Optical Multicast Protocol for LEO Satellite Networks

Maha Sliti, Walid Abdallah, Noureddine Boudriga
Communication Networks and Security Research Lab, University of Carthage
Ariana, Tunisia
e-mail: maha.sliti@supcom.tn, wabdallah_tn@yahoo.fr, nab@supcom.rnu.tn

***Abstract*—Satellite networks provide global coverage and support a wide range of services. Since Low Earth Orbit (LEO) satellites provide short round-trip delays, they are becoming increasingly important for real-time applications, such as voice, teleconferencing and video traffic. Many applications require a mechanism to deliver information to multiple recipients. In this context, we propose two all optical multicasting approaches based on codewords designed for LEO satellites: the first approach is based on the shortest paths and the second approach is based on the concept of virtual multicast trees. The proposed multicast approaches consider free space optical communication links between satellites, which provides high data rate for real time applications.**

***Index Terms*—LEO satellite, all optical multicast, optical codewords, tunable optical decoder.**

I. Introduction

Satellite networks provide global coverage and support a wide range of services. Since Low Earth Orbit (LEO) satellites provide short round-trip delays, they are becoming increasingly important for real-time applications, such as voice, teleconferencing and video traffic. Many applications require a mechanism to deliver information to multiple recipients. In the literature, several multicast routing protocols were proposed for satellite networks [1]–[4]. However, the majority of the proposed approaches are not developed primarily for LEO satellite constellations. In fact, they are mainly proposed in the context of IP and mobile networks and then adapted to support multicasting in LEO networks. Furthermore, the proposed approaches have not consider free space optical communication links between satellites, which are ideal for high data rate real-time applications, such as voice and video traffic.

In this paper, we propose two all optical multicasting approaches based on codewords designed for LEO satellites: the first approach is based on the shortest paths and the second approach is based on the concept of virtual multicast trees. Furthermore, we study the mobility management aspect for the two proposed approaches. The key contributions of the proposed multicast approaches with respect to the previously published research are:

1) The proposed multicast process is performed at the optical layer based on an optical switching concept, which allows the multicast packets to be processed at very high bit rates (gigabits per second) without conversion to the electronic domain. During the optical multicast process, the received packets are delayed in an optical buffer proposed in [5], in order to provide a tunable delay for real time traffic.
2) The optical switching concept is based on the optical codewords, which are represented by a sequence of pulses. Indeed, a codeword is assigned to each satellite in the network and serves as an optical identifier of the satellite. Based on the received codeword and the structure we build in, the traffic will be multicasted to one or several directions allowing to reach the destination satellites.
3) The proposed multicast approach is scalable since its performance is not affected by the multicast group size and the member combination in the multicast group. Therefore, the optical multicast module implemented in each intermediate satellite is at most composed of three tunable decoders.

The rest of the paper is organized as follows. Section 2 presents the proposed multicast approaches for the Leo constellation networks in the literature. The use of optical codewords for the multicast in LEO networks is described in Section 3. The all optical multicast approach based on the shortest paths is described in Section 4. The all optical multicast approach based on the virtual multicast trees is explained in Section 5. The mobility management in the two all optical multicasting approaches is discussed in Section 6. Simulations and experimental results are given in Section 7. Finally, Section 8 concludes the paper.

II. Multicast in LEO constellation networks

Satellite-based optical communication systems have become a most promising technology for high-speed inter-satellite and satellite-to-ground communication links due to their various advantages. A free space optical communication system includes optical transmitter and receiver satellites. The transfer of information between the two satellites is performed with optical rather than microwave radiation, which allows high data rate transfer and transparency to Radio Frequency (RF) interference. The advantages of an optical communication system compared with a microwave communication system in free space are: 1) high data rate, 2) less transmitter power consumption, 3) terminal design with reduced size and weight, and 4) transparency to RF interference.

In this paper, we are particularly interested in LEO satellite mobile systems. LEO satellites are orbiting at low earth orbits with an altitude generally between 500 km and 2000 km. Compared to communication satellites in geostationary orbit, the communication links to LEO satellites are characterized by lower propagation delay and lower link attenuation because of the shorter distance, resulting in the need for reduced transmission power.

