

On routing protocols in inter-satellite communications

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Abstract

Low earth orbit (LEO) satellite networks offer broadcasting to remote places or places at the time of natural or human-caused calamities. LEO satellites are preferable in a real-time communication compared to e.g. geostationary satellites due to smaller propagation delay and packet loss. Inter-satellite communication may further reduce the end-to-end delay between two terrestrial nodes. Routing of the networks will play a crucial role in optimizing the potential capacity of the network. We present and analyze a simple ALOHA type routing protocol for inter-satellite links in a satellite network.

1 Introduction

Routing protocols use different metrics to evaluate the best path for a packet to travel. Metric can measure path bandwidth, reliability, delay, current load on the path, etc. The computing time of routing algorithms increases in an over-linear time, hence algorithms that have to compute the shortest route in real-time can cause drastic delay to the signal. Different protocols are presented broadly in [1].

We present a contention-based protocol for inter-satellite communications in an LEO-satellite constellation. Only antenna beam steering capabilities and information on the location of the other satellites is required.

Briefly, the most simple ALOHA scheme is a routing protocol where – in each time slot – each transmitter tosses a coin whether to send a packet or not. Coin can have a weight $p \in [0, 1]$. The value of p plays an essential role in determining the capacity properties of the network. Indeed, as will be shown in this paper, we can find an optimal value for p which will maximize the throughput of the network, and this value will not be trivial.

2 Model

Leaving aside the down- and up-links in the satellite communication network, we will concern only on inter-satellite links. We assume that each satellite has a packet to send (received from earth-stations in an up-link), which they will be casting to desired satellites (which will eventually transmit the packet to addressed earth stations in downlink). Each packet will be put forward in a single time slot dedicated to the transmission. Often the packet has to travel through multiple satellites, which work as forwarding links for the message. Routing protocol presented here will be based on a scheme where each link sends a message to link j with independent probability p . The packet will travel to all destination nodes which are reachable in the chain of satellites connected in this sense (regardless of the metrics of the route, or where the packet is addressed).

A *Graph* consists of a set of nodes indexed by $i = 1, \dots, n$ and set of edges, or connections, between the nodes. Edges can have weights, and one natural case would be that the weights represent the spatial distance between the nodes. Edges can be directed, which means that the weight is different according to which direction one ‘is heading’. This can represent e.g. the interference conditions in the targeted nodes. An *Adjacency Matrix* A is a matrix representation for a graph. Its entries A_{ij} are the weights between nodes i and j . In that case of undirected graphs,

$A_{ij} = A_{ji}$ i.e. adjacency matrix is symmetric in that case. Adjacency matrix and graph will be considered as the same object from this on.

Consider a satellite constellation with Q satellites in P plane with inclination B . At each time moment, we can represent the connections between satellites as a graph A , of which entries $A_{ij} = 1$ if and only if satellites can i and j can ‘see’ each other. Otherwise, entry will be 0. Let D represent the spatial distances between each satellite. The distances D_{ij} can be derived from a formula^[4]:

$$D_{ij} = 2\sqrt{(R+h)^2 - (\cos(r_{ij})(R+h))^2}, \quad (1)$$

where

$$r_{ij} = 2 \arcsin \left\{ \left(\cos(B/2)^4 \sin((1/Q+1)(j-i)(\pi/P))^2 + \right. \right. \\ \left. \left. 2 \sin(B/2)^2 \cos(B/2)^2 \sin(1/Q(j-i)\pi/P)^2 + \right. \right. \\ \left. \left. \sin(B/2)^4 \sin((1/Q-1)(j-i)\pi/P)^2 + \right. \right. \\ \left. \left. 2 \sin(B/2)^2 \cos(B/2)^2 \sin((j-i)\pi/P)^2 \cos(2/Q(j-i)\pi/P) \right)^{1/2} \right\}. \quad (2)$$

Define a random matrix R , which entries are distributed as Bernoulli distribution with probability p . The diagonal of R is assumed to be 0. Random graph R is interpreted as a condition that each node i will be sending a package to node j with independent probability p . Consider that a satellite i is permitted to send a packet to a satellite j . We define the signal to interference plus noise ratio, SINR, in the edge between nodes i and j to be the ratio

$$\text{SINR}_{ij} = \frac{\frac{1}{D_{ij}^2}}{\sum_{k \neq i} \frac{A_{kj} R_{kj}}{D_{kj}^2} + N}, \quad (3)$$

where $N > 0$ is a constant noise-power.

We define throughput

$$T = \log(1 + \text{SINR}_{ij}) \quad (4)$$

between two satellites i and j to be **the minimum of the values $\{\log(1 + \text{SINR}_{pk})\}_{p,k=1,\dots,Q}$ between satellites $\{p,q\}_{p,q \in \{1,\dots,Q\}}$ in a path of satellites from satellite i to j . If there are multiple paths from i to j , the resulting T is determined by the maximum throughput of the paths.** This means in practice that only one route is considered as a channel of the desired transmission – other routes are treated as interference.

Optimal value for transmission probability p can be considered to be given by

$$p = \operatorname{argmax}_p \{\mathbb{E}[T_p]\}, \quad (5)$$

where T_p is defined as in (4) and $\mathbb{E}[\cdot]$ refers to expectation value.

