

A Theoretical Ad Hoc Lunar Communication Network With CubeSats as Secondary Payload of Lunar Missions

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ABSTRACT

Communication is a cornerstone of society. Global networks make it easy to connect with almost anyone, no matter where you are. With future plans to colonise the Moon, the necessity to set up a communications network is growing, but spaceflight is expensive. In order attempt to make the network less expensive, the possibility of sending CubeSats into orbit as a secondary payload of existing lunar missions is researched. With only these satellites and no ground network, enhanced Low-complexity Probabilistic Routing and a custom localisation algorithm are used in order to create LuCoN: a robust communication network for the Moon.

Keywords

CubeSat, Mesh Network, Ad Hoc, Localisation

1. INTRODUCTION

These days, modern society relies more and more on global communication systems, with mobile networks like 4G and the Internet being the best-known examples. These networks allow users to send messages to and receive messages from other users with only milliseconds of delay, even when contacting someone on the other side of the planet. Communication is almost as easy as talking to someone in the same room. Only a simple telephone or computer is needed in order to connect to the network and they are readily available, making the threshold to join incredibly low.

With the renewed interest in both lunar and interplanetary exploration, [11] though, the existing systems will soon no longer be enough: the signals of the satellites in orbit around Earth do not reach far enough to enable communication from one part of the Moon to another. Other planets in our solar system are even further out of range. Nevertheless, communication is still needed: it is instrumental in gathering data from a spacecraft, rover or astronaut, or to make them aware of dangers or new objectives. Besides this, it may be useful to gain information directly from other robots or humans on the Moon, without the need for first sending this information to Earth and then back. Thinking more about the future, humanity will at

some point start colonising the Moon, [21] and when it does, the new colonies will want easy communication options as they had on Earth.

A communications network around the Moon would solve this issue. This network would make use of a number of satellites that form a so-called satellite constellation: a group of satellites that work together to achieve the same goal. The satellites can all be on one orbital plane, but most of the time will be spread out over multiple planes.

For Earth, a comparable satellite constellation is Iridium Next: a constellation with six orbital planes and 66 active satellites spread out over them. The orbital planes have an altitude between 780 and 790 kilometres, which is called low Earth orbit. [8] This is to ensure a satellite is visible from any part of the world at any time and to make sure a handheld satellite phone's signal can reach it. Since the diameter of the Moon is 3.67 times as small as that of Earth, there is less area to be covered. This, in turn, means it is possible to cover the Moon with less than 66 satellites.

However, each of these satellites needs to be launched into the correct orbit, and Iridium Next satellites are bulky and heavy: 3.1 m x 2.4 m x 1.5 m in size, weighing about 860 kg. [8] To achieve the correct orbits, multiple launches are needed, as placing satellites in multiple orbital planes in one launch is difficult and costly at best. The costs of a launch lay in the range of hundreds of millions of Euros, while a single satellite easily costs 25 million Euros to develop and build. [5] Furthermore, it takes four to seven years from the early development stages to launch.

This is where CubeSats may offer a better solution. CubeSats are nanosatellites with standardised size, mass, power and launch configurations. The size and mass are expressed in units (U). Each U is a 10 cm x 10 cm x 10 cm cube with a maximum mass of 1.33 kg. [19] CubeSats are furthermore partially if not completely composed of Commercial Off-the-Shelf (COTS) parts. Both factors significantly bring down the cost and development time of the satellite. What CubeSats lack in power in comparison to traditional satellites can therefore easily be compensated for by simply increasing the number of CubeSats in orbit, lowering the load on each of the satellites. Besides this, it is possible for CubeSats to "hitch a ride" on a launch as a secondary payload because of their small size. This further decreases the cost of a CubeSat network.

Research into ad hoc constellations of CubeSats has been done already in the context of Earth. While the resulting mix of orbit parameters is heavily dependant on the orbit goal of the payload, it is nevertheless a cost-efficient way to set up a constellation. These constellations have a longer set-up time than an intentional constellation, but revisit time and performance are comparable. [19] How-

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ever, Marinan, Nicolas & Cahoy did not consider whether every place on Earth could always see at least one satellite, which is important in communications. It also has the context of Earth instead of the Moon.