In the literature, several multicast routing protocols were proposed for satellite networks. In [1], a new core-based shared tree algorithm, viz Core-Cluster combination-based Shared Tree (CCST) algorithm and the weighted version (i.e., w-CCST algorithm) are proposed in order to resolve the channel resources waste problem in typical source-based multicast routing algorithms in LEO satellite IP networks. The Rectilinear Steiner Trees (RST) [2] algorithm uses one of integer linear programming method for solving the minimum RST tree, so that the bandwidth of multicast routing using the least suitable non-real-time multicast applications, but more complicated calculation process. In [3], a fast iterative distributed multicast routing algorithm was developed based on the inherent characteristics of satellite networks, that consider distributed computing model and significantly reducing the algorithm computational complexity. In [4], a QoS-Guaranteed Secure Multicast Routing Protocol (QGSMRP) is proposed for satellite IP networks using the logical location concept to isolate the mobility of LEO and HEO satellites. a novel triple-layered satellite network architecture including Geostationary Earth Orbit (GEO), Highly Elliptical Orbit (HEO), and Low Earth Orbit (LEO) satellite layers is introduced. However, the majority of the proposed approaches are not developed primarily for LEO satellite constellations. In fact, they are mainly proposed in the context of IP and mobile networks and then adapted to support multicasting in LEO networks. Furthermore, the proposed approaches have not consider free space optical communication links between satellites, which are ideal for high data rate real-time applications, such as voice and video traffic.

III. Codeword based multicast

An optical codeword is composed of a sequence of pulses that represent the positions of the information bit "1". The transmitter does not produce any optical pulse when the information bit "0" is transmitted.

An optical codeword is assigned to each satellite in the LEO constellation network. Therefore, each satellite is uniquely identified by its assigned codeword which is similar to an address in our case. The total number of associated codewords is equal to $N * M$ with N is the number of orbits (planes) in the constellation, and M is the number of satellites in each orbit. We notice that the number of codewords used for a LEO constellation network (e.g., Global Positioning System (GPS)) is very reduced compared to current terrestrial networks (e.g., 24 codewords are required in the GPS network). We suppose that the codewords are generated, assigned and managed by a central entity implemented in a terrestrial station which is the ground station in our case.

To allow the application of our physical routing approach and discriminating data transmitted to different satellites, the optical codes should be orthogonal. In our case a codeword can be represented as an integer vector where each element identifies the position of a pulse (bit "1"). Thus, we adopted a generation process based on lattice point theory to satisfy this requirement. The code generation process is realized as follows: Consider a $m \times k$ integer lattice $L = Z_m \times Z_k$, which elements are labeled by points from the set $V = 1, 2, ..., mk$. Using a simple linear mapping function defined as:

$$l : L \to V, l(x, y) = mx + y + 1 \tag{1}$$

where $0 =< x <= k - 1$ and $0 =< y <= m - 1$.

The codewords are represented as lines connecting points of the rectangular integer lattice. The subset of points are referred to as lines, and the code spaces are defined as the sets of lines of different slopes. A line with a slope s, where $0 \leq s \leq m-1$, starting at the point (i, j), contains the following set of points:

$$(i; j + (s.imod(m)) : 0 \leq i \leq k - 1; 0 \leq j \leq m - 1 \tag{2}$$

Thus, for every slope s, the m codewords that can be obtained are $\nu = \nu_1, ..., \nu_m$, where $\nu_j = mi + j + (s.imod(m)) + 1; 0 \leq i \leq k - 1$ for every $0 \leq j \leq m - 1$. It can be shown in [6] that this method generates codewords with length equal to mk and weight k. The weight witch represents the number of bits "1" in the codeword. This is a very important parameter because it identifies the maximum value of the autocorrelation between codes and hence reflects the capability of the routing approach to separate traffics intended for specific destinations. It is noteworthy that, for every slope, the codewords obtained through the aforementioned process are orthogonal. According to this reasoning, every codeword ν_j can be represented as an integer vector $\nu_j = \nu_j^0, \nu_j^1 ..., \nu_j^{k-1}$ where $j \in 1, 2, ..., mk$ and ν_j^i is the i^{th} bit in the optical code ν_j.

