 from Huawei: http://www.3gpp.org/ftp/tsg_ran/WG2_RL2/TSGR2_67/Tdoclist/History/ADN_Tdoc_List_RAN2_67.htm.

Static Power: How Much Is It Important ?(1/2)

MIMO Gain WITHOUT Considering Circuit Power



Fig. 6. MIMO vs. SISO EE gain against the SE when considering the theoretical PCM.

Fig. 8. MIMO vs. SISO EE gain against the number of antenna elements $n_{\text{ant}} = t = r$ when considering the theoretical PCM.

F. Heliot, M. A. Imran, and R. Tafazolli, "On the energy efficiency-spectral efficiency trade-off over the MIMO rayleigh fading channel", IEEE Trans. Commun., vol. 60 n. 5, pp. 1345-1356, May 2012.

Static Power: How Much Is It Important ?(2/2)

MIMO Gain Considering Circuit Power



Fig. 7. MIMO vs. SISO EE gain against the SE for different types of BS when considering the double linear PCM of (6).

Fig. 9. MIMO vs. SISO EE gain against the number of antennas $n_{ant} = t = r$ for different types of BS when considering the double linear PCM of (6).

F. Heliot, M. A. Imran, and R. Tafazolli, "On the energy efficiency-spectral efficiency trade-off over the MIMO rayleigh fading channel", IEEE Trans. Commun., vol. 60 n. 5, pp. 1345-1356, May 2012.

SE vs. EE Tradeoff (1/2)

- □ SE-oriented systems are designed to maximize the capacity under peak or average power constraints, which may lead to transmitting with the maximum allowed power for long periods, thus deviate from EE design.
- □ EE is commonly defined as information bits per unit of transmit energy. It has been studied from the information-theoretic perspective for various scenarios.
- □ For an additive white Gaussian noise (AWGN) channel, it is well known that for a given transmit power, P, and system bandwidth, B, the channel capacity is:

$$R = (1/2)\log_2\left(1 + \frac{P}{N_0B}\right) = (1/2)\eta_{SE}$$

□ bits per real dimension or degrees of freedom (DOF), where N_0 is the noise power spectral density. According to the Nyquist sampling theory, DOF per second is 2B. Therefore, the channel capacity is C = 2BR b/s. Consequently, the EE is:

$$\eta_{EE} = \frac{C}{P} = \frac{2R}{N_0 \left(2^{2R} - 1\right)} = \frac{\eta_{SE}}{N_0 \left(2^{\eta_{SE}} - 1\right)}$$

□ It follows that the EE decreases monotonically with R (i.e., with SE).

Y. Chen et al., "Fundamental Tradeoffs on Green Wireless Networks", IEEE Commun. Mag., vol. 49, no. 6, pp. 30–37, June 2011.

SE vs. EE Tradeoff (2/2)



G. Y. Li et al., "Energy-Efficient Wireless Communications: Tutorial, Survey, and Open Issues", IEEE Wireless Commun. Mag., Vol. 18, No. 6, pp. 28-35, Dec. 2011.

Now, Imagine a New Modulation for MIMOs:

- Having one (or few) active RF chains but still being able to exploit all transmit-antenna elements for multiplexing and transmit-diversity gains
- Offering Maximum-Likelihood (ML) optimum decoding performance with single-stream decoding complexity
- Working without the need of (power inefficient) linear modulation schemes (QAM) or allowing us to use constantenvelope modulation (PSK) with negligible performance degradation

Spatial Modulation (SM) has the inherent potential to meet these goals

SM – In a Nutshell



SM – How It Works (3D Constellation Diagram)



M. Di Renzo, H. Haas, and P. M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems - A Survey", IEEE Communications Magazine, Vol. 49, No. 12, pp. 182-191, December 2011. 17

SM – How It Works (1/3)



M. Di Renzo, H. Haas, and P. M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems - A Survey", IEEE Communications Magazine, Vol. 49, No. 12, pp. 182-191, December 2011. 18

SM - How It Works (2/3)



M. Di Renzo, H. Haas, and P. M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems - A Survey", IEEE Communications Magazine, Vol. 49, No. 12, pp. 182-191, December 2011. 19

SM – How It Works (3/3)



M. Di Renzo, H. Haas, and P. M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems - A Survey", IEEE Communications Magazine, Vol. 49, No. 12, pp. 182-191, December 2011. 20



SM – Wireless Channel





Common Misunderstandings

- □ What is the difference with Transmit Antenna Selection (TAS)?
 - > TAS is closed-loop (transmit-diversity). SM is open-loop (spatial-multiplexing).
 - > In TAS, antenna switching depends on the end-to-end performance. In SM, antenna switching depends on the incoming bit-stream.
- □ SIMO: $\log_2(M)$ bpcu MIMO: $N_t \log_2(M)$ bpcu SM: $\log_2(N_t) + \log_2(M)$ bpcu. So, SM is spectral efficiency (SE) sub-optimal. Why using it?
 - > Correct. But what about signal processing complexity, cost, total power consumption, and energy efficiency (EE)?
 - > Are we looking for SE-MIMO? For EE-MIMO? Or for a good SE/EE tradeoff?
- □ SM needs many more transmit-antennas than conventional MIMO for the same SE. Is the comparison fair? Is having so many antennas practical?
 - What does fair mean? Same transmit-antennas? Same RF chains?
 - What about massive MIMOs? What about mm-Wave communications?
- □ Due to the encoding mechanism, is SM more sensitive to channel estimation errors than conventional MIMO?
 - ➢ No, it is as/more robust as/than MIMO and we have results proving it. 24

Our Proposal: Single-RF Large-Scale SM-MIMO

- □ The rationale behind SM–MIMO communications for the design of spectral and energy efficient cellular networks is based upon two main pillars:
 - 1) Minimize, given some performance constraints, the number of active antenna-elements in order to increase the EE by reducing the circuit power consumption (single-RF MIMO principle).
 - 2) Maximize, given some implementation and size constraints, the number of passive antenna-elements in order to increase both the SE and the EE by reducing the transmit power consumption (large-scale MIMO principle). This is realized by capitalizing on the multiplexing gain introduced by the "spatial-constellation diagram".