Furthermore, a 2018 study has laid out a design for a CubeSat lunar positioning system constellation with four orbital planes. It shows how full coverage can be achieved with 28 CubeSats. [29] This constellation is not made with secondary payloads, though, and as such it will still need at least four extra flights to the Moon in order to bring the CubeSats into the right orbit slots. Furthermore, the proposed constellation has an orbital radius of 4000 km, which means the orbital planes have an altitude of 2300 km. This is too far for, for example, modern satellite phone signals to bridge, and thus the constellation has to have a lower altitude.

As far as the author is aware, no truly comparable network exists as of yet. If anything, this paper provides a platform for future research, such that nanosatellites may be used in (temporary) communication networks, both on the Moon and in other places in the universe.

In this paper, the following research question is addressed:

How can a reliable ad hoc lunar communication network using CubeSats be set up?

To answer this question, it is divided into the following sub-questions:

1. *What launch opportunities exist, and what orbits do they enable?*
2. *What routing algorithms exist to facilitate networks of nanosatellites?*
3. *How can such a network keep track of its users?*

These questions will be answered primarily by means of a literature study. As such, the purpose of this research is to discover whether an ad hoc communications constellation of CubeSats around the Moon would be theoretically possible. A constellation like that would be significantly less expensive than the alternatives, and if it works on Earth's closest neighbour, it might possibly be utilised in other parts of the solar system as well.

The structure of this paper is as follows: In section 2, future Moon missions will be researched, and viable orbits for the constellation will be extracted from the mission details. In section 3, various routing algorithms for nanosatellites will be considered. Further on, in section 4, algorithms for user localisation and propagation of this information will be proposed. Section 5 will give an overview of how the total system will work when put together. Lastly follow suggestions for future work and the conclusion, respectively in sections 6 and 7.

2. THE CONSTELLATION

In this section, future Moon missions are considered. Possible orbits for the CubeSats will be extracted from the mission details. Using these orbits, it is researched how a uniform constellation can be created, and how much extra energy would be needed for this.

The constellation itself is perhaps one of the most fundamental parts of the network. It provides the hardware layer for the system without which nothing can run. Therefore, it is useful to think about the requirements and assumptions first, such that these may be kept in mind

while researching the possible constellations. Requirement-wise, the footprints of the satellites should cover 100% of the lunar surface. Furthermore, the constellation needs at least four orbital planes, as shown by Wijnen et al. [29] Lastly, orbit parameters should be as uniform as possible. If they are not, the difference in orbital speed may impede communication with other satellites and with users that move between the footprint of one orbital plane and another.

Various assumptions have been made as well. It is assumed that the Moon is a perfect sphere without geographical features. Furthermore, it is assumed that the CubeSats can be a secondary payload on any future Moon mission and that enough CubeSats can be taken to fill one orbital plane. Lastly, it is assumed that a CubeSat can be assembled that would fit the use case laid out in this paper.

Before considering how a lunar communication network could function, it is important to know what the topology of said network is. Thus, future Moon missions needed to be researched. Only missions with clear funding have been considered, as these have known launch dates, or, in case of those launches further in the future, known periods in which the launch will take place. Furthermore, the choice was made to limit the options to missions by governmental space agencies only, instead of also making use of missions by private organisations. This choice was made due to the lack of experience with lunar missions that private organisations have. Lastly, due to a lack of reliable available mission details, missions planned by CNSA (China National Space Administration) have been excluded as well.

The results of the research can be seen in Table 1. Based on this, six viable orbits can be identified, all of which are planned to go over both poles. Each mission would carry all CubeSats needed to fill one orbital plane. Together, these six orbits will form the basis of our theoretical Lunar Communication Network or "LuCoN".

However, since lunar gravity is not uniformly spread because of several mass concentrations under the lunar surface, there are only a few orbital inclinations that actually produce stable Low Lunar Orbits. These so-called frozen orbits have inclinations of 27° , 50° , 76° , and 86° . [2] Given that the possible orbits for LuCoN have different inclinations, this means that within a half a year, [20] the satellites will destabilise and inevitably crash into the lunar surface if constant corrections are not applied. However, these corrections cost fuel, and a satellite can only carry a finite amount. There are a few methods to prevent this: The first would be to change the inclination of the orbits to be the same as the frozen orbits, the second one would be to raise the orbital height such that the satellites are less affected by lunar gravity. For this paper, the assumption is made that a periapsis of 600 km gives us an orbit that needs no stationkeeping to correct for gravity anomalies. This assumption is based on the results of Meyer, Buglia & Desai. [20]