Since LEO satellites provide short round-trip delays, they are becoming increasingly important for real-time applications, such as voice and video traffic. Many applications require a mechanism to deliver information to multiple recipients, as illustrated by Figure 1.

Since each group of destination users has a geographic location, each group is covered by a different distribution satellite that we call also a destination satellite. At $t0$, a source user is attached to a source satellite and a group of destination users is served by a destination satellite via a wireless link. On the contrary, the links between satellites, which are free space optical communication links. During the communication period, the group of destination satellites are changed due to the mobility of the source and destination satellites. Thus, the management of the multicast process between the source and the destination satellites must be done during communication periods that may last for hours.

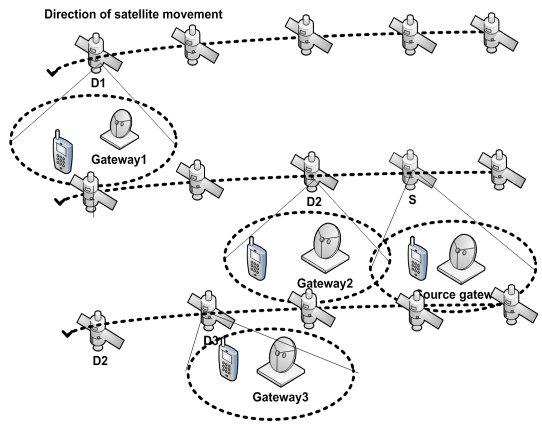

Figure 1. Multicasting in LEO satellite constellation.

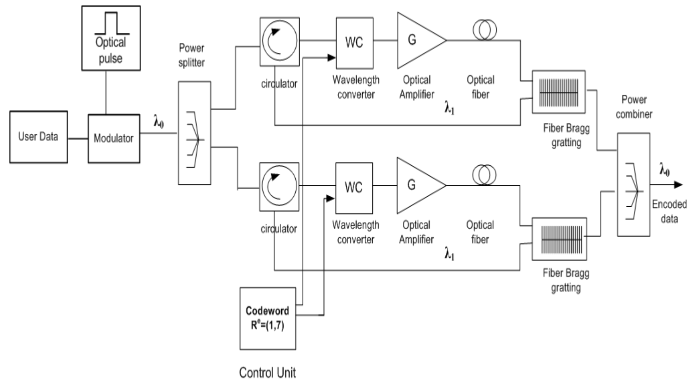

Figure 2. Tunable optical decoder architecture.

In this work, we propose an optical multicasting process based on codewords. Also, we provide a function so that each satellite can optically switch a multicasting traffic based on codewords properly structured. Thus, each satellite implements an optical switching module based mainly on two optical operations, which are the optical codeword matching and the deviation of the traffic to the adequate direction. The received codeword is split to a set of decoders; if a codeword is matched by a decoder, an optical switching gate will be activated by a pulse to forward the multicast traffic to the direction that allows reaching the destination satellite.

The physical implementation of the reconfigurable encoding is achieved by delaying pulses in a set of Optical Delay Line (ODL) loops. The positions of the pulses in the codeword define the number of rounds that must be performed by every pulse in each ODL-loop [7]. The optical sequence of code is then created by combining different delayed pulses at the output of ODLs.

