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ONLINE : WPI, INSPEC

(54) Method for establishing communication links between non-stationary units

(57) A method for establishing communication links (210, 216) between communications units such as satellites that are travelling in different determinable directions, e.g. in counter-rotating orbits (218, 220) includes calculating communication link boundary corridors (202, 204, 206, 208) within which communication between the two units is possible, generating a schedule informing the units when and how to establish and maintain a link, transmitting the schedule to the units, and establishing the link according to the schedule. Enabling such links between counter-orbiting satellites makes it unnecessary to route data packets over the poles.

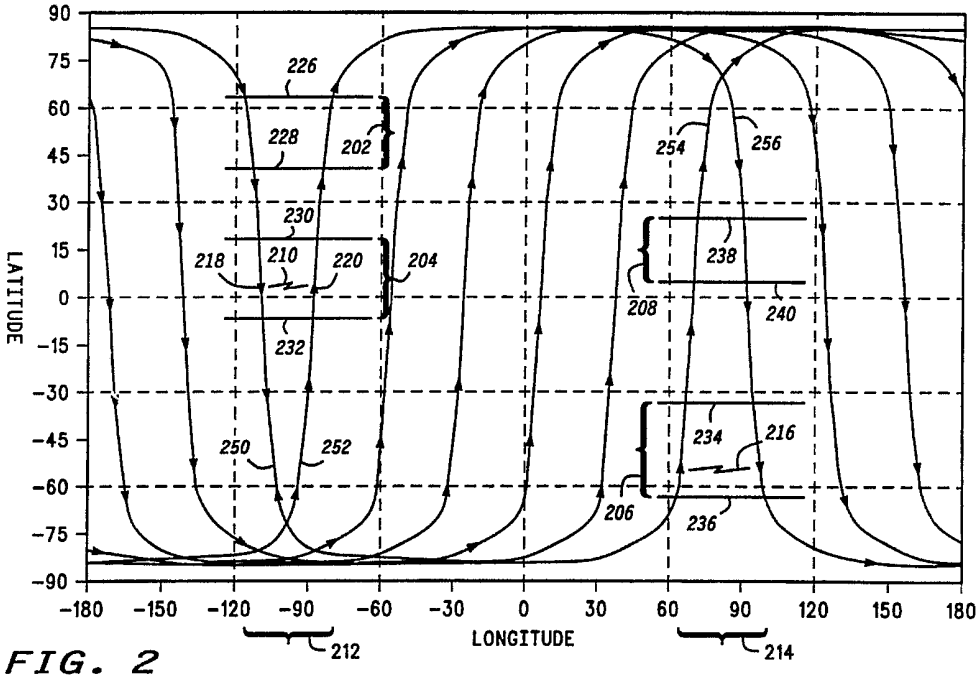


FIG. 2

GB 2 290 436 A

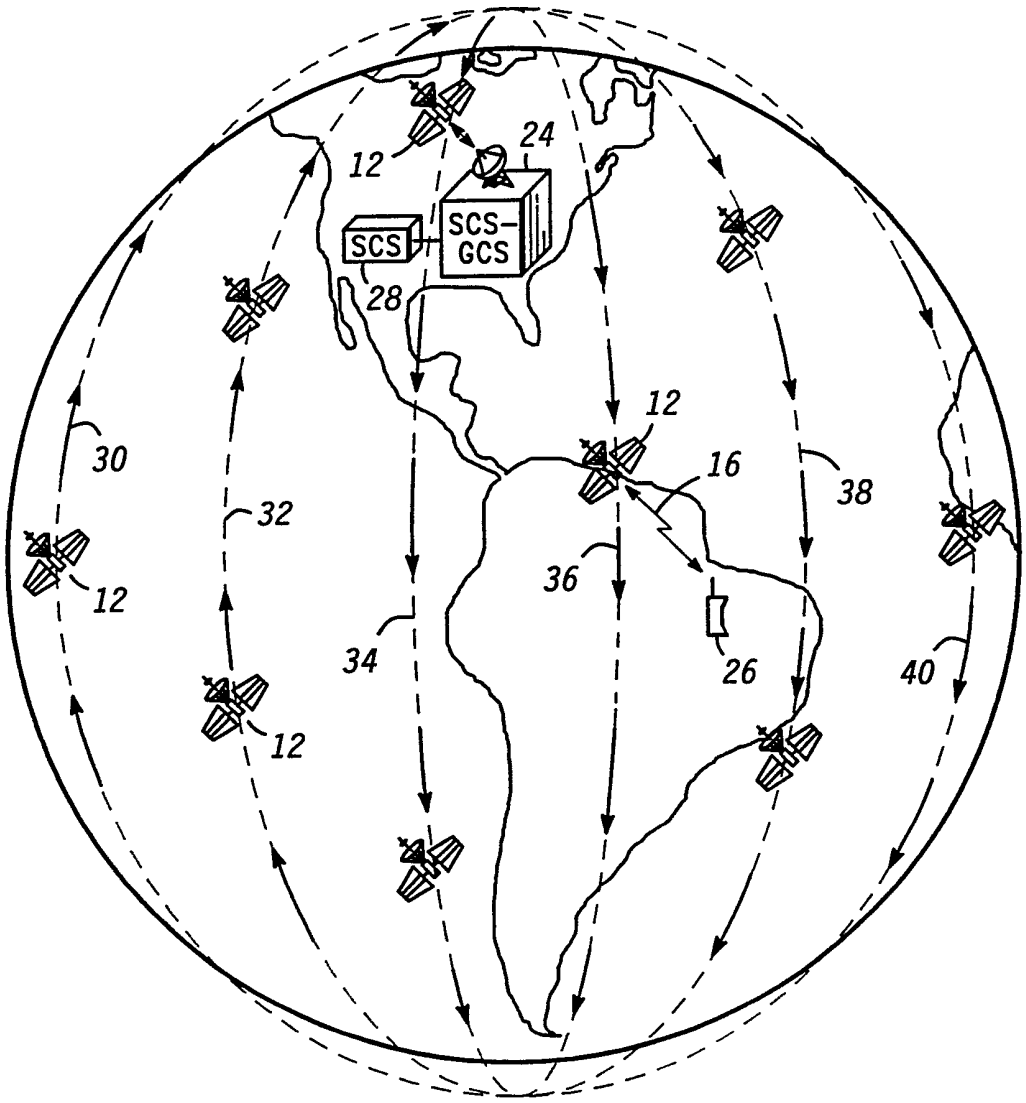


FIG. 1 10

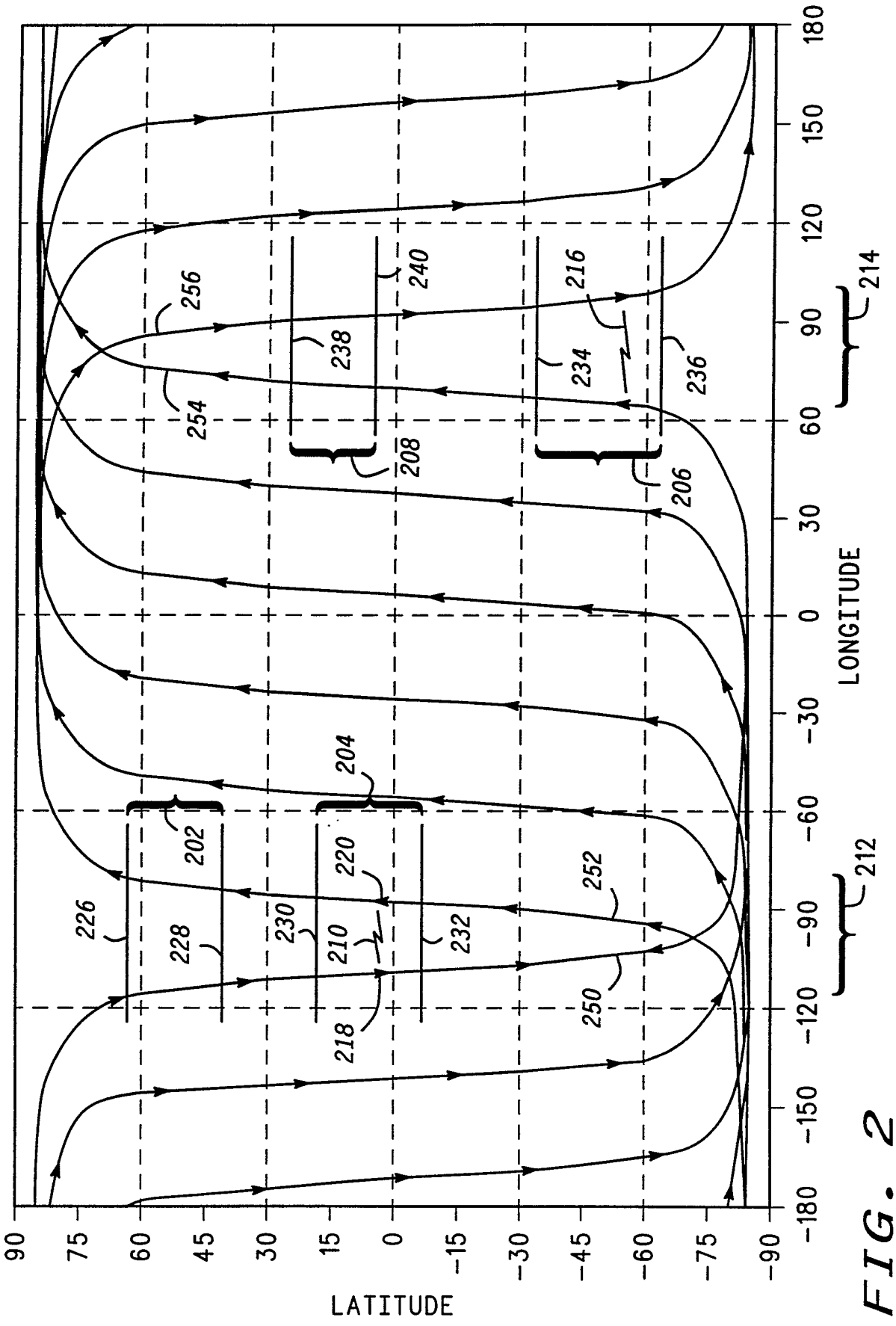

90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
LATITUDE
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
LONGITUDE
202
204
206
208
210
212
214
216
218
220
226
228
230
232
234
236
238
240
250
252
254
256

FIG. 2

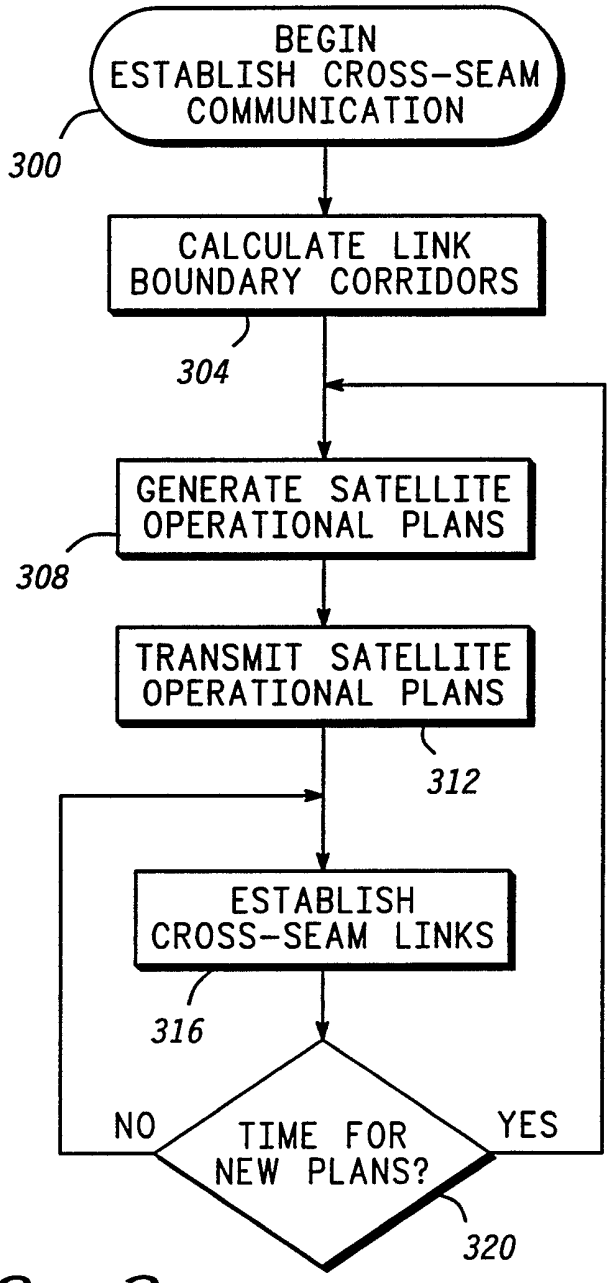
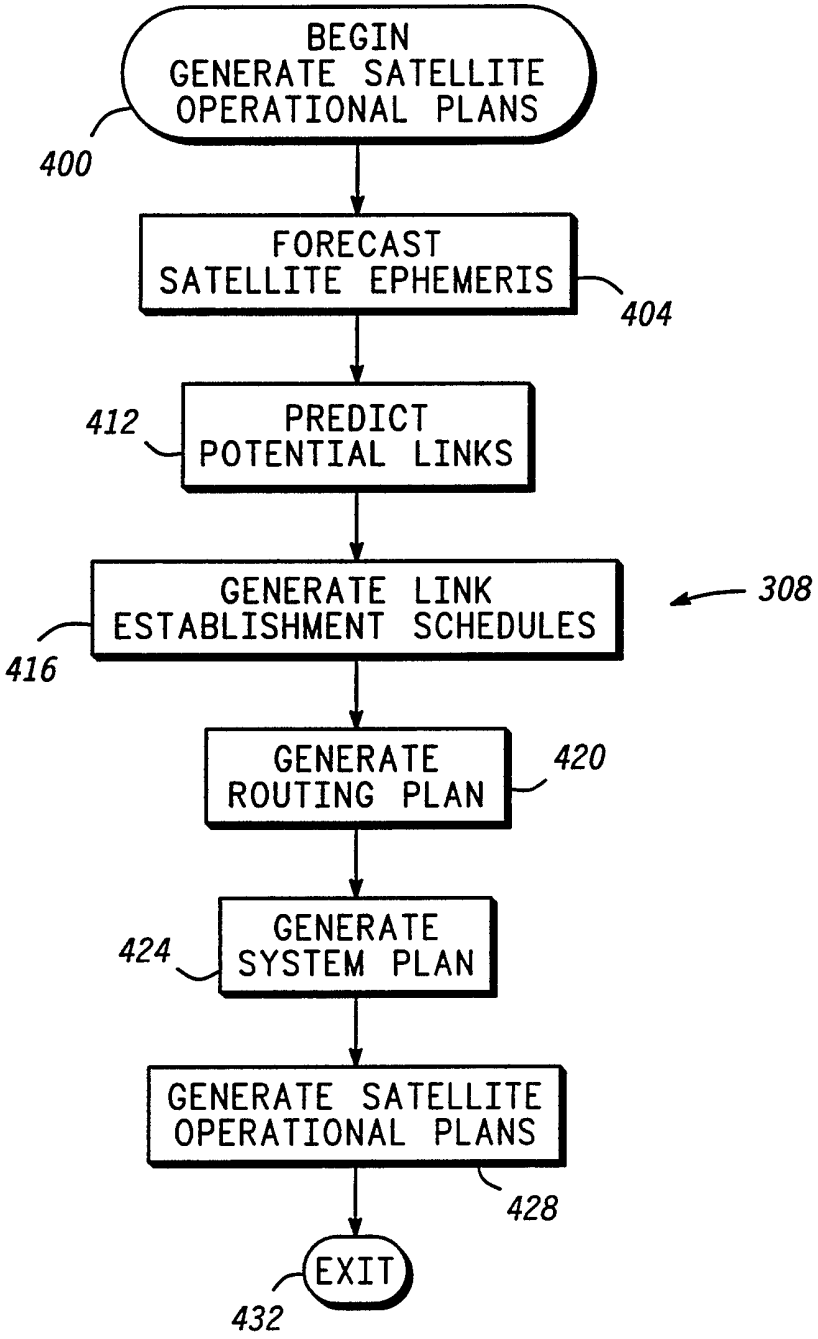

