SCP Technology – the New Challenge in Broadband Satellite Communications

D-r Veselin B. Demirev[1]

Abstract – **A new approach for solving the problems of the tracking antenna systems for broadband satellite communications is proposed. It includes additional pilot signal transmitted in the band of information signals and available in the receiver by one of the known methods of radio access. The receiver terminal is equipped with random phased antenna array. The random phase spread information and pilot signals correlate in a correlator. Its output signal at low intermediate frequency or at baseband is the recovered information signal. Matrix presentations of the signals in a SCP system, as well as their correlation matrix are given in the report. The Spatial Cross Correlation Function of a SCP system is defined as a measure of the isolation among the satellites, sharing the same frequencies.**

Keywords – **Spatial correlation processing, Broadband satellite communications, Tracking antenna array system**

I. INTRODUCTION

Satellite Communication Ground Systems (SCGS) are currently a strong growth market, driven chiefly by major projects to deploy vast regional or world-wide networks. One of the biggest technical problems of SCGS is the antenna system. The need to change the polarisation, to track Low Earth Orbiting Satellites (LEO,s) or to select one of several Geo Stationary Orbit Satellites (GSO,s) positions, as well as the requirements for mobile reception, low price and mass market production lead to unsolved by traditional antennas problems. The solving of the SCGS antennas problems needs entirely new approach, subject of this report. The name of the new technical proposal (Ref.1) is Spatial Correlation Processing (SCP). Its main objectives include:

- Receiving one or more radio signals coming from one or several spatially distributed sources (satellites), insuring high gain of the antenna systems and using fixed or mobile receiving terminals, equipped with SCP signal processing systems.
- Insuring spatial selectivity high enough to cancel the same frequency channel interference, coming from different space directions, using simple one-channel receiver and patented signal processing principle.

The objectives stated above are achieved by a method for radio communications, which proposes application of additional pilot signals transmitted in the band of information signals and available in the receiver by one of the known methods of access (Fig.1). The SCP receiver terminal antenna array is with equal in amplitude and random in phase aperture excitation. The phase shifts of the signals, received by the different antenna elements, are random at the antenna output regardless of the information source direction. These phase spread signals correlate with the recovered pilot signals, phase spread in the same manner. Since the pilots come from the same direction and propagate in the same random environment to the antenna output they should have the same phase spread ("poly-phased" signature) as the information signals. The results of the correlation process are the recovered information signals at low intermediate frequency or at base band. The signals coming from other satellites will propagate from antenna aperture to the antenna output in different random environment. Their phase spreads will be different from these of the chosen pilots and they will not correlate during the signal processing. This lack of correlation insures the spatial and polarization selectivity of the SCP system.

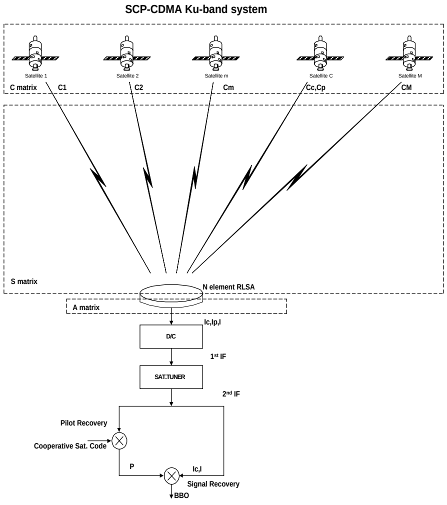

Fig.1

SCP system architecture

One of the main parts of the SCP system is the random phase antenna. In principle all kind of antenna arrays can be used, but for Ku band particular suitable for this purpose is the Radial Line Slot Antenna (RLSA). Until now it was used as phased array for fixed satellite reception. The main features of the SCP approach are:

- Simple and cheap passive RLSA, suitable for mass production in Ku and Ka frequency bands.
- One channel microwave receiver with simple signal processing.
- Omnidirectional for the cooperative satellite, but with high figure of merit G/T.