The initial constellation does not have uniform orbit parameters. Furthermore, both the periapsides (the lowest point of an orbit) and the apoapsides (the highest point of an orbit) of the orbits in Table 1 have very low altitudes, except for the apoapsis of the Smart Lander for Investigating Moon (SLIM) mission. [12] Lastly, only four frozen orbits exist, and LuCoN is projected to have six orbits. Thus, the choice is made to raise the orbits instead of change the inclination. This will not only protect the constellation from the gravity anomalies but will also provide an opportunity to ensure uniformity of the orbit

Mission	Launch Date	Orbit	Altitude
Chandrayaan-2[30]	9 July 2019	Circular polar	100 km
Artemis 1	June 2020[6]	Circular polar	100 km[14]
Korea Pathfinder Lunar Orbiter[31]	December 2020	Elliptical polar	100 +-30 km
Luna 25	July 2021[23]	Circular polar	100 km[32]
Smart Lander for Investigating Moon	Late 2020/early 2021[22, 25]	Elliptical polar	600x15 km[12]
Luna 26	2024[23]	Elliptical polar	100x150 km[1]

Table 1. Available orbits based on future moon missions

Mission	Δv (ms^{-1})
Chandrayaan-2	184.625853
Artemis 1	184.625853
KPLO	184.625853
Luna 25	184.625853
SLIM	107.622125
Luna 26	173.894890

Table 2. Δv needed to raise orbit altitude of a single satellite to 600 km

parameters.

Raising the orbit will take place via a Hohmann transfer orbit. [28] This type of transfer uses the minimal possible amount of energy, but may take longer in terms of time compared to other orbit alteration manoeuvres. This is acceptable, however, as CubeSats are limited in the amount of fuel that can be stored inside. Furthermore, since the first five orbital planes will be filled multiple years before the last plane, the Hohmann transfers will be completed far before that. Because the focus of this paper is not satellite design, no propulsion method for the LuCoN satellites has been decided upon. Thus, instead of calculating necessary fuel amount for the manoeuvre, Δv will be calculated instead. This signifies the total amount of change in speed the satellite will need in order to complete the manoeuvre. This amount may be calculated with the following formulas: [28]

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}} \left(\sqrt{\frac{2r_2}{r_1 + r_2}} - 1 \right) \quad (1)$$

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}} \left(1 - \sqrt{\frac{2r_1}{r_1 + r_2}} \right) \quad (2)$$

$$\Delta v = \Delta v_1 + \Delta v_2 \quad (3)$$

In equation 1, r_1 is equal to the radius of the current circular orbit, r_2 is equal to the radius of the desired circular orbit and μ is the standard gravitational parameter. Equation 1 gives the Δv needed to enter the elliptical Hohmann transfer orbit. In equation 2, r_1 is equal to the periapsis of the current elliptical orbit, r_2 is equal to the apoapsis of the current elliptical orbit and μ is the standard gravitational parameter. Equation 2 gives the Δv needed to exit the Hohmann transfer orbit and go into a circular orbit with radius r_2 . These equations may also be used to calculate the Δv needed to go from circular orbit to a regular elliptical orbit and vice versa. In the case of the Moon, $\mu = 4.9048695(9) \times 10^{12} m^3 s^{-2}$

Using these equations, the Δv per satellite necessary to change the orbit parameters to be circular polar orbits with an altitude of 600 km were calculated. These results can be found in table 2.

Given an orbit altitude of 600 km, the orbital speed of the

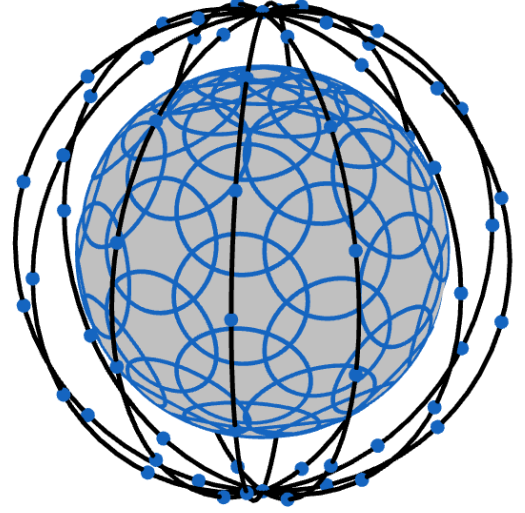


Figure 1. LuCoN constellation and satellite footprint

satellites can be calculated using the equation [3]

$$v = \sqrt{\frac{G * M_{central}}{R}} \quad (4)$$

where G is Newtons Gravitational Constant, $M_{central}$ is the mass of the body the satellite orbits (in this case, this is the Moon), and R is the radius of the orbit of the satellite. Together, this gives us an orbital speed of $1448.4 m/s^2$. This means the orbital period of a satellite is 169 minutes.