BEGIN
ESTABLISH CROSS-SEAM COMMUNICATION
300
CALCULATE LINK BOUNDARY CORRIDORS
304
GENERATE SATELLITE OPERATIONAL PLANS
308
TRANSMIT SATELLITE OPERATIONAL PLANS
312
ESTABLISH CROSS-SEAM LINKS
316
TIME FOR NEW PLANS?
NO
YES
320

FIG. 3

FIG. 4


BEGIN GENERATE SATELLITE OPERATIONAL PLANS
400
FORECAST SATELLITE EPHEMERIS
404
412
PREDICT POTENTIAL LINKS
GENERATE LINK ESTABLISHMENT SCHEDULES
308
416
GENERATE ROUTING PLAN
420
424
GENERATE SYSTEM PLAN
GENERATE SATELLITE OPERATIONAL PLANS
428
EXIT
432

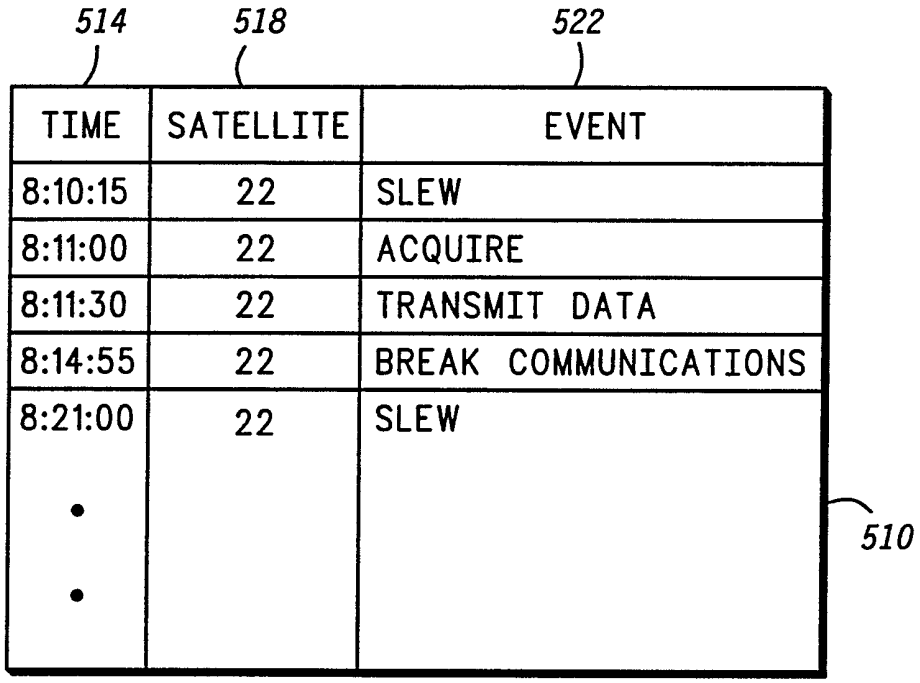

514
518
522
TIME
SATELLITE
EVENT
8:10:15
22
SLEW
8:11:00
22
ACQUIRE
8:11:30
22
TRANSMIT DATA
8:14:55
22
BREAK COMMUNICATIONS
8:21:00
22
SLEW
510