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[1] Veselin B. Demirev is with the Faculty of Communications and Communications technologies, TU – Sofia, "Kl. Ohridsky" blvd. N8, 1756 – Sofia, Bulgaria, E-mail: vedem@tu-sofia.bg

- Selection of different satellites and polarizations by PN-codes.
- Soft handover and virtual multibeams features.
- Receive only system, but with possible applications in transmitting systems too.
- Applications in existing S-DVB with minor modifications of the ground transmitters, compatible with the existing satellite transponders.
- High value of the patented intellectual property.
- Possible applications in fixed and mobile GSO S-DVB and in wideband GSO and NGSO satellite communication systems, as well as in the fixed and mobile terrestrial Local Multipoint Distribution Systems (LMDS).

II. BASIC MATRIX EXPRESSIONS OF THE SIGNALS IN A SCP SYSTEM

The SCP system is a multi source one output system and therefore can be represented by a block diagram, shown in fig. 1. Being a multi source system, it involves a cooperative signal source located in a position, given with its angular coordinates in the coordinate system (fig.2) and a number interference signal sources randomly distributed on both sides of the boresight. To analyze such a system, the most suitable mathematical tools available involve matrix and vector algebra. This results in relatively complex mathematical expressions which can be easy calculated by means of the Matlab software.

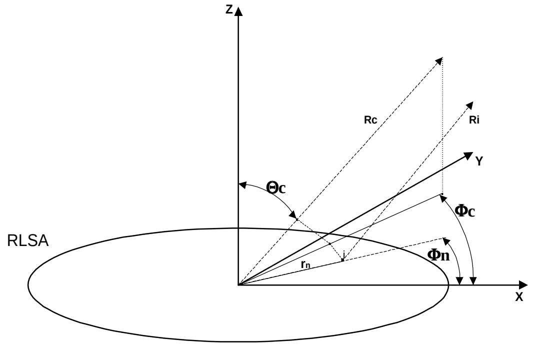

Fig. 2

SCP coordinate system

The SCP system under consideration involves both the cooperative information signal c_c with pilot c_p and the interference signal sources $c_{1,2,3...m...M}$ distributed throughout space. The signals from all of these sources will travel through space to reach the RLSA, where they will be picked up by every slot and collected by the Radial line to the input of the receiver. Here, after downconversion, the collected signals correlate with the recovered phase spread pilot signals for information signal recovery, result of phase despreading procedure. The cooperative signal source is located at angular coordinates ϕ_c, θ_c and distance R_c. The interference signal sources are located correspondingly to $\phi_{1,2...m...M}, \theta_{1,2...m...M}, R_{1,2...m...M}$.

Each slot of the N-elements RLSA will pick up signals from all the signal sources, cooperative and interference, and deliver them to its output. Thus the RLSA output will carry signals from all the signal sources. Let s_{nm} be the transfer function between m-th interference signal source and the n-th element of RLSA. Then

$$s_{nm} = L_{snm}.e^{-j\psi_{nm}} \qquad (1)$$

where L_{snm} are the space propagation losses, $\psi_{nm} = k.r_n.\sin\theta_m.\cos(\phi_m - \phi_n)$ is the phase of the signal received by n-th slot of RLSA relative to its center, $k = 2\pi/\lambda$ - free space phase constant, r_n, ϕ_n - the coordinates of the n-th slot of RLSA, ϕ_m, θ_m - the angular coordinates of m-th source.

Let $\mathbf{s}_m$ represents the transfer functions between m-th signal source and all slots of RLSA, then:

$$\mathbf{s}_\mathrm{m} = \left| \begin{matrix} s_{1m} \\ s_{2m} \\ \ldots\ldots \\ s_{nm} \\ \ldots\ldots \\ s_{Nm} \end{matrix} \right| \qquad (2)$$

where $\mathbf{s}_m$ is called a column matrix or vector. The transfers functions among all interference sources and RLSA slots can be represented by means of matrix $\mathbf{S}$, given by:

$$\mathbf{S} = \left|\mathbf{s}_1, \mathbf{s}_2, \ldots.\mathbf{s}_\mathrm{m} \ldots.\mathbf{s}_\mathrm{M}\right| = \left| \begin{matrix} s_{11} & s_{12}\ldots.s_{1m}\ldots.s_{1M} \\ s_{21} & s_{22}\ldots.s_{2m}\ldots.s_{2M} \\ \ldots\ldots\ldots\ldots & \ldots\ldots\ldots\ldots \\ s_{n1} & s_{n2}\ldots.s_{nm}\ldots\ldots s_{nM} \\ \ldots\ldots\ldots\ldots & \ldots\ldots\ldots\ldots \\ s_{N1} & s_{N2}\ldots.s_{Nm}\ldots.s_{NM} \end{matrix} \right| \qquad (3)$$