Thus, like the Iridium Next network, the CubeSats forming LuCoN will be flying in an organised constellation. Due to the nature of upcoming lunar missions, it is possible to create a similar constellation with polar orbits, which makes it highly predictable and more efficient than a random mix of orbit parameters. However, the constellation will not have on-ground infrastructures such as ground stations or glass fibre connections. Any and all data transfer needs to go through the satellite network, including data on where all connected devices are, or where they were seen last. This difference may make LuCoN more susceptible to delays and congestion.

This constellation, as shown in Figure 1, is a representative example of what is possible, but is not an actual mission. In regards to the CubeSats forming the constellation, the following assumptions have been made:

- The CubeSats are capable of carrying sufficient fuel and have thrusters capable of raising the orbit altitude and maintaining it.

- Each CubeSat has five sets of antennas: One per neighbour for inter-satellite links, and one for communication with the users.
- The antenna range for ground communication is at least 960 km, and the viewing angle between the satellite and a user in this range is never past the limits of the antenna.

These assumptions together ensure 100% coverage of the lunar surface, even at the seam, where two orbital planes move in opposite directions. Every point at the surface can see at least one satellite at all times, and even more when headed towards the edge of a satellite's range or when in polar regions.

Thus, it is possible to create a network of CubeSats that covers the lunar surface. This network would have six circular polar orbital planes with an altitude of 600 km. Each plane would have twelve CubeSats, to a total of 72 CubeSats. Bringing them all in place would take five years, based on carrier mission dates.

3. ROUTING ALGORITHM

In this section, various routing algorithms specifically tailored to satellites will be considered for LuCoN's use case. The network conditions of LuCoN will be laid out and based on this, the optimal routing algorithm will be chosen.

The satellites forming LuCoN are spread out over six orbital planes, with a total of 72 CubeSats in orbit. While theoretically, it would be possible to cover the surface area with 28 satellites, [29] the choice was made to lower the computational strain and angle of the cone of antenna signals of each of the satellites. This means that more satellites are needed to cover the same area, but each satellite receives less traffic in general.

Together, the CubeSats form a dynamic mesh. Each CubeSat is able to communicate with the satellite in front of it and that behind it on the same orbital plane. These are called intra-orbit inter-satellite links. Furthermore, each satellite, except those next to the seam, can communicate with the satellite next to it in the neighbouring orbital planes. These are called inter-orbit inter-satellite links. The layout flips 180 degrees at the polar regions. Due to this fact, the viewing angle between two satellites in neighbouring orbital planes becomes so sharp that the pointing, acquisition and tracking mechanisms of the antennas can no longer keep track of neighbours. Thus, in polar regions (latitude 60 and higher [10]) inter-orbit communications are turned off. [27] Given this information, LuCoN can be depicted as a dynamic 2D mesh network, as shown by Lu et al. [17]

However, traditional routing algorithms for mesh networks will not be sufficient: The satellite network is far more dynamic, with high transmission delays and a high probability of bit errors and packet loss. Secondly, a link that goes down will not be able to be repaired remotely in most cases, causing a broken link to stay broken for an indeterminate amount of time. Furthermore, the satellites are limited in storage and processing power, which means a lightweight algorithm is needed. Lastly, traffic in the network is not naturally distributed evenly. [24] All of these factors mean that a specialised algorithm is needed to ensure reliable transmission of packets between sender and receiver.