A codeword decoder, which is the main component of the proposed optical multicasting module, allows the matching of a codeword optically without the O/E/O conversion. The design of a tunable decoder was proposed in [7] in order to implement an optical filtering technique based on codewords. In each loop, we inject the optical pulse, which will be confined in the fiber until it performs the number of rounds needed to place it in the positions of a '1' bit in the optical code. It is obvious that the number of ones in the code sequence determines the number of optical loops needed. Consequently, we could easily control and modify the codeword by controlling the number of rounds performed by the optical signal in every optical loop. Unlike classical techniques, such as fixed length Optical Delay Lines and Fiber Bragg Gratings, in which modifying optical codes needs a physical intervention, our approach allows soft based controlling of the optical codewords by considering a control unit, even if it uses Fiber Bragg Gratings. A codeword is considered as an integer vector of k elements that presents the positions of ones in the codeword. Thus, an optical codeword is composed of optical pulses transmitted in specific bit intervals that correspond to positions of ones in the code sequence. This can be achieved by considering an on-off keying technique and modulating the label by a Gaussian optical pulse signal and a Mach-Zehender modulator. The tunable decoder, illustrated by Figure 2, generates an optical pulse on the receipt of a valid codeword that matches the configured code-word. The decoding operation is performed by delaying optical pulses that compose the received codeword until they superpose in the last bit interval.

IV. All Optical Multicast Based on the Shortest Paths

In this section, we present an optical multicast approach based on the shortest paths. In this approach, each intermediate satellite considers three codewords indicating its direct neighbors: two in the same orbit, and one in the following orbit. A shortest path is defined in term of number of hops and is established by favoring the inter-orbit on the intra-orbit hop. In order to establish the shortest paths to a list of destination satellites, the route discovery process is initiated by the source satellite. The source satellite duplicates a Route REQuest message (RREQ) in order to send it to d destination satellites. The considered RREQ message format is composed of: the message identifier, the codewords associated to destination satellites, the satellite source address, the satellite destination address, and the communication time between the source user and the destination users.

At the reception of a RREQ message, the intermediate satellite adds its codeword to the Multicast list address and sends it to the nearest neighbor based on the Destination address in the RREQ message. A destination satellite that receives the RREQ message, sends a Route RESponse (RREP) message, which contains the shortest path to the source satellite. A path is formed by a list of codewords that denote the intermediate nodes in the shortest path.

After the route discovery process, a source satellite sends the multicast traffic to the d destination satellites. Each multicast packet is duplicated on the shortest paths established to destination satellites. The paths are composed of a list of codewords that characterize the list of intermediate nodes on the shortest path. Thus, a header that contains the path to a destination satellite is associated to each packet.

The design of the multicast module implemented in each satellite is illustrated by Figure 3. Therefore, an intermediate node that receives a multicast packet examines the received header optically by considering the following steps:

- the first codeword in the header, which indicates the current satellite, is extracted from the received list of codewords that compose the header and dropped;
- the packet and the new header are delayed in a Virtual Optical Memory (VOM) based on optical delay lines, that we have developed in [5];
- during the buffering delay, the second codeword in the received header is extracted from the received list of codewords and split to three tunable decoders. Each decoder allows to match a codeword that characterize one neighbor of the current satellite;
- If the second codeword matches a configured codeword, then the delayed packet and its corresponding header will be sent to the adequate next neighbor that allows to reach the destination satellite.

V. ALL OPTICAL MULTICAST BASED ON MULTICAST TREES

In this section, we present an optical multicast approach based on the concept of virtual multicast trees. The virtual multicast paradigm is used in order to underline that the multicast tree is not physically established but only built on the codewords structure used to switch traffic contrary to the first proposed approach that requires a route discovery process preceding the routing of a multicast traffic. In this approach, the virtual tree establishment consists on the management of codewords structure. Thus, an optical codeword is structured in two parts as follows: the first part identifies the orbit and the direction (left or right) in this orbit, and the second part identifies uniquely a satellite in the LEO constellation network. Therefore, the destination satellite can be either on the left or on the right of an intermediate satellite or it can be localized in another orbit. The source satellite sends a multicast packet composed of the payload and a list of codewords that corresponds to the list of destination satellites. At the reception of a multicast traffic, an intermediate satellite can forward the traffic to the right or left if the destination satellite is in its orbit or it switches the traffic to the following orbit.

