Spatial Correlation Processing – the New Approach in the Broadband Satellite Tracking Systems

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Abstract- A new approach to solve the problems of the tracking antenna systems for broadband satellite communications, named SCP, is proposed in the paper. 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 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 paper. The Spatial Cross Correlation Function of a SCP system is defined as a measure of the isolation among the satellites, sharing the same frequency channel. The requirements to the pilot transmission technology are defined in the report. A proposal for CDMA pilot spreading and transmission in the frequency band of the information signal is given too. The basic SCP-CDMA systems parameters are defined by means of modified link budget calculations per unit antenna element. Matlab matrix simulations of a Ku band SCP-CDMA system, used for DVB-S, are given too. The probability theory is used to investigate some of the basic properties of the SCP technology. Central limit theorem is used to prove the gain of the random phased antenna array, as well as the Gaussian probability properties of the antenna array output signals.

Keywords- SCP Technology; DVB-S, Spatial Cross Correlation Function; Random Phase Process; Central Limit Theorem.

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 tracking of a satellite independently of mobile motion is an essential function for directional antenna systems used by Mobile Satellite Services (MSS) in Ku and Ka frequency bands. The tracking function needs two capabilities – beam steering and tracking control [1].

There are two types of beam steering methods. The first is mechanical steering, which physically directs the antenna to the satellite. The second is electronic steering, which directs the antenna beam by electronic scanning. A typical example of electronic steering is achieved through a phased array antenna. The main features of the two types of methods are listed below:

- Mechanical steering
  - Advantages: Technically easy to fabricate; Wide beam coverage; Good axial ratios in wide beam coverage.

- Electronic steering
  - Advantages: Light and low profile; High-speed beam scanning; High reliability.
  - Disadvantages: Technically difficult to fabricate; Narrow beam coverage; Narrow frequency working band; Poor axial ratios in wide scanned coverage; Excessive feeder loss; Extremely high cost (in order of hundred thousands US $).

There are also two methods to control tracking. The first is the closed loop method, which uses a signal from the satellite to search for and maintain in satellite direction. The second method is the open loop method, which does not use signals from a satellite. It uses compasses and rate sensors and is not applicable for MSS in Ku and Ka frequency bands, where high gain narrow beam antenna systems are used.

The tasks performed by the SCGS satellite tracking system include satellite acquisition and automatic tracking [2]. The acquisition system acquires the desired satellite by moving the antenna around the expected position of the satellite. Automatic tracking is initiated only after the received signal strength due to the beacon signal transmitted by the satellite is above a certain threshold value, which allows the tracking receiver to lock to the beacon. The automatic tracking ensures continuous tracking of the satellite. Figure 1 shows the generalized block schematic arrangement of the closed loop satellite tracking system. The SCGS antenna makes use of the beacon signal to track itself to the desired positions in both azimuth and elevation. The auto track receiver derives the tracking correction data that is used to drive the antenna. The tracking techniques are classified on the basis of the methodology used to generate angular errors. Commonly used tracking techniques include:

- Sequential Lobing
  - In sequential lobing, the beam axis is slightly shifted off the antenna axis. This squinted beam is sequentially placed in discrete angular positions, usually four, around the antenna axis. The angular information about the satellite to be tracked is determined by processing the received signals. The track error information is contained in the signal amplitude variations. The squinting and beam switching is done with the help of electronically controlled feed and therefore can be done very rapidly.
Conical Scan

This is similar to sequential lobing except that in the case of conical scan, the squinted beam is scanned rapidly and continuously in a circular path around the antenna axis. If the satellite to be tracked is off the antenna axis, the amplitude of the echo signal varies with antenna’s scan position. The tracking system senses the amplitude variations and the phase delay as function of scan position to determine the angular coordinates. The amplitude variation provides information on the amplitude of the angular error and the phase delay indicates direction. The angular error information is then used to steer the antenna axis to make it to coincide with the object location. The technique offers good tracking accuracy and an average response time.