Over the years, various algorithms have been developed for this exact purpose. Given our network topology, however,

a great amount of these can be disregarded. LuCoN is not a multi-layered network, and it will not have a ground station. Furthermore, LuCoN will consist of CubeSats, and not full-size satellites. While a multi-layered satellite network would have higher survivability and more flexible networking than a single-layered network, [24] there are simply no ad hoc opportunities to bring a secondary layer of satellites into orbit given the current list of planned moon missions. Thus, an algorithm for a single-layer polar low orbit constellation needs to be used. A lack of ground station means that every satellite needs to be able to remember the broad topology of the network, as well as be able to calculate the route for any packet passing through. Thus, an algorithm is needed that takes these factors into account as well. Lastly, CubeSats are smaller and can thus carry less solar panels or batteries than a full-sized satellite. This, in turn, means a CubeSat has a tighter energy budget, especially when in the Moon's shadow. Communication is the most power-intensive subsystem of the satellite, even more so when communication is done over long distances, as transmit power needs to be higher. Thus, communication overhead needs to be kept to a minimum, and the routing algorithm will need to facilitate this.

One option is to use an algorithm based on virtual topology. In this strategy, routing is done based on snapshots of the network: a model of the network given a small time period t . In this model, the cost change of a link during t is so small that it can be safely ignored. This makes it possible to describe the dynamic network in a fixed manner. However, the storage overhead of algorithms based on virtual topology is very high, as all snapshots need to be stored in each satellite. Furthermore, the algorithms do not take network delay, the flow of traffic and congestion into account. [24] Given that LuCoN is a communication network, in which traffic flow may be highly variable, and congestion may regularly occur around centres of activity, it is important for the routing protocol to be capable of handling this. Without it, delays in the network may quickly rise, or packets may be dropped when internal queues fill up.

Another option is to use an algorithm based on virtual nodes. In this approach, a snapshot of the network is made. The positions of the satellites become logical locations, which do not change as time progresses. A satellite is linked to the logical location as long as it is the closest satellite on the same orbital plane. When another satellite comes closer, the first satellite will transfer information necessary for a smooth handover. This information contains routing tables and allocated communication channels. The logical locations form a fixed network topology. During routing, it is assumed that each satellite is located in its logical location. Thus, routing is not dependant on the movements of satellites

Various algorithms that make use of the virtual node exist. Amongst these are the Datagram Routing Algorithm (DRA), Destruction-resistant On-Demand Routing (DODR), Localized Zone Distributed Routing (LZDR), and Low-complexity Probabilistic Routing (LCPR). DRA and DODR do not fit our requirements: DRA uses a ground station and has poor robustness in case of broken links, [7] while DODR uses flooding for each packet that needs to be sent, which causes a large communication overhead. [13] LZDR does not have these issues, but will nonetheless not suffice. It merges various virtual nodes into a zone and appoints a management node in each zone. Packets are first sent to the management node of the source zone and are then

propagated to the management node of the destination zone, after which it is delivered at the destination node. Network status information is strictly kept to each zone, and thus other nodes are not aware of traffic or congestion. [16] This may lead to high delays and dropped packets, which is not desirable.

The virtual node topology may be modelled as a Manhattan Street Network, given that the nodes and the connections have a highly predictable pattern to them. In order to keep delay as low as possible, the used communication algorithm should keep queues at intermediate hops into consideration. LCPR [15] was built for this exact purpose. This algorithm bases the next hop of a packet on the latitude and longitude of the destination, as well as on the queue lengths of the nodes adjacent to the current node. This ensures the packet will be sent to the node with the shortest queue, while still getting closer horizontally or vertically. However, LCPR assumes the network is complete and has no broken links or nodes. While this is true in the optimal case, in practice it may happen that a link or node breaks down. Thus, an unmodified version of LCPR would not satisfy all needs.

One way to combat this would be to add a system that detects broken links and propagates this information through the network. In LCPR, every node sends each of its neighbours a message with queue status every t seconds. Thus, if t seconds have passed, and no packet is received from that specific neighbour, a node may conclude that the link to the neighbour is broken. The only exception to this is if it is a horizontal neighbour and one or both nodes are in the polar regions, as inter-plane communication is turned off there. In order to exclude a corrupted or dropped packet as the cause of the nondelivery, the node should see if the next message does arrive. Should the message not arrive either, the node may put the loss of the link in its next queue status message. Thus, it will take $2t$ seconds to find a broken link, and from $3t$ onward, other nodes will be informed of this. These other nodes are then able to update their routing tables and forward the information in their own queue status messages. This forward will only take place the first time the node receives the information. Furthermore, the information is aggregated when it arrives at the node, such that duplicate information will not be sent. Since the node knows via which neighbours the information was sent originally, it is able to send the information through to all other neighbours. For example, consider node A , with neighbours B, C, D and E . When node A is informed by nodes B and C that link l is broken, this information will only be sent to nodes D and E . In this manner, each node can be informed of drastic changes in the network, such that routing probabilities when choosing the next hop may be adjusted to reflect this.

