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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Access, Terminals, Transmission and Multiplexing (ATTM).

Modal verbs terminology

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Introduction

It has been known for a long time that in order to improve theoretically the capacity of a given communication channel with maintaining the existing power at the transmitter and SNR at the receiver, the best solution is to dismantle the aggregate single channel into independent orthogonal sub-channels all using the same carrier frequency. To this theoretical improvement a considerable practical implementation can be added, given that with the distributing of payload among sub-channels the required order of the modulation scheme can be reduced. One example of exploiting this payload distribution method can be found in the existing "co-channel dual polarization" mode. With this implementation the aggregate payload is distributed between the both orthogonal independent sub-channels - the two perpendicular linear polarization carriers. The present document describes a new approach of orthogonalization , the spatial frequency re-use. As in the case of polarization, in order to perform the separation at the receiver, a special module should be incorporated - similar to the cross-polarization Interference Canceller (XPIC) - the Spatial Frequency Reuse Canceller (SFRC). In general, the SFR method is not limited to only two sub-channels as in the CCDP case, and systems that use it are able to double, triple or multiple the spectral efficiency without any trade off on the system gain as it is normally the case with improving the spectral efficiency by going to high order QAM modulation.

The present document includes an updated view of the SFR scheme using Multiple Antenna Techniques (MIMO). Furthermore, some theoretical aspect reviews, installation issues, results from a new in field trial, considerations about planning and, in the end, a living list for relevant standards modifications have been added.

Main changes reported in the present document are related to the MIMO system model, performance with non-optimal antenna spacings, installation issue, new field trial, antenna composite RPE and MIMO deployment status in Europe.

1 Scope

The present document provides, initially, a theoretical overview of how point-to-point systems that use SFRC could improve the link capacity and/or system gain, or could focus power in different directions or cover an area. Focus is put on LOS links.

In general these different results may "compete" with one another and for example an increase of capacity may require an increase of system gain. Few basic methods for implementing SFR are provided in the present document.

Simulation and field trial results are provided in order to show the discussed techniques and the main improvements for the SFRC over the "Internal" Co-Channel Interference (ICCI).

Main report subjects:

- Increase the link capacity (by increasing the spectral efficiency).
- Increase the link system gain (by increasing the receiver SNR).
- Methods of implementing SFR (by using MIMO).
- Verification by simulations and trials.
- Improvement parameter definition.
- Planning matters (installation issues and availability calculation).
- Living list for standard modifications.

2 References

2.1 Normative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the reference document (including any amendments) applies.

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The following referenced documents are necessary for the application of the present document.

Not applicable.

2.2 Informative references

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The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] Recommendation ITU-R F.699: "Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to about 70 GHz".

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

Eigenvalue (λ^2): Eigenvalues of the matrix **H × H$^{\mathbf{H}}$** are the root of the characteristic equation:

$$\det(H \times H^H - \lambda^2 I) = 0$$

expectation ($\mathbf{E_H}$): weighted average value of a Random Variable over all possible realizations that the Random Variable may assume

NOTE 1: The weight coefficients are the probability value that the Random Variable assumes that value.

NOTE 2: Subscript "**H**" refers to the name of the Random Variable, for the reference scope "**H**" is the Channel Matrix.

EXAMPLE: Mathematical formulation:

- **discrete scalar random variable "X":** "X" takes values "$x_1, x_2\ldots$" with probabilities "$p_1, p_2\ldots$"

$$E[X] = \sum_{i=1}^{\infty} x_i \times p_i$$

- **continuous scalar random variable "X":** "X" takes continuous values and *f(x)* is the probability density function

$$E[X] = \int_{-\infty}^{+\infty} x \times f(x) \cdot dx$$

- Matrix Random Variable "H":

$$E_H[H_{NM}] = E\begin{bmatrix} h_{11} & h_{12} & \ldots & \ldots & h_{1M} \\ h_{21} & h_{22} & \ldots & \ldots & h_{2M} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ h_{N1} & h_{N2} & \ldots & \ldots & h_{NM} \end{bmatrix} =$$

$$= \begin{bmatrix} E[h_{11}] & E[h_{12}] & \ldots & \ldots & E[h_{1M}] \\ E[h_{21}] & E[h_{22}] & \ldots & \ldots & E[h_{2M}] \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ E[h_{N1}] & E[h_{N2}] & \ldots & \ldots & E[h_{NM}] \end{bmatrix}$$

