LEOCast: An Optical Multicast Protocol for LEO Satellites based on Optical Codewords

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***Abstract*—Satellite networks provide worldwide coverage and support a large variety of services. Since Low Earth Orbit (LEO) satellites offer short round-trip delays, they are progressively becoming more and more important for real-time services, such as voice, data and video traffic. The majority of these services need a mechanism to deliver data to several receivers. In the present work, we propose the LEOCast protocol, which is an Optical Multicast Protocol for LEO Satellites based on Optical Codewords. This protocol can function in two modes: the first mode is based on the shortest paths and the second mode is based on the virtual multicast trees paradigm. The optical multicast protocol considers free space inter-satellites links that provide high data rate transmission for real time services and it is based on the optical switching concept using optical codewords. The two proposed multicast modes are compared in terms of the traffic load and the number of used decoding functions. It is shown that the optical multicast mode based on the virtual multicast tree concept generates less traffic and uses less decoding functions when performing the optical multicast process on each intermediate satellite. However, it is demonstrated that each multicast mode is adapted to a type of payload (packet/burst) depending on the required processing delay for each multicast mode.**

Keywords–LEO constellation; all optical multicast; virtual multicast tree; structured codewords; tunable optical decoder.

I. INTRODUCTION

Satellite-based optical communication systems have become a most promising technology for their global coverage and high-speed inter-satellite and satellite-to-ground communication links. Compared to communication satellites in geostationary orbit, the communication links to Low Earth Orbit (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. Consequently, LEO satellites are becoming increasingly important for real-time applications such as voice, teleconferencing and video traffic, which require a mechanism to deliver information to multiple recipients. However, due to the rapidly and periodically changing of the network topology caused by the high mobility of satellites, the routing in satellite networks face great challenges.

In [1], we propose the LEOCast protocol, which is an Optical Multicast Protocol for LEO Satellites based on Optical Codewords. This protocol can function in two modes: the first mode is based on the shortest paths and the second mode is based on the concept of virtual multicast trees. For the two modes, we identify each satellite in the LEO constellation network by an optical codeword. In the first mode, each intermediate satellite considers four codewords indicating its direct neighbors: two in the same orbit, and two in the neighboring orbits. A shortest path is defined in terms of the number of hops and is established by favoring the inter-orbit on the intra-orbit hop. In the second mode, 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 mode 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.

In the literature, several multicast routing protocols were proposed for satellite networks [2]–[11]. These approaches are mainly proposed in the context of IP (Internet Protocol) and mobile networks and then adapted to support multicast in LEO networks. However, the multicast process in satellite networks present more specific requirements compared to other types of networks such as the need of high data bit rate transmission and the scalability to support important multicast group and payload sizes. These requirements can be achieved by optical communication inter-satellite links.

The key contributions of our proposed LEOCast protocol with respect to the previously published research are:

1) The proposed multicast process is performed at the optical layer based on optical switching, which allows the multicast packets to be processed at very high bit rates (the order of gigabits/second) without conversion to the electronic domain. During the optical multicast process, the received packets are delayed in an optical buffer proposed in [12], in order to provide a tunable delay for real time traffic. We have chosen an optical multicast approach due to the fact that the transmission quality of the light beam is near perfect. Indeed, this latter will not be affected by the attenuation and the dispersion effects in free space.
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 LEOCast protocol 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 four tunable decoders.

4) The parameters of the proposed multicast module can be dimensioned depending on the traffic stream estimation. These parameters can be the number of tunable decoders, the number of loops that composes each decoder based on the length of codewords, the fiber length of the Virtual Optical Memory (VOM) [12] based on the size of packet, etc.

In this paper, we have extended the proposed work in [1], by adding the following contributions:

- At the presentation level: First, we have investigated recent multicast approaches proposed for LEO constellations, and we have presented the multicast requirements in such type of networks. Second, we have defined the optical codewords, their mathematical characteristics and the principle of their encoding/decoding process. Third, we have illustrated the optical codeword structures that are used by the two multicast modes, and we have discussed the type of payload (packet/burst) adapted to each multicast mode. Finally, we have presented the advantage of our multicast protocol compared to the other protocols by presenting the advantage of the optical link use. The new added points have allowed to complete and to extend our reference list.
- At the design level: we have improved the design of the optical multicast mode based on the virtual multicast tree concept. Indeed, the header attached to the payload is well structured in order to reflect the virtual multicast tree and to optically switch the multicast traffic without the need to establish the route from the source to destination satellites. We have also considered two multicast directions: front/backward instead of right/left. Infact, due to the mobility of satellites, we need to consider the direction of movement in the orbit and not the localization of satellites. Thus, each intermediate satellite must treat two types of traffic: an inter-orbit traffic appropriated to destination satellites in other orbits and an intra-orbit traffic appropriated to destination satellites in the same orbit.
- At the simulation level, we have extended the proposed simulation by assessing the optical signal quality when multicasted from a transmitter satellite to other satellite neighbors using Free Space Optical links (FSO) with specific characteristics (distance and wavelength). The objective is to evaluate the effect of these criteria on the output signal quality. The optical signal quality is assessed based on two main criteria: the wavelength and the distance between satellites. We can conclude, when performing the optical multicast process, that the optical signal quality increases when decreasing the FSO communication link wavelength and the distance between receivers.

The rest of the paper is organized as follows. Section II presents the proposed multicast approaches for the LEO constellation networks in the literature. The optical codeword concept, the code sequences characteristics and the codewords structures used by the two optical multicast modes are presented in Section III. The codeword based switching process, which is the main optical signal operation in each satellite, and the optical codeword association to each satellite in the constellation, are presented in Section IV. In Section V, the all optical multicast mode based on the shortest paths is described. In Section VI, the all optical multicast mode based on the virtual multicast trees is explained. The mobility management in the two all optical multicasting approaches is discussed in Section VII. Simulations and experimental results are given in Section VIII. Finally, Section IX concludes the paper.