In analogy the transfer function for information and pilot signals from the cooperative source will be given by:

$$\mathbf{s}_\mathrm{c} = \left| \begin{matrix} s_{c1} \\ s_{c2} \\ \ldots.. \\ s_{cn} \\ \ldots.. \\ s_{cN} \end{matrix} \right| \quad \text{and} \quad \mathbf{s}_\mathrm{p} = \left| \begin{matrix} s_{p1} \\ s_{p2} \\ \ldots\ldots \\ s_{p3} \\ \ldots\ldots \\ s_{pN} \end{matrix} \right| \qquad (4)$$

If $c_1, c_2, ..., c_m .....c_M$ are the signals transmitted by the interference signal sources 1,2,......*m*, respectively, then the signals at the n-th RLSA slot due to the signals from the m-th interference signal source will be given by:

$$x_{nm} = s_{nm}.c_m \tag{5}$$

and that from the cooperative signal source will be given by:

$$x_{cn} = s_{cn}.c_c, x_{pn} = s_{pn}.c_p \tag{6}$$

Therefore the signal vector, combining the signals from all signal sources, interference and cooperative, at the n-th slot of RLSA is:

$$\begin{aligned} \mathbf{x}_{\mathrm{n}} &= \left| \; x_{n1} \quad x_{n2} ....x_{nm} ....x_{nc} x_{np} \; \right| = \\ &= \left| \; s_{n1}.c_1 \quad s_{n2}.c_2 ....s_{nm}.c_m ....s_{nM}.c_M \quad s_{cn}.c_c \quad s_{pn}.c_p \; \right| \end{aligned} \tag{7}$$

Considering the interference signals only, the interference signal vector at all slots of RLSA due to interference signal sources can be represented by:

$$\begin{vmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ ...... \\ \mathbf{x}_{\mathrm{n}} \\ ...... \\ \mathbf{x}_{\mathrm{N}} \end{vmatrix} = \begin{vmatrix} s_{11} & s_{12} & s_{13} ...s_{1m} ...s_{1M} \\ s_{21} & s_{22} & s_{23} ...s_{2m} ...s_{2M} \\ \multicolumn{3}{c}{......................................} \\ s_{n1} & s_{n2} & s_{n3} ...s_{nm} ...s_{nM} \\ \multicolumn{3}{c}{......................................} \\ s_{N1} & s_{N2} ..... & s_{Nm} ...s_{NM} \end{vmatrix} X \begin{vmatrix} c_1 \\ c_2 \\ c_3 \\ .... \\ c_m \\ .... \\ c_M \end{vmatrix}$$

or $\mathbf{X} = \mathbf{S}.\mathbf{c}$, where

$$\mathbf{X} = \begin{vmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ ...... \\ \mathbf{x}_{\mathrm{n}} \\ ...... \\ \mathbf{x}_{\mathrm{N}} \end{vmatrix} \text{ and } \mathbf{c} = \begin{vmatrix} c_1 \\ c_2 \\ c_3 \\ .... \\ c_m \\ .... \\ c_M \end{vmatrix} \tag{8}$$

Thus the column vector $\mathbf{X}$ represents all signals from all interference signal sources at all slots of RLSA while column vector $\mathbf{c}$ represents all signals transmitted by all interference signal sources. In addition to the signals from all interference signal sources, all slots will also receive the information and pilot signals from the cooperative signal source, as follows:

$$\mathbf{x}_{\mathrm{c}} = \mathbf{s}_{\mathrm{c}}.c_c, \mathbf{x}_{\mathrm{p}} = \mathbf{s}_{\mathrm{p}}.c_p \tag{9}$$