Monopulse Tracking

One of the major disadvantages of sequential techniques including sequential lobing and conical scan is that the tracking accuracy is severely affected if the amplitude of the received signal from the tracked satellite changes during the time the beam was being switched or scanned to get the desired number of samples. Monopulse tracking overcomes these shortcomings by generating the required information on the angular error by simultaneous lobing of the received beacon. Monopulse tracking technique offers very high tracking accuracy and fast response time. Due to absence of any mechanical parts, the feed system requires very little maintenance. The disadvantages include high cost, large and complex feed system and need to have at least two-channel coherent receivers and good RF phase stability. It is commonly employed in large fixed SCGS and also in those earth stations that require accurate tracking of nongeostationary satellites.

The main disadvantages of the above listed closed loop tracking methods when used in MSS are:

- The use of satellite signals as essential factor. This is because received signal levels from satellites are not stable because of the severe propagation environment due to fading, blocking and shadowing.
- Long acquisition time period during the starting procedures, which is in order of one minute in real MSS systems. The same acquisition time is needed after the loose of the signal due to blocking in urban environment.
- The listed methods can be used for tracking only one communication satellite. In some cases, where very high reliability of MSS is necessary (Aeronautical MSS), the space diversity approach is used. It includes simultaneous communications and tracking of several satellites, obviously not achieved by the known tracking methods and systems.

The brief review of tracking antenna methods shows that the solving of tracking SCGS problems needs entirely new approach. The aim of this paper is to propose such approach, as well as to give mathematical explanation of the processes, some computer simulations of system resolution and a guide line to a practical realisation of such type communication systems. The name of the new technical proposal [3,4] is Spatial Correlation Processing (SCP).

The proposed SCP system 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.
- Insuring spatial selectivity high enough to cancel the same frequency channel interference, coming from different space directions, using simple one-channel receiver and signal processing circuits.

The above mentioned SCP system objectives solve simultaneously the problems of antenna beam steering and closed-loop satellite tracking. SCP system could be defined as virtually electronic steering and multiple satellites closed-loop tracking system. During the research it was known as “Demirev principle”. Because of the basic differences of the proposed new principle with the existing antenna steering and tracking methods, there are not other similar research group approaches and published results. The proposed theory was published in several regional Conferences as scientific reports, some of them in Bulgarian language. They are not available as journal papers in English language. The SCP approach is base for the later developed Random Phase Spread Coding (RPSC, or SCP,transmit) approach, as well as for the RPSC-Multiple Access techniques.

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the known methods of access (Fig. 2). The SCP receiver
terminal Random Phased Antenna Array (RPAA) 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 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.

The signal processing circuits, shown in fig. 2, could be
realized after the Intermediate Frequency Amplifier in
digital way. In such manner it is not problem to create
several similar circuits, working in parallel with another
satellites from the constellation.

One of the main parts of the SCP system is the RPAA.
In principle all kind of antenna arrays could be used, but for
Ku and Ka bands particular suitable for this purpose is the
Radial Line Slot Antenna (RLSA) with random distributed
and oriented slot radiators. Until now it was used as phased
array for fixed satellite reception [5]. The main features of
the SCP approach are:

- Simple and cheap passive RPAA, suitable for mass
  production in Ku and Ka frequency bands.
- One channel microwave receiver with simple signal
  processing.
- Omni-directional for the cooperative satellite, but
  with high figure of merit G/T.
- Selection of different satellites and polarizations by
  Pseudo-Noise (PN)-codes.
- Soft handover and virtual multi-beams features.
- Receive only system, but with possible applications
  in transmitting systems too.
- Applications in existing Digital Video Broadcasting
  Satellite (DVB-S) systems 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 Geo
  Stationary Orbit (GSO) DVB-S systems, in
  wideband GSO and Non-GSO satellite
  communication systems, as well as in the fixed and
  mobile terrestrial Local Multipoint Distribution
  Systems (LMDS), High Altitude Platform Systems
  (HAPS), etc.