II. MULTICAST IN LEO CONSTELLATION NETWORKS

With recent needs of high speed communication systems, Free Space Optical links (FSO) become a most promising technology for high-speed inter-satellite and satellite-to-ground communication links [13]–[15]. A free space optical communication system includes optical transmitter and receiver satellites.

This type of links is preferred over Radio Frequency (RF) communication because of having narrower beam widths due to use of lasers, reducing the size of used antenna, which reduces the weight of the satellite, minimizing the power used for the communication system, and offering higher data rate.

The advantages of an optical communication link compared to a RF link in free space are characterized by: 1) high data rate, 2) less transmitter power consumption, 3) terminal design with reduced size and weight, and 4) transparency to RF interference.

Satellites can be directly linked by Inter-Satellite Links (ISLs) to other satellites in the constellation as described in Figure 1. ISLs provide direct communication paths between satellites. The ISLs between a satellite and its neighbors in the same orbital plane are called intra-satellite links, and its links with its neighbors in neighboring orbits are called inter-satellite links.

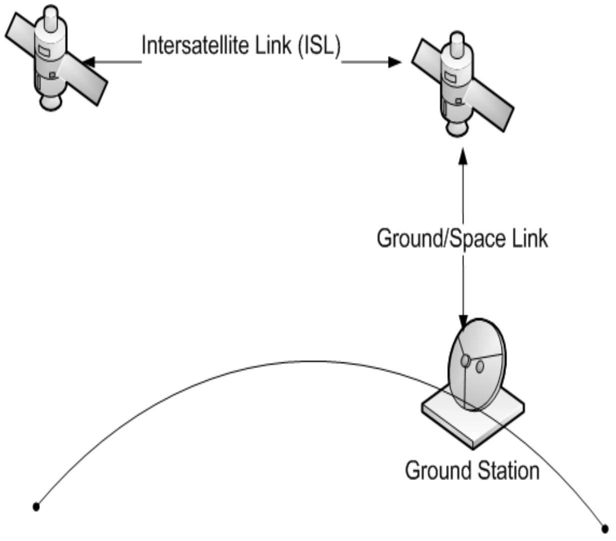


Figure 1. Inter-Satellite Links (ISL).

There are several orbits available for satellites to reside. The orbits are low Earth orbit (LEO), medium Earth orbit (MEO), highly elliptical orbit (HEO) and geosynchronous orbit (GEO). 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. Since LEO satellites, presented in Figure 2, provide low propagation delay and low power requirements, they are becoming increasingly important for real-time services, which require a mechanism to forward data to several receivers. However, LEO satellite systems have mobile network topologies and this dynamic topology makes data multicast difficult.

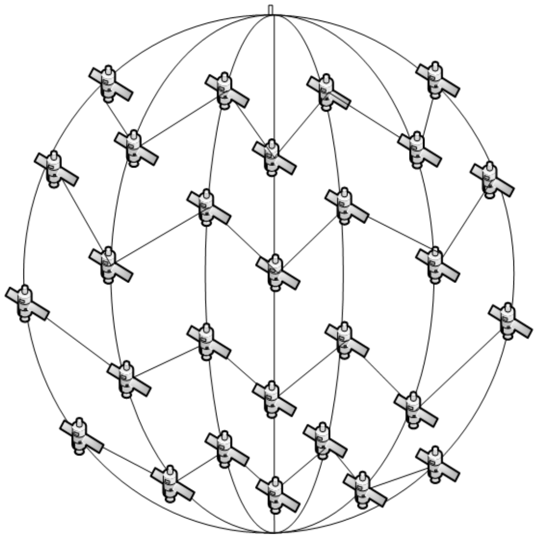


Figure 2. The topology of LEO satellite networks.

In the literature, some multicast protocols including Internet Group Management Protocol (IGMP) [2], Reverse-Path Multicast (RPM) [3], Distance Vector Multicast Routing Protocol (DVMRP) [4], and the Multicast Extensions to Open Shortest Path First (MOSPF) [5] consider periodic message exchanges for the establishment and the management of multicast trees, which can overload the network mainly in the case of long communication periods between source and destination users during a multicast session. At present, only a few multicast routing schemes in the literature, have been developed for satellite networks. In [6], 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. In [7], the authors associate to every multicasting routing problem a Steiner tree problem. In this paper, a dynamic QoS (Quality of Service) routing mechanism is proposed to support multiple Steiner trees. In [8], a fast iterative distributed multicast routing algorithm was developed based on the inherent characteristics of satellite networks, which using distributed computing model and significantly reducing the algorithm computational complexity. In [9], 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 GEO, HEO, and LEO satellite layers is introduced. In [10], combining LEO satellites' advantages on transmitting real-time information with GEO's ability of big computing, a GEO/LEO Double-Layer Multicast Routing Algorithm (DLMRA) is given. The proposed algorithm aims to minimize cost of multicast trees, under the condition of the available bandwidth bound and multicast tree delay bound. In [11], the authors proposed a multicast routing for LEO satellite constellation networks with high performance. The algorithm uses the group members' geographic information to route multicast packets, with less memory, computer power and signaling overhead.

The proposed approaches are mainly proposed in the context of IP and mobile networks and then adapted to support multicast in LEO networks. However, a multicast protocol used for LEO satellites must address more specific requirements. First, a multicast protocol must provide low latency and low overhead when transferring multicast packets in the network since multicast applications are high data rate real-time application (such as voice and video traffic) and the number of multicast packets can be very important. Second, a multicast protocol must provide scalability when considering different traffic sizes, groups and connection delays. Furthermore, a multicast protocol must insure the security of connections when establishing multicast trees, constructing and transferring packets in the network. Thus, optical communications between satellites, which are not considered by the proposed approaches, can fulfill the cited requirements for a multicast protocol in LEO satellite constellations. In the literature, several approaches studied the optical multicast aspect in Wavelength Division Multiplexing (WDM) networks [16]–[19]. In this context, we propose the LEOCast protocol, which is a multicast protocol based on free space optical communication links between satellites.