M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation", Proceedings of the IEEE, July 2013 (to appear). [Online]. Available: http://hal.archives-ouvertes.fr/docs/00/84/02/78/PDF/ProcIEEE_SM_FullPaper.pdf. 25

SM for Generalized MIMO



Massive MIMO (1/2)

🔘 GreenTouch

Large Scale Antenna Systems Demonstration



G. Wright "GreenTouch Initiative: Large Scale Antenna Systems Demonstration", 2011 Spring meeting, Seoul, South Korea. Available at: <u>http://www.youtube.com/watch?v=U3euDDr0uvo</u>.
T. L. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas", IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590-3600, Nov. 2010.

Massive MIMO (2/2) – In Formulas

□ Consider a MIMO Multiple Access (MAC - UPLINK) system with N antennas per BS and K users per cell:

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{h}_k x_k + \mathbf{n}$$

where channel and noise are i.i.d. RVs with zero mean and unit variance.

□ By the strong law of large numbers:

$$\frac{1}{N}\mathbf{h}_m^H\mathbf{y} \xrightarrow[N \to \infty]{\text{and } K = \text{const}} \mathbf{x}_m$$

□ Thus, with an unlimited number of BS antennas:

- Uncorrelated interference and noise vanish
- > The matched filter is optimal
- > The transmit power can be made arbitrarily small

T. L. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas", IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590-3600, Nov. 2010.

Massive MIMO vs. SM-MIMO

□ Massive MIMO:

- Many (hundreds or more) transmit-antennas
- All transmit-antennas are simultaneously-active: multi-RF MIMO but antennas are less expensive and more EE than state-of-the-art
- EE: reduction of transmit (RF) power

SM-MIMO:

- Many (hundreds or more) transmit-antennas
- One (or few) transmit-antennas are simultaneously-active: single-RF MIMO
- > EE: reduction of transmit (RF) power <u>and</u> circuits power

Transmission Concepts Related to SM (1/5)

Motivation:

... the mutual information was maximized under an assumption of a <u>limited output</u> <u>power</u>. However, in many applications it is desirable to instead limit the <u>total</u> <u>consumed power</u>, <u>consisting of both output power and losses in the transmitter</u> <u>chain</u>. The scientific literature agrees that the power amplifier is the largest source of losses in the transmitter.

Contribution:

...we utilize the analytic expression of amplifier losses to design MIMO beamforming schemes. We observe that our MISO solution, differently from the traditional MRT beamforming, is such that <u>some antennas in general are turned off</u>.

Takeaway Message:

The proposed procedure allows us to <u>turn off antennas while operating optimally</u>, which is beneficial in cases where dissipated power per antenna is significant. This also gives us the possibility to turn off whole radio frequency chains with filters and mixers, which saves additional power.

D. Persson, T. Eriksson, and E. Larsson, "Amplifier–aware multiple–input multiple–output power allocation", IEEE Commun. Lett., vol. 17, no. 6, pp. 1112-1115, June 2013.

Transmission Concepts Related to SM (2/5)

New multiple antenna designs based on compact parasitic architectures have been proposed to enable multiplexing gains with a single active RF element and many passive antenna elements. The key idea is to change the radiation pattern of the array at each symbol time instance, and to encode independent information streams onto angular variations of the far-field in the wave-vector domain.



A. Kalis, A. G. Kanatas, and C. B. Papadias, "A novel approach to MIMO transmission using a single RF front end", IEEE J. Select. Areas Commun., vol. 26, no. 6, pp. 972–980, Aug. 2008.
O. N. Alrabadi, C. Divarathne, P. Tragas, A. Kalis, N. Marchetti, C. B. Papadias, and R. Prasad, "Spatial multiplexing with a single radio: Proof–of–concept experiments in an indoor environment with a 2.6 GHz prototypes", IEEE Commun. Lett., vol. 15, no. 2, pp. 178–180, Feb. 2011.

Transmission Concepts Related to SM (3/5)

New MIMO schemes jointly combining multiple-antenna transmission and Automatic Repeat reQuest (ARQ) feedback have been proposed to avoid to keep all available antennas on, thus enabling MIMO gains with a single RF chain and a single power amplifier. This solution is named Incremental MIMO. The main idea is to reduce complexity and to improve the energy efficiency by having one active antenna at a time, but to exploit ARQ feedback to randomly cycle through the available antennas at the transmitter in case of incorrect data reception.



P. Hesami and J. N. Laneman, "Incremental use of multiple transmitters for low-complexity diversity transmission in wireless systems," IEEE Trans. Commun., vol. 60, no. 9, pp. 2522-2533, Sep. 2012. 32

Transmission Concepts Related to SM (4/5)

New directional modulation schemes for mm-Wave frequencies have been proposed to enable secure and low-complexity wireless communications. The solution is named Antenna Subset Modulation (ASM). The main idea in ASM is to modulate the radiation pattern at the symbol rate by driving only a subset of antennas in the array. While randomly switching antenna subsets does not affect the symbol modulation for a desired receiver along the main direction, it effectively randomizes the amplitude and phase of the received symbol for an eavesdropper along a sidelobe.



N. Valliappan, A. Lozano, and R. W. Heath Jr., "Antenna subset modulation for secure millimeter-wave wireless communication", IEEE Transactions on Communications, vol. 61, no. 8, pp. 3231-3245, Aug. 2013.