B. Matrix Expression 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. 2. 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.3) and a number
interference signal sources randomly distributed on both
sides of the bore sight. To analyse 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. The SCP system under
consideration involves both the cooperative information
signal $c_i$ with pilot $c_p$ and the interference signal sources
$c_{1,2,3,\ldots, M}$ distributed throughout space. The signals from
all of these sources will travel through space to reach the
RPAA, where they will be picked up by every antenna array
element and collected by the distribution network to the
input of the receiver. Here, after down-conversion, the
collected signals correlate with the recovered phase spread
pilot signals for information signal recovery, result of phase
spreading procedure. The cooperative signal source is
located at angular coordinates $\phi_i, \theta_i$ and distance $R_i$. The
interference signal sources are located correspondingly to
$\phi_{1,2,3,\ldots, M}$, $\theta_{1,2,3,\ldots, M}$ and $R_{1,2,3,\ldots, M}$.

Each element of the N-elements RPAA will pick up
signals from all the signal sources, cooperative and
interference, and deliver them to its output. Thus the RPAA
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 RPAA. Then
\[
s_{nm} = L_{nm} \eta_{nm} e^{-j\psi_{nm}}
\]  
(1)
where \( L_{nm} \) are the space propagation losses, \( \eta_{nm} = k r_n \sin \theta_m \cos (\phi_m - \phi_n) \) is the phase of the signal received by \( n \)-th element of RPAA relative to its centre, 
\( k = 2\pi / \lambda \) - free space phase constant, \( r_n, \phi_n \) - the coordinates of the \( n \)-th element of RPAA, \( \phi_m, \theta_m \) - the angular coordinates of \( m \)-th source.

\[\text{Fig.3 SCP coordinate system}\]

Let \( s_m \) represents the transfer functions between \( m \)-th signal source and all elements of the RPAA, then:
\[
s_m = \begin{bmatrix} \ldots s_{1m} \\ s_{2m} \\ \ldots \\ s_{nm} \\ \ldots \end{bmatrix}
\]  
(2)
where \( s_m \) is called a column matrix or vector. The transfers functions among all interference sources and RPAA elements can be represented by means of matrix \( S \), given by:
\[
S = \begin{bmatrix} s_{11} & s_{12} & \ldots & s_{1M} \\ s_{21} & s_{22} & \ldots & s_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \ldots & s_{nM} \\ \vdots & \vdots & \ddots & \vdots \\ s_{N1} & s_{N2} & \ldots & s_{NM} \end{bmatrix}
\]  
(3)

In analogy the transfer function for information and pilot signals from the cooperative source will be given by:
\[
s_c = \begin{bmatrix} \ldots \\ s_{c1} \\ s_{c2} \\ \ldots \\ s_{cn} \\ \ldots \end{bmatrix}
\]  
(4)

\( s_c \) and \( s_n \) are the signals transmitted by the interference signal sources 1, 2, ..., \( M \), respectively, then the signals at the \( n \)-th RPAA element due to the signals from the \( m \)-th interference signal source will be given by:
\[
x_{nm} = s_{nm} e_m
\]  
(5)
and that from the cooperative signal source will be given by:
\[
x_{cn} = s_{cn} e_c, \quad x_{cp} = s_{cp} e_p
\]  
(6)
Therefore the signal vector, combining the signals from all signal sources, interference and cooperative, at the \( n \)-th element of RPAA is:
\[
x_n = \begin{bmatrix} x_{n1} \\ x_{n2} \\ \ldots \\ x_{nm} \\ \ldots \\ x_{cp} \end{bmatrix}
\]  
(7)

