US009270372B2

(12) **United States Patent**
Miniscalco

(10) **Patent No.: US 9,270,372 B2**
(45) **Date of Patent: Feb. 23, 2016**

(54) **FREE-SPACE OPTICAL MESH NETWORK**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/069,464**

(22) Filed: **Nov. 1, 2013**

(65) **Prior Publication Data**

US 2014/0376914 A1 Dec. 25, 2014

Related U.S. Application Data

(60) Provisional application No. 61/839,045, filed on Jun. 25, 2013.

(51) **Int. Cl.**

H04B 10/112	(2013.01)
H04B 10/114	(2013.01)
H04B 10/00	(2013.01)

(52) **U.S. Cl.**

CPC ***H04B 10/1129*** (2013.01); *H04B 10/1141* (2013.01); *H04B 10/1143* (2013.01); *H04B 10/1149* (2013.01); *H04B 10/22* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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Primary Examiner — Darren E Wolf

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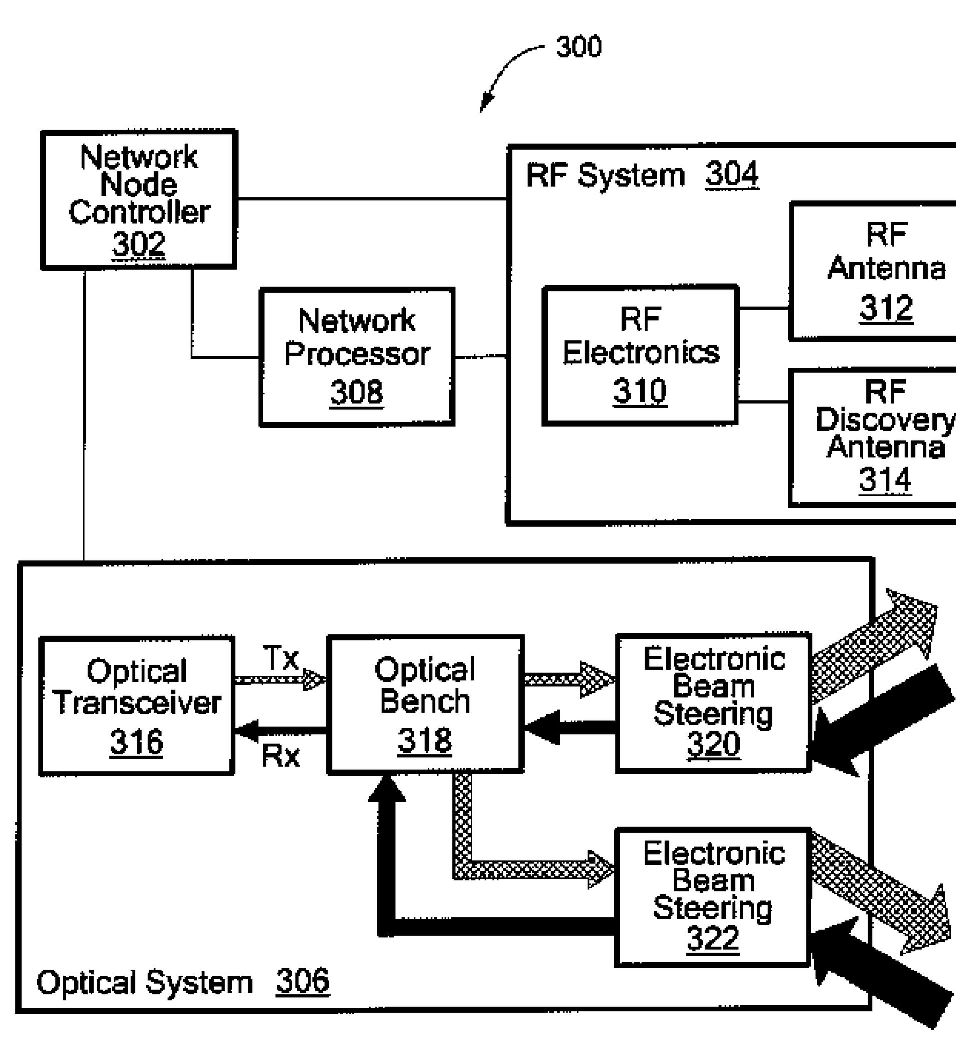
(57) **ABSTRACT**

The disclosure provides a practical system and methods for implementing an adaptive free-space optical network with a high-connectivity, dynamic mesh topology. The network can have operational characteristics similar to those of RF mobile ad-hock networks. Each node has one or more optical terminals that may utilize space-time division multiplexing, which entails rapid spatial hopping of optical beams to provide a high dynamic node degree without incurring high cost or high size, weight, and power requirements. As a consequence the network rapidly sequences through a series of topologies, during each of which connected nodes communicate. Each optical terminal may include a plurality of dedicated acquisition and tracking apertures which can be used to increase the speed at which traffic links can be switched between nodes and change the network topology. An RF overlay network may be provided to act as a control plane and be used to provide node discovery and adaptive route planning for the optical network.

22 Claims, 8 Drawing Sheets



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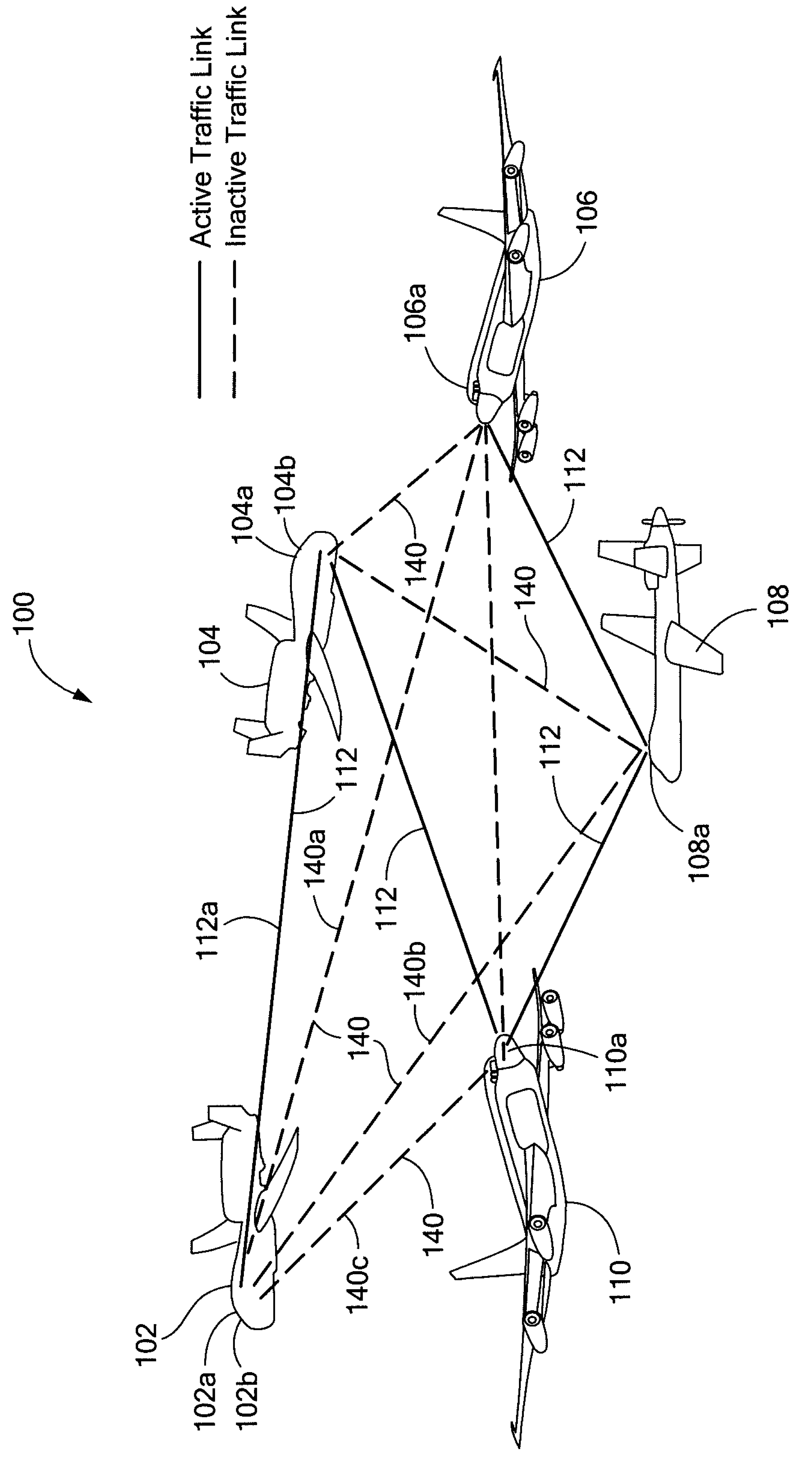
Active Traffic Link
Inactive Traffic Link
100
102
102a
102b
104
104a
104b
106
106a
108
108a
110
110a
112
112a
140
140a
140b
140c

