THE DEVELOPMENT OF STARMESH GLOBAL™ Satellite Technologies

This paper presents various aspects of the stochastic/random orbit satellite concept underlying pioneering STARMESH GLOBAL™ LEO ("Low Earth Orbit") technology, with reference to the five patent families (below), which can be accessed from our website at www.STARMESHGLOBAL.com. Many of the same topics and concepts are discussed in our White Paper No. 1 (also available at our website), but this paper covers them in greater detail and with specific reference to salient features disclosed in Star Mesh's international patent portfolio.

Currently, Star Mesh has five standalone patent families (Families A through E) and many open provisional applications that we expect to spawn additional families. Star Mesh's international portfolio reflects the evolution of its pioneering satellite communication technology from the first family, which is particularly adapted to provide service between two ground stations via a single satellite, into more and more complex satellite-based communications systems. The technology has culminated (for now) in a system with sophisticated ground-to-satellite and multi-satellite routing algorithms adapted to exploit artificial intelligence that can provide worldwide space-based internet. The below summaries of our Patent Families illustrate the progression and refinement of STARMESH GLOBAL™ LEO satellite systems from their inception to the present,

<u>FAMILY A:</u> U.S. Patent No. 10,084,536: "Bent Pipe"

A principal focus of the '536 Patent is the creation of radio routes between two ground locations via a single satellite ("bent pipe"), although many of the concepts disclosed are applicable to other aspects of Star Mesh's technology. These are some of the features covered in the '536 Patent:

- Satellites with no attitude control to allow them to "tumble" while they orbit.
- A low duty cycle for individual satellites allowing for solar panels that cover 40%–70% of the surface to provide adequate service.
- Since parabolic antennas have dimensions at least twice the radio signal wavelength, operation at typical satellite frequencies will require antennas with diameters of about 4–8 inches, so that StarMesh™ satellites can be as small as 8–16 inches in diameter.
- The utilization of solar wings (more mature designs will likely have solar panels on or recessed into the spherical surface of a StarMesh™ satellite).
- Radio signals from existing CubeSats with omnidirectional antennas having minimal gain will reach the ground. StarMesh™ satellites having parabolic antennas, with their higher gain, will easily support a bent pipe STARMESH GLOBAL™ satellite system.

A StarMesh™ satellite can easily support antennas over about 30% of the satellite surface. The probability that a single satellite tumbling in orbit can simultaneously create an up-link and a down-link is thus 0.30 × 0.30, or about 0.09. Accordingly, a <u>single</u> satellite has less than a 10% chance of communication with two ground stations. However, in a system with a large constellation of inexpensive StarMesh™ satellites, say at least 200, orbiting at an altitude of 500 miles, any given ground station would "see" about 12 satellites ('536 Patent, column 8, lines 10–15). Consequently, the chances of sending data from one ground station to another via a direct bent-pipe route is close to 70%. Thus, at any given time, most ground stations will get service on demand. And even though there may be minimal delays in message transmission until the relative attitudes of one or more satellites change to align their antennas, we believe that will be acceptable in most service applications.

However, we anticipate that judicious engineering will be able to increase the portion of the satellite surface comprising antennas and thereby substantially improve bent pipe performance. For example, with antennas constructed to cover 40% of the satellite surface the probability of immediate bent pipe service on demand increases to about 90%.

The '536 Patent Family A further includes a pending application which will extend existing coverage of certain foundational aspects of STARMESH GLOBAL™ technology.

<u>FAMILY B:</u> U.S. Patent No. 10,447,381: "Rotating Satellites"

An improvement added by the '381 Patent to Bent Pipe Family A is spinning the satellites to improve the statistical opportunities for route creation. As pointed out in the '381 Patent, one revolution per second will increase the chances of creating a radio link with a satellite, including links between satellites. In one variation the satellites would spin about different, randomly oriented axes.

Thus, instead of a particular satellite having only a 9% chance of serving a particular pair of ground sites, a spinning satellite would, depending upon the number of antennas, present six to eight more chances. In another adaptation slightly variable spin rates could further enhance the probability of making radio links.

We also recognize that rotating the satellites raises signal strength and signal-to-noise issues by virtue of the fact that rotating satellites have less time during which their antennas are linked. However, the antenna design described below in Patent Family C addresses these issues and will improve signal strength, while Patent Family E below further describes a method for controlling satellite spin rate.

The '381 Patent Family B also includes a pending U.S. application that will enable Star Mesh to continue to tailor and expand the scope of STARMESH GLOBAL™ intellectual property as we and the satellite-based communications industry continue to evolve. The '381 Patent has been filed in 15 foreign jurisdictions, including group filings in the European Patent Office (covering all EU countries), the African Regional Intellectual Property Organization (covering 19 countries), and Hong Kong. Patents Many of these jurisdictions have already granted patents to Star Mesh.

<u>FAMILY C:</u> U.S. Patent No. 10,085,200: "Star Antenna"

When increasing the amount of data over a radio channel, the radio bandwidth increases proportionally and the receiver (whether an amplifier, correlation device, or other type) receives an increased proportional amount of background noise. One solution would be to increase transmitter power; however, decreasing the antenna beam width instead can provide a compensating result for a greater data rate. As a step in that direction, the '200 Patent suggests several solutions:

- Make the antennas larger to reduce beam width.