Considering the interference signals only, the interference signal vector at all elements of the RPAA due to interference signal sources can be represented by:
\[
x = \begin{bmatrix} x_1 \\ x_2 \\ \ldots \\ x_N \end{bmatrix}
\]  
(8)
Thus the column vector \( x \) represents all signals from all interference signal sources at all elements of the RPAA while column vector \( c \) represents all signals transmitted by all interference signal sources. In addition to the signals from all interference signal sources, all elements will also receive the information and pilot signals from the cooperative signal source, as follows:
\[
x_c = x_c e_c, \quad x_p = x_p e_p
\]  
(9)
As it was mentioned above, the RPAA will transport all signals, received by different elements, to its output and the SCP receiver. Let the transfer functions between all RPAA elements and its output be represented by the column vector \( a \):
\[
a = \begin{bmatrix} a_1 \\ a_2 \\ \ldots \\ a_N \end{bmatrix}
\]  
(10)
where \( a_n = L_{\text{out}} e^{j\alpha_n} \), \( L_{\text{out}} \) - gain of a single element, RPAA propagation losses are included, \( \phi_n = 2\pi r_n / \lambda_c + \Delta \phi_n \) where \( 2\pi r_n / \lambda_c \) - phase shift due to RPAA, \( \Delta \phi_n \) - phase shift due only to the inner elements and to the element inclination if Circular Polarization (CP) is used.

Due to the finite transfer function that exists between the input and output ports of a RPAA, the signals appearing at its output will be those at the input slots modified by the transfer function \( a \). The vector signal \( i \), combining all interference signals appearing at the RPAA output, is:

\[
I = \begin{bmatrix} a_1 x_1 & a_2 x_2 & \cdots & a_n x_n & \cdots & a_N x_N \end{bmatrix} = a X
\]

(11)

In analogy the signal vectors, combining all cooperative information \( i_c \) and pilot \( p \) signals will be given by:

\[
i_c = \begin{bmatrix} a_1 x_{c1} & a_2 x_{c2} & \cdots & a_n x_{cn} & \cdots & a_N x_{cN} \end{bmatrix} = a x_c
\]

(12)

\[
p = \begin{bmatrix} a_1 x_{pl} & a_2 x_{p2} & \cdots & a_n x_{pn} & \cdots & a_N x_{PN} \end{bmatrix} = a x_p
\]

(13)

The received by the RPAA signals are amplified in Low Noise Amplifier (LNA), down-converted, 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:

\[
G = G_{\text{LNA}} G_{\text{DC1}} G_{\text{IFAI}} G_{\text{DC2}} G_{\text{IFAI2}}
\]

(14)

where \( G_{\text{LNA}} \) is the gain of the LNA, \( G_{\text{DC1}} \) is the gain of the first down-converter, \( G_{\text{IFAI}} \) is the gain of the first IFA, \( G_{\text{DC2}} \) is the gain of the second down-converter and \( G_{\text{IFAI2}} \) is the gain of the second IFA.

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

\[
G(i_c, p) = G = \begin{bmatrix} i_{c1} p_1 & i_{c2} p_1 & \cdots & i_{cN} p_1 \\
i_{c1} p_2 & i_{c2} p_2 & \cdots & i_{cN} p_2 \\
\vdots & \vdots & \ddots & \vdots \\
i_{c1} p_n & i_{c2} p_n & \cdots & i_{cN} p_n \\
i_{c1} p_N & i_{c2} p_N & \cdots & i_{cN} p_N 
\end{bmatrix}
\]

(15)

Where the term \( j - k \) consists of:

\[
(i_{cj} p_k) = i_n e^{j (\theta_n - \phi_k) + k r_j}
\]

(16)

In Eq. (16) \( i_n \) 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:

\[
\text{Re}((i_{cj} p_k) = \cos \left( k r_j \sin \theta_n \cos (\theta_n - \phi_k) \right) + k r_j \sin \theta_n \cos (\phi_k - \phi_n)
\]

(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 omni-directional 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), RPAA is frequency dispersive and the process of correlation is digital. The real part of the \( n \)-th diagonal term of matrix (15) consists of:

\[
\text{Re}((i_{cn} p_n) = \cos \left( a r_n \right) + \sin \theta_n \cos (\phi_k - \phi_n) + k r_j
\]

(18)

Equation (18) can be presented by means of Eq.

\[
\cos^2 A = 0.5 \left( 1 + \cos 2A \right)
\]

as follows:

\[
\text{Re}((i_{cn} p_n) = -0.5 i_n \cos (2 a r_n + \ldots)
\]

(19)

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

\[
\text{BBO}_c = 0.5 G I_c \cdot N
\]

(20)

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

\[
\text{BBO}_c = \text{timeaver} G(i_c, p) = G \cdot \text{Tr}(i_c, p^H)
\]

(21)

where \( p^H \) is the Hermitian (transpose and conjugate) matrix of \( p \).