III. CODEWORD BASED SIGNAL STRUCTURES

In this section, we introduce the optical codeword concept and its characteristics. Then, we present the codewords' structures used by the two modes of the LEOCast protocol: 1) the mode based on the shortest paths, and 2) the mode based on the virtual multicast trees.

A. *Codeword concept*

Optical encoding is based on optical codeword sequences. An optical codeword is a set of ("0","1") sequences of length N that satisfies certain auto-correlation and cross-correlation constraints. Each "0" or "1" of a sequence is called a chip.

Optical encoding has a wide range of novel and promising applications, such as label switching and Optical Code Division Multiple Access (OCDMA) multiplexing technology. In OCDMA, each transmitted data bit is optically encoded by a specific pulse sequence. The optical encoding operation consists in representing the data bit by a code sequence either in the time domain, the wavelength domain, or a combination of both (2D-coding) [20]. The decoding operation is performed by the receiver to recover the original data. We define optical

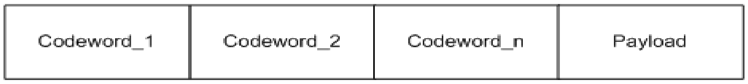


Figure 3. Shortest path structure.

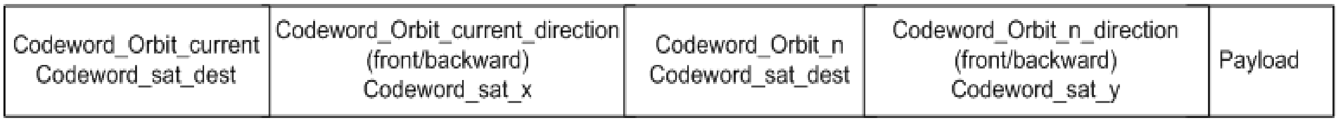


Figure 4. Virtual tree structure.

coding/decoding as the process by which a code is inscribed into, and extracted from, an optical signal.

B. Code sequences characteristics

An optical orthogonal code [21]–[23] is a family of ("0", "1") sequences with maximum auto-correlation and minimum cross-correlation in order to optimize the differentiation between correct signal and interference. Code family that have the best orthogonal propriety is optical orthogonal codes (OOC). An OOC is defined as a collection C of codewords $C = \{c^1, ..., c^m\}$, characterized by a 4-uplet $(N, w, \lambda_a, \lambda_c)$, where N is the length of a codeword, and w is the Hamming distance of a codeword, and for each c^i, c^j:

- $\sum_{t=0}^{N-1} c_t^i c_{t+k}^i \leq \lambda_a$ for every $k \neq 0$
- $\sum_{t=0}^{N-1} c_t^i c_{t+k}^j \leq \lambda_c$ for every k

Hence, λ_a and λ_c define the constraints on the auto-correlation and the cross-correlation functions, respectively. The above conditions indicate:

- The number of ones in the zero-shift discrete auto-correlation function should be maximized.
- The number of coincidences of non-zero shift discrete auto-correlation function should be minimized.
- The number of coincidences of the discrete cross-correlation function should be minimized.

In the case where $\lambda_a = \lambda_c = \lambda$, the OOC is represented by the 3-tuple (N, w, λ) and called optimal OOC. $\mid C \mid = m$ is the cardinality of the code (i.e., the number of codewords contained in the code family). For a code characterized by (N, w, λ) the maximum number of codewords that belong to this code family, denoted by $\Phi(N, w, \lambda)$ should satisfy [24]:

$$\Phi(N, w, \lambda) \leq \frac{(N-1)(N-2)....(N-\lambda)}{w(w-1)(w-2)...(w-\lambda)} \tag{1}$$

For $\lambda = 1$, the number of codewords is upper-bounded by:

$$\mid C \mid \leq \left\lfloor \frac{(N-1)}{w(w-1)} \right\rfloor \tag{2}$$

where $\lfloor C \rfloor$ denotes the integer portion of the real number C.

A (N, w, λ) OOC can be considered as a family of sets (of cardinality w) composed by integers modulo N. Each among these sets specifies the positions of the nonzero bits in the codeword. For instance, the codeword 1101000 in the OOC characterized by $(7, 3, 1)$ can be represented by $\{0, 1, 3\}mod(7)$ because the positions of the bits set to one are respectively 0, 1, and 3.

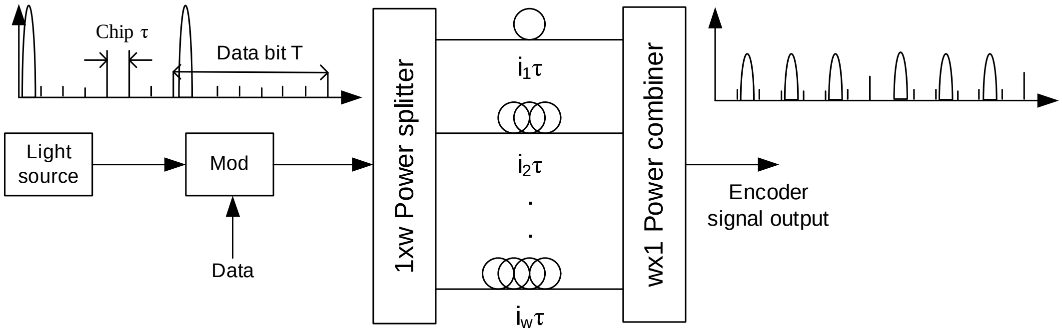
C. Path and tree based codeword for signal transmission

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 is very reduced compared to current terrestrial networks. 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.