FIG. 1A

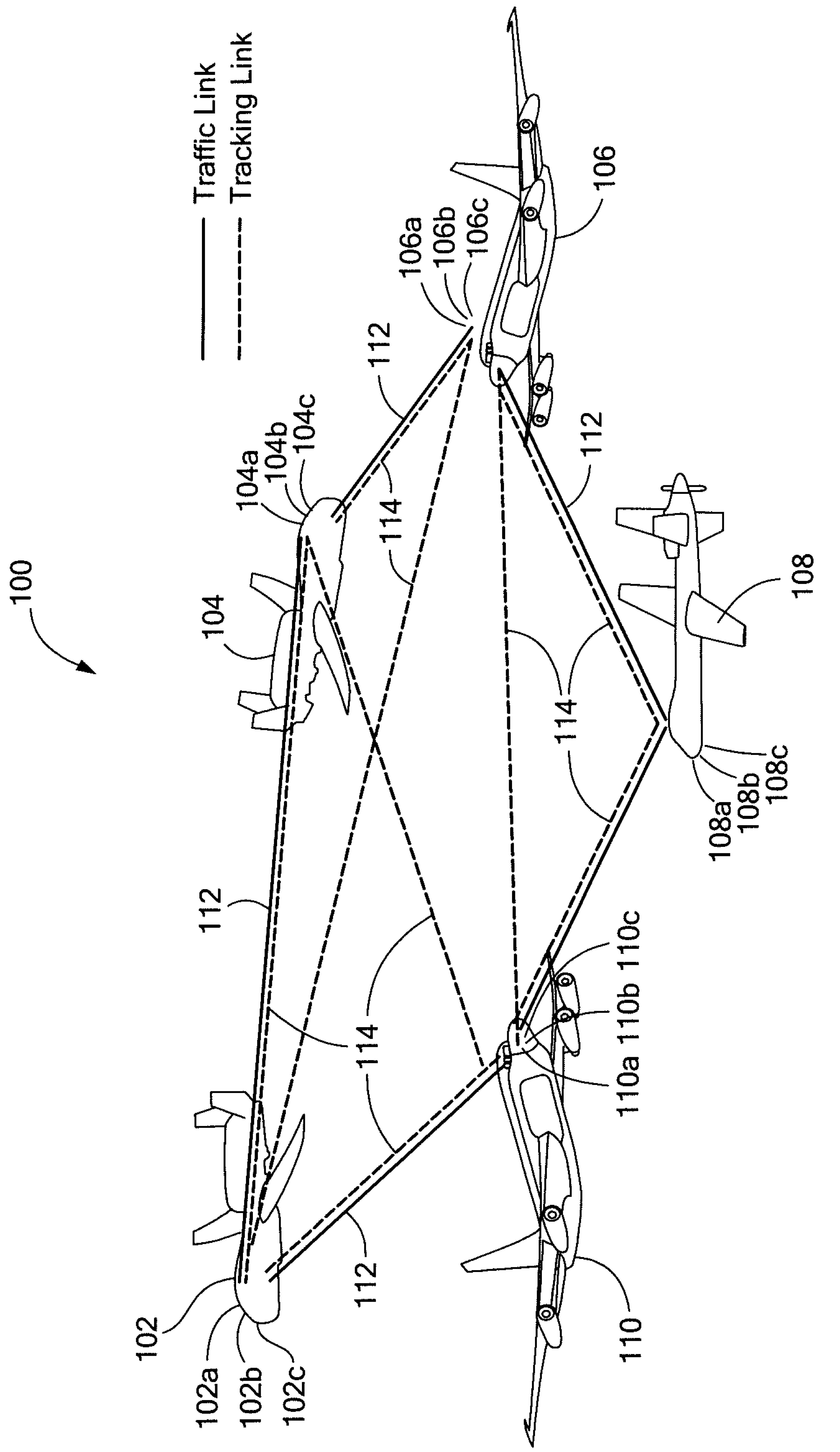
Traffic Link
Tracking Link
100
102
102a
102b
102c
104
104a
104b
104c
106
106a
106b
106c
108
108a
108b
108c
110
110a 110b 110c
112
114