Transmission Concepts Related to SM (5/5)



N. Valliappan, A. Lozano, and R. W. Heath Jr., "Antenna subset modulation for secure millimeter-wave wireless communication", IEEE Transactions on Communications, vol. 61, no. 8, pp. 3231-3245, Aug. 2013.

To Summarize: SM-MIMO Advantages...

- □ Higher throughput
- □ Simpler receiver design
- □ Simpler transmitter design
- □ Lower transmit power supply
- □ Better efficiency of the power amplifiers

M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation", Proceedings of the IEEE, July 2013 (to appear). [Online]. Available: http://hal.archives-ouvertes.fr/docs/00/84/02/78/PDF/ProcIEEE_SM_FullPaper.pdf. 35 ... and Some Disadvantages/Trade-Offs

□ Spectral efficiency sub-optimality

- □ Fast antenna switching
- □ Time-limited pulse shaping
- □ Favorable propagation conditions
- **Training overhead**

□ Directional beamforming (for mmWave applications)

M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation", Proceedings of the IEEE, July 2013 (to appear). [Online]. Available: http://hal.archives-ouvertes.fr/docs/00/84/02/78/PDF/ProcIEEE_SM_FullPaper.pdf. 36
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A Glimpse into the History of SM



[2001] Y. Chau, S.-H. Yu, "Space Modulation on Wireless Fading Channels", IEEE VTC-Fall

[2002] H. Haas, E. Costa, E. Schultz, "Increasing Spectral Efficiency by Data Multiplexing Using Antennas Arrays", IEEE PIMRC

[2004] S. Song, et al., "A Channel Hopping Technique I: Theoretical Studies on Band Efficiency and Capacity", IEEE ISCA

[2006] R. Y. Mesleh, H. Haas, et al., "Spatial modulation - A New Low Complexity Spectral Efficiency Enhancing Technique", ChinaCom

[2008] Y. Yang and B. Jiao, "Information-Guided Channel-Hopping for High Data Rate Wireless Communication", IEEE Commun. Lett.

[2008] R. Y. Mesleh, H. Haas, et al., "Spatial Modulation", IEEE Trans. Veh. Technol.

[2009] J. Jeganathan, A. Ghrayeb, et al., "Space Shift Keying Modulation for MIMO Channels", IEEE Trans. Wireless Commun.

[2011] M. Di Renzo, H. Haas, P. M. Grant, "Spatial Modulation for Multiple-Antenna Wireless Systems - A Survey", IEEE Commun. Mag.

[2012/2013] N. Serafimovski, A. Younis, M. Di Renzo, H. Haas, et al., "Practical Implementation of Spatial Modulation", IEEE Trans. Veh. Technol., (to appear, IEEE Early Access) 38

Research Groups Working on SM

- □ University of Edinburgh, UK (H. Haas)
- CNRS SUPELEC University of Paris-Sud XI, France (M. Di Renzo)
- **Concordia University, Canada (A. Ghrayeb)**
- □ University of Tabuk, Saudi Arabia (R. Y. Mesleh)
- □ University of Southampton, UK (L. Hanzo)
- □ Princeton University, US (V. Poor)
- □ Istanbul Technical University, Turkey (E. Basar, E. Panayirci)
- **Tokyo University, Japan (S. Sugiura)**
- Indian Institute of Science, India (K. V. S. Hari and A. Chockalingam)
- Québec University INRS, Canada (S. Aissa)
- □ The University of Akron, US (H. R. Bahrami)
- □ Academia Sinica, Taiwan (a large group)
- □ Tsinghua University and many other universities, China (many groups)
- □ Le Quy Don Technical University, Vietnam (T. X. Nam)
- □ etc., etc., etc...
- Collaborations with: Univ. of L'Aquila (Italy), CTTC (Spain), Univ. of Bristol (UK), Heriot-Watt Univ. (UK), EADS (Germany), etc...

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Energy Efficiency (1/8)

- □ The EARTH power model is a very simple and elegant model that relates the transmitted power of a BS to the total power consumed
 - G. Auer et al., "Cellular Energy Evaluation Framework," IEEE VTC-Spring, May 2011

$$P_{\text{supply}} = \begin{cases} N_{\text{RF}}P_0 + mN_{\text{RF}}P_{\text{t}}, & 0 < P_{\text{t}} \le P_{\text{max}} \\ P_{\text{sleep}}, & P_{\text{t}} = 0. \end{cases}$$

- \triangleright **P**_{supply} is the total power supplied to the BS
- \succ N_{RF} is the number of RF chains at the BS
- P_0 is the power consumption per RF chain at the least transmission power
- m is the slope of the load-depended power consumption
- \triangleright **P**_t is the **RF** transmit-power per antenna
- \triangleright **P**_{max} is the maximum transmit-power per antenna

A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 41

Energy Efficiency (2/8)

POWER MODEL PARAMETERS FOR DIFFERENT BS (SOTA 2010)

BS type	P_0 (W)	m	P_{\max} (W)	$P_{\text{sleep}}(W)$
Macro	118.7	2.66	40.0	63
Micro	53.0	3.1	6.3	-
Pico	6.8	4.0	0.13	-
Femto	4.8	7.5	0.05	-

Simulation Parameters	Values			
BS Type Power Model Parameters	Macro, Micro, Pico, Femto	BS type	d _{min} (m)	d _{max} (m)
Carrier Frequency	2 GHz	Macro	10	5000
Path Loss Model	3GPP NLOS [14]	Pico	10	150
Iterations (Number of Channels) Bandwidth	100000 10 MHz	Femto	5	50
Operating Temperature	Outdoor:290 K, Indoor: 293.5 K			