Hadamard product (∘): operation that takes two matrices of the same dimensions, and produces another matrix where each element "ij" is the product of elements "ij" of the original two matrices

Hermitian transpose $(\cdot)^{\mathbf{H}}$: N × M matrix "**H**" with complex entries is the M × N "**H***" matrix obtained from "**H**" by taking the transpose and then taking the complex conjugate of each matrix entries

NOTE: Also known as Complex Transpose.

matrix trace (Tr): trace of an N × N square matrix "**Q**" is defined to be the sum of the elements on the main diagonal

$$Tr(Q) = q_{11} + q_{22} + \ldots q_{NN} = \sum_{i=1}^{N} q_{ii} = \sum_{i=1}^{N} \lambda_i$$

power constraint: constraint applicable to the total transmission power level of the MIMO system (P_{MIMO}) with respect to the transmitted power level by the SISO system (P_{SISO})

NOTE: If the MIMO system transmits the same power level of the reference SISO system then the power constraint holds. Otherwise if P_{MIMO} is higher than P_{SISO}, e.g. in case of N × M MIMO → $P_{MIMO} = N \times P_{SISO}$, the constraint does not hold.

singular value (λ): defined as the square root of the Eigenvalues

3.2 Symbols

For the purposes of the present document, the following symbols apply:

α	Transmission Power Weight (for Water Filling/Pouring)
A	Free Space Loss and Fading Attenuation Effects Matrix
argmin(.)	Argument which minimize the brackets content
B	Bandwidth
C	Capacity [bit/s/Hz]
dB	decibel
dBc	decibel relative to mean carrier power
dBi	decibel relative to an isotropic radiator
dBm	decibel relative to 1 milliWatt
dBW	decibel relative to 1 Watt
d_{opt}	Optimal Distance between Antennas
E_H	Expectation over variable H
H	NxM Channel Matrix
I	Unitary Matrix
λ	Singular Value of Channel Matrix (**H**)
λ^2	Eigenvalue of Matrix $\mathbf{H} \cdot \mathbf{H}^{\mathbf{H}}$
M	Number of Transmit Antennas
m	Modulation Order
N	Number of Receive Antennas
N_0	Noise Power Spectral Density
P	Transmission Power Level
P_{MIMO}	Transmission Power Level of MIMO system (total)
P_{SISO}	Transmission Power Level of SISO system
ppm	parts per million
ρ	SNR
$\overline{S}$	Average Received Power
X	Polarization Effects Matrix (XPD)
det	Matrix Determinant
Tr	Matrix Trace
$\circ$	Hadamard Product
$\lvert\cdot\rvert$	Absolute Value
$(\cdot)^H$	Hermitian Transpose

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AWGN	Added White Gaussian Noise
BER	Bit Error Ratio
BLAST	Bell Laboratories Layered Space Time
C/N	Carrier to Noise
CCDP	Co-Channel Dual Polarization
CEPT	Comité Européen des Postes et Télécommunications
CS	Channel Separation

CTF	Channel Transfer Function
ECC	Electronic Communication Committee
FS	Fixed Service
ICCI	"Internal" Co-Channel Interference
IDU	InDoor Unit
ITU-R	International Telecommunication Union - Radiocommunication
LOS	Line Of Sight
MIMO	Multiple Input Multiple Output
ML	Maximum-Likelihood
MMSE	Minimum Mean Square Error
MP	Multi-Path
MSE	Mean Square Error
MW	MicroWave
nLOS	near-Line Of Sight
NLOS	Non-Line Of Sight
PP	Point-to-Point
PTP	Point To Point
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RIC	Radio Interface Capacity
RPE	Radiation Power Envelope
RSL	Received Strength Level
Rx	Receiver
SAW	Surface Acoustic Wave
SDG	Spatial Diversity Gain
SFR	Spatial Frequency Re-use
SFRC	Spatial Frequency Reuse Canceller
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
STD	Standard Deviation
SVD	Singular Value Decomposition
T	Symbol Period
Tx	Transmitter
UCA	Uniform Circular Array of antenna
ULA	Uniform Linear Array of antenna
URA	Uniform Rectangular Array of antenna
VBLAST	Vertical Bell Laboratories Layered Space Time
XPD	Cross-Polarization Discrimination
XPIC	Cross-Polarization Interference Canceller
ZF	Zero-Forcing