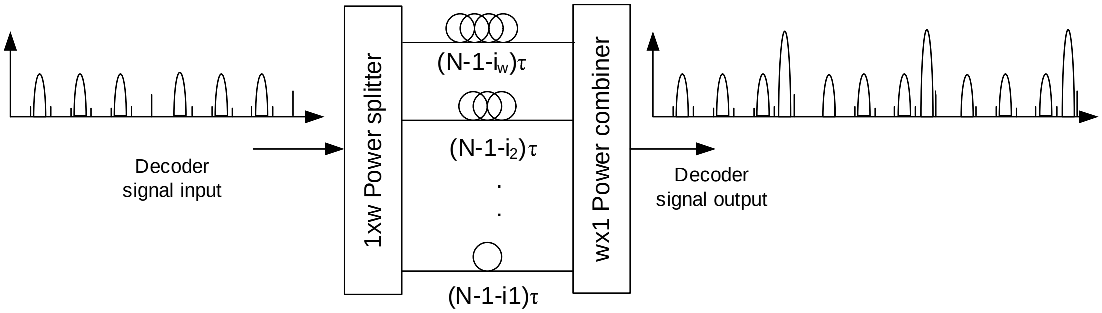
For the two optical multicast modes based the shortest paths and the virtual multicast trees, we consider the following header structures composed of a set of codewords. Figure 3 describes the header structure considered by the first proposed multicast mode based on the shortest paths and that will be presented in the following section. In this approach, we associate to the payload a set of optical codewords that indicate satellites in a shortest path. Figure 4 presents the header structure considered by the second proposed multicast mode, which is based on the paradigm of the virtual multicast trees that will be described in the next sections. As we can notice, the structure of codewords associated to the payload is more complicated compared to the first mode. Indeed, each codeword is structured in two parts: the first part identifies the orbit in the LEO constellation and the second part identifies a satellite in the constellation.

IV. CODEWORD BASED MULTICAST

In this section, we present the codeword based switching process, which is the main optical signal operation performed by each satellite. Furthermore, we describe the optical codeword association to each satellite in the constellation.



(a) All-optical encoder



(b) All-optical decoder

Figure 5. All-Optical Encoding/Decoding

A. *Codeword based switching*

In this work, we propose an optical multicast process based on codewords. Also, we provide a function so that each satellite can optically switch a multicast 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. Indeed, each decoder is configured with a codeword associated to a satellite neighbor. Consequently, each multicast module is composed of only 4 tunable decoders associated to the 4 satellite neighbors.

One of the key issues to consider OOC codewords in the optical signal processing operations is how to encode and decode the received OOC. Thus, we need to design and develop encoding and decoding techniques that can generate and reliably recognize appropriate code sequences. Optical encoders and decoders are major components to achieve optical processing signal operations. The optical encoder encodes only the information bit ”1” and does not produce any optical pulse when the information bit ”0” is transmitted.

In a direct sequence optical code, each codeword can be presented by its corresponding codeword block, where each element in every block indicates the position of ”1” in the codeword. Therefore, the structures and operational principles of any temporal incoherent optical encoders/decoders are similar with each other. Each codeword in an OOC $(N, w, \lambda_a, \lambda_c)$ corresponds to a codeword block $\{i_1, i_2, ..., i_w\}$, where i_j represents the position of the j^{th} ”1” of the codeword, $0 \leq i_j \leq N-1$. A fixed and tunable one-dimensional incoherent optical encoder and decoder can be composed of an optical power splitter, a number of fixed or tunable optical delay lines and an optical power combiner.

As it is shown in Figure 5a [25], an optical encoder for a 1-D $(N, w, \lambda_a, \lambda_c)$ OOC consists of a $1 \times w$ optical power splitter, w fiber-optic delay lines and a $w \times 1$ optical power combiner. The delay of the j^{th} fiber-optic delay line is $i_j\tau$, $0 \leq i_j \leq N-1$, where N is the code length of the optical orthogonal code, w is the code weight, and τ is the width of a chip (i.e., the time-width of an optical pulse). At the beginning of a data bit cycle of a user, the light source sends an optical pulse with time-width τ into the optical modulator. The optical modulator outputs an optical pulse when the data bit is “1” and the optical modulator outputs nothing when the data bit is “0”. Then, the optical pulse corresponding to the data bit “1” is encoded by an optical encoder whose output is an optical pulse-signal waveform matching an optical orthogonal codeword. Because there is no optical signal to be input into the optical encoder for a data bit “0”, nothing is output from the optical encoder.

As depicted in Figure 5b [25], a fixed optical decoder whose structure is the same as its corresponding encoder except that the delay of its j^{th} fiber-optic delay line is changed into $(N-1-i_j)\tau$, $0 \leq i_j \leq N-1$. When the input of the decoder is the output signal from its corresponding encoder, its output is an auto-correlation function of its corresponding OOC codeword.

Finally, the data bit will be restored after the optical-to-electrical conversion and threshold decision. If the decoder

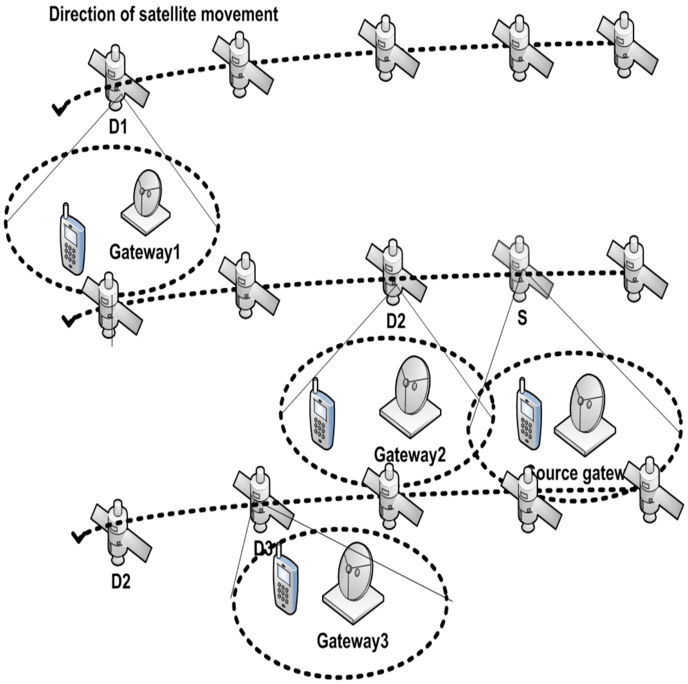


Figure 6. Multicasting in LEO satellite constellation (Figure 1, [1]).

input is an encoded waveform from other OOC codeword, its output is a cross-correlation function. Since an auto-correlation peak does not occur there is no data output.