A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 42 Energy Efficiency (3/8)

$$C_{\rm SM} = C_1 + C_2 \approx C_1 = \frac{W}{N_t} \sum_{m=1}^{N_t} \log_2 \left(1 + \frac{P}{N_0} \| \mathbf{h}_m \|_2^2 \right)$$
$$C_{\rm STBC} = WR_{\rm STBC} \log_2 \left(1 + \frac{P}{N_0 N_t} \sum_{m=1}^{N_t} \| \mathbf{h}_m \|_2^2 \right)$$
$$C_{\rm MISO} \left(\text{CSIT} \right) = W \log_2 \left(1 + \frac{P}{N_0} \| \mathbf{h} \|_2^2 \right)$$
$$\text{EE} = \frac{\text{Capacity}}{P_{\text{supply}}}$$

A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 43



A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 44



A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 45



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A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation", IEEE CAMAD, Sep. 2012, Barcelona, Spain. 47



Urban Macro BS: 4xN, (SotA 2010)



Urban Micro BS: 4xN_(SotA 2010)







A. Stavridis, S. Sinanovic, M. Di Renzo, and H. Haas, "Energy evaluation of spatial modulation at a multiantenna base station," IEEE Veh. Technol. Conf. - Fall, pp. 1-5, Sep. 2013. 48

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Spatially-Modulated Space-Time-Coded MIMO (1/12)

The Alamouti Scheme



S. M. Alamouti, "A simple transmit diversity technique for wireless communications", IEEE J. Sel. Areas Commun., vol. 16, no. 8, pp. 1451–1458, Oct. 1998. 50

Spatially-Modulated Space-Time-Coded MIMO (2/12)

Opportunities and Challenges for SM



- **Opportunity: Transmit-diversity with rate greater than one**
- □ Challenge: Transmit-diversity with rate greater than one and single-stream decoding complexity

Spatially-Modulated Space-Time-Coded MIMO (3/12)



M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013

Spatially-Modulated Space-Time-Coded MIMO (4/12)

$$\begin{split} (\hat{\alpha}, \hat{\mu}) &= \underset{\mathbf{a}^{(\hat{\alpha})} \in \mathcal{A}, \ \hat{\mu} = \begin{bmatrix} \hat{\mu}_{1} \in \mathcal{M}, \hat{\mu}_{2} \in \mathcal{M}, \dots, \hat{\mu}_{N_{M}} \in \mathcal{M} \end{bmatrix}^{T}}{\underset{\mathbf{x}^{(\hat{\alpha})} \in \mathcal{A}, \ \hat{\mu} = \begin{bmatrix} \hat{\mu}_{1} \in \mathcal{M}, \hat{\mu}_{2} \in \mathcal{M}, \dots, \hat{\mu}_{N_{M}} \in \mathcal{M} \end{bmatrix}^{T}} \underbrace{\left\{ \underbrace{\sum_{s=1}^{N_{x}} \sum_{r=1}^{N_{r}} \int_{(s-1)T_{s}}^{ST_{s}} \left| z_{s,r}\left(\xi\right) - \sqrt{\frac{E_{s}}{\|\mathbf{a}^{(\hat{\alpha})}\|_{F}^{2}} \sum_{t=1}^{N_{t}} \left[\mathbf{X}_{s,t}^{(\hat{\alpha})}\left(\hat{\mu}\right) \mathbf{H}_{r,t}w_{t}\left(\xi-(s-1)T_{s}\right) \right] \right|^{2} d\xi \right\}}_{\Lambda(\hat{\alpha},\hat{\mu})} \\ \mathbf{ABEP} \leq \sum_{\mathbf{x}} \frac{1}{\mathsf{AM}^{N_{M}}} \sum_{\tilde{\mathbf{\chi}} \neq \mathbf{\chi}} \frac{\mathcal{H}_{d}\left(\mathbf{\chi}, \tilde{\mathbf{\chi}}\right) \mathsf{APEP}\left(\mathbf{\chi} \to \tilde{\mathbf{\chi}}\right)}{\log_{2}\left(\mathsf{A}\right) + N_{\mathsf{M}}\log_{2}\left(\mathsf{M}\right)} \\ \mathbf{\rho}_{\mathsf{X} \to \tilde{\mathbf{\chi}}}(\mathsf{H}) = \sum_{s=1}^{N_{s}} \sum_{r=1}^{N_{r}} \left\{ \sum_{t_{1}=1}^{N_{t}} \sum_{t_{2}=1}^{N_{t}} \left[\left(\frac{\mathbf{X}_{s,t_{1}}^{(\hat{\alpha})}\left(\hat{\mu}\right)}{\|\mathbf{a}^{(\hat{\alpha})}\|_{F}^{2}} - \frac{\mathbf{X}_{s,t_{1}}^{(\alpha)}\left(\mu\right)}}{\|\mathbf{a}^{(\alpha)}\|_{F}^{2}} \right) \left(\frac{\mathbf{X}_{s,t_{2}}^{(\hat{\alpha})}\left(\hat{\mu}\right)}{\|\mathbf{a}^{(\alpha)}\|_{F}^{2}} - \frac{\mathbf{X}_{s,t_{2}}^{(\alpha)}\left(\mu\right)}{\|\mathbf{a}^{(\alpha)}\|_{F}^{2}} \right)^{*} \mathbf{H}_{r,t_{1}} \mathbf{H}_{r,t_{2}}^{*} \int_{0}^{T_{s}} w_{t_{1}}\left(\xi\right) w_{t_{2}}\left(\xi\right) d\xi \right] \right\} \\ \gamma_{\mathbf{\chi} \to \tilde{\mathbf{\chi}}}\left(\mathbf{H}\right) = \mathbf{\eta}\left(\mathbf{H}\right)^{H} \mathbf{\Psi}\left(\mathbf{\chi}, \tilde{\mathbf{\chi}}\right) \mathbf{\eta}\left(\mathbf{H}\right) \end{split}$$

