Modification of the IEEE 802.16 Standard in Application to the "Distributed Satellite"

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Abstract— The WiMAX network modification to adapt the "distributed satellite" specifications was considered. The measuring approach based on the WiMAX wideband access mobile network utilization was proposed for evaluation of micro satellites and cubes-satellites relative position during their clustering flight in close proximity to one another.

Keywords— Low-orbit satellite system, distributed satellite, cube-sat mutual position, two-dimensional distance matrix, multidimensional matrix of angle, WiMAX wideband radio access network, adaptation, IEEE 802.16 standard, information exchange.

Introduction

LEO satellite systems are used in various applications: telecommunications, remote sensing, scientific projects, technological and demonstration experiments, academic programs [1]. One of the direction of the LEO systems development is the systems' construction based on the "distributed satellite" architecture [2], aimed on solving complex multifunctional problems using the cubes-sats (with 1-10 kg mass). The cube-sats limited mass-and-size and energy capabilities conflict with the requirements for informational efficiency and satellite systems' orbital operation terms. The "distributed satellite" architecture makes it possible to measure the cube-sate orbital motion based on the measurement of their relative position. As a result, it is possible to increase the efficiency of cube-sats utilization with deactivation of the part of equipment responsible for the orbital measurement and control.

The Relative Determination Approach

The relative determination of the satellites being allotted to the "distributed satellite" is based on range measuring between them. The relative determination approach provisionally consists of two parts: static and dynamic.

Fig.1 shows an example of relative determination between satellites being allotted to the "distributed satellite", consisting of a core satellite N and five edge satellites N.1 ... N.5.

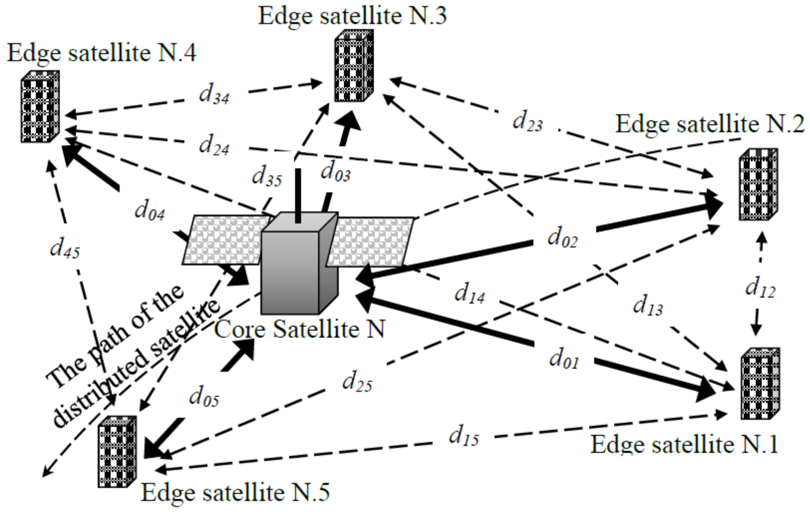

Fig.1 Relative determination between satellites being allotted to the "distributed satellite"

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The results of the relative determination make it possible to form a relative distances matrix D, in this case of 6×6 dimension (1)

$$D = \begin{bmatrix} 0 & d_{01} & d_{02} & d_{03} & d_{04} & d_{05} \\ d_{01} & 0 & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{02} & d_{12} & 0 & d_{23} & d_{24} & d_{25} \\ d_{03} & d_{13} & d_{23} & 0 & d_{34} & d_{35} \\ d_{04} & d_{14} & d_{24} & d_{34} & 0 & d_{45} \\ d_{05} & d_{15} & d_{25} & d_{35} & d_{45} & 0 \end{bmatrix} \quad (1)$$

In the distance matrix D, the row and column numbers correspond to the satellite number from the "distributed satellite". Based on the cosine theorem [3], a three-dimensional angles' matrix (2) is formed (in the 2[d] expression two layers of a three-dimensional matrix for the core satellite and one edge satellite are shown).