FIG. 1B

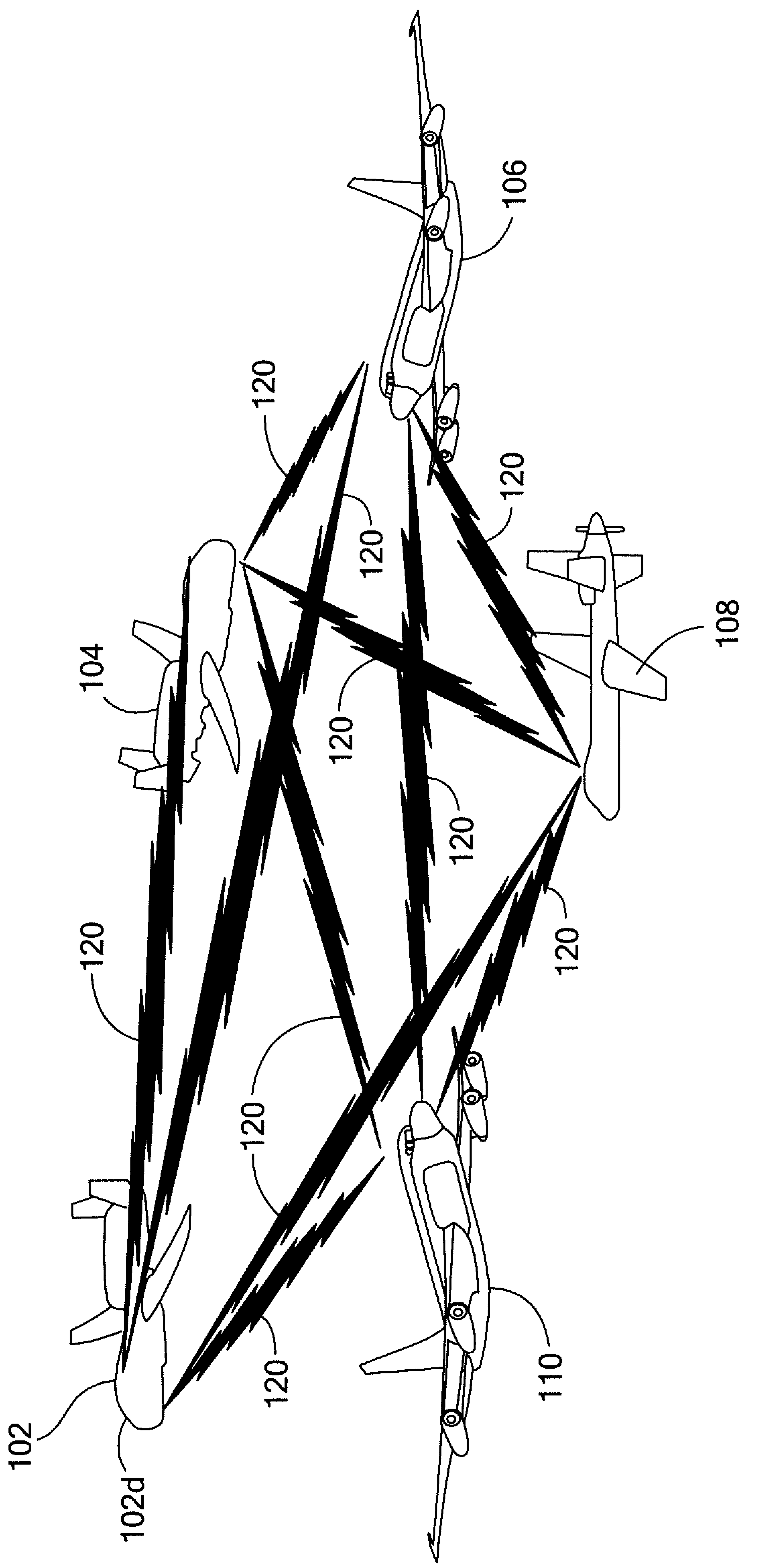

FIG. 1C

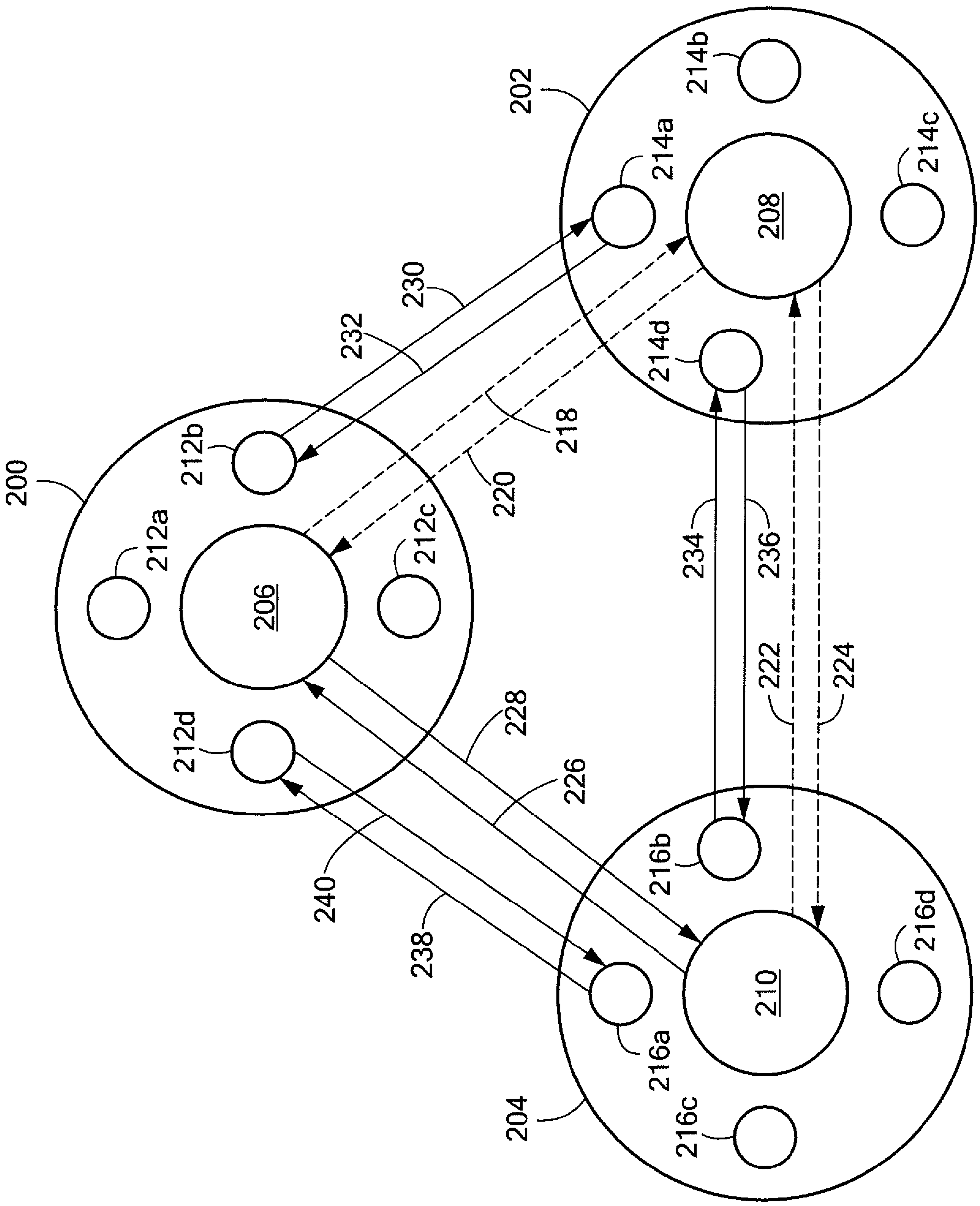
200
202
204
206
208
210
212a
212b
212c
212d
214a
214b
214c
214d
216a
216b
216c
216d
218
220
222
224
226
228
230
232
234
236
238
240

FIG. 2

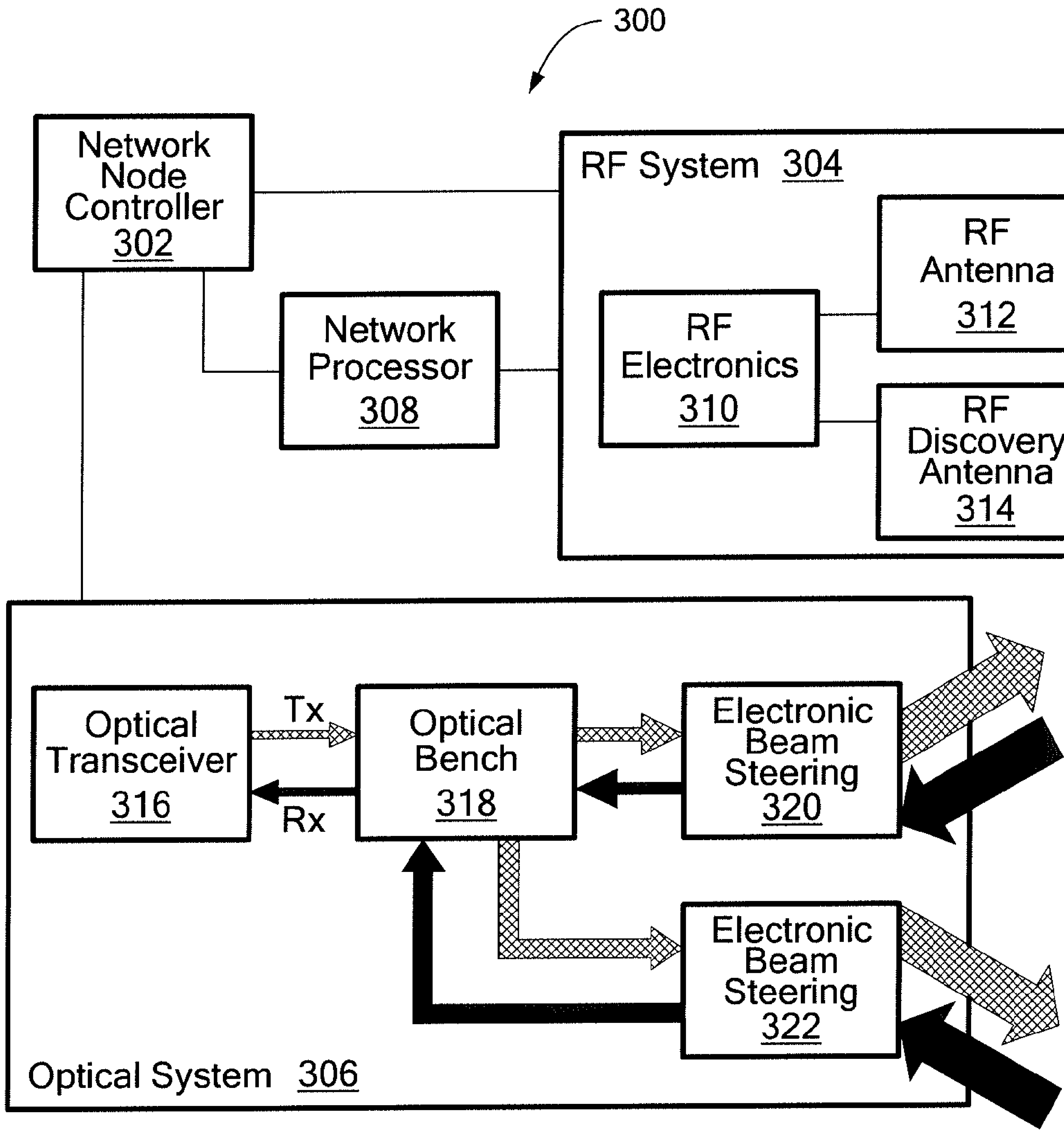
300
Network Node Controller 302
RF System 304
RF Antenna 312
Network Processor 308
RF Electronics 310
RF Discovery Antenna 314
Optical Transceiver 316
Tx
Rx
Optical Bench 318
Electronic Beam Steering 320
Electronic Beam Steering 322
Optical System 306