FIG. 5

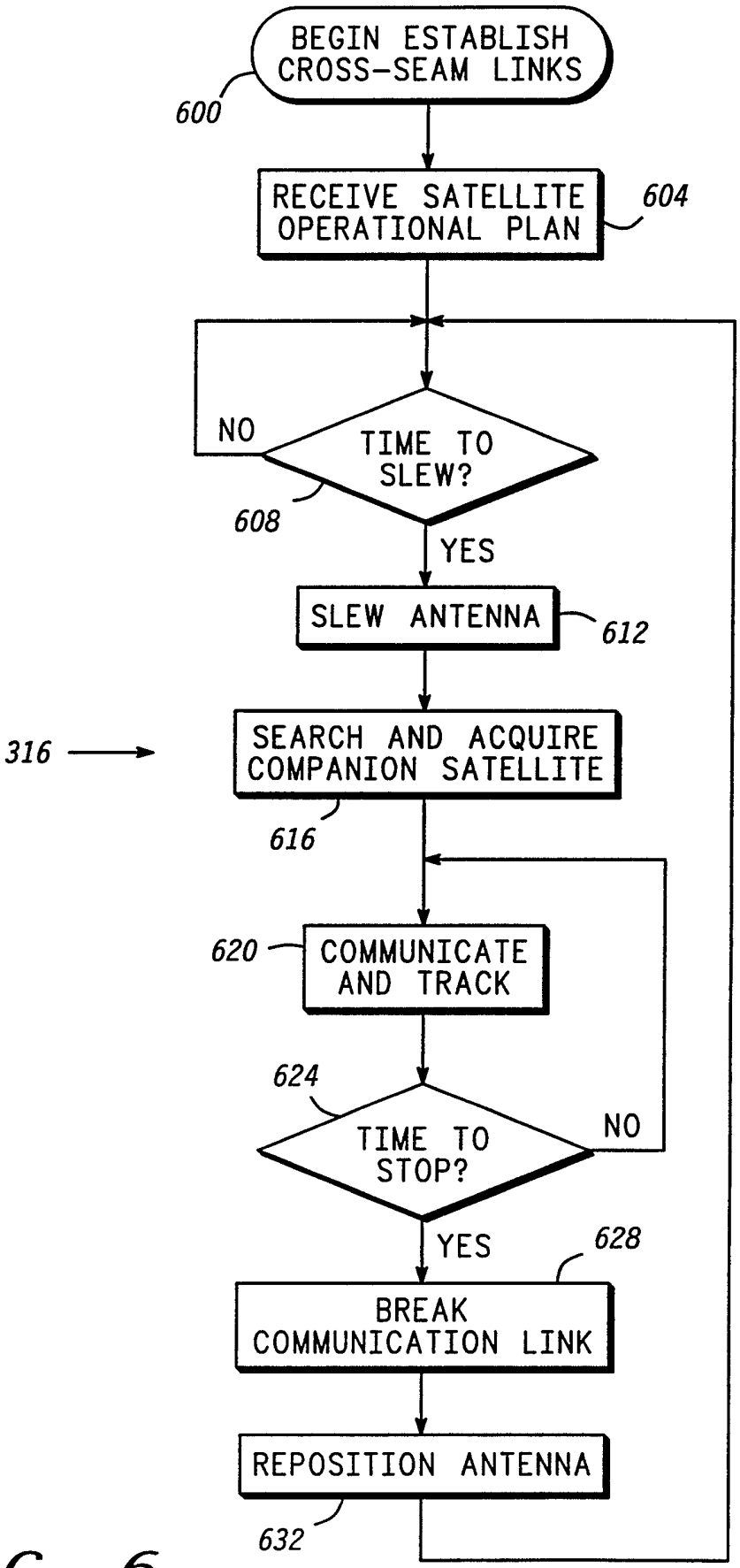

BEGIN ESTABLISH CROSS-SEAM LINKS
600
RECEIVE SATELLITE OPERATIONAL PLAN
604
NO
TIME TO SLEW?
608
YES
SLEW ANTENNA
612
316
SEARCH AND ACQUIRE COMPANION SATELLITE
616
620
COMMUNICATE AND TRACK
624
TIME TO STOP?
NO
YES
628
BREAK COMMUNICATION LINK
REPOSITION ANTENNA
632

FIG. 6

METHOD AND APPARATUS FOR ESTABLISHING COMMUNICATION LINKS BETWEEN NON-STATIONARY COMMUNICATION UNITS

Cross-Reference to Related Applications

This application is related to co-pending EPC Patent Application Serial Number 94117233.0, filed on November 2, 1994, entitled "Satellite Cellular Network Resource Management Method and Apparatus" (Docket no. IRI03094), which is assigned to the same assignee as the present application.

Field of the Invention

The present invention relates generally to establishing communication links in communication systems, and particularly to establishing satellite cross-links in satellite communication systems which have non-stationary communication units.

Background of the Invention

In a typical satellite communication system, satellites may be required to communicate with other satellites to transfer data from a source node to a destination node. A source node or destination node may, for example, be a ground-based cellular telephone. Communication between satellites may be performed by transmitting information from a satellite associated with the source node (hereinafter "source satellite") to a satellite associated with the destination node (hereinafter "destination satellite") or to another intermediate satellite.

A direct communication link between two satellites is referred to herein as a "cross-link". A cross-link is maintained where both the source and the destination or intermediate satellite's communication antennas are pointed toward each other and data communication is occurring. In a satellite communication system where satellites travel in the same direction, only small adjustments to a communication antenna's position are necessary to maintain a cross-link.

During each orbit, a non-geosynchronous satellite will travel in both an ascending (i.e., northbound) and a descending (i.e., southbound) direction. Where multiple, parallel orbital planes exist, satellites in a first orbital plane may travel in the same direction as satellites in an adjacent orbital plane, or the satellites in the first orbital plane may travel in the opposite direction (e.g., satellites in a first orbital plane are ascending and satellites in an adjacent orbital plane are descending). The space between these "counter-rotating" orbital planes is referred to herein as a "seam".

Typical satellite communication systems do not provide a method or apparatus for maintaining a cross-link with satellites in adjacent orbital planes that are traveling in opposite directions. Because of this, a data packet intended for a destination satellite that is traveling in an opposite direction from the source satellite may not be transmitted directly to the destination satellite. The data packet must be transmitted through intermediate satellites traveling in the same or a parallel orbital plane until it reaches an intermediate satellite that is traveling in the same direction as the destination satellite. Then the data packet may be transmitted, potentially through additional intermediate satellites, to the destination satellite. Often times, data packets destined for the other side of a seam must be routed over one of the poles.

Each intermediate satellite that a data packet must be transferred through increases the amount of time it takes for the data packet to travel from its source to its destination. In a communication system that transmits data packets containing voice data, multiple satellite transfers results in a noticeable delay in receipt of a voice signal. Such delays may be annoying to users of the communication system.

Additionally, routing data packets over the poles may also add traffic congestion on the over-the-pole links that exceeds the link capacity of the over-the-pole links. When communication link capacity is exceeded, data packets must be dropped, thus never reaching their destination.

Therefore, what is needed is a method and apparatus for establishing and maintaining communication links between

satellites traveling in different directions so that the number of satellites a data packet must be transferred through to go from a source satellite to a destination satellite are minimized. Minimizing the number of satellite transfers would also minimize the time between origination of a data packet and receipt, thus enhancing system performance. What is also needed is a method and apparatus to increase overall system capacity such that data packets that cannot be transmitted via over-the-pole links may be otherwise transmitted.

Brief Description of the Drawing

The invention is pointed out with particularity in the appended claims. However, a more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the figures, wherein:

FIG. 1 illustrates a simplified diagram of satellite-based, cellular communications system in accordance with the present invention;

FIG. 2 illustrates a diagram of link boundary corridors in accordance with the present invention;

FIG. 3 illustrates a flowchart of a method for establishing communication traffic across a seam in accordance with the present invention;

FIG. 4 illustrates a flowchart of a method for generating satellite operational plans in accordance with the present invention;

FIG. 5 illustrates an exemplary link establishment schedule in accordance with the present invention; and

FIG. 6 illustrates a flowchart of a method of establishing cross-seam links in accordance with the preferred embodiment of the invention.

The exemplification set out herein illustrates a preferred embodiment of the invention in one form thereof, and such exemplification is not intended to be construed as limiting in any manner.

Detailed Description of the Drawing

Generally, the present invention provides an apparatus and method for establishing communication links between communication units traveling along different paths. In the preferred embodiment, the present invention may be used to establish communication links between orbiting satellites traveling in opposite directions. Although the preferred embodiment applies the present invention to a satellite network, any network utilizing non-stationary communication units (e.g., satellites, ships, trains) that travel in predictable paths may utilize the present invention.

FIG. 1 illustrates a simplified diagram of satellite-based, cellular communications system 10, dispersed over and surrounding a celestial body (e.g., earth) through use of orbiting satellites 12. Satellites 12 occupy orbits 30, 32, 34, 36, 38, 40 that may be low-earth orbits, medium-earth orbits, geosynchronous orbits, or a combination thereof. Low-earth orbits are typically at an altitude range of about 600 km to 2000 km, medium-earth orbits at about 2000 km to 20,000 km and geosynchronous orbits at about 42,165 km, but other altitudes can also be used. In the example shown, communications system 10 uses six polar orbital planes, with each orbital plane holding eleven satellites 12 for a total of sixty-six satellites 12. However, this is not essential and more or fewer satellites or more or fewer orbital planes or combinations of orbiting and geosynchronous satellites, may be used. For clarity, FIG. 1 illustrates only a few of satellites 12.

In the preferred embodiment, satellites 12 in adjacent orbital planes generally travel in the same direction (e.g., ascending or descending). Satellites 12 traveling in orbital planes 30, 32 are shown during an ascending portion of their orbits. After satellites 12 in orbital planes 30, 32 cross over the north pole, they will then be in a descending portion of their orbits until they cross over the south pole. Therefore, each satellite 12 will experience an ascending and a descending portion of each orbit. Satellites 12 traveling in

orbital planes 34, 36, 38, 40 are shown during the descending portions of their orbits. As is indicated in FIG. 1, satellites 12 in adjacent orbital planes 32, 34 are traveling in opposite directions. The space between these "counter-rotating" orbital planes is a seam. In the preferred embodiment, there is one seam on each side of the earth. In alternate embodiments, a seam will exist between every adjacent orbital plane where satellites travel in opposite directions. For example, if six orbital planes exist, and every other orbital plane travels in an opposite direction, ten seams would exist.