4 Overview

4.1 Capacity improvement of the MIMO system (Spatial Multiplexing)

For an N × N MIMO systems the "Spatial Multiplexing" refers to the promising Capacity improvement. Basically, "N" independent orthogonal sub-channels, are provided on the same communication channel (CS), then the SISO maximal achievable spectral efficiency (C) is multiplied by a factor "N" without adding any power resource (i.e. for the MIMO system the single transmitter level is P/N). Figure 4.1 shows a Single Input Single Output (SISO) system compared with a Multiple Input Multiple Output (MIMO) using the same physical resource i.e. the given channel (CS).

This is valid only in some conditions: when the sub-channels are orthogonal or independent which means that the statistical expectation of the product of samples of the signals taken from any pair of the independent sub-channel is very low or ideally null.

For the purpose of such capacity improvement any orthogonalization method is valid, either polar or spatial. In addition to the theoretical capacity improvement there is also the available practical improvement. In practice the division of the aggregate payload among the sub-channels facilitates lowering the order of the modulation. For example, aggregate capacity of 156 Mbit/s over 28 MHz, when divided between two sub-channels, each one of them carrying only 78 Mbit/s over 28 MHz channel. In comparison, a single channel payload implementation requires 128 QAM constellations, while with the sub-channel approach a 16 QAM per carrier is sufficient. From the equations in figure 4.1 it can be concluded that the theoretical difference between the two approaches is 9 dB, however due to practical considerations such as linearity and phase noise, the gain improvement is higher, i.e. around 11 dB.