FIG. 3

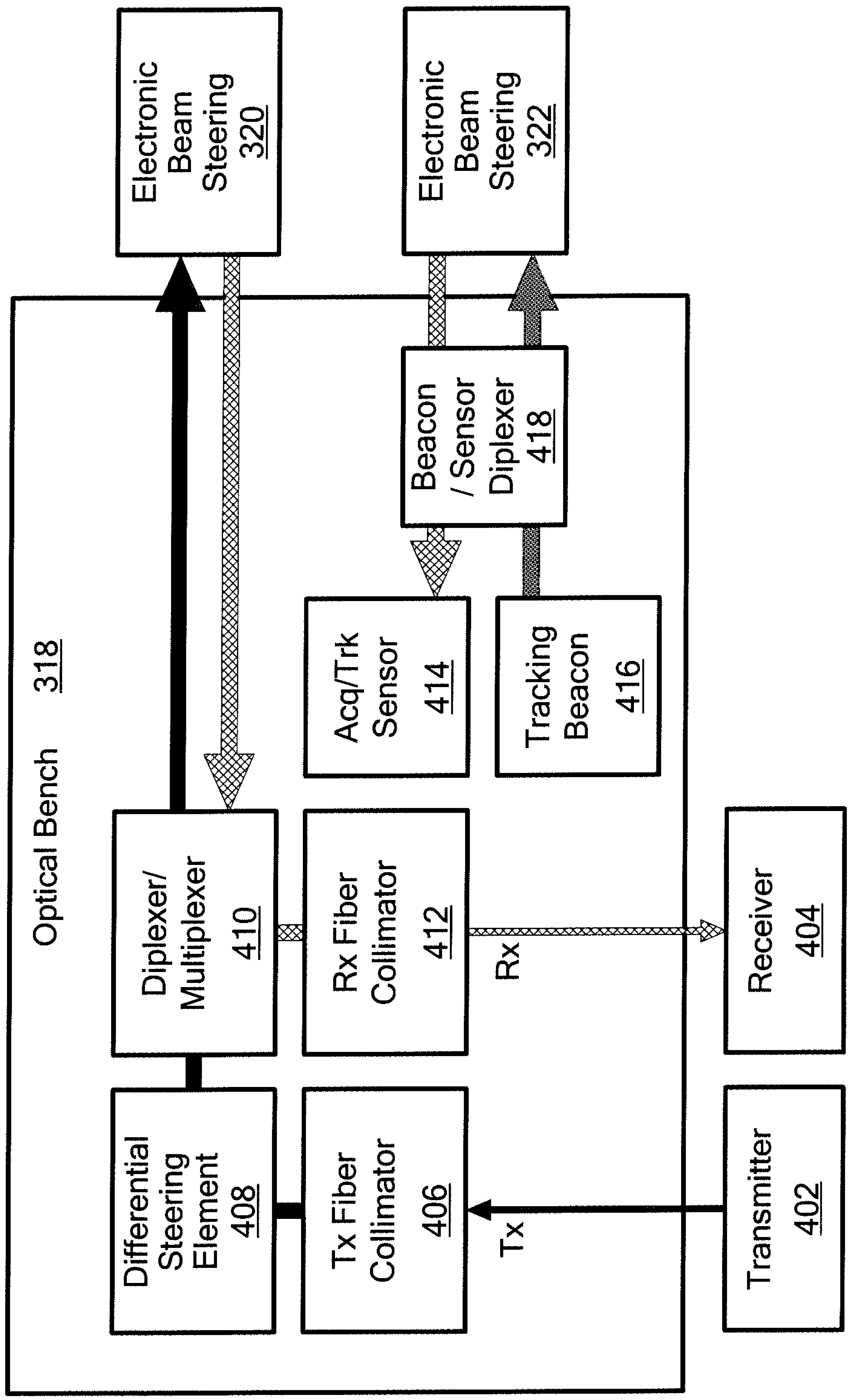
Electronic Beam Steering 320
Electronic Beam Steering 322
Optical Bench 318
Beacon / Sensor Diplexer 418
Acq/Trk Sensor 414
Tracking Beacon 416
Diplexer/ Multiplexer 410
Rx Fiber Collimator 412
Rx
Receiver 404
Differential Steering Element 408
Tx Fiber Collimator 406
Tx
Transmitter 402