Satellites 12 communicate with terrestrial equipment which may be, for example, a Subscriber Unit 26 (SU). A SU 26 may, for example, be a cellular telephone unit. A SU 26 may be the source or destination of a data packet. Where a SU 26 is a source of a data packet, the satellite 12 which it communicates with is referred to herein as a source satellite. Where a SU 26 is a destination of a data packet, the satellite 12 which it communicates with is referred to herein as a destination satellite.

In an alternate embodiment, satellites 12 may communicate with a "gateway" (not shown) that interfaces communication system 10 with a terrestrial telephone network (e.g., a public switched telephone network (PSTN), not shown). A source of a data packet may be, for example, a gateway or a telephone unit connected to a PSTN.

Satellites 12 also desirably communicate with terrestrial equipment such as a System Control Segment Ground Communication Station 24. A "Ground Communication Station" (GCS) is defined herein as a terrestrial communication facility capable of interfacing ground based equipment (e.g., System Control Segment 28) with satellites 12. FIG. 1 shows System Control Segment GCS 24 (SCS-GCS) associated with System Control Segment 28. SCS-GCSs 24 desirably perform data transfer and telemetry, tracking, and control functions for the constellation of satellites 12.

A "System Control Segment" 28 (SCS) is defined herein as a control facility, typically ground-based, which controls operation of communication system 10. SCS 28 communicates with

the rest of communication system 10 via SCS-GCS 24. SCS 28 need not be co-located with SCS-GCS 24. SCS 28 is preferably coupled to SCS-GCS 24 via land-lines, although this is not essential. In an alternate embodiment, SCS 28 may be coupled to SCS-GCS 24 via fiber optic links, radio links or other transmission mediums.

In the preferred embodiment, SCS 28 establishes "link boundary corridors" that are defined by upper and lower latitudes. FIG. 2 illustrates a diagram of link boundary corridors 202, 204, 206, 208 in accordance with the preferred embodiment of the invention. Link boundary corridors 202, 204, 206, 208 are regions in which satellites traveling in opposite directions along seams 212, 214 are designated to communicate with each other. Each link boundary corridor is bounded by upper latitudes 226, 230, 234, 238 and lower latitudes 228, 232, 236, 240.

FIG. 2 shows orbit paths 250, 252, 254, 256 that border seams 212, 214. Satellites are represented by arrows that indicate their direction of travel. Satellites traveling in orbit paths 250, 254 are in an ascending portion of their orbits, and satellites traveling in orbit paths 252, 256 are in a descending portion of their orbits.

After two satellites 12 have entered a link boundary corridor 202, 204, 206, 208 from either direction, the satellites may acquire each other and establish a communication link (e.g., communication links 210, 216). For example, FIG. 2 shows that satellites 218, 220 have entered link boundary corridor 204 and have established communication link 210.

Two satellites capable of communicating with each other while traveling within a link boundary corridor 202, 204, 206, 208 are referred to herein as a "link companion pair". For example, satellites 218, 220 form a link companion pair within link boundary corridor 204. A particular link companion pair will only exist during the time that the satellites are both within a link boundary corridor 202, 204, 206, 208.

With a communication link 210 established, the link companion pair may transfer data packets across the seam 212. The link companion pair may maintain the communication link 210 as long as the satellites 218, 220 remain within the upper

latitude 230 and the lower latitude 232 of the link boundary corridor 204. When the satellites 218, 220 exit the link boundary corridor 204, the communication link 210 between satellites 218, 220 is broken.

In a preferred embodiment two link boundary corridors are established across each seam 212, 214, resulting in four link boundary corridors 202, 204, 206, 208. These link boundary corridors are designated as either primary link boundary corridors 204, 208 ("primary corridors") or secondary link boundary corridors 202, 206 ("secondary corridors"). In an alternate embodiment, any number of link boundary corridors may be used as is understood by those of skill in the art based on the description herein.

Occasionally, it may be impossible or undesirable to have communication links across all link boundary corridors 202, 204, 206, 208 simultaneously. A corridor that has an active link across it at a given time is referred to herein as an "operational corridor". FIG. 2 shows that link boundary corridors 204, 206 currently have active communication links 210, 216 established across them. Therefore, link boundary corridors 204, 206 are currently considered operational corridors. Because link boundary corridors 202, 208 do not have active communication links, they are not currently considered operational corridors.

FIG. 3 illustrates a flowchart of a method for establishing communication traffic across a seam (e.g., seams 212, 214, FIG. 2) in accordance with the preferred embodiment of the invention. The Establish Cross-Seam Communication process in FIG. 3 will be discussed in conjunction with FIG. 2 for clarity and ease of understanding.

The Establish Cross-Seam Communication process begins (block 300) by performing the Calculate Link Boundary Corridors process (block 304). The Calculate Link Boundary Corridors process (block 304) is desirably performed by SCS 28 (FIG. 1) and determines the latitude boundaries (e.g., 226, 228, 230, 232, 234, 236, 238, 240, FIG. 2) of at least one link boundary corridor based on satellite constraints, predicted areas of communication traffic congestion, and other system design

requirements. Latitude boundaries are defined by corridor location and corridor width, expressed in degrees latitude.

The Calculate Link Boundary Corridors process (block 304) desirably determines corridor location by considering system performance criteria and satellite constraints. In the preferred embodiment, system performance is enhanced by locating a link boundary corridor where the most communication traffic is predicted to exist. Because a delay is added to the transfer time of a data packet each time the data packet is transferred from one satellite to another, it is desirable to minimize the number of satellite transfers (or "hops") between the source of the data packet and the destination. By locating a link boundary corridor where the most communication traffic is predicted to exist, satellite hops are minimized for the majority of data packets. This decreases delay and enhances system performance. Thus, a prediction of the geographical locations of data packet origins and destinations is desirably used to situate a link boundary corridor were it can minimize satellite hops for a maximum number of data packets. In FIG. 2, for example, link boundary corridors 204, 208 are located near the equator in order to minimize packet hops between northern and southern latitude regions.

Satellite constraints also affect the placement of link boundary corridors. For example, a satellite may have a range rate limitation that limits the Doppler effects a satellite may accommodate. Because satellites traveling in opposite directions are either converging or diverging, Doppler effects are introduced to the data being transferred across the communication link. Satellite antennas may be able to accommodate Doppler effects up to a point. Therefore, the link boundary corridors are desirably located where the Doppler effects introduced are capable of being accommodated by the satellite. For example, in FIG. 2, southern-hemisphere satellites traveling opposite seam 212 are converging and diverging faster than northern-hemisphere satellites traveling opposite seam 212. If the southern-hemisphere satellites are not capable of handling the increased Doppler effects, the southern-hemisphere is an undesirable location for a link boundary corridor. Thus, link boundary corridor 202 is located

in the northern hemisphere where Doppler effects are capable of being accommodated by the northern-hemisphere satellites.