B. Multicast

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 in Figure 6.

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 t_0, 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.

V. LEOCAST PROTOCOL: ALL OPTICAL MULTICAST MODE BASED ON THE SHORTEST PATHS

In this section, we present an optical multicast mode based on the shortest paths. In this approach, each intermediate satellite considers four codewords indicating its direct neighbors: two in the same orbit, and two in the neighboring orbits. 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 (RRES) 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 in Figure 7. 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 VOM

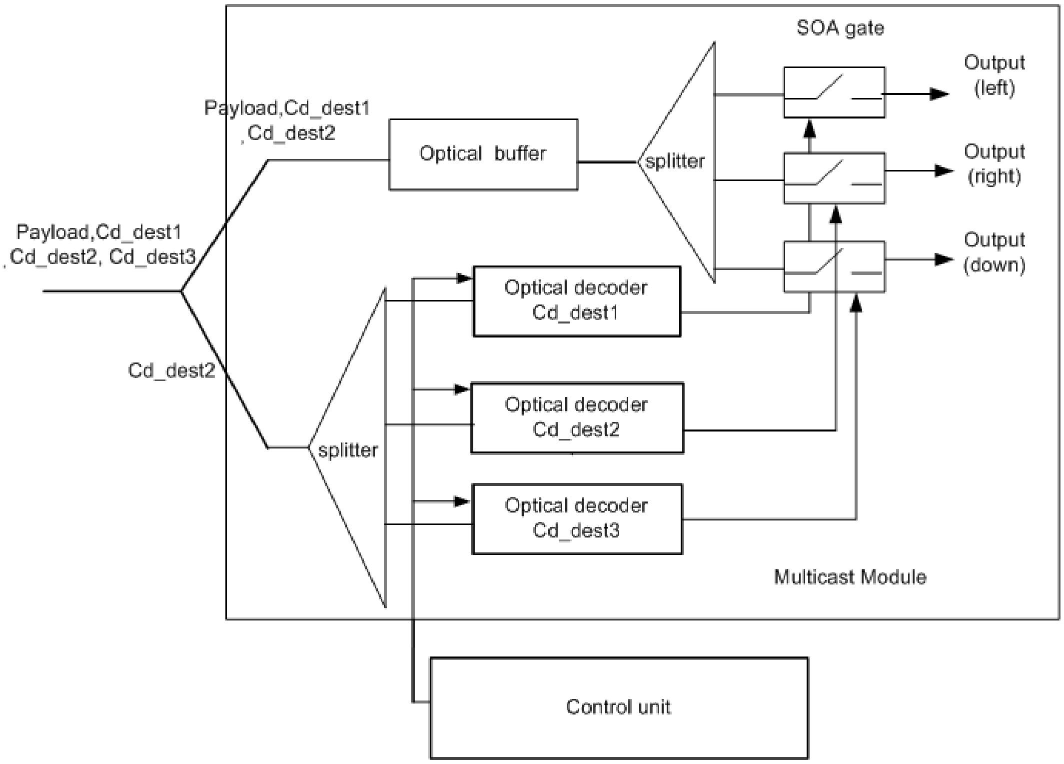


Figure 7. All optical multicast based on the shortest paths (Figure 3, [1]).

based on optical delay lines that is developed in [12];

- during the buffering delay, the second codeword in the received header is extracted from the received list of codewords and split to foure tunable decoders. Each decoder allows to match a codeword that characterize one neighbor of the current satellite; and
- 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.

The multicast approach based on the shortest paths is more adapted to a payload with small size, which corresponds to a packet. Thus, the proposed multicast process requires a buffering delay of the payload in the optical buffer in order to optically switch the received payload to the next satellite in the shortest path in order to reach the destination satellite. Consequently, the buffering delay must not be more important than the size of the payload in order to have an optimized utilization of the bandwidth. In the proposed approach, the required buffering delay is simply the delay required to perform the matching process of one the four codewords corresponding to the direct neighbors of the current satellite.

VI. LEOCAST PROTOCOL: ALL OPTICAL MULTICAST MODE 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 (front or backward) conforming to the direction of the satellite movement 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 front or on the backward 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 front or backward 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 example illustrated in Figure 8. Therefore, from a source satellite, the header to be sent, which is composed of a set of codewords, has the following structure: $CdOrbit_f^2$ CdD_1 CdD_3 — $CdOrbit_b^2$ CdD_2— $CdOrbit_b^3$ CdD_4 — $CdOrbit_f^3$ CdD_5, where $CdOrbit_f^i$ is the codeword that identifies the front direction in the $Orbit^i$ conforming to the satellite movement, $CdOrbit_b^i$ is the codeword that identifies the backward direction in the $Orbit^i$ conforming to the satellite movement, and CdD_j is the codeword that identifies the destination satellite D_j in the LEO constellation network. Thus, each optical codeword identifying an orbit is succeeded by a set of optical codewords identifying destination satellites in this

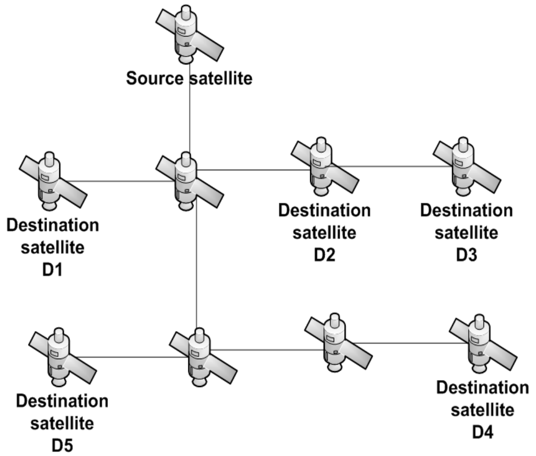


Figure 8. Virtual tree example (Figure 4, [1]).

orbit in a specific direction, front or backward (depending on the direction of the satellite movement in the orbit).