FIG. 4

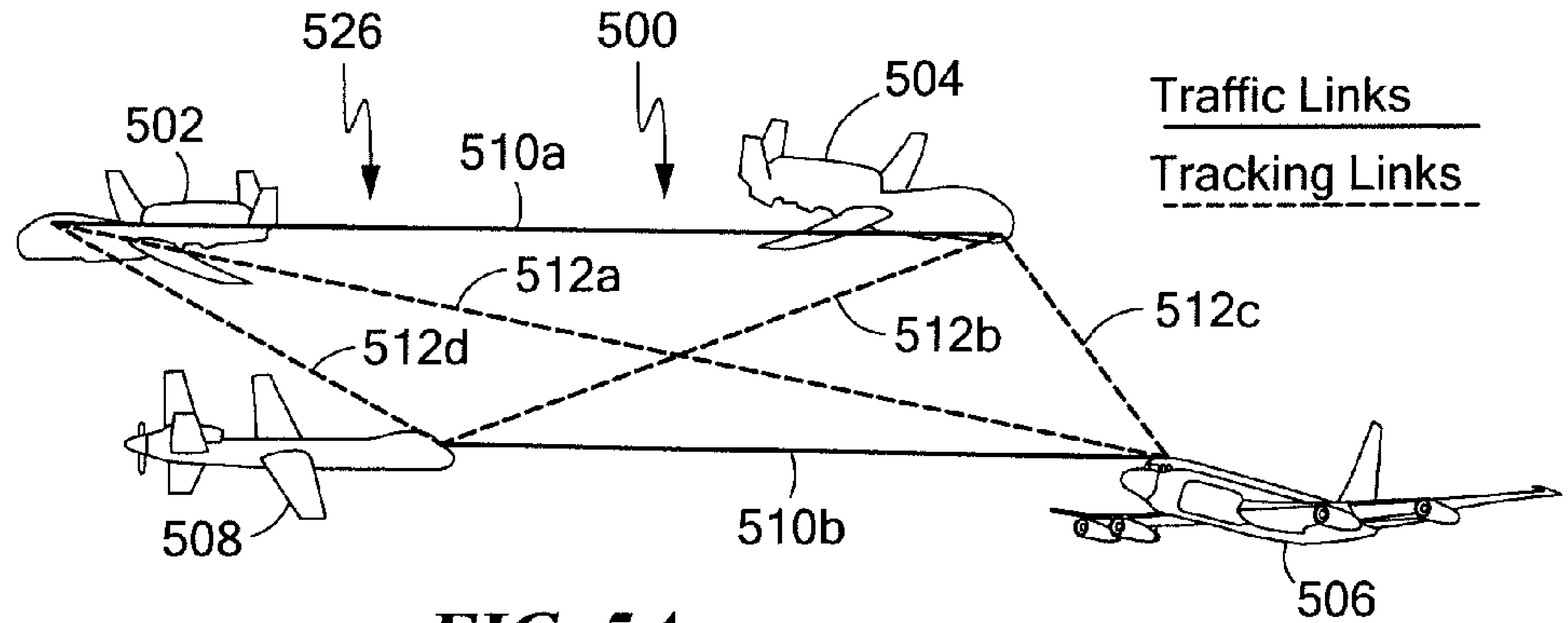

FIG. 5A

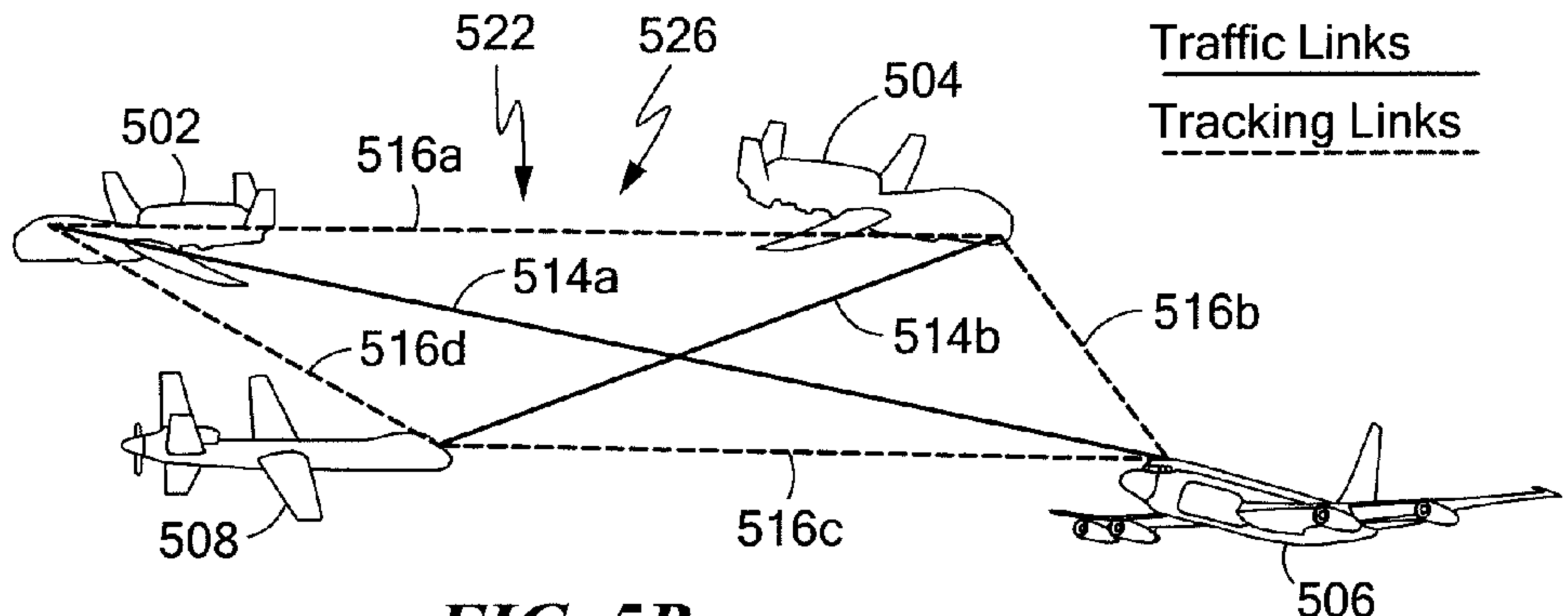

FIG. 5B

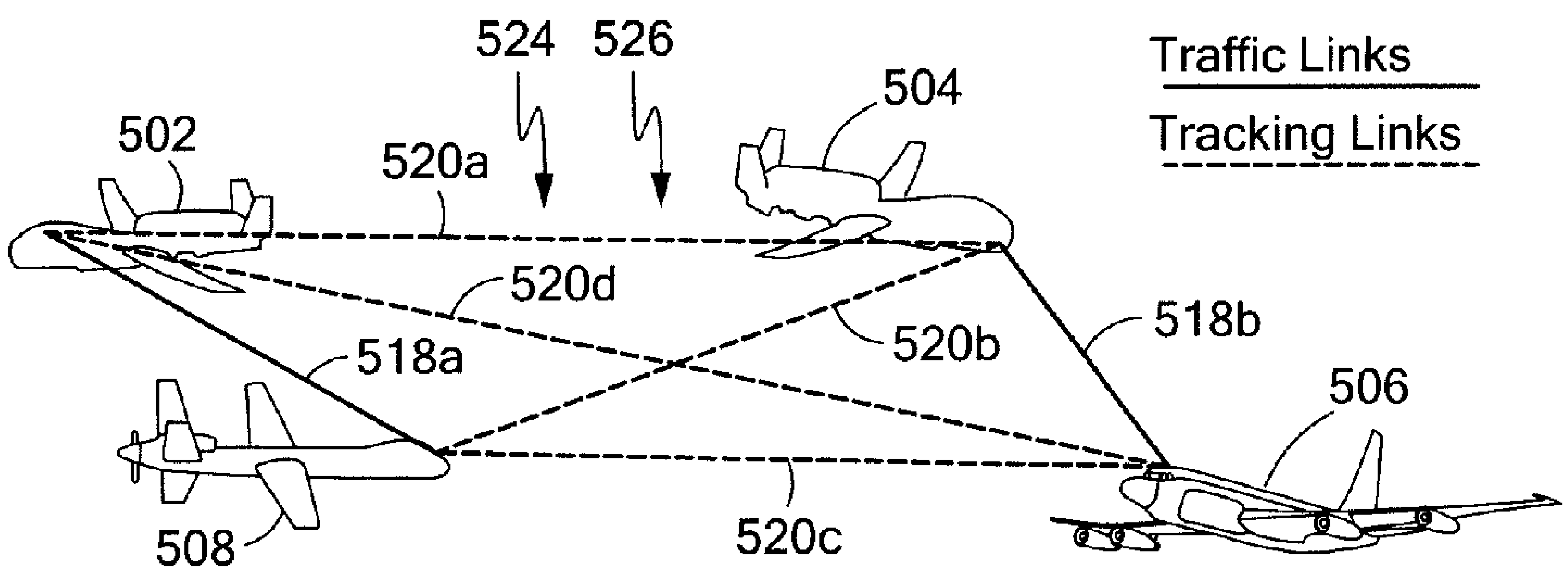

FIG. 5C

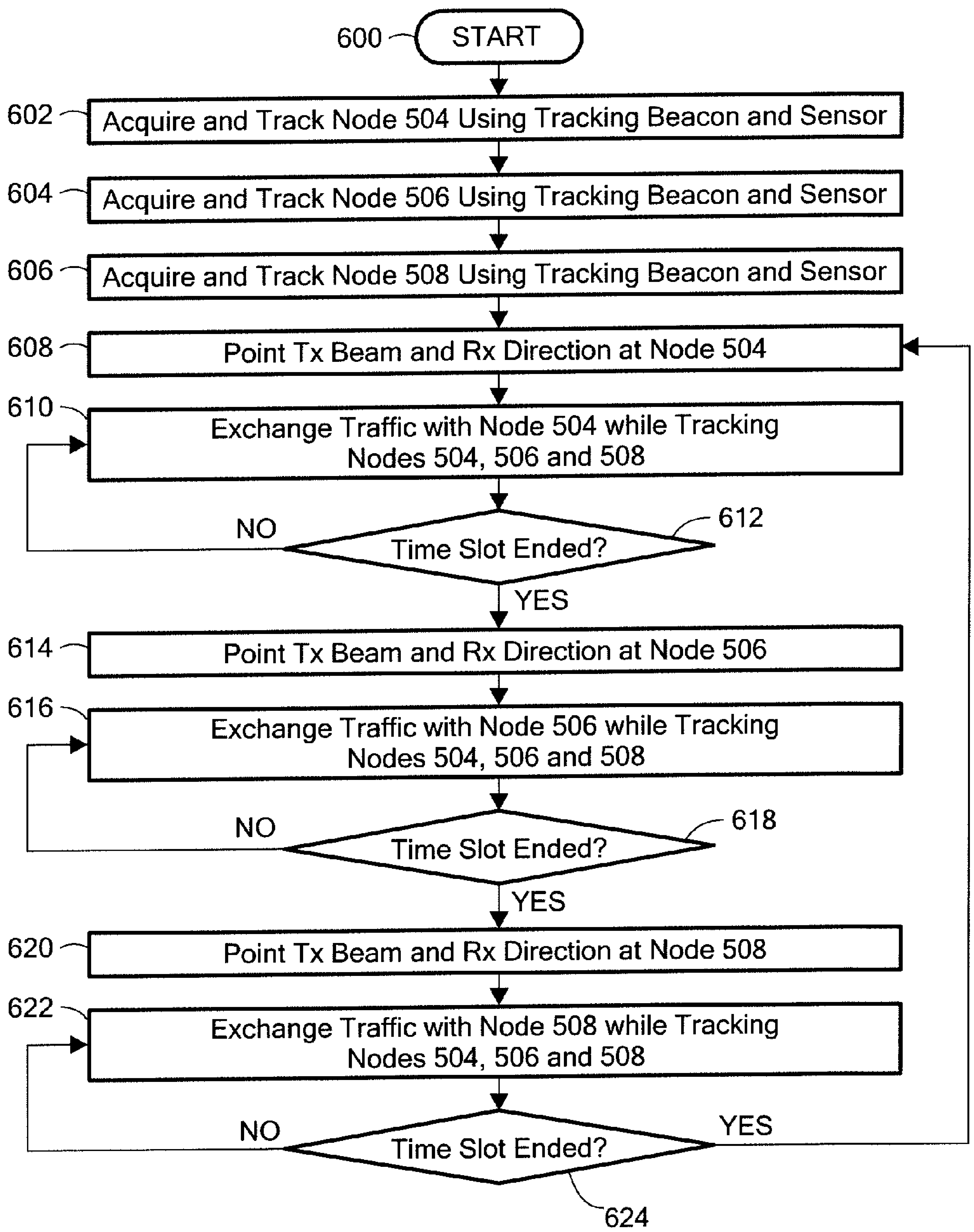
600
START
602
Acquire and Track Node 504 Using Tracking Beacon and Sensor
604
Acquire and Track Node 506 Using Tracking Beacon and Sensor
606
Acquire and Track Node 508 Using Tracking Beacon and Sensor
608
Point Tx Beam and Rx Direction at Node 504
610
Exchange Traffic with Node 504 while Tracking Nodes 504, 506 and 508
NO
Time Slot Ended?
612
YES
614
Point Tx Beam and Rx Direction at Node 506
616
Exchange Traffic with Node 506 while Tracking Nodes 504, 506 and 508
NO
Time Slot Ended?
618
YES
620
Point Tx Beam and Rx Direction at Node 508
622
Exchange Traffic with Node 508 while Tracking Nodes 504, 506 and 508
NO
Time Slot Ended?
YES
624