In analogy the interference signals:

\[
\text{BBO}_{\text{interference}} = \text{timeaver} G(I, p) = G \cdot \text{Tr}(I, p^H)
\]

(22)

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

\[
\text{SCCF}(\phi, \theta)(dB) = 10 \log \left( \text{BBO}_{\text{interference}}(\phi, \theta)/\text{BBO}_c \right)
\]

(23)

C. Pilot Signal Transmission

The practical implementation of the SCP approach leads to the problem of pilots transmission through the same propagation environment as that of the cooperative information signals. The requirements to the pilot transmission technology could be summarized as follows [6]:

\[
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\]

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It should occupy minimum additional frequency spectrum resources, as well as additional hardware.

It should not cause interference over the cooperative information signals.

It should ensure easy access to the chosen combination of pilots in the case of mass implementation of SCP technology in satellite communications.

It should not generate any significant intermodulation noise in the satellite transponders, working near to the saturation point (zero back-off).

Bearing in mind the frequency dispersive phase shifts, introduced by RPAA to the information and to the pilot signals, their career frequencies should be as close as it is possible.

Bearing in mind the frequency dispersive phase shifts, introduced by RPAA to the information and to the pilot signals, their career frequencies should be as close as it is possible.

The common used methods for access in wireless communications are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). All of them could to be used for pilot transmission in SCP technology, but the CDMA approach matches in the best way to the above mentioned requirements. The system architecture is shown in fig.2. The frequency spectrum of a SCP-CDMA system is shown in fig.4.

III. SCP GSO CDMA SYSTEM PARAMETERS

As a result of the random RPAA elements distribution and inclination, the different slots signals phases are random, uniformly distributed between 0 and 360 degrees. Their amplitudes can be calculated, using conventional link budget equations with the following assumptions for simplicity:

- The antenna element (slot in RLSA) directivity pattern is omni directional (which is exactly correct for high elevation angles).
- The slot gain $G_s=1.6$ dbi (based on published experimental results for RLSA, the transmission losses in the antenna are included).
- Simplified forms of link budget equations are used.
- The “cosines” dependence of the effective array aperture is neglected, which is strictly true only for small tilt angles.

Bearing in mind the above simplifications and the particular values for a DVB-S satellite:

- $EIRP=50$ dbw for each component of the QPSK modulated signals,
- $S=38000$ km (distance to the GSO satellite),
- $f=12.5$ GHz (microwave frequency in the middle of the Ku band),
- $L=206$ db (calculated propagation losses)
- $R=20$ MBt/s (standard information signal data rate),
- $R_c=1.23$ MCh/s (chosen spreading code chirp rate for the pilots),
- System noise temperature $T_s=125$ grad. K, $T_s(db)=21$ dbgrad.K,
- $G/T$ per slot=$-19.4$ dbi/gradK (calculated),
- $L_{add}=2$ db (additional losses due to propagation phenomena),
- $L_{pol.loss}=3$ db (because of the circular polarization),
- $N=2700$ (number of available slots in 60 cm diameter RLSA according to the published data), $N(db)=34.3$db

For the parameters listed above, the following values are computed:

- Information signal to noise ratio per slot $(E_b/N_0)_{ps}=-24.81$ db.
- Information signal power per slot $C_{ips}=-159.4$ dbW.