Each intermediate satellite manage a multicast traffic arriving in the same orbit (inter-orbit traffic) and from different orbits (intra-orbit traffic). This is achieved by considering a multicast module, which design is described in Figure 9. The multicast module is mainly composed of a set of optical buffers, tunable decoders and a control unit. The optical buffers delay the payload and the header during the matching process. The tunable decoders are configured by the control unit at the establishment of the multicast connection with the adequate codewords in order to send the multicast payloads to the destination satellites, which can be in the same orbit as the intermediate satellite or in the next orbits. At the reception of a payload and its corresponding header, which presents the multicast tree, the optical multicast process will be performed as follows:

- Different headers are extracted of the received header in order to obtain a separate header for each multicast direction (front, backward, next orbit conforming to the satellite movement in the orbit) and delayed with the received payload in different optical buffers. The considered optical buffer is called a VOM [12].
- The header, which corresponds to a list of structured codewords, is split in order to sequentially treat the codewords by the multicast module. The latter is composed of a set of tunable decoders configured with the following codewords by the control unit:
  - $CdOrbit^{current}CdD_{sat_dest}$, which indicates that the current satellite is a destination satellite.
  - $CdOrbit_f^{current}CdD_{sat_id}$, which indicates that the sat_id situated in front of the current satellite is a destination satellite.
  - $CdOrbit_b^{current}CdD_{sat_id}$, which indicates that the sat_id situated in backward of the current satellite is a destination satellite.
- A matching process is performed by the set of configured decoders on the received codewords that compose the header.
- Based on the result of the matching operation, the received payload will be multicast to one or several directions: front of the current satellite, backward of the current satellite and down to reach next orbits. Indeed, if $CdOrbit^{current}CdD_{sat_dest}$ is matched then the delayed payload will be treated. If $CdOrbit_f^{current}$ is matched then an optical switching gate is activated in order to send the delayed payload and its corresponding header to the neighbor satellite in front of the current satellite in order to reach destination satellites in this direction. The new header associated to the payload is composed only of codewords relative to destination satellites in front of the current satellite. If $CdOrbit_b^{current}CdD_{sat_id}$ is matched then the delayed payload and its corresponding header will be sent to the neighbor satellite in backward of the current satellite. If none of the configured codewords is matched, then a threshold detector commands an optical switching gate in order to send the delayed payload and its corresponding header to the neighbor satellite situated in the next orbit in order to reach destination satellites in other orbits.

  In our case, we need a high speed optical switching gate with a switching time window in order to get out the delayed signal from the VOM, which can be achieved for example by a Semiconductor Optical Amplifier gate (SOA). One of the most desirable properties of the considered SOA gate is the fast switching speed. Depending of the type of the SOA gate and the key temporal parameters of the SOA transit time, we obtain different switching window widths [26]–[28] as illustrated in Figure 10. For high-speed processing, short switching window is used. In our case, we have a synchronization issue that must be considered. Indeed, the switching window width T_{soa} must be sufficient to extract the header relative to a direction T_e and to get a copy of the delayed optical signal in the VOM T_s. Thus, in order to satisfy the synchronization constraint, we define the following relation: $T_s + T_e < T_{soa}$.