In the unlikely event that a broken link is fixed, the same manner of information propagation may be used to inform others. In this case, however, a singular status message from the neighbouring node is enough to consider the link repaired. Thus, node information will take place from $2t$ seconds onward.

Upon shift between two logical locations, or "handover", all satellites must update their routing tables such that the links shift the same amount. For example, assume the link between logical locations A_1 and B_1 is broken. Once the satellites shift between logical locations, they need to update their routing tables to reflect that now, the link between logical locations A_2 and B_2 is broken.

4. USER LOCATIONS

The third important part of LuCoN is the link between the satellites and the users. More specifically, this section is about how LuCoN knows which user is where in the service area of which logical location, how it stores this information and how this information is passed on in the network. As such, it tries to answer the third subquestion.

In this section, it is assumed that each device knows the path of the satellites and the positions of the logical locations. Furthermore, the assumption is made that the network is time-synchronised.

4.1 User Localisation

On Earth, users are localised either by making use of a global navigation satellite system (GNSS) such as GPS, by cell-tower multilateration, by WiFi trilateration, or by a combination of the three. On the Moon, no dedicated GNSS network exists, nor has any kind of ground network been established. While it is possible to use Earth's GNSS satellites to aid positioning on the near side of the Moon, [18] this means another method of positioning will still need to be found in order to have accurate user locations over the whole lunar surface. These locations are needed in order to aim antennas at users when they are the destination of a packet. Therefore, highly accurate locations would be preferred. However, at any given time, large areas will only have a single satellite flying overhead. This makes accurate localisation challenging at best. Thus, the choice is made to store location data as a presence in a predefined zone. This reduces the need for perfect accuracy.

Storing the location as a zone has a secondary advantage: the satellite network does not have to be made aware of every slight bit of movement. Instead, a device can simply keep track of the zone it is in, and the last zone it reported being in. Once the zone changes, the device sends an update message to the satellite in the logical location that the zone belongs to. This update message will contain the zone the device is in, the time, and a unique identifier such as the device's MAC address. This protocol is the same as mobile phones on Earth use. [4]

The zones would partially overlap at the edges, such that minute deviations between the actual location and the calculated location do not immediately mean repeated movement between two zones, but rather a singular switch. After this switch, a larger amount of movement is necessary to make the device switch back to its earlier zone. Each zone would be linked to a single logical location, and each satellite has data on which zone is linked to which location. These zones are reminiscent of traditional cells in a cell phone network. [26]

The consequence of using zones instead of exact locations is that a handshake is necessary to initiate contact between a satellite and a device. The satellite would first send a beam to the zone to request the device to come in, which will then send an acknowledgement. This gives the satellite a location that is accurate enough to aim its antennas properly.

In order to find the zone a device is in, the following method is proposed: every t seconds, each satellite sends out a beacon signal containing the identifier of the satellite, the virtual node it is currently filling and the system time. Each online device in the network catches the signal. The difference between the timestamp of the beacon signal and the time of signal arrival can then be used in order to find the circle on the lunar surface on which the device is

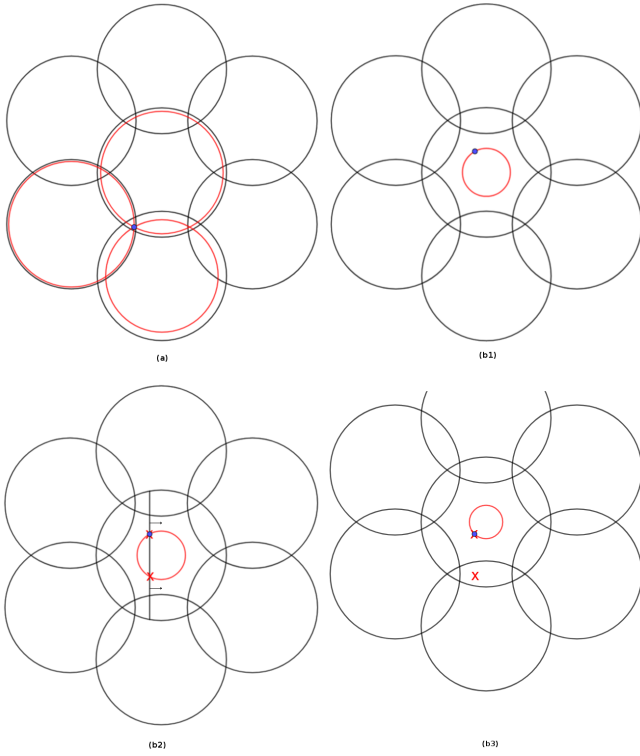


Figure 2. Localisation algorithm visualised. (a) classical trilateration. (b1) distance measurement first beacon signal. (b2) sweeping beam reduces the number of possible locations. (b3) distance measurement second beacon signal, zone found.