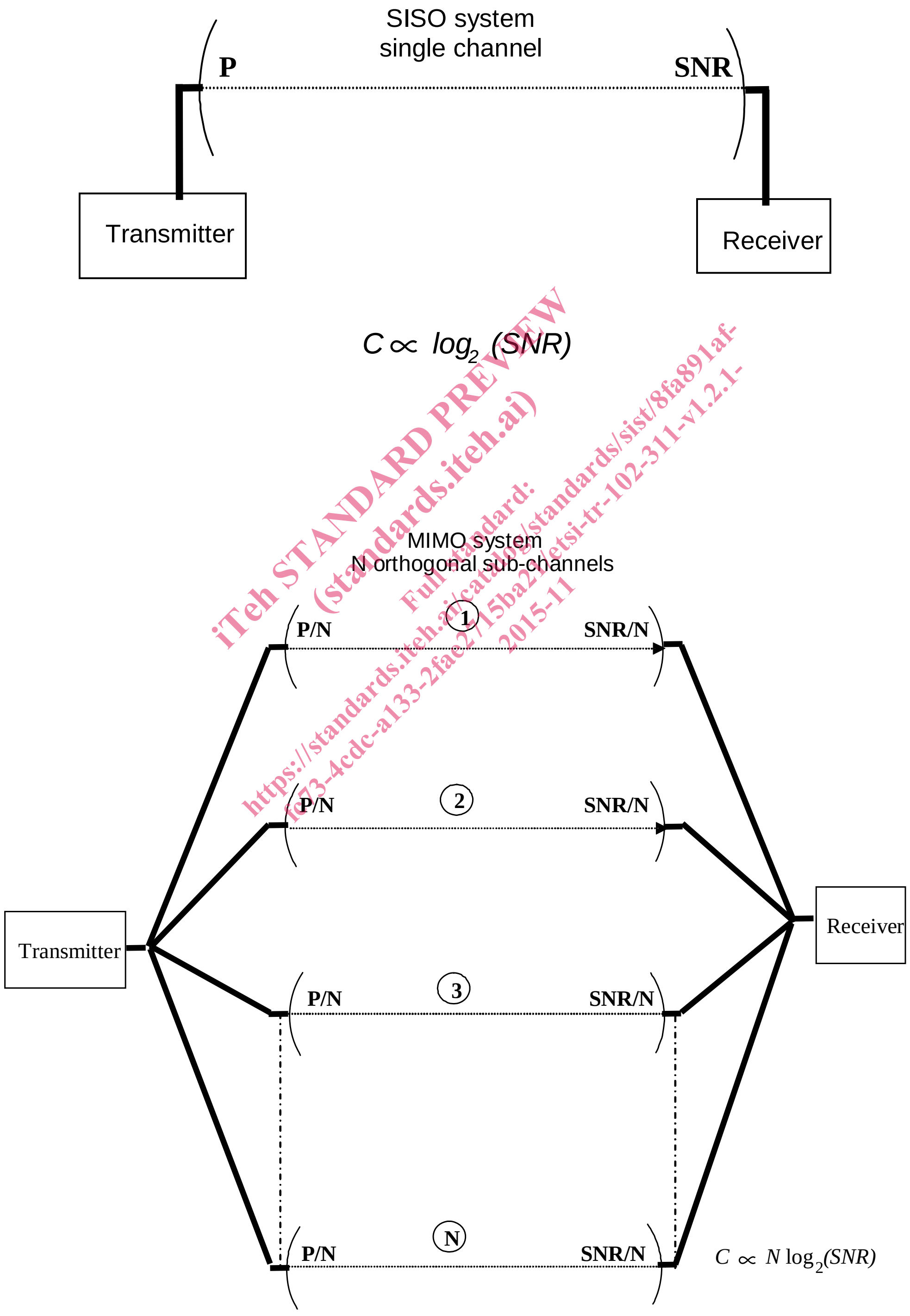

Figure 4.1: Comparison between SISO system and MIMO system

4.2 Difference between Cross-Polarization and Spatial Frequency Reuse (MIMO)

Unlike from the cross-polarization case, e.g. used in CCDP systems, where the Cross Polarization Discrimination (XPD) in "normal" conditions limits that the energy of one polarization signal falls back into the other polarization status, in a spatial frequency reuse system the energy of all sub-channels are at similar levels and all mixed together creating a lot of mutual interference between sub-channels.

Figure 4.2 compares the receiving sections of a cross-polarization system against spatial frequency reuse system (2 × 2 MIMO). The meanings of the variables in the figure 4.2 are:

- r^{i}_{xi} : received signal component at antenna element i-th (i = 1, 2) generated by the transmitted signal x_i.
- y^{i}_{xi} : i-th (i = 1, 2) demodulated signal component generated by transmitted signal x_i and received at antenna element i-th (i = 1, 2).
- r^i : the whole received signal at antenna element i-th (i.e. $r^1 = r^1_{x1} + r^1_{x2}$ and $r^2 = r^2_{x1} + r^2_{x2}$).
- y^i : the whole demodulated signal from antenna element i-th (i.e. $y^1 = y^1_{x1} + y^1_{x2}$ and $y^1 = y^1_{x1} + y^1_{x2}$).

Thus two cases arise:

1) Cross-Polarization System

   In this system two antennas, one for each polarization status (e.g. horizontal and vertical) are present.

   In an ideal case without any cause of depolarization, e.g. the antenna XPD is high enough and no rain or other atmospheric phenomena are active, at V-polarized antenna (i = 1) the received signal power level of the V-polarized transmitted signal (r^1_{x1}) is much higher than the received signal power level of the H-polarized transmitted signal (r^1_{x2}). The same stands with inversed behaviour between the polarization status signals for the second antenna (i = 2).

   XPIC algorithm cancels the self-interference of the unwanted polarization signal, for example H for the first antenna and V for the second one.

2) Spatial Frequency Reuse (MIMO) System

   Even in this system two antennas, or more, are present but they may use the same polarization (in the example the vertical one).

   In this case the received signal components, the couple (r^1_{x1} , r^1_{x2}) for antenna 1 and (r^2_{x1}, r^2_{x2}) for antenna 2, at each antenna have similar power level and the received signal components are not orthogonal to each other. Thus the difference in the phase of the signals, due to different sub-channel paths (space diversity), generated by MIMO antenna arrangement forms a kind of "orthogonality" or diversity between y^1 and y^2.

   An SFRC algorithm can facilitate the separation of the mixed input signals for data detection and, as well, the cancellation of the generated self-interference preventing any degradation on the received threshold.