M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013 Spatially-Modulated Space-Time-Coded MIMO (5/12)

M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013

 $\stackrel{E_S/N_0 \gg 1}{\to} \left(G_c \left(\chi, \tilde{\chi} \right) \frac{E_S}{4N_0} \right)^{-G_d(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}})}$

Spatially-Modulated Space-Time-Coded MIMO (6/12)

$$G_{c}\left(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}\right) = \left(\tilde{G}_{c}\left(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}\right) \prod_{\bar{\lambda}_{q} \in \mathcal{K}(\mathbf{R}_{\eta} \Psi(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}))} \bar{\lambda}_{q}^{-1} \right)^{-1/G_{d}\left(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}\right)}$$
$$G_{d}\left(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}\right) = \operatorname{card}\left\{ \mathcal{K}\left(\mathbf{R}_{\eta} \Psi\left(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}\right)\right) \right\}$$

$$\mathbb{D} = \min_{(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}})} \{ G_d(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}}) \} \\= \min_{(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}})} \{ \operatorname{card} \{ \mathcal{K} (\mathbf{R}_{\boldsymbol{\eta}} \Psi(\boldsymbol{\chi}, \tilde{\boldsymbol{\chi}})) \} \}$$

M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013

Spatially-Modulated Space-Time-Coded MIMO (7/12)

Description of Transmission Modes

GSSK (Generalized Space Shift Keying) – The spatial-constellation diagram is chosen such that its symbols $\mathbf{a}^{(\alpha)} \in \mathcal{A}$ have $N_{\alpha} = N_{\bar{\alpha}}$ for $\alpha = 1, 2, ..., A$ and $A = 2^{\lfloor \log_2 [\binom{N_t}{N_{\bar{\alpha}}} \rfloor \rfloor}$. This implies $\mathcal{A} \subseteq \mathcal{U}$.

MRSSK (Max–Rate Space Shift Keying) – The spatial–constellation diagram is chosen such that it contains the largest number of symbols $\mathbf{a}^{(\alpha)} \in \mathcal{A}$ with N_{α} assuming all possible values in $[0, N_t]$ for $\alpha = 1, 2, ..., A$ and $A = 2^{N_t}$. This implies $\mathcal{A} = \mathcal{U}$.

MRSSK_{\0} (Max-Rate Space Shift Keying "without the all-zero symbol") – The spatial-constellation diagram is chosen such that it contains the largest number of symbols $\mathbf{a}^{(\alpha)} \in \mathcal{A}$ with N_{α} except $\mathbf{a}^{(\alpha)} = \mathbf{0}_{N_t}$ with N_{α} assuming all possible values in $(0, N_t]$ for $\alpha = 1, 2, ..., A$ and $A = 2^{N_t - 1}$. This implies $\mathcal{A} \subseteq \mathcal{U}_{\setminus 0}$.

SMSTT (Spatially-Modulated Space-Time-Transmission) – The spatial-constellation diagram is chosen such that its symbols $\mathbf{a}^{(\alpha)} \in \mathcal{A}$ have $N_{\alpha} = N_{\bar{\alpha}}$ for $\alpha = 1, 2, ..., A$ and $A = 2^{\lfloor \log_2 \left[\binom{N_t}{N_{\alpha}} \right] \rfloor}$. This implies $\mathcal{A} \subseteq \mathcal{U}$. The mother space-time code $\mathbf{M}(\cdot)$ is transmitted from the active antennas in $\mathbf{a}^{(\alpha)} \in \mathcal{A}$ over N_s time-slots.

Rand (Random) – The symbols of the spatial–constellation diagram $\mathbf{a}^{(\alpha)} \in \mathcal{A} \subseteq \mathcal{U}$ are randomly chosen but kept fixed for the whole communication.

SetPart (Set Partitioning) and NuSetPart (Non–Uniform Set Partitioning) – The symbols of the spatial–constellation diagram $\mathbf{a}^{(\alpha)} \in \mathcal{A} \subseteq \mathcal{U}$ are chosen such that the active antennas in each symbol result in a partition of the antenna–array. Once chosen, the symbols are kept fixed for the whole communication. SetPart is obtained if $N_{\alpha} = N_{\overline{\alpha}}$ for $\alpha = 1, 2, ..., A$. NuSetPart is obtained if N_{α} can be different for $\alpha = 1, 2, ..., A$.

ISF (Identical Shaping Filters) – The shaping filters are the same for all the antenna-elements, *i.e.*, $w_t(\xi) = w_0(\xi)$ for $t = 1, 2, ..., N_t$.

OSF (Orthogonal Shaping Filters) – The shaping filters are different and time–orthogonal for all the antenna–elements, *i.e.*, $\int_0^{T_s} w_{t_1}(\xi) w_{t_2}(\xi) d\xi = 0$ for $t_1 \neq t_2 = 1, 2, ..., N_t$.

SWOSF (Symbol–Wise Orthogonal Shaping Filters) – Let $\mathbf{a}^{(\alpha_1)} \in \mathcal{A}$ and $\mathbf{a}^{(\alpha_2)} \in \mathcal{A}$ be two generic symbols of the spatial–constellation diagram for $\alpha_1 \neq \alpha_2 = 1, 2, ..., A$. Let $w_{\alpha}(\cdot)$ be the common shaping filter used by all active antennas in $\mathbf{a}^{(\alpha)}$. Then the shaping filters are chosen such that $\int_{0}^{T_s} w_{\alpha_1}(\xi) w_{\alpha_2}(\xi) d\xi = 0$. Unlike OSF, the active antennas in $\mathbf{a}^{(\alpha)}$ have the same shaping filter.