located. The localisation may then be further refined by using the beacon signals of other satellites, should they be available.

After this step, the satellite will send out a more focused beam that spans the height of the service area and scans from left to right, as seen from the satellite. The information in this signal will consist of the satellite identifier and the angle the beam has at that moment. The device picks up this signal, and based on the angle the signal had when it was at its strongest, combines this data with the earlier calculated circle to narrow down its location. This will result in one or two possible locations, depending on where the device is located.

Another t seconds later, another (set of) circle(s) may be drawn. The data coming from this can then be compared to the previous data, and the estimated location can be updated and refined to a single zone. This process can be seen in figure 2. When the location of the device is in the area where two zones overlap, it will choose the zone which has the closer centre.

Should a device have accelerometers, then enhanced localisation is possible. The device would be able to keep track of its movements and cross-reference the expected location based on the last known location and movement with the location as calculated via the time difference and sweeping beam. This could potentially improve localisation efficiency.

4.2 Location Storage

In the routing algorithm, it is assumed that each satellite knows the rough location of each device. Without this information, the satellite cannot send a packet in the correct

direction. The closer it is to the device, the more accurate and up to date this information should be. For example, it is acceptable for a satellite at the other side of the Moon to only know that device x is in the area of logical location y_0 , while the satellite in logical location y_0 needs to know that the device has actually just moved to zone z , which is linked to its neighbour, logical location y_1 .

As such, each satellite will keep a small database with four columns: *deviceId*, *logicalLocation*, *zone*, and *lastUpdated*. Of these, only three will need to be filled at most times, given that only seven satellites at most need to store up to date information on the zone of a device: the satellite filling the logical location that the zone is bound to, and the six satellites in the logical locations surrounding it. This is because the ranges of these satellites overlap and may be able to reach the device without an additional hop. For all others, knowing the logical location of a device is enough.

4.3 Information Propagation

Location information has to be propagated through the network in order to be useful. A distinction between two types of propagation may be made: propagation at handover, and intermediate propagation. The latter can be further divided into propagation to neighbours ("zone propagation") and propagation to non-neighbours ("location propagation").

Once a satellite receives an update message from a device, it first checks whether it already has the device in its database, and update the corresponding table row (if it exists) with the zone information, as well as updating the lastUpdated column. After this, the satellite will proceed to propagate the information via zone propagation.

4.3.1 Zone Propagation

Zone propagation is perhaps the quickest of the three types of propagation. In this case, a satellite will append a row containing the *deviceId*, *zone* and *lastUpdated* values for the device that has moved to the LCPR update message, which will then be sent to the neighbours. These will update their own tables accordingly. After this, the neighbours in the same orbital plane as the original device will append the table row to their LCPR message to the other two overlapping neighbours. If the device has moved from one logical location to the next, the satellites will furthermore initiate the location propagation step.

4.3.2 Location Propagation

In location propagation, a satellite appends a row containing the *deviceId*, *location* and *lastUpdated* values to their LCPR update message. Thus, any satellite that will not directly communicate with the device will only know its logical location, and only shifts in this are propagated through the network. Because of this, an effect similar to Fisheye State Routing [9] is achieved: the closer to the destination, the more detailed location information is. Furthermore, by only propagating large changes in device location, fewer updates need to be propagated through the system, which reduces communication overhead. It does, however, mean that more specific information needs to be sent upon handover.

4.3.3 Handover

Handover is perhaps the most important step of information propagation. During this stage, each satellite composes a message containing the table rows relevant for its successor. That is to say, all zone information of devices in the upcoming logical location, as well as that of its three top neighbours. The table rows of the handover message

are then compared to the database rows of the internal database, which will be updated where necessary.

5. SYSTEM OVERVIEW

This section offers an overview of the entire system, from localising devices to sending a message from one user to another.