FIG. 6

FREE-SPACE OPTICAL MESH NETWORK

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit and priority of U.S. Provisional Patent Application No. 61/839,045 filed on Jun. 25, 2013, which application is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not Applicable.

FIELD OF THE INVENTION

This invention relates generally to a free-space optical communication system and, more particularly, to a free space optical mesh network.

BACKGROUND OF THE INVENTION

Highly-connected radio frequency and microwave communication networks, commonly referred to as mesh networks, are known. Mesh networks provide high availability by maintaining a high degree of connectivity between nodes. Compared to RF communications, Free-Space Optical (FSO) communications provide higher data rates, lower probability of detection, and are less susceptible to jamming. In addition, FSO communications are not subject to spectrum usage limits. While RE mesh networks are widely used in tactical situations, FSO systems generally remain a collection of point-to-point links (node degree≤2). Such low-connectivity systems may have high latency, low throughput, and poor resilience as any single broken optical link may partition the network into disconnected segments.

Attempts have been made to achieve FSO networks having a higher node degree. Some systems provide multiple (N) optical terminals at each node (node degree=N). However, this approach does not scale in practice, as each increase in node degree requires an additional high-speed optical communications terminal and thus significantly increases the cost and size, weight, and power (SWaP) characteristics. It will be appreciated that a small aircraft or vehicle may support at most two optical communications terminals (node degree≤2). Other systems may increase availability by providing an RE overlay network in addition to optical point-to-point links, wherein the RE network can provide backup and control capabilities. However, such hybrid networks do not actually achieve a higher optical node degree and thus may suffer from degraded data rates, higher probability of detection, and lower jam resistance when a single optical traffic link is broken. Therefore, there is a need for a FSO network with a high node degree and which requires a minimal number of optical communications terminals at each node.

SUMMARY OF THE INVENTION

In accordance with one aspect, the present disclosure provides a free-space optical network comprising three or more nodes. Each node has a communications terminal with a specialized optical aperture providing optical beam spatial hopping capability to connect to at least two remote nodes using optical links. At least two of the nodes are connected in a first networked topology during a first period of time and at least two of the nodes are connected in a second networked topology during a second period of time. A first data path is established among the nodes during the first period of time and a second data path is established among the nodes during a second period of time. Thus, the present disclosure provides a practical free-space optical mesh network with a high dynamic node degree using a single optical terminal at each node.

According to another aspect, a method for transmitting data in a free-space optical network includes pointing an optical data beam from a first node to a second node during a first period of time, transmitting data from the first node to the second node during the first period of time, pointing the optical data beam from the first node to a third node during a second period of time, and transmitting data from the first node to the third node during the second period of time.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of the disclosure, as well as the disclosure itself may be more fully understood from the following detailed description of the drawings, in which:

FIG. **1**A is a network diagram showing nodes and traffic links in an illustrative Free-Space Optical (FSO) mesh network;

FIG. **1**B is a network diagram showing nodes, traffic links, and tracking links in an illustrative FSO mesh network;

FIG. **1**C is a network diagram showing an RF overlay network in an illustrative FSO network;

FIG. **2** is a network diagram showing optical terminals in an illustrative FSO mesh network;

FIG. **3** is a block diagram showing an illustrative optical terminal for use in the network of FIGS. **1**A and **1**B;

FIG. **4** is a block diagram showing an illustrative optical bench for use in the optical terminal of FIG. **3**;

FIGS. **5**A-**5**C are pictorials collectively showing reconfiguration of traffic and tracking links in an illustrative FSO mesh network; and

FIG. **6** is a flowchart illustrating reconfiguration of traffic links at one node in the FSO mesh network of FIGS. **5**A-**5**C.

DETAILED DESCRIPTION OF THE INVENTION

Before describing the present disclosure, some introductory concepts and terminology are explained. The term "node degree" is herein used to refer to the number of links terminating at a given node within a network. The term "meth network" is herein used to refer to any network with a high node degree, generally greater than 2. The term "optical terminal" refers to any apparatus or device capable of transmitting and/or receiving free-space optical beams. It will be appreciated that the optical terminals herein may further be capable of receiving data and/or tracking remote optical terminals. The terms "hop", "hopping", and "beam hopping" all generally refer to the process of repointing a transmitted free-pace optical beam from a first direction to a second direction and/or reconfiguring an optical terminal to receive such a beam. The term "traffic link" refers to any communications link capable of carrying user data at a high data rate and may be either unidirectional or, more commonly, bidirectional. The term "tracking link" refers to an optical link used primarily for tracking the position of other terminals to the precision required for optical communications between them. The term "spatial acquisition" refers to the act of determining the direction of another node that is not currently being tracked with sufficient precision that it can be tracked. For discussion purposes the characteristics of a terminal located on a specific platform may be referred to in terms of its interaction with another terminal, referred to as the remote terminal, located on a distant platform. It should be noted that this terminology is relative and both terminals will generally have the same capabilities. The term "optical aperture" refers to the part of the terminal that controls the optical beams entering and exiting the terminal. Reference will be made herein to "RF overlay networks," however it should be understood that such overlay networks may utilize either radio frequency (RF) communications and/or microwave communications.

Embodiments of the disclosure will now be described in detail with reference to the drawing figures wherein like reference numerals identify similar or identical elements.

Referring to FIG. **1**A, an illustrative Free-Space Optical (FSO) mesh network **100** includes nodes **102**, **104**, **106**, **108**, and **110**, active traffic links **112**, and inactive traffic links **140**. In FIG. **1**A, the nodes **102-110** are shown as aircraft, however it will be appreciated that each node could be any structure capable of supporting an optical communications terminal as described herein. For example, each node could be a structure in geostationary orbit around Earth such as a satellite, an aerial vehicle such as a manned aircraft or an unmanned aerial vehicle (UAV), a land-based vehicle such as a tank, personnel carrier, or armored vehicle, or a sea-based vehicle such as a ship or submarine.

Each of nodes **102-110** has generally the same optical communications capabilities as every other node in the network **100**. Thus, a discussion of any node will generally apply to every other node. For simplicity of explanation, the capabilities and structure of node **102** will be discuss herein.