Spatially-Modulated Space-Time-Coded MIMO (8/12)

ML-Optimum Single-Stream Decoding: TM2–SMSTT–SetPart–OSF and TM2–SMSTT–SetPart–SWOSF

Alamouti Mother STBC

$$\begin{aligned} (\hat{\alpha}, \hat{\mu}_{1}, \hat{\mu}_{2}) &= \underset{\mathbf{a}^{(\tilde{\alpha})} \in \mathcal{A}, \ \tilde{\mu}_{1} \in \mathcal{M}, \ \tilde{\mu}_{2} \in \mathcal{M}}{\arg\min} \left\{ \Lambda_{1}\left(\tilde{\alpha}, \tilde{\mu}_{1}\right) + \Lambda_{2}\left(\tilde{\alpha}, \tilde{\mu}_{2}\right) \right\} \\ & \left(\underset{\mathbf{a}^{(\tilde{\alpha})} \in \mathcal{A}}{\overset{(\tilde{\alpha})}{\underset{\mu_{1} \in \mathcal{M}, \ \tilde{\mu}_{2} \in \mathcal{M}}{\min}} \left\{ \Lambda_{1}\left(\tilde{\alpha}, \tilde{\mu}_{1}\right) + \Lambda_{2}\left(\tilde{\alpha}, \tilde{\mu}_{2}\right) \right\} \right\} \\ & \left(\underset{\mathbf{a}^{(\tilde{\alpha})} \in \mathcal{A}}{\overset{(\tilde{\alpha})}{\underset{\mu_{1} \in \mathcal{M}}{\min}}} \left\{ \underset{\tilde{\mu}_{1} \in \mathcal{M}}{\min} \left\{ \Lambda_{1}\left(\tilde{\alpha}, \tilde{\mu}_{1}\right) \right\} + \underset{\tilde{\mu}_{2} \in \mathcal{M}}{\min} \left\{ \Lambda_{2}\left(\tilde{\alpha}, \tilde{\mu}_{2}\right) \right\} \right\} \end{aligned}$$

M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013 57

Spatially-Modulated Space-Time-Coded MIMO (9/12)

Step 1: For every hypothesis $\mathbf{a}^{(\tilde{\alpha})} \in \mathcal{A}$ of the spatial-constellation diagram, compute:

$$\hat{\mu}_{1}\left(\tilde{\alpha}\right) = \underset{\substack{\tilde{\mu}_{1} \in \mathcal{M}}{\arg\min}}{\arg\min} \left\{\Lambda_{1}\left(\tilde{\alpha}, \tilde{\mu}_{1}\right)\right\}$$
$$\hat{\mu}_{2}\left(\tilde{\alpha}\right) = \underset{\substack{\tilde{\mu}_{2} \in \mathcal{M}}{\arg\min}}{\arg\min} \left\{\Lambda_{2}\left(\tilde{\alpha}, \tilde{\mu}_{2}\right)\right\}$$

Step 2: Compute the estimate of the symbol belonging to the spatial–constellation diagram as follows:

$$\hat{\alpha} = \operatorname*{arg\,min}_{\mathbf{a}^{(\tilde{\alpha})} \in \mathcal{A}} \left\{ \Lambda_1 \left(\tilde{\alpha}, \hat{\mu}_1 \left(\tilde{\alpha} \right) \right) + \Lambda_2 \left(\tilde{\alpha}, \hat{\mu}_2 \left(\tilde{\alpha} \right) \right) \right\}$$

Step 3: Compute the estimates of the two symbols belonging to the signal–constellation diagram as follows:

$$\hat{\mu}_1 = \hat{\mu}_1 \left(\hat{\alpha} \right) \quad \text{and} \quad \hat{\mu}_2 = \hat{\mu}_2 \left(\hat{\alpha} \right)$$

M. Di Renzo and H. Haas, "On Transmit–Diversity for Spatial Modulation MIMO: Impact of Spatial– Constellation Diagram and Shaping Filters at the Transmitter", IEEE Transactions on Vehicular Technology, Vol. 62, No. 6, pp. 2507–2531, July 2013

Spatially-Modulated Space-Time-Coded MIMO (10/12)

Multi vs. Single-Stream Decoding ($\mathbf{R} = 4$ bpcu)



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Spatially-Modulated Space-Time-Coded MIMO (11/12)



 $N_r = 1$ R = 4 bpcu

Spatially-Modulated Space-Time-Coded MIMO (12/12)



 $N_r = 2$ R = 6 bpcu

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SM in Heterogeneous Cellular Networks (1/17)



SM in Heterogeneous Cellular Networks (2/17)

- Heterogeneous cellular systems are networks with different types of cells providing different QoS requirements to the users, which coexist and contend the wireless medium (macro, pico, femto, relays, DAEs, cognitive radios, etc.)
- □ Thus, interference should be properly managed and/or exploited for reliable communications and energy efficiency

Overlaid multi-tier heterogeneous scenario



SM in Heterogeneous Cellular Networks (3/17)

- Conventional approaches for the analysis and design of (heterogeneous) cellular networks (abstraction models) are:
 - > The Wyner model
 - The single-cell interfering model
 - The regular hexagonal or square grid model
- □ However, these abstraction models:
 - > Are over-simplistic and/or inaccurate
 - Require intensive numerical simulations and/or integrations
 - Provide information only for specific BSs deployments
 - No closed-form solutions and/or insights

J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks", IEEE Trans. Commun., vol. 59, no. 11, pp. 3122–3134, Nov. 2011.

M. Di Renzo, C. Merola, A. Guidotti, F. Santucci, and G. E. Corazza, "Error Performance of Multi-Antenna Receivers in a Poisson Field of Interferers – A Stochastic Geometry Approach", IEEE Trans. Commun., Vol. 61, No. 5, pp. 2025–2047, May 2013.

M. Di Renzo, A. Guidotti, and G. E. Corazza, "Average Rate of Downlink Heterogeneous Cellular Networks over Generalized Fading Channels – A Stochastic Geometry Approach", IEEE Trans. Commun., Vol. 61, No. 7, pp. 3050-3071, July 2013.