In a communication system having primary corridors (e.g., 204, 208, FIG. 2) and secondary corridors (e.g., 202, 206, FIG. 2), satellite constraints are taken into consideration in determining where the primary and secondary corridors should be located with respect to each other. For example, a satellite traveling along orbit path 250 will first enter secondary corridor 202, then will enter primary corridor 204. The satellite may be required to establish a communication link within both the secondary corridor 202 and later the primary corridor 204 during that orbit. After breaking the communication link in secondary corridor 202, the satellite must slew its communication antenna toward its next companion satellite in order to communicate with the companion satellite in primary corridor 204. The amount of time it takes to slew the communication antennas is dependent upon the slew rate of the communication antennas. Secondary corridor 202 and primary corridor 204 should have a gap between them to allow the satellite to slew its antenna to the new position.

System design requirements may also affect the locations of the link boundary corridors. For example, one system design requirement may be that a communication link must always exist across a seam. Based on the orbit paths of the satellites, the link boundary corridors are desirably located such that a link companion pair always exists within a seam's link boundary corridor.

The Calculate Link Boundary Corridors process (block 304) also determines the corridor width. Corridor width is desirably expressed in degrees latitude. For example, FIG. 2 shows link boundary corridor 202 with corridor width of approximately 25 degrees latitude. The corridor width is determined from the corridor location and the operational and physical constraints of the satellite. For example, a satellite's communication antenna has a finite range. The corridor width is desirably determined such that any two satellites within the corridor are within range of each others' communication antennas. Therefore, a link companion pair attempting to establish communication with each other desirably

does not need to determine whether the companion satellite is within range. Any two satellites within the corridor are within range. Corridor width may also be affected by the degree range through which the communication antennas are physically capable of being moved.

Corridor location also affects corridor width. For example, FIG. 2 shows that for seam 212, orbital planes 250, 252 are further apart near the north pole and closer together near the south pole. Because the corridor width is desirably chosen such that all satellites within a corridor are within communication range of each other, a link boundary corridor located near the north pole would require a narrower corridor than a link boundary corridor located near the south pole. The increased distance between satellites in orbital planes 250, 252 would force the corridor width to be narrower near the north pole.

Different communication systems may have one or multiple link boundary corridors across one or all seams. System design requirements define the number of link boundary corridors. In a system with the requirement that a communication link must always exist across each seam, multiple corridors may be desirable. A continuous link may not be possible with only one link boundary corridor. Thus, in the preferred embodiment both primary corridors (e.g., 204, 208, FIG. 2) and secondary corridors (e.g., 202, 206, FIG. 2) exist across each seam. At times when a communication link is impossible within a primary corridor, a communication link may be established within a secondary corridor.

Often, it may be possible to have an active communication link within the primary and the secondary corridors simultaneously. However, the communication system may decide to establish a communication link within only one corridor (i.e., only one corridor would be an operational corridor at a given time). To determine which corridor should be the operational corridor at a given time, a priority scheme exists for the preferred embodiment.

For example, a primary corridor (e.g., 204, FIG. 2) may be chosen over a secondary corridor (e.g., 202, FIG. 2) as the operational corridor because utilizing the primary corridor

minimizes satellite hops on average. Thus, primary corridor 204 would have priority over secondary corridor 202. Primary corridor 204 is desirably the operational corridor as long as there is a communication link (e.g., 210, FIG. 2) possible in primary corridor 204. When a communication link is not possible in primary corridor 204, secondary corridor 206 will desirably become the operational corridor until a communication link can be re-established in primary corridor 208.

Additional link boundary corridors may also be desirable where existing link boundary corridors are incapable of accommodating the quantity of data packets that need to cross the seam. Additional link boundary corridors would allow more data to be transferred across the seam.

Referring back to FIG. 3, after the Calculate Link Boundary Corridors process (block 304), the Generate Satellite Operational Plans process (block 308) is performed. The Generate Satellite Operational Plans process (block 308) is desirably performed by SCS 28 (FIG. 1). The Generate Satellite Operational Plans process (block 308) creates individual satellite operational plans that each satellite uses to establish communication links within the link boundary corridors. The satellite operational plans may also contain information the satellite uses to determine how to route data packets. The Generate Satellite Operational Plans process (block 308) is desirably executed periodically (e.g., once per day). The Generate Satellite Operational Plans process (block 308) is described in more detail in conjunction with FIG. 4.

After the Generate Satellite Operational Plans process (block 308), the Transmit Satellite Operational Plans process (block 312) transmits each satellite's individual operational plan to each satellite. The Transmit Satellite Operational Plans process (block 312) is desirably performed by SCS 28 (FIG. 1) in conjunction with SCS-GCS 24 (FIG. 1). In order to have cross-seam communication, each satellite must know how to establish cross-seam connectivity. Therefore, an individual operational plan is desirably resident on-board each satellite.

The Establish Cross-Seam Links process (block 316) utilizes the satellite operational plan on-board each satellite to establish cross-seam communication links. The Establish

Cross-Seam Links process (block 316) is desirably performed by satellites 12 (FIG. 1). The Establish Cross-Seam Links process (block 316) controls the positioning of the satellite's communication antenna toward a companion satellite, acquiring the companion satellite, transferring data packets while tracking the companion satellite, and breaking communications with the companion satellite.

The satellite operational plans for a future time period must be generated (block 308) and transmitted (block 312) to satellites prior to the future time period. After a current satellite plan has begun execution in the Establish Cross-Seam Links process (block 316), a determination is made (block 320) whether it is time for a new plan to be generated for a future time period. When it is not time for a new plan to be generated (block 320), the Establish Cross-Seam Links process (block 316) continues as shown in FIG. 3. When it is time for a new plan to be generated (block 320), the Generate Satellite Operational Plans process (block 308) is performed and the procedure iterates as shown in FIG. 3.

Occasionally, new satellite operational plans are generated (block 308) when telemetry information received from satellites indicates that the currently executing satellite operational plan is no longer achieving acceptable system performance. For example, unacceptable system performance may be the result of heavier than expected traffic demand or an outage of one of the satellites.

FIG. 4 illustrates a flowchart of a method for generating satellite operational plans in accordance with the preferred embodiment of the invention. The Generate Satellite Operational Plans process begins (block 400) with the Forecast Satellite Ephemeris process (block 404). The Forecast Satellite Ephemeris process (block 404) uses an orbit propagation algorithm to forecast the locations (or "ephemeris") of each satellite during the future time period. Orbit propagation algorithms are commonly known to those of skill in the art.

Based on the satellite ephemeris information, the Predict Potential Links process (block 412) determines link companion pairs that may potentially exist during the future time period.

In the preferred embodiment, where multiple link companion pairs exist at a given time, the Predict Potential Links process (block 412) desirably selects one link companion pair that will be operational during that time. The selection may be based on satellite operability and system design requirements. In an alternate embodiment, the Predict Potential Links process (block 412) may select all or some subset of the potential link companion pairs to be operational at a given time.

The Predict Potential Links process (block 412) selects an operable link companion pair based on whether the satellites in each potential link companion pair are operable (i.e., capable of establishing a link). A satellite may be inoperable, for example, when there is a hardware failure or low power availability on-board the satellite. Where a satellite of a link companion pair is incapable of establishing a link, the Predict Potential Links process (block 412) will select different link companion pairs to establish links during that time.

Where a system design requirement mandates a continuous link across the seam, the Predict Potential Links process (block 412) desirably selects link companion pairs that ensure make-before-break link establishment. The Predict Potential Links process (block 412) also desirably selects link companion pairs that are capable of sustaining communication links for the longest durations. For example, a link companion pair comprised of two satellites that have recently entered the link boundary corridor will be capable of sustaining a link longer than a link companion pair where both satellites will soon exit the link boundary corridor. The Predict Potential Links process (block 412) desirably selects the former link companion pair to establish a link rather than the latter link companion pair.