The multiplication of the information and the pilots signals from a given slot in the Correlator unit and the following Low Pass Filtering (LPF) is process of coherent demodulation. The result is $N$ in phase base band components, which sum is the demodulated base band signal. Bearing in mind that the signal to noise ratio for the pilot is about 20 db higher than the same for the information signal (approximately it is noise free), the total $(E_b/N_0)_t=N,(E_b/N_0)_ps,(E_b/N_0)_{(db)=N(db)+(E_b/N_0)_{(db)}ps=34.3-24.81=9.49}$ db. The last result is several db above the specified standard values.

In analogy the total figure of merit $(G/T)_t(db)=N(db)+(G/T) per slot(db)=34.3-19.4=14.9$dbi/grad.K.

It was shown that the SCP requirement to obtain smooth omnidirectional cooperative pattern needs the off-diagonal output signals to cancel for all possible elevation and azimuth angles of the cooperative satellite. It is zero when the antenna slots signals phase probability density function is uniform from 0 to 360 deg. for all spatial angles of the signal direction. A random distribution of the slots over RLSA surface was proposed for this purpose. The slots coordinates were chosen by means of random generator with some restrictions. The practical implementation of this procedure was not quite successful because:
• There were areas on the RLSA surface where the neighbour slots were at equal distance to the centre of the RLSA. As a result the signals from these slots are in phase (they are strong correlated) and the phase probability density function has maximum for low phase values.

• The neighbour slots were placed close and at equal distances each other in radial direction. Bearing in mind the low permittivity of the RLSA core, the signals from these slots were close in phase. The phase probability density function has maximum for low phase values too. The RLSA works as a leaky-wave antenna in this particular case.

• The small inter-slots spacing (used for high efficiency of the RLSA) leads to high values of mutual coupling among the neighbour slots. The result is the existence of high correlated areas on the RLSA surface, due to non-random phase excitation.

The existence of strong correlated areas leads to statistically uncompensated cros signal output (the BBO correlation matrix is not equal to its trace). The cros output is summed with the omnidirectional cor output and as a result the high ripples in the SCP output signal appear. It means that the system sensitivity is not equal for the different azimuth and elevation angles. The only way to obtain smooth SCP cooperative pattern is to decorrelate as much as it is possible the signals from the RLSA slots, bearing in mind the influence of the RLSA core, to receive with low signal to noise ratio (where the AWGN channel theory is valid) and to use digital correlators with high sampling time period.

The latest algorithm for the slots distribution and orientation represents a combination of the previously used approaches for phase randomization and radial distributed pins fed slots with the following characteristics:

• random element position.
• the slots are normal, or at angles ±45 deg to the radius of the antenna, or radial with exciting pins
• the positions of the exciting pins are alternatively changed so that the phase difference for the radial slots equally spaced from the antenna centre and with different pins positions is 180 deg.

One of the most important parameters of the receiving DVB-S systems is the cross polarization isolation between Left and Right Hand Circular Polarization (LH, RH, CP). The problem here is its degradation for high tilt angles. The cross polarization isolation and the switching of the received polarizations in the SCP systems are based on entirely new principle of operation. The slots design assures the both CP to be received in the most efficient way. The choice of the polarization is based on the correlation of the chosen pair of pilots for given CP with the corresponding information signals. The signals, received by LH and RH CP, are not correlated because of the opposite direction of rotation and about 15 MHz frequency offset between the selected pilot signals and the opposite CP signals. Very good cross polarization properties, independent on the tilt angles, are expected in this way.

The developed math model of the SCP system, as well as the Mathlab simulations, does not include the polarization properties of the RLSA slots. As it was stated early, the best way to randomise the phase distribution is to incline the slots in random manner and to use circular polarization. The math description of the SCP approach in this case should to involve the antenna-wave interaction from polarization point of view. The detailed developing of this method for the SCP case should to be done in the future works.

The developed math model for the slots signals phases deals with the space distribution among antenna slots and the cooperative satellite (the outer solution), as well as the slots positions on the RLSA aperture (the inner solution). It does not include the influence of the inner slots and fed probes to the outer slots signal phases, as well as the mutual coupling phenomena.