The data obtained makes it possible to construct an intermediate rectangular coordinate system with its center in the core satellite center of mass and to determine the coordinates of all edge satellites in this interim coordinate system relative to the core satellite.

$$\Phi_0 = \begin{bmatrix} 0 & \alpha_{12} & \alpha_{13} & \alpha_{14} & \alpha_{15} \\ \alpha_{12} & 0 & \alpha_{23} & \alpha_{24} & \alpha_{25} \\ \alpha_{13} & \alpha_{23} & 0 & \alpha_{34} & \alpha_{35} \\ \alpha_{14} & \alpha_{24} & \alpha_{34} & 0 & \alpha_{45} \\ \alpha_{15} & \alpha_{25} & \alpha_{35} & \alpha_{45} & 0 \end{bmatrix} \ldots$$

$$\ldots\Phi_A = \begin{bmatrix} 0 & \beta_{02} & \beta_{03} & \beta_{04} & \beta_{05} \\ \beta_{02} & 0 & \beta_{23} & \beta_{24} & \beta_{25} \\ \beta_{03} & \beta_{23} & 0 & \beta_{34} & \beta_{35} \\ \beta_{04} & \beta_{24} & \beta_{34} & 0 & \beta_{45} \\ \beta_{05} & \beta_{25} & \beta_{35} & \beta_{45} & 0 \end{bmatrix} \ldots (2)$$

The distance matrix D analysis allows to select the most distant extreme satellite, the direction to which is pointed as the x' axis of the intermediate coordinate system (see Fig.2). The coordinates of the point A of the edge satellite N.1 are defined as $x'_A, 0, 0$, where $x'=d_{01}$.

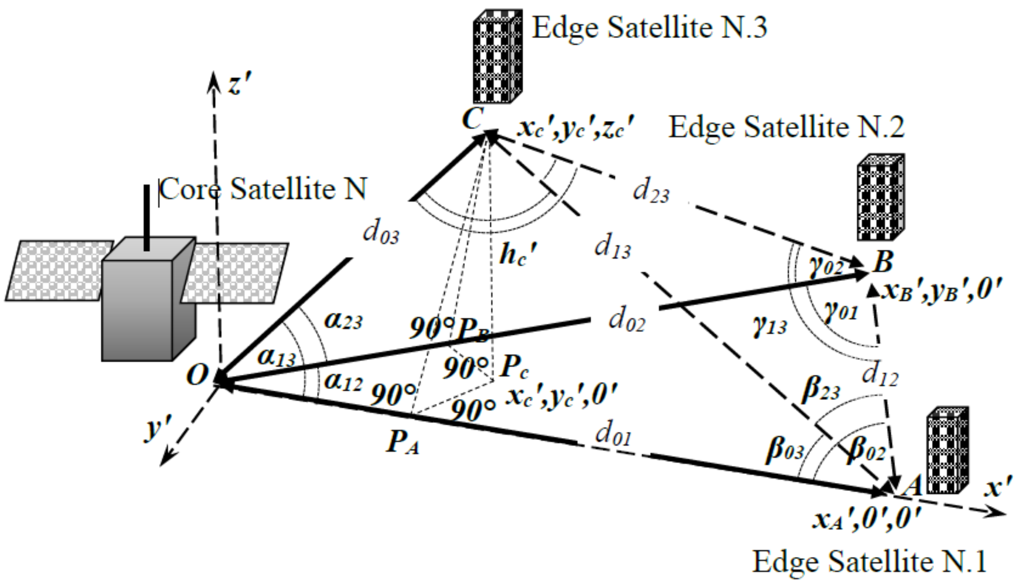

Fig.2 Determination of edge satellite coordinates in intermediate coordinate system