In the following example, we consider the virtual tree structure illustrated by Figure 4. Therefore, from a source satellite, the header to be sent, which is composed of a set of codewords, has the following structure: $CdOrbit_r^2$ CdD_1| $CdOrbit_l^2$ CdD_2| $CdOrbit_l^2$ CdD_3 | $CdOrbit_l^3$ CdD_4 | $CdOrbit_r^3$ CdD_5, where $CdOrbit_r^i$ is the codeword that identifies the right direction in the $Orbit^i$, $CdOrbit_l^i$ is the codeword that identifies the left direction in the $Orbit^i$, and CdD_j is the codeword that identifies the destination satellite D_j in the LEO constellation network.

Each intermediate satellite integrates a multicast module, which design is described by Figure 5. The optical multicast

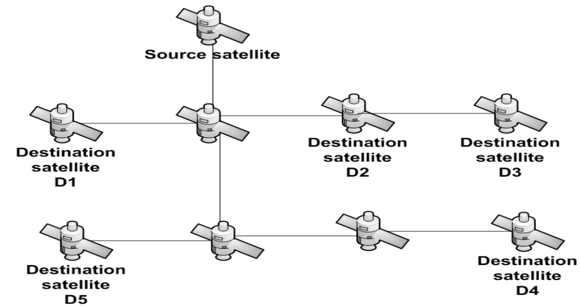

Figure 4. Virtual tree structure.

process is performed as follows:

- The received payload is extracted and delayed in the optical buffer called Virtual Optical Memory (VOM), proposed in [5];
- The list of received codewords are extracted and separately treated by the multicast module. If the intermediate satellite is not a destination satellite, it split the received codewords to three tunable decoders. Each decoder allows to match a received codeword in the header. The matching operation is performed in serial by treating each time one codeword until treating all the codewords that compose the received header. And, the matching is performed only on the first part of the codeword that indicates the switching direction: left or right if the destination satellite is in the same orbit as the intermediate satellite, or down if the destination satellite is in the following orbits. If the intermediate satellite is a destination satellite, based on the received codewords, it performs the matching operation based on the other received codewords in the header and does not consider its codeword. Indeed, a satellite needs to perform a matching operation on the second parts of the received codewords that uniquely identify a satellite in the LEO constellation network before performing the optical switching operation based on the matching of the first parts of codewords that identify the forwarding direction.
- If a codeword is matched then an SOA gate (Semiconductor Optical Amplifier gate) is activated in order to pass the delayed payload to the new header generation module. This module generates a new header for the payload by considering only the codewords of the satellites that are reachable by the forwarding output port. Indeed, the group of destination satellites is divided in each intermediate satellite based on the fact that the traffic that is forwarded to a direction (left, right, down) must only contain in its header the codewords corresponding to the destinations located in this direction.

VI. MULTICAST COPING WITH LONG PERIOD SERVICES

Satellite movement results in challenging mobility management problems in LEO satellite networks. Due to the movements of the satellites and according to the movements