The link companion pairs selected to operate at given times during the future time period define which link boundary corridors are the operational corridors during those times.

After the Predict Potential Links process (block 412), the Generate Link Establishment Schedules process (block 416) generates schedules that function to inform each satellite when

to perform certain actions. Desirably, make-before-break link establishment schedules are generated which ensure that a communication link is not broken until another communication link is first established across a seam. FIG. 5 illustrates an exemplary link establishment schedule 510. The link establishment schedule 510 indicates times 514 when a particular satellite 518 should perform certain events 522. For example, the first entry in link establishment schedule 510 indicates that when the system time reaches 8:10:15, satellite # 22 should perform the event of slewing its communication antenna toward a companion satellite.

With knowledge of operational corridors and link companion pairs, the Generate Routing Plan process (block 420) generates a data packet routing plan that functions to inform satellites to which neighboring satellite they must transmit a data packet with a particular destination address. Which link boundary corridor is active at a particular time is relevant to the routing decision. For example, if at a first time primary corridor 204 (FIG. 2) is the operational corridor, the routing plan will desirably inform satellite 218 (FIG. 2) to transmit packets destined for the other side of seam 212 (FIG. 2) to satellite 220 (FIG. 2). If a communication link is subsequently set up in secondary corridor 202 (FIG. 2), and communication link 210 (FIG. 2) is broken, secondary corridor 202 becomes the operational corridor. The routing plan will desirably inform satellite 218 to transmit its data packets to a satellite following satellite 218 in orbit path 250 (FIG. 2) so that the data packets may be transmitted across the communication link in secondary corridor 202. In the preferred embodiment, the routing plan will not inform a satellite to route data across a different link boundary corridor until a communication link is completely established across that link boundary corridor.

In the preferred embodiment, the Generate System Plan process (block 424) then combines the link establishment schedule and the routing plan into one system plan. The system plan is desirably a master plan that will inform all satellites of the communication system how to perform communication link

establishment and data packet routing. The system plan may contain other information as well.

The Generate Satellite Operational Plans process (block 428) then divides the system plan into individual satellite operational plans. A unique satellite operational plan is generated for each satellite. Each satellite operational plan functions to inform each satellite of its unique portion of the system plan. The satellite operational plan contains time-dependent information that each satellite uses to perform communication link establishment and data packet routing.

The Generate Satellite Operational Plans process then exits (block 432).

In an alternate embodiment, the system plan is not divided (block 428) into individual satellite operational plans. Instead, the entire system plan is transmitted (block 312, FIG. 3) to each satellite, and each satellite sorts through the system plan to determine its portion of the plan.

In another alternate embodiment, the link establishment schedule and the routing plan are not combined (block 424, FIG. 4) into a system plan. Instead, they remain separated and all or a portion of the link establishment schedule and the routing plan are transmitted (block 312, FIG. 3) to each satellite.

In another alternate embodiment, SCS 28 does not generate (block 424, FIG. 4) a system plan and transmit (block 312, FIG. 3) all or a portion of the system plan to each satellite. Instead, each satellite has sufficient knowledge of the state of the system and the ephemeris of other satellites, and each satellite generates its own link establishment schedule and routing plan.

Similar variations of the preferred embodiment and the alternate embodiments should be obvious to those of skill in the art based on the description herein and are intended to be incorporated within the scope of this invention.

FIG. 6 illustrates a flowchart of a method of establishing cross-seam links in accordance with the preferred embodiment of the invention. The Establish Cross-Seam Links process begins (block 600) when a satellite receives (block 604) an individual satellite operational plan from the SCS-GCS 24 (FIG. 1) or from another satellite 12.

A satellite operational plan is desirably a table of time-dependent information similar to the link establishment schedule illustrated in FIG. 5. When the command time of a particular table entry is reached, the satellite will conform operations according to the particular table entry. Certain types of table entries are relevant to the Establish Cross-Seam Links process. As shown in FIG. 5, these relevant entries desirably indicate slew time, acquire time, data transmission time, and break communications time.

When a particular table entry command time has been reached, the satellite will determine (block 608) whether the table entry indicates that it is time to slew the satellite's communication antenna toward a companion satellite. When it is time to slew the communication antenna, the Slew Antenna process (block 612) will position the satellite's communication antenna to the proper azimuth and elevation. The direction may be specified in the satellite operational plan or it may be determined by the satellite using an orbit propagation tool that is well known to those of skill in the art.

After the Slew Antenna process (block 612), the Search and Acquire Companion Satellite process (block 616) undertakes a search and acquire protocol. The purpose of this protocol is to establish a communication link between the companion satellite pair. In the preferred embodiment, the protocol repeatedly transmits an inquire message toward the companion satellite. The satellite makes fine adjustments to the communication antenna's azimuth and elevation angles until the satellite receives a response from the companion satellite. When a response is received, the companion satellite is acquired and the communication link is established.

When an entry in the satellite operational plan indicates that it is time to begin transferring data packets, the Communicate and Track process (block 620) is performed. The satellite begins transmitting data packets to the companion satellite. Data packets are transmitted to the companion satellite when the routing instructions contained within the satellite operational plan so specify. Each satellite tracks its companion satellite by slewing its antennas and continuing

to execute the protocol described in the Search and Acquire Companion Satellite process (block 616).

When an entry in the satellite operational plan indicates that it is time to stop transmitting data packets to the companion satellite (block 624), the Break Communication Link process (block 528) informs the satellite to cease transmitting data packets to the companion satellite. Additionally, tracking the companion satellite also ceases.

In a preferred embodiment, the Reposition Antenna process (block 532) then slews the communication antenna to a neutral position. Although the Reposition Antenna process (block 532) is not necessary for the present invention, it may be beneficial to the satellite's health or it may decrease the time the Slew Antenna process (block 508) will require to slew the antenna toward the next companion satellite.

In summary, a method and apparatus have been described that allow communication links to be established and maintained across a seam. The advantages over the prior art are reduced transmission times between a source and destination of a data packet, and an increased number of communication links that allow the communication system to accommodate more data packets.

Without cross-seam communications capability, data packets destined for the other side of a seam must be routed over one of the poles. Routing data packets over the poles introduces additional satellite transfers that result in substantial delays. These delays may be particularly troublesome where the data packets contain voice information.

Additionally, routing data packets over the poles may also add traffic congestion on the over-the-pole links that exceed the communication link capacity. When communication link capacity is exceeded, data packets must be dropped, thus never reaching their destination. Cross-seam links allow data packets destined for the other side of a seam to be communicated with a minimum number of satellite hops and, thus, minimal delays. In addition, cross-seam links increase the overall data-handling capacity of the communication system by providing cross-seam links in addition to the over-the-pole

links. Thus system performance and capacity is greatly enhanced through the present invention.

Although the preferred embodiment of the invention describes a satellite communication system, the invention would apply equally well to other communication systems where communication units follow determinable paths. For example, the present invention may apply to communications between trains or ships.

It is to be understood that the phraseology or terminology employed herein is for the purpose of description, and not of limitation. Accordingly, the invention is intended to embrace all such alternatives, modifications, equivalents, and variations as fall within the spirit and broad scope of the appended claims.