To determine the $x'Oy'$ plane, select the second most distant edge satellite (in Fig.2, the terminal satellite N.2, designated as point $B(x'_B, y'_B, 0)$). The y' axis will be in the same plane with the direction d_{12} and perpendicular to the x' axis. The coordinates of the point B in the $x'Oy'$ plane are calculated on the basis of the distance d_{02} and the angle α_{12}.

$$\begin{aligned} x'_B &= d_{02} \cdot \cos\alpha_{12} \\ y'_B &= d_{02} \cdot \sin\alpha_{12} \end{aligned} \quad (2)$$

The z' axis completes the intermediate coordinate system to a full 3-dimensional coordinate system.

In the intermediate coordinate system, the coordinates of all terminal satellites are determined. Fig.2 shows the determination of the coordinates of the satellite $C(x'_C, y'_C, z'_C)$ on the basis of the trihedral pyramid $OABC$. The base of the pyramid ΔOAB is in the $x'Oy'$ plane. The coordinate z'_C is defined as the height of the pyramid h'_C.

The transition to a satellite coordinates system with the center at the center of mass of the core satellite is possible after a session of measurements of the orbital parameters of three spacecrafts selected for constructing an intermediate coordinate system (see Fig.3). The measurement is carried out by radio and/or optic methods. Maximum distance between the selected spacecrafts simplifies measurements and improves their accuracy.

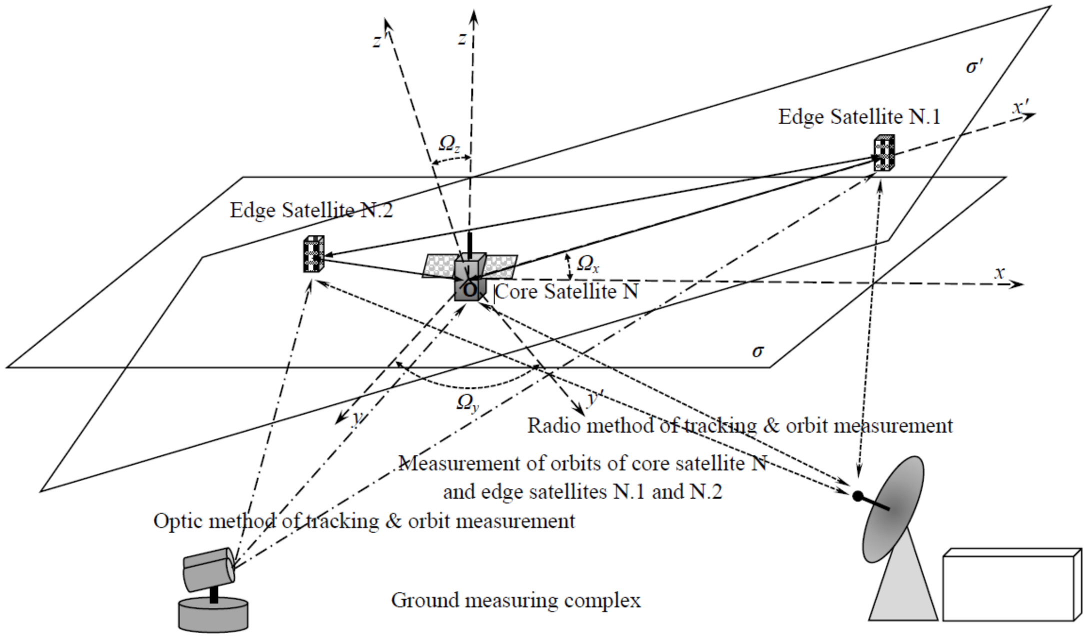

Fig.3 Determination of the direction cosines for the transition from the intermediate coordinate system to the satellite coordinate system.

As a result of measuring the orbit parameters, the angles Ω_x, Ω_y, Ω_z are calculated between the axes of the intermediate coordinate system *x'*, *y'*, *z'* and the satellite coordinate system with the *x*, *y*, *z* axes. The transition from the intermediate coordinate system to the satellite system is carried out using the direction cosines [3].