The multicast approach based on the virtual multicast tree

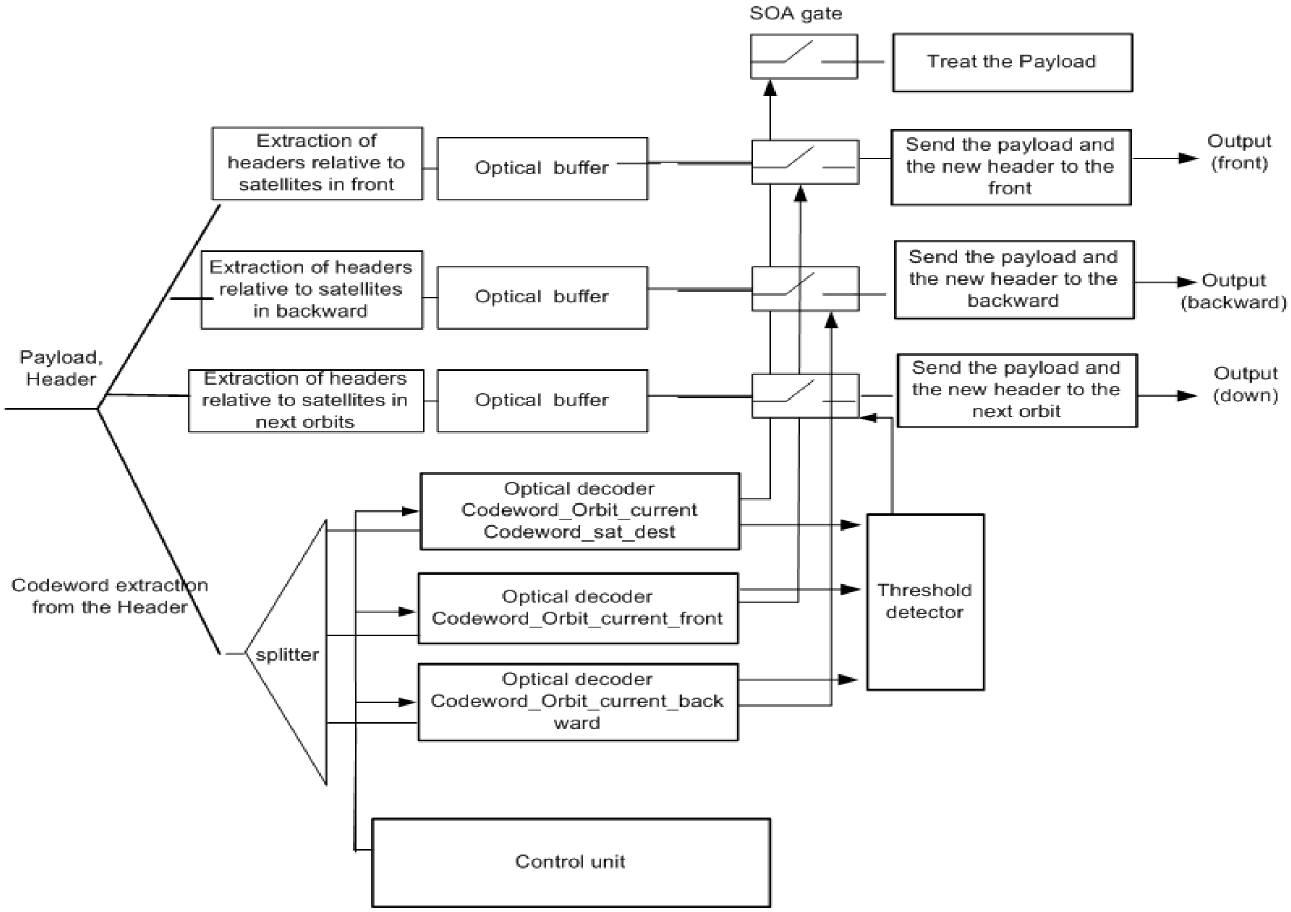


Figure 9. All optical multicast based on the Virtual multicast tree.

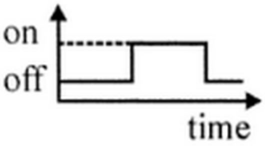


Figure 10. Switching window.

paradigm is adapted to a payload with important size, which corresponds to a burst (association of packets). Thus, the proposed multicast process requires a buffering delay of the payload in the optical buffer. This delay corresponds to the treatment of the set of codewords in the header sequentially and the generation of the new header to each burst to be switched to the adequate direction in order to reach destination satellites.

VII. MULTICAST COPING WITH LONG PERIOD SERVICES

In this section, we study the mobility management in the two all optical multicast modes of the proposed LEOCast protocol.

A. *Mobility management*

Satellite movement results in challenging mobility management problems in LEO satellite networks. Due to the movements of the satellites and according to the movements 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, when transmitting voice/data/video to users in the earth. 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.

1) 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.

2) 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, therefore, 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 (front or backward) 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.

3) 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 front and backward 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.

VIII. 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 GE Starsys constellation topology [29], which forms a LEO network (6 orbits, each orbit has 4 satellites), a traffic load matrix. The traffic load matrix considers a traffic load only between each satellite and its four neighbors (up and down, front and backward). 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, 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 in Figure 11, 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).

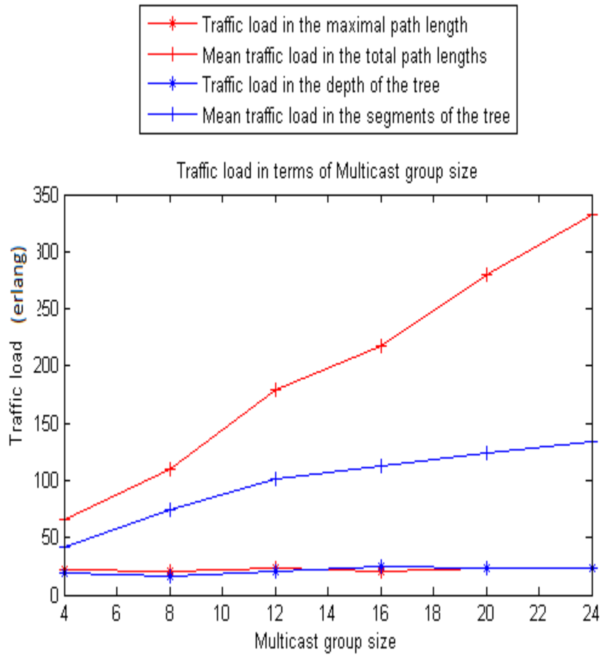


Figure 11. Traffic load in terms of multicast group size (Figure 6, [1]).

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.

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 in Figure 12, 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 the fact that the virtual multicast tree eliminates segments redundancy observed in the shortest paths approach.

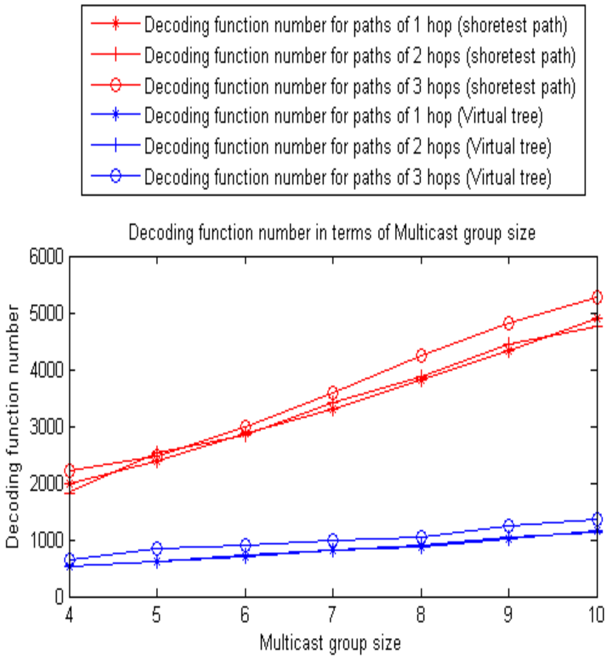


Figure 12. Decoding function number in terms of multicast group size (Figure 7, [1]).

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.

In Figure 13, we assess the optical signal quality after the multicast process to three receivers, which correspond to the three direct neighbors of the transmitter. To this objective, we consider Optiwave Optisystem as a simulation platform. We consider a transmitter with a frequency of 353 THz and a power of 12 dBm, and we choose an Avalanche Photo Diode (APD) detector receiver, which is commonly used as FSO receiver [30], [31]. The optical signal quality is assessed based on two main criteria: the wavelength and the distance between satellites.