- Use a multi-feed approach to direct the antenna beams more accurately.

- Use real-time "dynamic antenna pairing." Current satellite communication systems commonly pre-focus their antennas by relying on precise knowledge of the location and orientation of the system nodes (satellites, ground stations, personal computing devices, etc.). However, many antenna designs create side lobes and gaps in coverage, so that pre-focused beams may not always work as expected. The approach in the '200 Patent ignores satellite location and orientation and permits two nodes in a system to dynamically pair their antennas in real time. Although a detailed explanation is beyond the scope of this White Paper, this dynamic antenna pairing approach is an important feature of STARMESH GLOBAL™ technology, and will permit better reception and in most cases require less transmitted power (thus requiring fewer solar panels).

- Future implementations using narrow light beams rather than radio signals.

The '200 Patent Family C also includes continuation U.S. Patent No. 10,791,493 that extends the coverage provided by the '200 Patent. A further continuing application has been filed that will enable us to enhance protection of this pioneering StarMesh™ technology. Furthermore, the '200 Patent has been filed in 16 foreign jurisdictions, including the European Patent Office and the African Regional Intellectual Property Organization.

<u>FAMILY D:</u> U.S. Patent No. 10,291,316: "Routes by Orbital Knowledge"

Some conversations in the traditional satellite communications industry were tending toward development of systems in which all satellites know their own orbits. The '316 Patent extends this concept to the proprietary STARMESH GLOBAL™ approach, which uses satellites in unconstrained orbits, to the special case wherein the satellites know their own orbits and the orbits of all the other satellites. The routing algorithms disclosed in the '316 Patent use the orbital information of all the satellites to create single- and multiple-satellite radio routes.

The STARMESH GLOBAL™ routing methods described in this patent can also disseminate information virtually simultaneously throughout a constellation of satellites distributed worldwide, which enables the creation of a secure distributed ledger physically located 100% in space. This property of the STARMESH GLOBAL™ system will be extremely useful in various blockchain applications and the implementation of digital currencies.

The '316 Patent Family D also includes continuation U.S. Patent No. 10,784,953. A third, just-filed child application will enable STARMESH GLOBAL™ patent coverage to continue to account for future developments in this type of satellite-based communication. Furthermore, the '316 Patent has been filed in 16 foreign jurisdictions, including the European Patent Office and the African Regional Intellectual Property Organization.

<u>FAMILY E:</u> Intl. Pub. No. WO 2020/14497 (PCT/US19/041428): "Routing Algorithms for Stochastic-Orbit Satellites"

The underlying PCT application has been filed in its entirety in the U.S. as Patent Application No. 16/955,451 (collectively the "'497 Publication"). An extensive foreign filing program will be undertaken by the 2021 deadline. Furthermore, there are numerous inventions, perhaps up to a dozen, disclosed in this publication, and Star Mesh will be filing many patent applications from this comprehensive disclosure. In some ways this application represents a culmination to date of work done to extend the reach of the STARMESH GLOBAL™ technology disclosed in the earlier patent families discussed above.

A major emphasis in the '497 Publication is the creation of links and routes with satisfactory signal strength to enable new types of satellite-based systems, methods, and algorithms. The disclosed proprietary routing algorithms are adaptable to implementation by artificial intelligence to enhance a satellite's ability to analyze attributes of radio signals exchanged by system nodes as the satellite's time in service increases. Together with the technological concepts in the earlier patent families (above), the '497 Publication provides a multi-faceted toolbox for designers of satellite communications systems.

The following outlines some of the salient aspects of the systems and methods described in the '497 Publication with reference to figures in the publication. The discussion that follows provides a closer look at some of the pioneering characteristics of the StarMesh™ proprietary routing solutions disclosed in the '497 Publication.

I. The STARMESH GLOBAL™ route creation system in the '497 Publication selects from millions of potential routes, with the optimum route being based on maximizing signal quality over the entire route and not using links with poor signal quality. This required many new and unique steps and measurements. The new STARMESH GLOBAL™ system, method, and algorithms are decentralized to spread the route creation computational load across multiple nodes.

Preliminary communication between nodes for route creation is almost eliminated since each node makes its own routing decisions. The amount of calculation required by each node in a multi-stage decision process is greatly reduced. Route creation is totally decentralized as no controlling or central computer is needed. Even though the stochastic distribution of the satellites, coupled with a typical orbital velocity of 18,000 mph, limit the length of time any particular node-to-node link in a route remains stable, the StarMesh™ algorithms are powerful enough to refresh existing routes or create new routes at suitable intervals (say every three seconds). This is sufficient to support multiple data transmissions, which take only a fraction of the time that a route between particular ground locations is stable. Further transmissions are seamlessly conveyed by the refreshed or newly assembled route. Figure 6 of the '497 Publication and the accompanying text present a spanning tree example that embodies this concept.