Given the influence of perturbation factors on the orbital motion of all spacecrafts in a "distributed satellite", it is necessary to measure the relative velocity of the edge and core satellites. The determination of the relative motion vector is a dynamic part of the measurement of the relative position of spacecraft in the "distributed satellite".

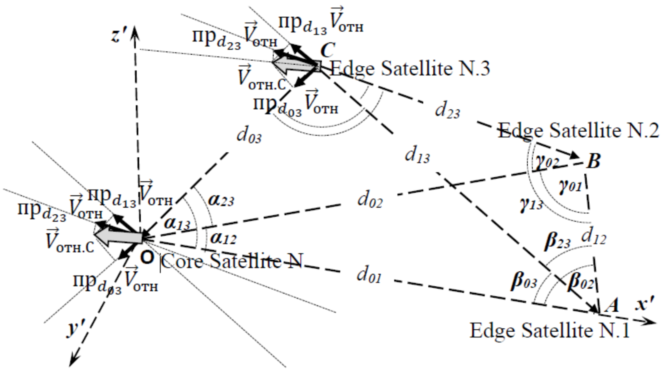

Fig.4 Determination of the relative velocity vector of the edge satellite.

The vector of the relative velocity of the edge satellite N.3 relative to the core satellite *O* (see Fig.4) decomposes onto the projections $пр_{d_{03}}\vec{V}_{отн}$, $пр_{d_{13}}\vec{V}_{отн}$, $пр_{d_{23}}\vec{V}_{отн}$, on d_{03}, d_{13}, d_{23}, which are the edges of the triangular pyramid *OABC*. Using the expressions [4], known from analytic geometry, the vectors of the vector projection are transferred to the origin of the intermediate (in this case) or satellite coordinate system. The direction and magnitude of the relative velocity vector is defined in a rectangular coordinate system as the intersection point of three planes constructed perpendicular to the three transferred projection vectors $np_{d_{03}}\vec{V}_{отн.}$, $np_{d_{13}}\vec{V}_{отн.}$, $np_{d_{23}}\vec{V}_{отн.}$ - at the end points of the vectors.

Adaptation of wideband access networks IEEE 802.16

The desire to minimize the list of active CubeSat equipment caused the desire to make maximum use of the included systems and equipment of the spacecraft. The connection between the core and edge satellites in the "distributed satellite" is provided on the basis of the WiMAX wireless wideband access network of the IEEE 802.16 family of standards [1].

The IEEE 802.16 standard provides a large set of tools for measuring the distance between the base station (BS) and the mobile stations (MS) [5] in a sufficiently wide range of mutual rates between the BS and the MS.

It is necessary to perform the following measurements in the "distributed satellite":

- distance between spacecrafts;
- measurement of the projection of the relative velocity vector.

The WiMAX system in the "distributed satellite" operates in the frequency division duplexing mode of the uplink and downlink (Frequency Division Duplexing, FDD) with a bandwidth of 20 MHz. This ensures the maximum throughput of the WiMAX network [5], [6]. Built-in algorithms for primary initialization of MS in the WiMAX network and periodic ranging allow to determine the distance from the core to the edge satellites.

Measurement of the distance between the edge satellites is performed as follows.

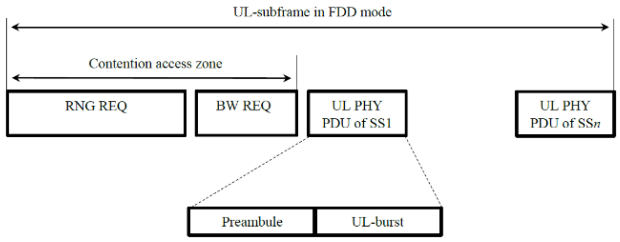

Fig.5 The structure of the uplink sub-frame in the FDD frequency multiplexing mode

The uplink sub-frame (see Fig.5) of the WiMAX network in FDD mode contains two fields: the connection initialization slot and the bandwidth request slot, which form the contention access zone. The time domain of the contention access zone is used to measure distances between edge satellites.