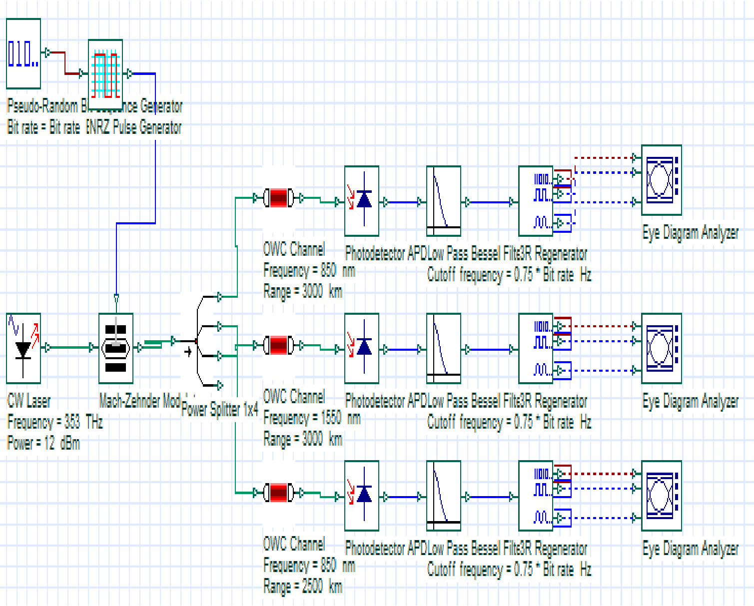
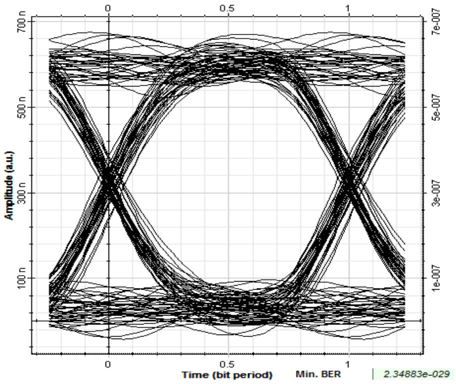


Figure 13. FSO link application in LEO networks.

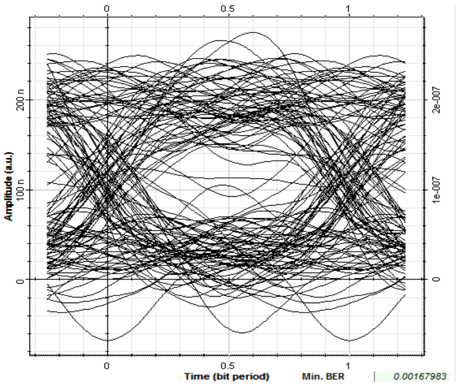
The eye diagram and the bit error rate are used as performance estimators in this simulation. Figure 14 describes the eye diagrams obtained when observing the received signal at the output of each receiver. The first eye diagram corresponds an ISL as an optical link with 850 nm and 3000 km. The second eye diagram corresponds to an ISL optical link with 1550 nm and 3000 km. The third eye diagram corresponds to an ISL optical link with 850 nm and 2500 km. Distortions shown on the eye diagram demonstrate that the best signal quality is obtained for the third receiver and the worst signal quality is obtained for the second receiver. Furthermore, the bit error rate obtained for the third receiver is lower than 10^{-9}, which is considered as an acceptable Bit Error Rate (BER) threshold, while the BER for the second receiver is greater than 10^{-9}. We can conclude that the optical signal quality increases when decreasing the FSO communication link wavelength and the distance between receivers when performing the multicast process optically. Furthermore, 1550nm lasers transmit more power than 850nm lasers for eye safety reasons (i.e. more power can be transmitted to overcome attenuation by aerosols). However, detectors in the 1550nm are typically less sensitive and have a smaller receive surface area when compared to silicon APD detectors that operate in the 850 nm wavelength.

IX. CONCLUSION

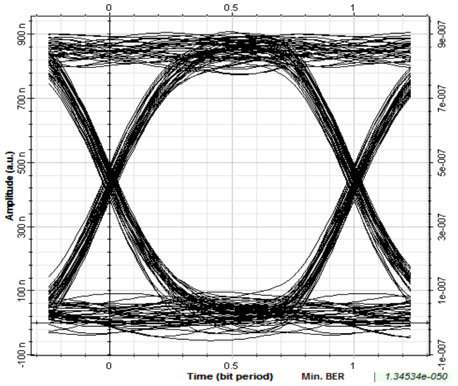
In this work, we propose an all optical multicast protocol LEOCast based on an optical switching technique that allows to perform the multicast of received traffic streams based on their optical codewords. Furthermore, this optical switching



(a) Wavelength:850nm, Distance:3000km



(b) Wavelength:1550nm, Distance:3000km



(c) Wavelength:850nm, Distance:2500km

Figure 14. Eye diagrams related to three receivers.

technique allows to perform several other functions with an optimized resource utilization. However, it is possible to use FSO links and consider an other switching technique with assuming the optical-electronic-optical conversion on intermediate satellites.

The proposed LEOCast protocol offers two multicast modes: the shortest path multicast mode and the virtual multicast tree mode. Each multicast mode is adapted depends on the buffer The multicast approach based on the shortest paths is more adapted to a payload with small size, which corresponds to a packet. Thus, the proposed multicast process requires a buffering delay of the payload in the optical buffer in order to optically switch the received payload to the next satellite. In this mode, the required buffering delay is simply the delay required to perform the matching process of one of the four codewords corresponding to the direct neighbors of the current satellite. The multicast approach based on the virtual multicast tree paradigm is adapted to a payload with important size, which corresponds to a burst (association of packets). This is due to the fact that this mode requires a more important buffering delay compared to the first mode. This latter corresponds to the treatment of the set of codewords in the header sequentially and the generation of the new header to each burst to be switched to the adequate direction in order to reach destination satellites.

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