Node **102** includes at least one optical terminal **102***a* having at least one optical communications aperture **102***b*. Optical communications terminal **102***a* may support high-rate data transfer of 1 Gbps, 10 bps, or greater. In some embodiments, optical terminal **102***a* may also include a plurality of acquisition and tracking (acq/trk) apertures as discussed below in conjunction with FIG. **1**B.

Optical terminal **102***a* is capable of transmitting and receiving spatially agile FSO beams. Spatial agility means that an FSO beam can be repointed from one direction to another direction rapidly without sweeping the arc between the two directions. In addition to the behavior of a beam being transmitted from an optical aperture, spatial agility also applies to the direction from which an optical aperture can receive an incoming beam. In embodiments, optical terminal **102***a* may use Optical-Phased Arrays (OPAs) to electronically steer their transmit beam and receive directions. As is known in the art, OPAs can electronically repoint a transmit beam in a fraction of the time required by a mechanical steered aperture. Electronic steering allows the nodes **102-110** to rapidly repoint ("hop") their optical communications in order to optically send and receive data in different directions. Of importance here, the hopping time does not depend on the angle between the remote terminal on which the hop is initiated and the remote terminal on which it is terminated as seen from an optical terminal. While this system can operate at any wavelength, a certain embodiment operates at the 1550 nm standard optical communications wavelength. Recent measurements of OPA switching times at other wavelengths can be extrapolated to a beam switching time of ~0.1 ms at 1550 nm. At these switching times, beams can be hopped at such a high rate with so little repointing time that a system with these changing sequential connections closely approximates one with a large number of parallel connections.

In certain embodiments, each active traffic link **112** represents a bidirectional communications link formed by a pair of co-aligned optical beams propagating in opposite directions. In these embodiments, a single communications aperture, such as **102***b* and **104***b*, may be capable of both transmitting an optical communications beam and receiving an optical communications beam. Thus, a bidirectional traffic link **112***a* may be formed between nodes **102** and **104** by pointing the optical aperture **102***b* in the direction of an optical aperture **104***b* and by pointing the aperture **104***b* at the aperture **102***b*. As such, node **102**'s transmit beam direction is pointed at node **104**'s receive direction and node **104**'s transmit beam is pointed at node **102**'s receive direction, thus a bidirectional communications link is formed. In embodiments, OPAs, which are capable of accurate steering, may be used to co-align optical transmit beams and receive directions.

In other embodiments, each active traffic link **112** represents a unidirectional communications link formed by one transmit beam aligned with one remote receive direction. In these embodiments, each optical terminal, such as **102***a* and **104***a*, may have separate apertures for transmitting and receiving data. Thus, for example, terminal **102***a* may include a transmit aperture aligned to terminal **104***a* and terminal **104***a* may include a receive aperture aligned to terminal **102***a*, while terminal **102***a* may include a separate receive aperture aligned to terminal **104***a* and terminal **104***a* may include a transmit aperture aligned to terminal **102***a*. Alternatively, the receive aperture of terminal **102***a* and the transmit aperture of terminal **104***a* may be aligned to different optical terminals, for example **110***a* and **106***a*.

In the exemplary network **100** shown in FIG. **1**A, each node **102-110** includes one optical communications terminal, such as **102***b*, and thus may have at most one active traffic link, such as **112***a*, at any given time. It will be appreciated that each node may include more than one optical terminal and in general the number of active traffic links is determined by the number of communications terminals provided. Multiple terminals per node enable each node to be simultaneously connected to multiple other nodes. This can provide a complete path through the network at all times and eliminates or reduces the need for data buffering. It also enables optical burst transmission, as discussed further below.

In addition to the active traffic links **112**, the network **100** includes a plurality of "inactive" traffic links **140**, which represent a mutual intent by two nodes to establish an active traffic link. The techniques by which two nodes may mutually plan to establish a link will be discussed further below. Suffice it to say here, each inactive traffic link **140** may become an active link in the near future, and likewise, each active traffic link **112** may become an inactive link in the near future. For example, inactive traffic link **140***a* represents a mutual intent by nodes **102** and **106** to establish an active (i.e. actual) traffic link in the near future by repointing their respective transmit beam and receive directions. Likewise, inactive link **140***b* represents a mutual intent by nodes **102** and **108** to establish a traffic link and inactive link **140***e* represents a mutual intent by nodes **102** and **110** to establish a traffic link. In certain embodiments, optical terminals **102***a*, **104***a*, **106***a*, **108***a*, **110***a* utilize OPAs capable of rapid transmit beam and receive direction repointing on the time scales discussed above. It will now be appreciated that node **102** may be capable of rapidly switching between the active traffic link **112***a* to node **104** to an active traffic link to any of nodes **106**, **108**, and **110**. Thus, for certain purposes discussed further below, there is no practical difference between active traffic links **112** and inactive traffic links **140** and the dynamic node degree for each of the nodes **102-110** is the sum of its active and inactive traffic links.

It will be appreciated that the FSO mesh network **100** requires each node **102-110** to be aware of the position of one or more neighboring nodes, or more specifically, the position of one of those node's optical communications aperture, such as **102***b*. In certain embodiments, the number and relative position of nodes is generally static, and thus each node's position may be preprogrammed into a control system of each other node. In other embodiments, network **100** is a mobile ad-hoc network (MANET), and thus spatial coordination is required wherein each node is capable of dynamically determine the existence and position of neighboring nodes. This process, herein referred to as spatial acquisition, is discussed further below in conjunction with FIG. **2**.

In addition to spatial coordination, temporal coordination among the nodes **102-110** is required to allow synchronization of the pointing directions between communicating nodes. Thus, both spatial coordination and temporal coordination are required. In certain embodiments, Space-Time Division Multiplexing (STDM) is used to provide space-time coordination. Using STDM, each node **102-110** points its transmit beam and receive direction at a specified neighboring node during planned periods of time (referred to as "time slots"). Thus, there is a programmed progression of communications among its neighbors. This progression of communications, including the order of progression, the time at which communications occurs, and the duration of communications (dwell time), is referred to as a communications cycle or hopping sequence. In a typical hopping sequence, each neighboring node is assigned a time slot coincident with the dwell time of the communications beam on that neighbor node during which traffic data is exchanged. An illustrative STDM hopping sequence is shown in FIGS. **5A-5C** and **6**. STDM as discussed above is used in a peer network and requires that all nodes be aware of the hopping schedule. A related technique, Space-nine Division Multiple Access (STDMA) can be used in an access network for which multiple client nodes are connected to the network through an aggregation node. STDMA is further described in U.S. Pat. No. 8,116,632 (which is hereby incorporated by reference).

In certain embodiments, a hopping sequence may be preplanned and preprogrammed into each node's network processor (**308** in FIG. **3**). Preplanned sequences may be used wherein FSO mesh network **100** has a generally static number of nodes and node positions and where link failures are rare.

In embodiments, the hopping sequences are adaptive and computed in real-time or near real-time using approaches and techniques similar to those used for some RF MANETs. Adaptive hopping sequences may be used wherein FSO mesh network **100** is a mobile network, a MANET, and/or where link failures are common. Adaptive hopping sequences may be based on traffic requirements, node states, link states, and/or environmental conditions. Traffic loads and node and link states may be communicated via an RF overlay network (**122** in FIG. **1**C) and each node's network processor **308** may operate to maintain the topology of a network and participates in the distributed calculation of primary and backup routes and stores the results. For example, the topology of the traffic links and their dwell times can be altered to accommodate changes in traffic patterns or the changes in locations or number of nodes. If a link or node outage is detected, a node network controller may reroute traffic around the impairment. If the capacity of the remaining unimpaired links is not adequate to carry all the blocked traffic, lower priority traffic may be discarded or queued for later transmission. The operation of network processor **308** is discussed further below in conjunction with FIG. **3**. Any given hopping sequence may not include active traffic links to every possible node and may include multiple traffic links between certain nodes.

In some embodiments, several or all nodes in network **100** may be synchronized together for arbitrary periods of time to provide long data paths for bursting traffic through the network. Thus, the FSO mesh network **100** provides for burst mode transmission in addition to hopping sequences.

As is known in the art, network performance is commonly measured by its average throughput/bandwidth, average latency, and jitter. It will be appreciated that achieving a high throughput and a low latency and jitter is generally desirable, although often there is a tradeoff between these measures in a STDM system and the specific applications may demand one more than the other. For example, buffered video streaming generally demands a relatively high throughput and low jitter, but may tolerate a relatively high latency.