SM in Heterogeneous Cellular Networks (4/17)

An Emerging (Tractable) Approach

RANDOM SPATIAL MODEL for Heterogeneous Cellular Networks (HCNs):

- K-tier network with BS locations modeled as independent marked Poisson Point Processes (PPPs)
- PPP model is surprisingly good for 1-tier as well (macro BSs): lower bound to reality and trends still hold
- > PPP makes even more sense for HCNs due to less regular BSs placements for lower tiers (femto, etc.)

Stochastic Geometry emerges as an effective tool for analysis, design, and optimization of HCNs

SM in Heterogeneous Cellular Networks (5/17)

How It Works (Downlink – 1-tier)



SM in Heterogeneous Cellular Networks (6/17)





SM in Heterogeneous Cellular Networks (7/17)



Probe mobile terminal

PPP-distributed macro base station

SM in Heterogeneous Cellular Networks (8/17)

How It Works (Downlink – 1-tier)



SM in Heterogeneous Cellular Networks (9/17)

Worldwide Base Station Locations Available via OpenCellID



Base station distribution in Taipei City, Taiwan, shown on Google Map. Blue Δ 's are the locations of base stations

C.-H. Lee, C.-Y. Shihet, and Y.-S. Chen, "Stochastic geometry based models for modeling cellular networks in urban areas", Springer Wireless Netw., 10 pages, Oct. 2012. Open source project OpenCellID: http://www.opencellid.org/

SM in Heterogeneous Cellular Networks (10/17)

PPP better than (or same accuracy as) Hexagonal



C.-H. Lee, C.-Y. Shihet, and Y.-S. Chen, "Stochastic geometry based models for modeling cellular networks in urban areas", Springer Wireless Netw., 10 pages, Oct. 2012. Open source project OpenCellID: http://www.opencellid.org/
SM in Heterogeneous Cellular Networks (11/17)

PPP better than (or same accuracy as) Hexagonal



C.-H. Lee, C.-Y. Shihet, and Y.-S. Chen, "Stochastic geometry based models for modeling cellular networks in urban areas", Springer Wireless Netw., 10 pages, Oct. 2012. Open source project OpenCellID: http://www.opencellid.org/

SM in Heterogeneous Cellular Networks (12/17)



PPP-distributed interfering lower-tier (e.g., femto) base stations

Tagged macro base station at a fixed distance \rightarrow ad hoc network deployment ⁷⁴

SM in Heterogeneous Cellular Networks (13/17)

A Key Result from Stochastic Geometry and PPP Theory

$$\underbrace{\underbrace{A}_{\text{Decision}}}_{\text{Metric}} \propto \underbrace{\left| \underbrace{\Delta_{0}}_{0} \right|^{2} U}_{\text{Useful}} + \underbrace{\underbrace{2 \operatorname{Re} \left\{ \Delta_{0}^{*} \overline{N} \right\}}_{\text{AWGN}} + \underbrace{\underbrace{2 \operatorname{Re} \left\{ \Delta_{0}^{*} \overline{I}_{\text{AGG}} \right\}}_{\text{Aggregate}}}_{\text{Interference}}$$

$$\overline{I}_{\text{AGG}} = \underbrace{\sum_{i \in \Phi_{\text{ppp}}} \left(\frac{\overline{Z}_{i}}{d_{i}^{b_{I}}} \right)}_{i} \Rightarrow \overline{I}_{\text{AGG}} = B_{I}^{1/2} \overline{G}_{I} \sim S \alpha S \left(\alpha_{I} = 2/b_{I}, \gamma_{I} \right)}$$

$$\widehat{I}_{\text{AGG}} = \underbrace{B_{I} \sim S \left(1/b_{I}, 1, \cos^{b_{I}} \left(\pi/2b_{I} \right) \right)}_{i} = \exp \left(-s^{1/b_{I}} \right)$$

 $\left| G_{I} \sim CN(0, 4\gamma_{I}^{b_{I}}) \right|$

SM in Heterogeneous Cellular Networks (14/17)

Equivalent AWGN Channel



STEP 1: The frameworks developed without interference can be applied by conditioning upon B_I

STEP 2: The conditioning can be removed either numerically or analytically (preferred)

SM in Heterogeneous Cellular Networks (15/17)



Fig. 1. ASEP as a function of E_P/N_0 , N_t and λ . Setup: $\Omega_P = \Omega_I = 1$; b = 4; $X_0^2 = 1$; $N_r = 2$; $E_P = E_I$; PSK modulation with M = 8. The solid lines show the framework in (21), (23) and (26), the dashed lines the asymptotic framework in (29), and the markers the Monte Carlo simulations.

 W. Lu and M. Di Renzo, "Performance Analysis of Spatial Modulation MIMO in a Poisson Field of Interferers", IEEE International Conference on Computing, Networking and Communications, Honolulu, USA, February 3–6, 2014 (to appear).

SM in Heterogeneous Cellular Networks (16/17)



Fig. 2. ASEP as a function of E_P/N_0 , N_t and λ . Setup: $\Omega_P = \Omega_I = 1$; b = 4; $X_0^2 = 1$; $N_r = 2$; $E_I/N_0 = 40$ dB; PSK modulation with M = 16. The solid lines show the framework in (21), (23) and (26), the dashed lines the asymptotic framework in (23), and the markers the Monte Carlo simulations.

 W. Lu and M. Di Renzo, "Performance Analysis of Spatial Modulation MIMO in a Poisson Field of Interferers", IEEE International Conference on Computing, Networking and Communications, Honolulu, USA, February 3–6, 2014 (to appear).