The matrix simulations of a SCP-CDMA system, K-u band version, used for DVB-S application, should start with a simplified analysis. For this purpose the following assumptions and simplifications are used in the calculations:

• space propagation losses \( L_{\text{sum}} = 1 \), \( \lambda = 2.5 \text{cm} \),
• \( r_m = 5 - 28.5 \text{cm}, \phi_m = 0 - 360^\circ \).
• \( \phi_m, \theta_m \) – angular coordinates of interference satellites, entries for \( S \) -matrix calculation, \( \phi_c, \theta_c, \phi_p, \theta_p \) – angular coordinates of the cooperative satellite. Three possible scenarios should be calculated – in zenith, 30 and 60 degrees tilt from zenith, pure south.
• \( c_1 = c_2 = \ldots = c_M = c_p = c_c = 1 \) – amplitudes of interference, pilot and cooperative information signals.
• RLSA propagation losses \( L_{\text{an}} = 1 \). The phase shift due to inner slots and slot inclination \( \Delta \phi_n = 0 \).
• The total receiver gain \( G=1 \).

![Fig.5 SCCF of RLSA Diameter – 0.57 m](image)

\( N = 2501, \lambda = 2.5 \text{cm}, \phi_p = 0^\circ, \theta_p = 0^\circ, \phi_m = 0^\circ, \theta_m = -70^\circ + 70^\circ \)
A basic property of the SCP approach is the random phase spread among the signals, received by the different antenna array elements. Consider [7,8] the theory of a random process, which in the best way describes the SCP signals. Consider the time function:

$$X(t) = A \cos(\omega_0 t + \theta)$$  \hspace{1cm} \text{for} \hspace{1cm} \infty < t < \infty \hspace{1cm} (24)$$

Where $A, \omega_0$ are constants, $\theta$ is the random variable with uniform probability density function in the interval $[0,2\pi]$. The collection of all possible such waveform together with the underlying probability assignment is called a phase random process. Each realization of a particular waveform is referred as a sample function. In SCP case each such sample function corresponds to a particular signal, obtained from a given antenna array element. Uniform amplitude distribution ($A=$const.) is considered for simplicity.

The mean value of the random phase process, given with Eq. (24) is:

$$E[X(t)] = \int_0^{2\pi} A \cos(\omega_0 t + \theta) \frac{d\theta}{2\pi} = 0 \hspace{1cm} (25)$$

The mean square value is:

$$E[X^2(t)] = \int_0^{2\pi} A^2 \cos^2(\omega_0 t + \theta) \frac{d\theta}{2\pi} = \frac{A^2}{2} \hspace{1cm} (26)$$

The variance is:

$$\sigma_x^2(t) = E[X^2(t)] - [E[X(t)]]^2 = \frac{A^2}{2} - 0 = \frac{A^2}{2} \hspace{1cm} (27)$$

The autocorrelation function is:

$$R_x(t,t+\tau) = E[X(t)X(t+\tau)] = \int_0^{2\pi} A^2 \cos(\omega_0 t + \theta) \cos(\omega_0 (t+\tau) + \theta) \frac{d\theta}{2\pi} = \frac{A^2}{2} \cos \omega_0 \tau \hspace{1cm} (28)$$

If the random variables [9] $X_1, X_2, \ldots, X_n$ are independent and identically distributed with probability density functions $f_x(x)$, means $\mu_x$ and variance $\sigma_x^2$, then the probability distribution function of such sum $Y = X_1 + X_2 + \ldots + X_n$ is approximately Gaussian with mean $\mu_y = n \mu_x$ and variance $\sigma_y^2 = n \sigma_x^2$. as long as $n$ is “large enough”. This result is called the Central Limit Theorem (CLT).