As it was mentioned above, the RLSA will transport all signals, received by different slots, to the RLSA output and the SCP receiver. Let the transfer functions between all RLSA slots and its output be represented by the column vector $\mathbf{a}$:

$$\mathbf{a} = \begin{vmatrix} a_1 \\ a_2 \\ a_3 \\ ..... \\ a_n \\ ..... \\ a_N \end{vmatrix} \tag{10}$$

where $a_n = L_{an}.e^{j\varphi n}$, L_{an} - gain of a single slot, RLSA propagation losses are included, $\varphi_n = 2\pi.r_n / \lambda_g + \Delta\varphi_n$, where $2\pi.r_n / \lambda_g$ - phase shift due to RLSA, $\Delta\varphi_n$ - phase shift due only to the inner slots and to the slot inclination if Circular Polarization (CP) is used.

Due to the finite transfer function that exists between the input and output ports of a RLSA, the signals appearing at its output will be those at the input slots modified by the transfer function $\mathbf{a}$. The signal vector $\mathbf{I}$, combining all interference signals appearing at the RLSA output, is:

$$\mathbf{I} = \left| \; a_1.\mathbf{x}_1 \quad a_2.\mathbf{x}_2 \quad a_3.\mathbf{x}_3 .... \quad a_n.\mathbf{x}_{\mathrm{n}} .... \quad a_N.\mathbf{x}_{\mathrm{N}} \; \right| = \mathbf{a}.\mathbf{X} \tag{11}$$

In analogy the signal vectors, combining all cooperative information $\mathbf{i}_c$ and pilot $\mathbf{p}$ signals will be given by:

$$\begin{aligned} \mathbf{i}_{\mathrm{c}} &= \left| \; a_1.x_{c1} \quad a_2.x_{c2} \quad a_3.x_{c3} .... \quad a_n.x_{cn} .... \quad a_N.x_{cN} \; \right| \\ &= \mathbf{a}.\mathbf{x}_{\mathrm{c}} \end{aligned} \tag{12}$$

$$\begin{aligned} \mathbf{p} &= \left| \; a_1.x_{p1} \quad a_2.x_{p2} \quad a_3.x_{p3} .... \quad a_n.x_{pn} .... \quad a_N.x_{pN} \; \right| \\ &= \mathbf{a}.\mathbf{x}_{\mathrm{p}} \end{aligned} \tag{13}$$

The received by RLSA signals are amplified in Low Noise Amplifier (LNA), downconverted, amplified and correlated in the Correlator unit. Consider for simplicity the process without math description of code spreading and dispreading, which in principle will not change the investigated interference environment and thermal noise properties. The total receiver gain *G*, product of the above mentioned procedures, will be:

$$G = G_{LNA}.G_{DC1}.G_{IFA1}.G_{DC2}.G_{IFA2} \tag{14}$$

where G_{LNA} is the gain of the LNA, G_{DC1} is the gain of the first downconverter, G_{IFA1} is the gain of the first IFA, G_{DC2} is the gain of the second downconverter and G_{IFA2} is the gain of the second IFA.

The output signal, product of the multiplication process, will be:

$$G(\mathbf{i}_{\mathrm{c}}.\mathbf{p}) = G\begin{vmatrix} i_{c1}.p_1 & i_{c2}.p_1\ldots. & i_{cn}.p_1\ldots. & i_{cN}.p_1 \\ i_{c1}.p_2 & i_{c2}.p_2\ldots. & i_{cn}.p_2\ldots. & i_{cN}.p_2 \\ \ldots\ldots\ldots\ldots & & & \\ i_{c1}.p_n & i_{c2}.p_n\ldots. & i_{cn}.p_n\ldots. & i_{cN}.p_n \\ \ldots\ldots\ldots\ldots & & & \\ i_{c1}.p_N & i_{c2}.p_N\ldots. & i_{cn}.p_n\ldots. & i_{cN}.p_N \end{vmatrix} \qquad (15)$$

Where the term $j-k$ consists of:

$$\begin{aligned}(i_{cj}.p_k) = \pm\, i_c.e^{j\left[\omega_{II}.t - k.r_j.\sin\theta_c.\cos(\phi_c-\phi_j)+k_g.r_j\right]} \\ .e^{j\left[\omega_{II}.t - k.r_k.\sin\theta_c.\cos(\phi_c-\phi_k)+k_g.r_k\right]}\end{aligned} \qquad (16)$$

In Eq. (16) $\pm i_c$ is the amplitude of the information signal per slot (BPSK modulation and uniform amplitudes of the antenna elements are considered), the same for the pilot is chosen to be 1. Assume the pilots are noise free due to the high CDMA Processing gain *PG).