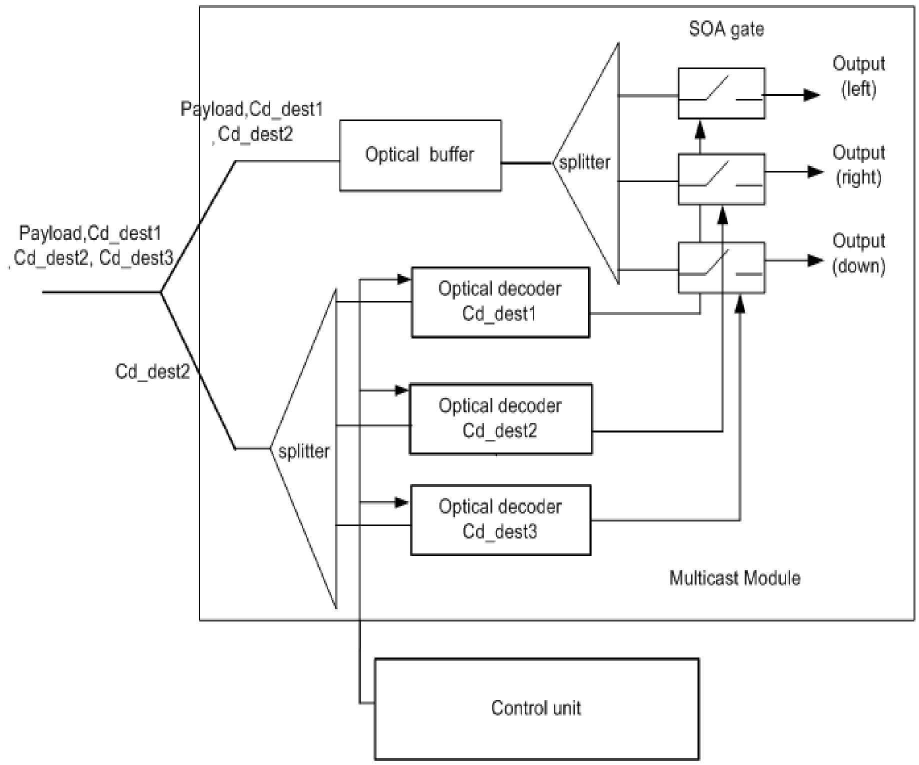

Figure 3. All optical multicast based on the shortest paths.

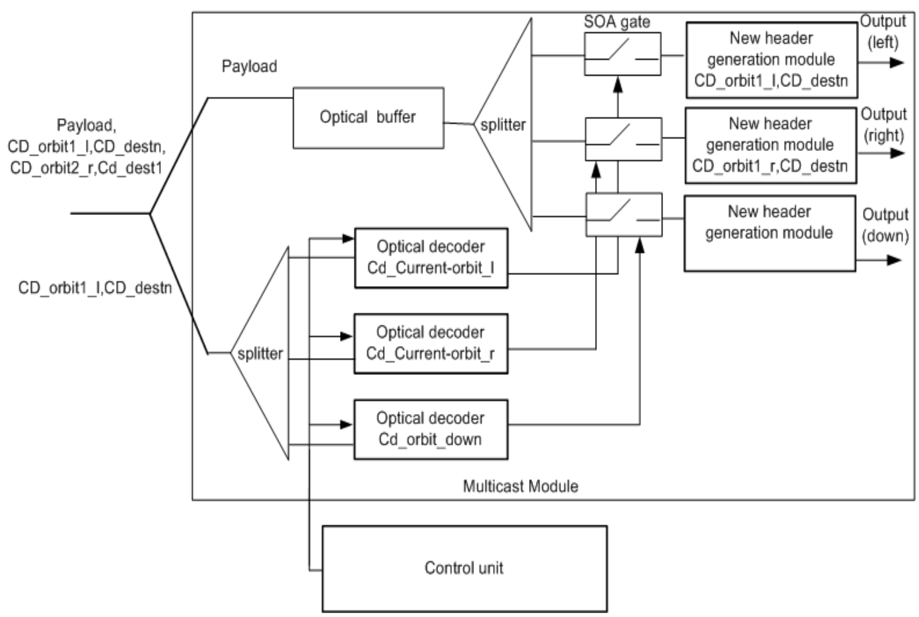

Figure 5. All optical multicast based on the Virtual multicast tree.

of their coverage area and footprints, a group of destination users are served by several groups of satellites during a communication period that may lasts for hours. In this section, we present the mobility management for the two proposed optical multicasting approaches. For the two approaches, three types of handovers can occur during a multicast session period T. The first type of handover occurs when the source satellite moves and will not serve the users source of the traffic anymore. The second type of handover occurs when a destination satellite will not serve any destination user therefore it will be deleted from the group of the destination satellites. The third type of handover occurs when a destination satellite is added to the group of the destination users in order to serve one or several destination users.

A. Shortest paths management

The optical multicasting based on the Shortest paths requires the initiation of a novel Route request discovery process to the destination satellites when a source satellite is not in the coverage of source users anymore. The ground station must send the current list of codewords, that indicate the current list of destination satellites, to the new source satellite. In the case where a destination satellite will not serve any destination user, it will be deleted from the group of destination satellites. This type of mobility does not require any treatment in the intermediate satellites. In fact, the multicast traffic to be switched by the intermediate satellites will no longer be switched in the direction of the deleted satellite since it is not in the coverage of the destination users. An updated list of codewords, that corresponds to the new list of destination satellites, will be sent to the source satellite from the ground station. In the case where a destination satellite is added to the group of destination users in order to serve one or several destination users, the shortest path from the source to the new destination satellite must be established. An updated list of codewords will be sent to the source satellite from the ground station.