However, when simulating the situation, finding the optimal route for maximum SINR becomes computationally very harsh. Thus we will relax the problem and find a semi-optimal route by Dijkstra algorithm by minimizing the directed route in a graph defined by **directed weights SINR_{ij}^{-1}** and considering the maximum edge value in that route as the resulting throughput. To put it together, results in the next section are considered to be the *lower bound* for the capacity of the network.

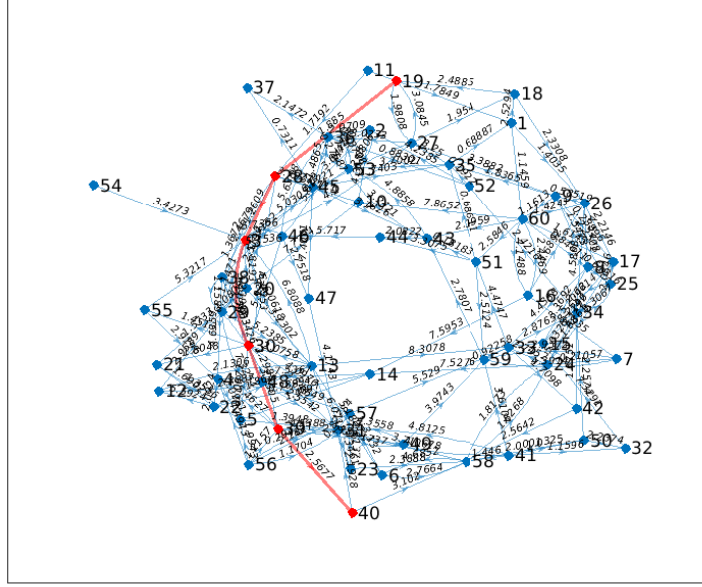


Fig. 1: A realization of the connectivity graph with $p = 0.25$ and route from node 19 to 40.

The inverse values of signal to interference SINR^{-1} in the graph can be now defined as

$$\text{SINR}_{ij}^{-1} = R_{ij}A_{ij}D_{ij}^2 \left(N + \sum_{k \neq i} \frac{R_{kj}A_{kj}}{D_{kj}^2} \right), \quad (6)$$

where noise power N is assumed to be 10^{-10} . Each value SINR_{ij}^{-1} will be considered as **directed weight between edges ij** .

3 Results

The resulting computational values for average lower bounds for throughput between each node and total throughput between all nodes are plotted in figure 2. We assume 6 satellites evenly distributed in 10 planes in some fixed phase with inclination $\pi/4$. The altitude of satellites is 1000 km. The average latency of transmission is around 30 ms with each p , and the deviation is of course large. It can be seen that the optimal value for p is somewhere between 0.15 and 0.25 if the potential total throughput is to be maximized.

Figure 1 shows one realization of the graph with value $p = 0.25$. One can see that the graph is already connected (excluding the directions) with chosen value of p (it is certainly connected with $p = 1$).

4 Considerations

The model presented here is a simple proposal of an ALOHA protocol for inter-satellite communications. There are considerable downsides as the desired destination of a packet is not necessarily part of the network in a single time slot, thus reducing the effective throughput as the package is forced to be sent in another time slot. The protocol should be further investigated in this context.

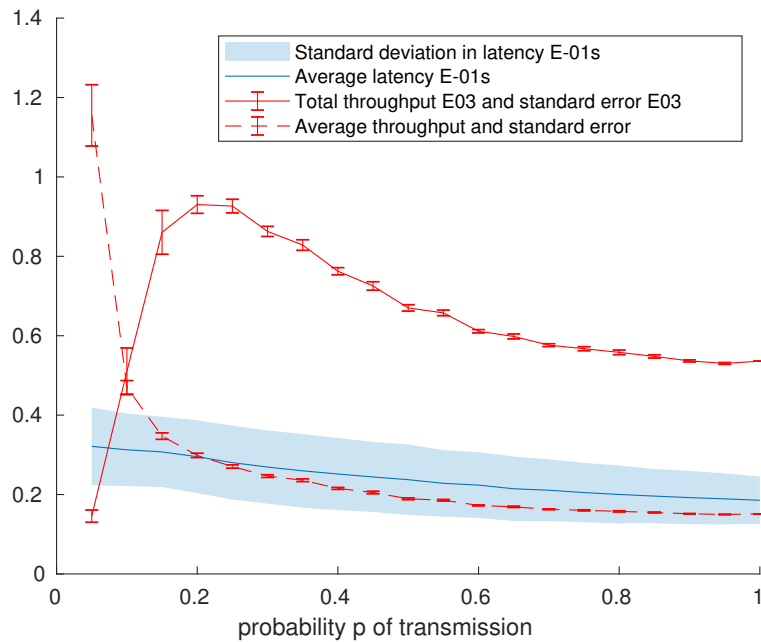


Fig. 2: Lower bounds for troughputs with varying value of p .

Analytical results^{[2],[3]} for random graphs could be needed when analyzing larger constellations as the computational time of finding the shortest route increases at least in the second exponent.

References

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