By means of Eq.

$$\cos A.\cos B = 0{,}5\cos(A-B) + 0{,}5\cos(A+B)$$

Eq. (16) can be represented in real form as:

$$\begin{aligned}\mathrm{Re}(i_{cj}.p_k) = \pm\, 0{,}5.i_c.\cos\big[-k.r_j.\sin\theta_c.\cos(\phi_c-\phi_j) \\ +k_g.(\ r_j - r_k\ ) + k.r_k.\sin\theta_c.\cos(\phi_c-\phi_k)\big] \\ \pm 0{,}5.i_c\,(2\omega_{II}t + \ldots..)\end{aligned} \qquad (17)$$

The second term of Eq. (17) is with double intermediate frequency and after Low Pass Filtering (LPF) it cancels.

A basic requirement of the SCP technology (in order to obtain smooth omnidirectional cooperative pattern) is the sum of the off-diagonal terms of the matrix (15) to be zero. This requirement is fulfilled when the signals phase Probability Density Function (PDF) is uniform in the interval 0 – 360 degrees, the channel is real with Additive White Gaussian Noise (AWGN), RLSA is frequency dispersive and the process of correlation is digital. The real part of the n-th diagonal term of matrix (15) consists of:

$$\begin{aligned}\mathrm{Re}(i_{cn}.p_n) = \pm\, i_c.\cos^2\big[\omega_{II}.tr_n \\ -k.r_n.\sin\theta_c.\cos(\phi_c-\phi_n) + k_g\big]\end{aligned} \qquad (18)$$

Equation (18) can be presented by means of Eq. $\cos^2 A = 0{,}5.(1+\cos 2A)$ as follows:

$$\mathrm{Re}(i_{cn}.p_n) = \pm\, 0{,}5.i_c \pm 0{,}5.i_c.\cos(2\omega_{II}.t + \ldots..) \qquad (19)$$

The second term of Eq. (19) vanishes after LPF. The first term represents the demodulated information signal per antenna element at baseband. The total baseband output signal will be N times more, equal to the trace of the matrix (15) (the N diagonal elements of (15) are in phase):

$$\mathbf{BBO}_c = \pm\, 0{,}5.G.i_c.N \qquad (20)$$

The formal mathematical way to describe the above mentioned correlation process and the result (20) in matrix form is:

$$\mathbf{BBO}_{\mathrm{c}} = \mathrm{timeaver}\,G.(\mathbf{i}_{\mathrm{c}}.\mathbf{p}) = G.\mathrm{Tr}(\mathbf{i}_{\mathrm{c}}.\mathbf{p}^{\mathrm{H}}) \qquad (21)$$

where $\mathbf{p}^{\mathrm{H}}$ is the Hermitian (transpose and conjugate) matrix of $\mathbf{p}$.

In analogy the interference signals:

$$\mathbf{BBO}_{\mathrm{interference}} = \mathrm{timeaver}\,G.(\mathbf{I.p}) = G.\mathrm{Tr}(\mathbf{I.p}^{\mathrm{H}}) \qquad (22)$$

The Spatial Cross - Correlation Function (SCCF) can be introduced for the spatial interference analysis, as follows:

$$\mathbf{SCCF}(\phi,\theta)(dB) = 10\lg\left[\mathbf{BBO}_{\mathrm{inter.}}(\boldsymbol{\varphi},\boldsymbol{\theta}) / \mathbf{BBO}_{\mathrm{c}}\right] \qquad (23)$$

The total system interference from several satellites could be represented by means of Protection Ratio (PR), defined as the ratio of the cooperative BBO to the total interference.

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