CLAIMS

What is claimed is:

1. A method of establishing communication links in a communication system having multiple communication units, the method comprising steps of:
   a. forecasting first locations of first communication units traveling in a first path and second locations of second communication units traveling in a second path which is different from the first path during a future time period;
   b. from the first locations and the second locations, determining link companion pairs comprising a first communication unit and a second communication unit that are capable of communicating with each other during the future time period;
   c. predicting link opportunity times based on the link companion pairs;
   d. generating link establishment schedules based on the link opportunity times; and
   e. establishing the communication links according to the link establishment schedules.

2. The method as claimed in claim 1 further comprising a step of transmitting at least one link establishment schedule to one or more link companion pairs.

3. A method of establishing communication links in a communication system having multiple communication units, the method comprising steps of:
   a. calculating one or more link boundary corridors;
   b. generating link establishment schedules based on which of the multiple communication units should be located within the one or more link boundary corridors during a future time period; and
   c. establishing the communication links according to the link establishment schedules.

4. The method as claimed in claim 3 further comprising a step of transmitting the link establishment schedules to the multiple communication units.

5. The method as claimed in claim 3 further comprising steps of:

d. determining whether to generate new link establishment schedules; and

e. when step (d) determines to generate the new link establishment schedules, repeating steps b-c.

6. The method as claimed in claim 3 wherein the one or more link boundary corridors comprise a major link boundary corridor, and wherein step (a) comprises a step of:

a.1. determining the major link boundary corridor having an upper latitude and a lower latitude based on communication unit constraints,

and step (b) comprises steps of:

b.1. forecasting first locations of communication units traveling in a first path and second locations of communication units traveling in a second path different from the first path during the future time period;

b.2 from the first locations and the second locations, determining major link companion pairs comprising a first communication unit and a second communication unit that are capable of communicating with each other while the major link companion pairs are located within the major link boundary corridor;

b.3. predicting major link opportunity times based on the major link companion pairs; and

b.4. generating the link establishment schedules based on the major link opportunity times.

7. The method as claimed in claim 6 wherein the one or more link boundary corridors further comprise a minor link boundary corridor, and wherein step (a) further comprises a step of:

a.1. determining the minor link boundary corridor having a second upper latitude and a second lower latitude based on the communication unit constraints,

and step (b) comprises steps of:

b.1. from the first locations and the second locations, determining minor link companion pairs comprising a third communication unit and a fourth communication unit that are capable of communicating with each other while the minor link companion pairs are located within the minor link boundary corridor;

b.2. predicting minor link opportunity times based on the minor link companion pairs; and

b.3. generating the link establishment schedules based on the minor link opportunity times.

8. A method of operating a communication system comprising steps of:

a. forecasting first locations of first communication units traveling in a first path and second locations of second communication units traveling in a second path different from the first path during a future time period;

b. from the first locations and the second locations, determining link companion pairs comprising the first communication units and the second communication units that are capable of communicating with each other during the future time period;

c. predicting link opportunity times based on the link companion pairs;

d. generating link establishment schedules based on the link opportunity times that function to inform the first communication units and the second communication units when one or more opportunities exist of establishing communication links between the first communication units and the second communication units; and

e. transmitting at least one link establishment schedule to one or more of the first communication units and the second communication units such the each link

companion pairs may establish the communication links according to the link establishment schedules.

9. The method as claimed in claim 8 wherein step (d) comprises a step of generating link establishment schedules such that the communication links between the link companion pairs provide continuous communication between the first communication units and the second communication units.

10. The method as claimed in claim 8 wherein the link opportunity times comprise major link opportunity times, and wherein step (c) comprises steps of:

c.1. determining a major link boundary corridor having an upper latitude and a lower latitude based on communication unit constraints; and

c.2 from the first locations and the second locations, predicting the major link opportunity times when first link companion pairs are capable of communicating with each other while the first link companion pairs are located within the major link boundary corridor.

11. The method as claimed in claim 10 wherein the link opportunity times further comprise minor link opportunity times, and wherein step (c) further comprises steps of:

c.3. determining a minor link boundary corridor having a second upper latitude and a second lower latitude based on the communication unit constraints; and

c.4 from the first locations and the second locations, predicting minor link opportunity times when second link companion pairs are capable of communicating with each other while the second link companion pairs are located within the minor link boundary corridor.

12. The method as claimed in claim 12 wherein step (c.3) further comprises a step of determining the minor link boundary corridor such that the minor link boundary corridor does not intersect the major link boundary corridor.

13. The method as claimed in claim 11 wherein step (d) comprises a step of generating link establishment schedules such that an existing communication link is continuously capable of existing within either the minor link boundary corridor or the major link boundary corridor.

14. A method of establishing communication links in a communication system having multiple communication units, each having one or more communication antennas, the method executed by a communication unit comprising steps of:

a. receiving a link establishment schedule that informs the communication unit to establish communications with a companion communication unit when the communication unit and the companion communication unit are within a link boundary corridor;

b. slewing a communication antenna of the communication unit toward the companion communication unit at a slew time indicated by the link establishment schedule;

c. acquiring the companion communication unit at an acquire time indicated by the link establishment schedule; and

d. establishing communication between the communication unit and the companion communication unit during a link time period.

15. The method as claimed in claim 14 wherein step (d) further comprises a step of tracking the companion communication unit during the link time period.

16. The method as claimed in claim 14 further comprising a step of breaking communications with the companion communication unit at a break time indicated by the link establishment schedule.

17. The method as claimed in claim 14 further comprising a step of slewing the communication antenna of the

communication unit toward a next companion communication unit after the link time period has ended.

18. A method of establishing communication links in a communication system having multiple communication units, each having one or more communication antennas, the method executed by a communication unit comprising steps of:

a. determining whether the communication unit and a companion communication unit are located within a link boundary corridor;

b. when the communication unit and the companion communication unit are located within the link boundary corridor, determining whether the communication unit is capable of establishing a communication link with the companion communication unit;

c. when the communication unit is capable of establishing the communication link with the companion communication unit, acquiring the companion communication unit; and

d. when the companion communication unit is acquired, communicating with the companion communication unit.

19. The method as claimed in claim 18 further comprising a step of, when the communication unit is not located within the link boundary corridor, slewing a communication antenna of the communication unit toward another companion communication unit.

20. The method as claimed in claim 18 further comprising a step of breaking communication when the communication unit is no longer located within the link boundary corridor.

21. A communication system comprising:

communication units, each having at least one communication antenna, where the communication units establish communication links according to link establishment schedules; and

at least one control facility that calculates one or more link boundary corridors, generates the link establishment schedules based on which of the communication units should be located within the one or more link boundary corridors during a future time period, and transmits the link establishment schedules to the communication units.

22. A communication system comprising communication units, where at least one of the communication units calculates one or more link boundary corridors, generates link establishment schedules based on which of the communication units should be located within the one or more link boundary corridors during a future time period, and establishes communication links according to the link establishment schedules.

23. A method of establishing communication links substantially as hereinbefore described with reference to the accompanying drawings.

24. A method of operating a communication system substantially as hereinbefore descried with reference to the accompanying drawings.

25. A communication system substantially as hereinbefore described with reference to the accompanying drawings.

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Databases (see below)
(i) UK Patent Office collections of GB, EP, WO and US patent specifications.

(ii) ON-LINE: WPI, INSPEC

Documents considered relevant following a search in respect of Claims :-
1-25

Categories of documents

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Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 2281014 A	(KOKUSAI) see abstract	1, 3, 8, 14 18, 21, 22
X	EP 0637142 A1	(MOTOROLA) see abstract	1, 3, 8, 14 18, 21, 22
X	EP 0569693 A1	(MOTOROLA) see abstract	1, 3, 8, 14 18, 21, 22

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