NOTE: Orthogonality between two signals can be defined as a zero expectation of their sampled product over the symbol period T.

Spatial Frequency Reuse and Cross-Polarization may be exploited together in order to increase the number of independent sub-channels (Multi-Polarized MIMO).

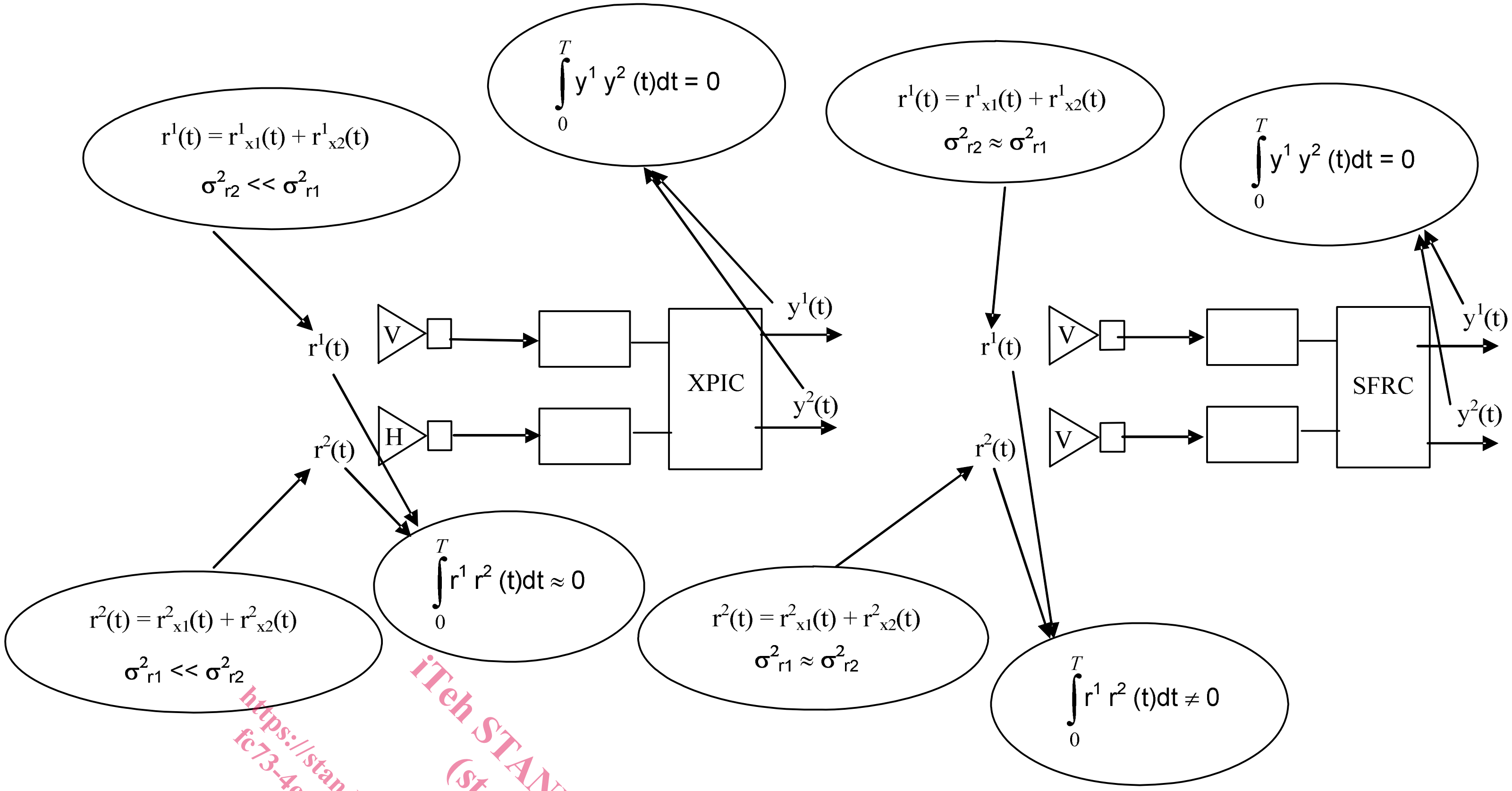

Figure 4.2: Cross-polarization versus spatial frequency reuse