Applying CLT to the SCP random phase process, we obtain for the RPAA output signal the sum $Y = X_1 + X_2 + \ldots + X_n$ with mean $\mu_y = n \mu_x = 0$ and variance:

$$\sigma_y^2 = n \sigma_x^2 = n \frac{A^2}{2} \hspace{1cm} (29)$$

In this particular case (zero mean), the variance is equal to the mean square value (the energy of the signal, or to the autocorrelation value at zero time offset) resp. of the individual antenna element and of the total SCP antenna. The equation (29) proves the basic SCP property that the total antenna gain is sum of the gains of the individual slot radiators.

The sum $Y$ is Gaussian with Probability Distribution Function (PDF) [9,10], given by:

$$p_y(\alpha) = \frac{1}{\sqrt{2\pi \sigma_y}} e^{-\alpha^2/2\sigma_y^2} \hspace{1cm} (30)$$

The Cumulative Distribution Function (CDF) of such process is given by:

$$F_y(\alpha) = \Pr[Y \leq \alpha] = \int_{-\infty}^{\alpha} \frac{1}{\sqrt{2\pi \sigma_y}} e^{-\lambda^2/2\sigma_y^2} \ d\lambda = 1 - Q(\alpha/\sigma_y) \hspace{1cm} (31)$$
Where $Q(\alpha)$ is defined as Complementary Cumulative Probability Distribution Function (CCCDF) of a standard zero-mean, unit variance Gaussian random variables, $G(0,1)$:

$$Q(\alpha) = \frac{1}{\sqrt{2\pi}} \int_\alpha^\infty e^{-\frac{x^2}{2}} \, dx$$

The root mean square value of the envelope of such process (Rayleigh) is:

$$R_{\text{rms}} = \sqrt{2\sigma_v}$$

The matrix presentation of the RLSA poly-phase signals, as well as matrix description of the SCP correlation processes are given above only for BPSK modulated signals. In the real broadband satellite systems QPSK modulation is used in order to double the system information capacity. An important issue of QPSK SCP systems is the isolation between $I$ and $Q$ channels. This isolation depends on the cross-correlation properties between $I$ channel pilot signal $P_I$ and $Q$ channel information signal $I_Q$ (and vice versa). For this reason the cross-correlation properties of orthogonal poly-phase spread signals are considered below, following [12].

Consider the above-mentioned pair of QPSK SCP signals $P_I(t)$ and $I_Q(t)$ that is related to a random wide-sense stationary process $X(t)$ as follows:

$$P_I(t) = X(t)\cos(2\pi f_c t + \theta)$$  
$$I_Q(t) = X(t)\sin(2\pi f_c t + \theta)$$

Where $f_c$ is a carrier frequency, and the random variable $\theta$ is uniformly distributed over the interval $(0,2\pi)$. Moreover, $\theta$ is independent of $X(t)$. One cross-correlation function of $P_I(t)$ and $I_Q(t)$ is given by:

$$R_{P_I I_Q}(\tau) = E[P_I(t)I_Q(t-\tau)] = E[X(t)X(t-\tau)\cos(2\pi f_c t + \theta)\cos(2\pi f_c (t-\tau) + \theta)] = 0.5R_X(\tau)\cos(2\pi f_c \tau)$$

Where in the last line we have used the fact that $X(t)$ as computer simulations of the virtual antenna patterns are given too. The Probability Theory, based on CLT, is shown for better understanding of the unique SCP technology properties.

The derived Eq.(20) shows, that the power of the received signal at base-band is equal to that, obtained by phased to the satellite direction array antenna. The power does not depend on the azimuth and elevation angles, which means that the obtained antenna gain is omnidirectional. Eq. 20 and the Matlab simulations of the Spatial Cross Correlation Function (SCCF) shows that SCP system space resolution between two adjacent satellites is equal to that, obtained by circular phased antenna array with the same diameter as that of the used in the simulations circular Random Phased Antenna Array.

The preliminary research results, shown in the paper, promise excellent parameters of the future SCGS, based on SCP approach. The practical SCP principles implementations will drastically change the existing paradigm in the satellite communication business in general. Many of the existing problems of the proposed satellite systems, dealing with frequency and orbital resource sharing, beam pointing, beam shadowing, etc., will be solved successfully.

**REFERENCES**


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