B. Virtual tree management

When a source satellite is not in the coverage of source users anymore, the optical multicasting based on the virtual tree concept does not require any route reestablishment process initiation to discover the routes to the destination satellites as it is the case in the optical multicasting based on the Shortest paths. Indeed, the multicast tree will be implicitly established by sending a multicast traffic that requires at each intermediate satellite to be optically switched. The ground station must send the current list of codewords, that indicate the current list of destination satellites, to the new source satellite. In the case where a destination satellite will not serve any destination user, it will be deleted from the group of destination satellites. The ground station must send the current list of codewords to the new source satellite. And, the source replaces the codeword corresponding to the deleted destination satellite by the codeword associated to the new destination satellite and adds to the codeword, a special codeword that identifies the destination orbit and the direction (left or right) in the orbit. The new codeword will be added to the header of the multicast traffic. In the case where a destination satellite is added to the group of the destination users in order to serve one or several destination users, its corresponding codeword will be added to the header of the multicast traffic.

C. Comparison

First, the two proposed optical multicasting approaches are compared in term of the number of used segments. The segments used by the approach based on virtual trees are those in the tree axis and in the left and right of the axis. And, the segments used by the approach based on the shortest paths are the total segments that compose the shortest paths to the destination satellites. Thus, the number of segments used in the first approach avoids the segments redundancy and consequently it is smaller than the number of segments used in the second approach.

Second, the virtual tree construction favors the inter-orbit over the intra-orbit hop, which allows to have only one possible path to the destination satellite. This method is also considered in order to establish the shortest paths in the second approach. Indeed, the association of all established shortest paths gives the constructed virtual tree in the first approach.

Third, in the approach based on the shortest paths, when a satellite leaf handover occurs in the direction of satellites movement, a segment is removed of the path and the codeword of the removed destination satellite is removed of the list of destination satellites. In the contrary case, a segment will be added to the path and the codeword of the new destination satellite is added to the list of destination satellites. Thus, the handover in this approach consists on the increase or the narrowing of paths. When we consider the approach based on virtual trees, the destination satellites can be either a leaf or an intermediate satellite, which minimizes the increase or the narrowing of paths due to handovers compared to the first approach.

VII. Simulations and experimental results

In this section, we assess the performance of the two proposed optical multicasting approaches in terms of traffic load (in erlang) and number of decoding functions. As simulation environment, we have considered Matlab tool. For simulation purpose, we consider: the Global Positioning System (GPS) constellation topology, which forms a LEO network (6 orbits, each orbit has 4 satellites), a traffic load matrix. The traffic load matrix is a matrix that considers a traffic load only between each satellite and its four neighbors (up and down, left and right). For each simulation, a source satellite number and destination satellite numbers are randomly generated.

In order to compare the efficiency of the two multicasting approaches in terms of the traffic load criteria, we calculate the traffic load for each approach by considering the maximal path length/multicast tree depth and the mean on all shortest paths/segments of the tree. As illustrated by Figure 6, we can notice the similarity between the traffic load curves computed on the maximal path length and the depth of the multicast tree and considered for several multicast group sizes (4,8,12,16,20,24). This similarity can be justified by the fact that the maximum path length corresponds to the depth of the multicast tree. We notice also that the mean traffic load on the total segments of the multicast tree is the half for a multicast group size equals to 24 satellites, which is optimized compared to the mean traffic load on the total path lengths. Therefore, we can deduce that the all optical multicasting approach based on the virtual multicast tree has the advantage to eliminate the redundant segments in the shortest paths established in the all optical multicasting approach based on the shortest paths.