The numbers of the edge satellites, between which the measurement is to be taken, are determined in the special MAC-command of the core satellite.The distance measurement is based on measuring of the propagation delay. Fig.6 shows a time chart of measurements of the mutual distance between edge satellites, which functions in the "distributed satellite" of the telecommunications system are performed by satellites-transponders.

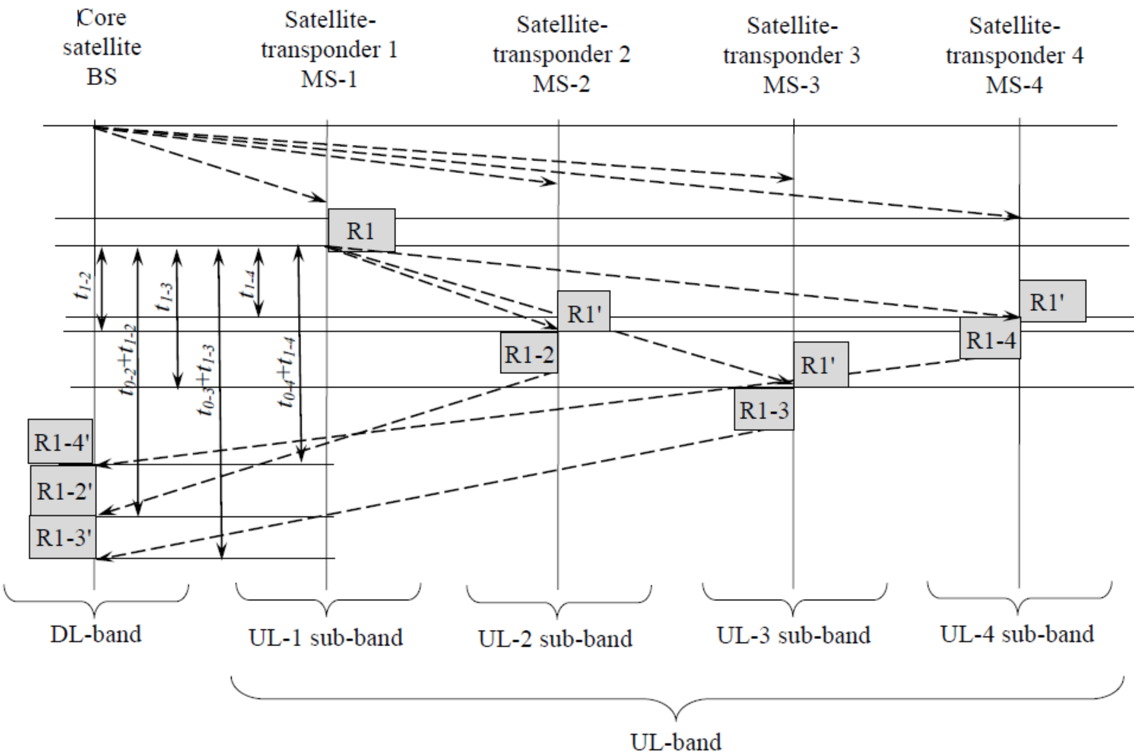

Fig. 6 Time chart of measuring the range between edge satellites.

The WiMAX network operates using the Orthogonal Frequency Division Multiply Access (OFDMA) method with the separation of frequency and time zones [6]. Each satellite-transponder operates in a separate 5 MHz sub-band. The core satellite, performing the BS functions in the packet of the broadcast MAC-message of the downlink sub-frame, determines the number of the satellite-transponder (in Fig. 6 this satellite is marked as MS-1), initiating the distance measurement, and numbers of the satellites-transponders participating in the measurement (in Fig.6, satellites MS-2, MS-3, MS-4 respectively), as well as the segment number of the pseudo-random sequence used for the measurements. The IEEE 802.16 group standards assume the use of a distance probe for segments of the Zadoff-Chu sequence as a probing signal [6].