For this, we assume device a has been active for a longer time and its location is known by all satellites. Device b is new in the network and has only just gone online.

After t seconds, b picks up a beacon signal from the satellite overhead. It uses the difference in timestamps and its knowledge on where the satellites are to calculate how far from the satellite it is. Only one satellite is visible, so it cannot find its location yet. It waits until the sweeping beam comes and sees when the signal is strongest. Using the angle as received via the sweeping beam message, the device manages to calculate two possible locations. Another t seconds later, the b picks up a second beacon signal and it is able to calculate its location and its zone. Device b then connects to the satellite and lets it know its zone.

At this point, the satellite adds b to its database and appends the zone information to the next queue update message. At $3t$ seconds, the satellite sends this update message containing its queue states and location updates to its neighbours. These process the information, adjust their routing tables if necessary, and compose their own update messages. This means stripping away the zone information where necessary, as satellites further away from b do not need this. This process continues every t seconds until all satellites are made aware of the location.

Now device a tries to send a message to b . It first sends the message to the satellite overhead. This satellite then looks up the location of b in its database. It finds only a logical location and no zone for b . From this, it can derive how many horizontal hops and how many vertical hops need to be made in which direction to get to the correct logical location. It looks up the queue status of its neighbours and finds that the queue of the satellite in the correct horizontal direction is full. Thus, the satellite sends the packet containing the message in the correct vertical direction.

The satellite that now has the packet follows the same steps. An amount of time later, the packet arrives at a satellite that does know the zone of device b . This satellite looks up whether the zone is in range. It is not, and thus it sends the packet to the next satellite. This satellite finds that the zone is in range, and sends out a signal for device b to report itself. The device does so, and the satellite is able to deliver the packet.

6. DISCUSSION & FUTURE WORK

In this section, some choices made during the research will be discussed. Furthermore, suggestions for future work will be made.

During the research, a number of assumptions and choices have been made. One of these is the deliberate choice to ignore private organisations in section 2. While they, as stated, do not have experience with Moon missions, this may be a negligible fact in the context of this research. After all, the certainty of a mission reaching its objective has not been considered anywhere, merely the possibility of certain orbits. In future research, these organisations may be worth looking into when considering launch opportunities.

Furthermore, the research highly depends on the existence of a CubeSat design that can fulfil the needs of the network. Such a design has not yet been made, and it is necessary for future research to consider the viability of such a design.

A further issue is that the localisation algorithm shifts the problem from how to localise an asset to how to time-synchronise the network. This too is a non-trivial problem and is one that needs to be researched further.

It needs to be noted that the systems proposed for LuCoN in sections 3 and 4 are primarily theoretical possibilities for how a communication network with severe restrictions could function. These possibilities have not been extensively tested and are possibly not the most efficient manner of solving the issues at hand. Especially the localisation algorithm can be improved upon, making it more accurate, faster, more efficient, or a combination of those.

The specifics of information propagation may be optimised as well. To do this, an in-depth study into the effects of an extended form of zone propagation can be done. This may reveal a way in which to balance zone propagation, location propagation and handovers, such that these are most efficient bandwidth- and energy-wise.

Ultimately, the solutions presented in this paper are meant to spark interest in the problems they attempt to solve, not to be the definitive answer to them.

7. CONCLUSION

This paper presented the theoretical lunar communication network LuCoN. It showed how CubeSats may piggyback future lunar missions in order to form a satellite constellation that achieves a 100% coverage rate on the lunar surface. Existing communication technology was reviewed, and a modification to Low-complexity Probabilistic Routing was proposed to better suit LuCoN's needs. This enables robust low-delay routing within the network. Furthermore, a new zone-based localisation algorithm for satellite-only localisation was described. Storage of user locations was considered, as well as an information propagation method reminiscent of Fisheye State Routing.

LuCoN shows a stepping stone for communication in the least favourable conditions, and invites researchers to help bring down one of the largest hurdles for space colonisation: communication with a minimum of infrastructure. It offers new algorithms that may be refined and optimised and furthermore attempts to improve an existing one in order to make it more robust.

All in all, LuCoN will hopefully be a step on the way of humanity's joint interest in what lies beyond Earth's atmosphere. It may still have its issues, and it may always have them, but that should not stop us from wanting to improve and reach for the stars. Communication is that which unites us, both down here on Earth and in our pursuit of the final frontier that is space.

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