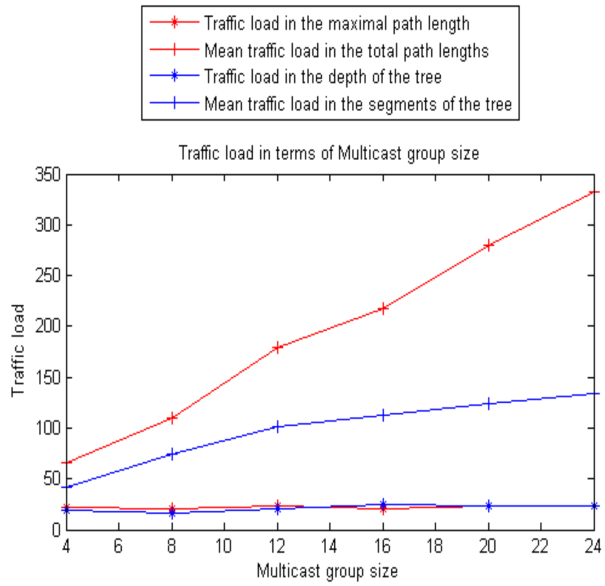

Figure 6. Traffic load in terms of multicast group size.

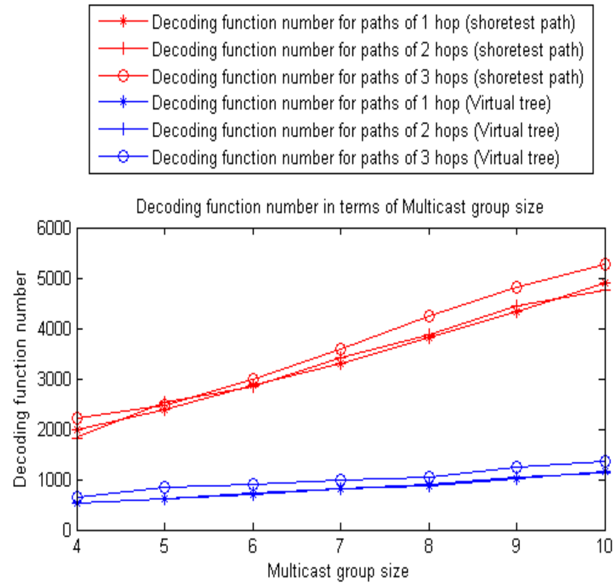

Figure 7. Decoding function number in terms of multicast group size.

The efficiency of the two multicasting approaches in terms of the number of used decoding functions is also assessed. We have considered a communication period of one hour between a source and destination users. During this period and due to the mobility of satellites, four source satellites and four multicast groups are considered. We calculate the number of used decoding functions for: 1) different multicast group sizes (4,5,6,7,8,9,10), 2) three path lengths less or equal to 1,2,3 hops. As illustrated by Figure 7, we notice that the number of used decoding functions for optical multicasting approach based on the shortest paths is five times greater than the number of used decoding functions for optical multicasting approach based on the virtual multicast tree for a multicast group size equals to 10 satellites. This can be justified by the fact that the virtual multicast tree eliminates segments redundancy observed in the shortest paths approach. Consequently, the optical multicasting approach based on the virtual tree decreases the traffic load observed in the network segments and uses less decoding functions for the optical multicasting. Thus, this approach is more efficient than the approach based on the shortest paths.

VIII. Conclusion

In this work, we have proposed two all optical multicasting approaches based on codewords designed for LEO satellites: the first approach is based on the shortest paths and the second approach is based on the concept of virtual multicast trees. For the two approaches, we identify each satellite in the LEO constellation network by an optical codeword. The proposed multicast process is performed at the optical layer based on an optical switching concept, which allows the multicast packets to be processed at very hight bit rates by considering optical codewords. Indeed, a codeword is assigned to each satellite in the network and serves as an optical identifier of the satellite. Based on the received codeword, the traffic will be multicast to one or several directions allowing to reach the destination satellites. Furthermore, the proposed multicast approach is scalable since its performance are not affected by the multicast group size and the member combination in the multicast group. Therefore, the optical multicast module implemented in each intermediate satellite is at most composed of three tunable decoders.

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