A satellite-transponder, initiating a distance measurement (in Fig.6, MS-1 satellite), in its UL-1 frequency band emits a signal R1. The signal is received by the receivers of the MS-2, MS-3, MS-4 satellites-transponders. Receiving satellites-transponders perform the correlation processing of the received signal in the frequency domain. When fixing the fact of receiving the probing signal R1', the satellites-transponders re-emit signals R1-2, R1-3, R1-4 in their UL-2, UL-3, UL-4 frequency sub-bands. The core satellite performs independent reception of the signals R1-2 ', R1-3', R1-4 'in the frequency sub-bands UL-2, UL-3, UL-4, respectively.

The core satellite using the WiMAX network synchronization procedures has information about the time of the beginning of the procedure for measuring the mutual distance by the MS-1 satellite-transponder. Prior to measuring the distance between satellites-transponders, the core satellite already has information about the distance to each satellite-transponder that it receives on the basis of the regular BS-MS distance measuring procedures for the WiMAX network. The core satellite determines the distance between the satellites-transponders as the difference between the reception time of the corresponding signal R1-2', R1-3', R1-4' and the time corresponding to the distance to each satellite-transponder. For the satellite-transponder shown in Fig.6

$$\begin{aligned} t_{1-2} &= t_{R1-2'} - t_{0-2} \\ d_{12} &= t_{1-2} \cdot c \\ t_{1-3} &= t_{R1-3'} - t_{0-3} \\ d_{13} &= t_{1-3} \cdot c \\ t_{1-4} &= t_{R1-4'} - t_{0-4} \\ d_{14} &= t_{1-4} \cdot c \end{aligned} \quad (6)$$

where t_{0-2}, t_{0-3}, t_{0-4} is the time corresponding to the distance from the core satellite BS to the MS-2, MS-3, MS4 satellites-transponders, and c - is the speed of light.

The merits of the Zadoff-Chu sequences include the fact that as a result of performing a Fast Fourier Transform (FFT) sequence over a segment of the Zadoff-Chu sequence, the obtained sequence of samples in the frequency domain is also a Zadoff-Chu sequence [7]. The use of this property together with the correlation processing of the FFT results, makes it possible to determine the Doppler shift Δfd for each received signal R1': Δf_{D1-2}, Δf_{D1-3}, Δf_{D1-4}. The received Doppler frequency shift estimates are transmitted to the BS core satellite by the MS-2, MS-3, MS-4 satellites-transponders in the measurement report package. The information obtained is used to estimate the projection of the relative velocity vector of the MS-1 satellite-transponders on the distance line with neighboring satellites-transponders (see Fig.4).

Conclusions.

1. In order to optimize the useing of energy capabilities of CubeSats and increase the efficiency of performing functional tasks according to the mission, it is proposed to transfer the channel for measuring the orbital motion and controlling the flight of CubeSat to the WiMAX network, and to disconnect the command-and-telemetric radio link, which is new and has never been applied in the world practice.

2. Measurement of the distance between spacecrafts in a "distributed satellite" allows to determine the mutual positions of spacecrafts, and to measure the relative motion velocity of edge and core satellites. The data obtained is the starting point for calculating the parameters of the orbital motion of each spacecraft.

3. The WiMAX network, taking into account the modernization of the MAC-level protocols, allows maximum and complex use of the potential capabilities of WiMAX equipment, and allows to avoid the installation of additional equipment for determination of the mutual position of spacecrafts. As a result, the mass of spacecrafts is minimized and their energy consumption is optimized.

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