SM in Heterogeneous Cellular Networks (17/17)



Fig. 3. ASEP as a function of E_P/N_0 , N_r and λ . Setup: $\Omega_P = \Omega_I = 1$; b = 4; $X_0^2 = 1$; $N_t = 8$; $E_I/N_0 = 40$ dB; PSK modulation with M = 32. The solid lines show the framework in (21), (23) and (26), the dashed lines the asymptotic framework in (30), and the markers the Monte Carlo simulations.

 W. Lu and M. Di Renzo, "Performance Analysis of Spatial Modulation MIMO in a Poisson Field of Interferers", IEEE International Conference on Computing, Networking and Communications, Honolulu, USA, February 3–6, 2014 (to appear).

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Experimental Evaluation of SM (1/12)

- Performance assessment via channel measurements
 - Urban scenario (Bristol/UK) @ 2GHz carrier frequency



MIMO channel sounder





Post-processing

□ Testbed implementation (NI-PXIe-1075 @ Heriot-Watt Univ. / UK)

Laboratory environment: 2x2 MIMO @ 2.3GHz carrier frequency



Experimental Evaluation of SM (2/12)

Channel Measurements

- MIMO channel measurements are taken around the center of Bristol city (UK), using a MEDAV RUSK channel sounder
- The setup consists of a 4×4 MIMO, with 20 MHz bandwidth centered at 2 GHz
- The transmitter consists of a pair of dual polarized (±45°) Racal Xp651772 antennas separated by 2m, positioned atop a building, providing elevated coverage of central business and commercial districts of Bristol city



A. Younis, W. Thompson, M. Di Renzo, C.-X. Wang, M. A. Beach, H. Haas, and P. M. Grant, "Performance of Spatial Modulation over Correlated and Uncorrelated Urban Channel Measurements", IEEE VTC-Fall, 2013.

Experimental Evaluation of SM (3/12)

Channel Measurements

- ❑ At the receiver, two different receiver devices are used, both equipped with four antennas:
 - A reference headset, which is based on 4-dipoles mounted on a cycle helmet, thus avoiding any shadowing by the user
 - A laptop , which is equipped with 4 Printed Inverted F Antennas (PIFA) fitted inside the back of the display panel





A. Younis, W. Thompson, M. Di Renzo, C.-X. Wang, M. A. Beach, H. Haas, and P. M. Grant, "Performance of Spatial Modulation over Correlated and Uncorrelated Urban Channel Measurements", IEEE VTC-Fall, 2013.

Experimental Evaluation of SM (4/12)

Channel Measurements

□ 58 measurement locations are chosen around the city

- At each location the user walked, holding the laptop in front of him and the reference device on his head, in a straight line roughly 6 m long, until 4096 channel snapshots were recorded
- □ Two MIMO test cases are investigated:
 - Small-scale" MIMO, which are the original 4x4 channel measurements
 - "Large-scale" MIMO, where, by manipulating the original measurements, larger virtual MIMO systems are created

A. Younis, W. Thompson, M. Di Renzo, C.-X. Wang, M. A. Beach, H. Haas, and P. M. Grant, "Performance of Spatial Modulation over Correlated and Uncorrelated Urban Channel Measurements", IEEE VTC-Fall, 2013.

Experimental Evaluation of SM (5/12)



Fig. 1. ABER versus the SNR for SM over an uncorrelated channel. m = 4, $N_t = N_r = 4$.

Experimental Evaluation of SM (6/12)



Fig. 2. ABER versus the SNR for SM over a correlated channel. m = 4, $N_t = N_r = 4$.

Experimental Evaluation of SM (7/12)



Fig. 5. ABER versus the SNR for SM and SMX over real measured channels. $m = 8, N_r = 4.$

Experimental Evaluation of SM (8/12)

Indoor Testbed



- □ The binary data to be broadcast is first passed through the digital signal processing algorithm at the transmitter (DSP-Tx)
- The processed data is then passed to the physical transmitter on the National Instruments (NI)-PXIe chassis (PXIe-Tx)
- □ Each transmit antenna ('Tx1' and 'Tx2') is then activated according to the SM principle at a carrier frequency of 2.3 GHz
- □ The receiver then detects and processes the radio frequency (RF) signal in PXIe–Rx. Lastly, the receive side digital signal processing algorithm (DSP–Rx) recovers the original data stream

N. Serafimovski, A. Younis, R. Mesleh, P. Chambers, M. Di Renzo, C.-X. Wang, P. M. Grant, M. A. Beach, and H. Haas, "Practical Implementation of Spatial Modulation", IEEE Trans. Veh. Technol., to appear. IEEE Early Access. 88

Experimental Evaluation of SM (9/12)

Laboratory Setup



Experimental Evaluation of SM (10/12)



Fig. 3. Binary data encoder (DSP-Tx) and decoder (DSP-Rx) algorithms for SM.

Experimental Evaluation of SM (11/12)

The Received Signal (Examples of Frames)



Experimental Evaluation of SM (12/12)



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The Road Ahead – Open Research Challenges/Opportunities

- Appraising the Fundamental Trade-Offs of Single- vs. Multi-RF MIMO Designs
- □ Large-Scale Implementations: Training Overhead for CSIT/CSIR Acquisition
- From Single-User Point-to-Point to Multi-User Multi-Cell SM-MIMO Communications
- □ Millimeter-Wave Communications: The Need for Beamforming Gains
- Small Cell Heterogeneous Cellular Networks: Towards Interference Engineering
- **Radio Frequency Energy Harvesting: Taking Advantage of the Idle Antennas**
- Leveraging the Antenna Modulation Principle to a Larger Extent
- Open Physical-Layer Research Issues

M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation", Proceedings of the IEEE, July 2013 (to appear). [Online]. Available: http://hal.archives-ouvertes.fr/docs/00/84/02/78/PDF/ProcIEEE_SM_FullPaper.pdf. 94



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