A criteria (or "figure of merit") statement in the routing algorithm can be reduced to a single digit. Potential examples are: elimination of sub-routes with the weakest signal strength or exclusion of sub-routes with a figure of merit below a certain threshold. Any list of variables including remaining battery life, length of queues of unsent messages, signal to noise ratio and other parameters, thresholds, or rules can be used in calculating an appropriate figure of merit.

II. An important consequence of the new routing techniques in the '497 Publication is applicable to the Bent Pipe system (see Family A above). As noted, STARMESH GLOBAL™ Bent Pipe systems in their first attempt might obtain only about 70% of the required connections. When given a case of no-route, the more robust routing technology presented in the '497 Publication Family E will automatically create a multi-link route to send the data on its way. See Figure 10 of the '497 Publication. In this diagram GN1 wants to send data to GN2. However, L89 and L162 and others do not have antennas that line up. Therefore, a route (four links) is automatically created for data transfer. In other words, in a STARMESH GLOBAL™ system there will almost always be a route from a particular originating ground location to a desired destination.

For example, assume that Cairo has a good cable connection. Cairo desires to send a packet to southern Egypt near Sudan. Say bad luck ensues and no single-satellite connection is available to create a Bent Pipe route. In the system in the '497 Publication the packet can instead be instantly sent to a satellite over Saudi Arabia, say, then perhaps to one near Greece, then possibly to one over England, then one to over Libya, and finally to the destination in southern Egypt.

III. One embodiment in the '497 Publication discloses a non-spherical satellite with a large solar panel on top with antennas pointing to the side and bottom. This should permit a slight decrease in the number of transceivers required. This will also increase the horizontal coverage of the antennas and provide better statistical results. See Figures 12 and 14 of the '497 Publication.

This satellite design required addressing the problem of satellite orientation, which can be achieved using electromagnetic rods (Figure 16 of the '497 Publication) actuated in a predetermined fashion to interact with the earth's magnetic field. This same construction can be used to control the satellite's spinning rate. In this type of system, the spin rate of satellites in a multi-link satellite route will spin more slowly than discussed in other patent families, perhaps at rates of one or two revolutions per minute.

The '497 Publication also discloses a way of maintaining a satellite oriented to within ±10° of horizontal. This will enhance the stability of a given route by maintaining internodal antenna pairing for longer periods. In other words, the precision control of satellite orientation employed by other satellite communication systems is not required to support the innovative routing algorithms disclosed in the '497 Publication.

IV. The STARMESH GLOBAL™ routing technology supports satellites orbiting at different altitudes. Routes can be selected that use higher altitude GEO ("Geosynchronous") or MEO ("Medium Earth Orbit") satellites for long routes that can minimize the number of links. Although the '497 Publication satellite environment appears to be chaotic, route creation based on route quality will be very effective in creating multi-satellite routes. Some idea of how this works can be seen by considering Figures 9 and 22 of the '497 Publication and the description of the route creation process in the text associated with those figures.

OTHER COMMENTS

LEO De-orbiting/Drag & Signal Strength:

Because STARMESH GLOBAL™ satellites cost so little, the option of a system operator using them in very low earth orbits (less than 300 miles) becomes feasible. This permits adoption of several important features.

- The improved signal strength (compared, say, to Iridium) would permit IoT applications that would work through rooftops and perhaps automobile tops. A closed loop power control could let the system have both rooftop penetrations in some cases and reduced power in others.

- A higher-orbit backbone of GEO and/or MEO satellites can be easily incorporated into StarMesh™ routing logic.

- Because a StarMesh™ satellite can be built and launched at a fraction of the cost of existing communications satellites, the loss of LEO satellites due to atmospheric drag can be accommodated by simply launching a sufficient number or replacements. A single StarMesh™ satellite is expected to cost less than $10K to build and launch.

- Since StarMesh™ satellites could orbit below most other satellites, and are small and light, they will be easily designed so that they burn up safely as they lose altitude. At the same time, lower orbits reduce the amount of power required to link the satellites with the ground, which also reduces the number of batteries and solar panels the satellites have to carry, and thereby reduces satellite weight and cost even further.

Doppler Effects and Channel Assignment:

We recognize that Doppler shift due to the satellites' relative velocities will affect the frequency of internodal radio transmissions. We are aware of possible techniques that can compensate for Doppler effects in a STARMESH GLOBAL™ system.

Channel assignment will also have to be addressed within the context of the frequency band available to the system. Numerous channel assignment and/or spread spectrum strategies can be adopted to provide effective communications between system nodes.

Pending Provisional Applications:

In addition to the patents and applications in the above five patent families, STARMESH GLOBAL™ continues to file provisional applications on even more aspects of its forward-looking technology:

Application No. 62/931,388 for Satellite Mesh System Serving Moving Users

Application No. 62/931,395 for Cellular Radio Connectivity Through Satellites

Application No. 62/964,669 for Radio System for Worldwide Internet

Application No. 63/026,180 for Radio Transmission Systems and Methods for Satellite Communications

Application No. 63/061,528 for Communication System for Facilitating Connections Between Unevenly Distributed Ground Nodes

Application No. 63/069,076 for Content-Dependent Satellite Communications