One performance cost of STDM is that, because a node's transmit/receive facility has a fixed data rate and is shared among all neighbors, the average bandwidth, and thus throughput, per effective traffic link goes down as the number of neighbors increases. This is a common situation in multiple-access networks (e.g. cable internet access and fiber-to-the-home) and can be addressed through policy-based quality-of-service (QoS) management with resource scheduling. Wavelength Division Multiplexing (WDM) can also be used to increase the bandwidth of the transmit/receive facility and thereby the bandwidth per effective traffic link with a modest increase in cost and SWaP. Another performance cost is the latency produced by the time a node spends communicating with other neighbors. For a beam control aperture that requires 10 milliseconds or more to repaint a beam between remote terminals, this results in a trade-off between bandwidth efficiency and latency and buffer size. This trade-off can be adjusted dynamically on a per-neighbor basis as part of the QoS policy negotiation. However, the fast switching sub-millisecond time of recent OPAs largely eliminates this issue, enabling high throughput to be obtained with low latency using short dwell times.

It should be appreciated that the aggregate bandwidth of a terminal is shared among the number of neighboring nodes. Some bandwidth inefficiency is inherent in the hopping (space division) operation because it takes a certain amount of time to settle and reform the beam on each remote terminal. This time depends upon the steering mechanism. Mechanically steered beams would be too slow for hops greater than the field-of-view of a telescope, typically ≤2° In one embodiment, electronic beam steering is used because of its speed and open-loop precision. For typical heated optical phased arrays (OPAs) using current generation nematic liquid crystals, the time to redirect a bean between arbitrary angles is approximately 5-10 ms depending upon the type of liquid crystal and the wavelength used. The hopping time does not depend on the angle as seen from an optical terminal between the remote terminal on which the hop is initiated and the remote terminal on which it is terminated. Other types of liquid crystals are much faster than the above-noted steering time and can reduce this beam redirection time by more than an order of magnitude. Those of ordinary skill in the art will appreciate how to select an appropriate liquid crystal device for a particular application, including the considerations of speed, steering efficiency, and reliability.

Latency is determined by the hopping sequence, specifically, the time it takes for a terminal to revisit the same neighbor's terminal in the process of cycling through all the neighbors. STDM may utilize buffering and burst mode transmission, and thus may not be suitable for traffic that requires very low latency. However, unidirectional streaming traffic (e.g. video) can be handled by means of buffering at each end (i.e., both at the ingress and egress nodes) to reduce jitter to an acceptable level.

It should also be appreciated that there is a trade-off between bandwidth efficiency and latency due to the dead-time caused by hopping a beam. As the number of neighbors increases, the throughput efficiency can be kept constant by maintaining the ratio between the beam repointing time and dwell time constant and increasing the cycle time, however it is understood that this increases latency. Maintaining a fixed latency requires decreasing the dwell time as users are added, but this decreases throughput efficiency. It will be appreciated that the magnitude of this effect depends on the repointing time of the steering aperture and that a new generation of fast OPAs, which have repointing times≤10 ms, minimize this effect because they are able to maintain a high throughput efficiency at very short dwell times.

It should now be appreciated that the present disclosure provides a FSO mesh network **100** with a high dynamic node degree, high throughput efficiency, and low latency by utilizing high-speed spatially agile FSO beams and space-time coordination among node pointing directions. The network may enable hopping and burst mode transmission while maintaining negligible throughput loss and low latency. The network may use adaptive routing and link switching to adjust to traffic conditions, changes in number and locations of nodes, and to overcome link and node impairments. Further, the disclosure may incorporate techniques and operations which have been developed for RF mesh networks, such as optimal switching and routing protocols, into FSO networks while retaining the advantages of highly directional optical beams with high data rates.

Referring now to FIG. 1B, a FSO mesh network **100** includes nodes **102-110**. Node **102**, which is representative of all other nodes, includes an optical terminal **102***a*. The optical terminal **102***a* includes an optical communications aperture **102***b* and one or more optical acquisition and tracking (acq/trk) apertures **102***c*. The acq/trk apertures **102***c* are capable of transmitting a tracking beacon using a beacon source and also receiving a remote tracking beacon using a beacon sensor. In some embodiments, the acq/trk apertures **102***c* may utilize OPAs for steering and, further, the respective tracking beacons may comprise spatially agile beams. The acq/trk apertures **102***c* can be less complex than the communication apertures **102***b* and therefore may have lower cost and size, weight, and power (SWaP) characteristics than the respective communication apertures. Thus, whereas a small aerial or ground vehicle may be capable of supporting at most two optical communications apertures, such a vehicle may be capable of supporting one or more acq/trk apertures in addition to the communications apertures. In a like manner, node **104** includes optical terminal **104***a* having optical communications aperture **104***b* and acq/trk aperture **104***c*, node **106** includes optical terminal **106***a* having optical communications aperture **106***b* and acq/trk aperture **106***c*, node **108** includes optical terminal **108***a* having optical communications aperture **108***b* and acq/trk aperture **108***c*, and node **110** includes optical terminal **110***a* having optical communications aperture **110***b* and acq/trk aperture **110***e*.

In some embodiments, a dedicated acq/trk aperture **102***c* is provided and can be used by node **102** to continuously track and provide beacons or other signals to other nodes for the purposes of spatially acquiring or locating other nodes and subsequently maintaining tracking links **114** between those nodes. Optical tracking links are required because the divergence of the traffic link beams is so small that precise pointing information is required in order to obtain adequate signal strength. Acq/trk links can be maintained even when no traffic link **112** has been established between those nodes. Since an optical tracker may require a beacon or other signal to track (which can be at a communication wavelength), the nodes at both ends of a tracking link **114** are mutually aware, meaning both nodes can point their beacons at each other and maintain precise relative position at the same time. Although acq/trk aperture **102***c* may be separate from the communications aperture **102***b*, the respective tracking beams and transmit beams may be co aligned. Co-alignment is feasible because both types of apertures may use OPAs to provide precise, accurate, electronic steering.

In other embodiments, the tracking is performed using the communication aperture **102***b*, and no dedicated acq/trk aperture **102***c* is needed, in these embodiments, tracking data can be updated by momentarily hopping the transmit beam and receive directions of the communication aperture between the node with which a traffic link **112** is being maintained and those nodes being tracked for potential traffic links **114**. This may involve very fast beam repointing in order to maintain high information throughput on the traffic link **112**. It may also involve temporal coordination so that the beacon source and the beacon receiver are aimed at each other at the appropriate time. However, this approach may reduce throughput efficiency because the time spent performing the tracking function increases communications deadtime.

As shown, nodes **102-110** are connected by a series of (active) traffic links **112** and tracking links **114**. As in FIG. **1**A, traffic links **112** in FIG. **1**B may represent either bidirectional or unidirectional communications links formed by co-aligned optical transmit beams and receive directions. Tracking links **114** may represent either one tracking beacon and one sensor, or a bidirectional pair of tracking beacons and sensors. Before a traffic link **112** can be established, a tracking link **114** may be established to maintain precise pointing directions between two nodes. Thus, the tracking links **114** represent paths that could potentially be converted into communications links, and thus may correspond to inactive traffic links **140** in FIG. **1**A.

One purpose of acq/trk apertures **102***c* is to facilitate the transmit/receive repointing process and thus further reduce the performance costs associated beam hopping. Acq/trk apertures may track network nodes that are already in the hopping sequence or that are candidates for inclusion. Since the nodes connected by the tracking links **114** are able to maintain their relative position (pointing direction) and the condition of the path, between then in real time, the repointing of their communication apertures towards each other and the establishment of an active traffic link between them can occur very quickly. Another purpose of acq/trk apertures **102** is to enable nodes to join the network without interfering with communications by existing network nodes. Yet another purpose of acq/track apertures **102***c* is that the tracking links maintained by these apertures also provide information on the quality of potential communications links for input to the route computation process.

Referring now to FIG. 1C, the FSO mesh network **100** in FIGS. **1**A and **1**B is shown with a RF overlay network **122**. The RF overlay network **122** includes nodes **102-110** and wireless RF links **120**. The RF links **120** may include radio frequency, microwave, or other non-optical electromagnetic communication links allowing the nodes **102-110** to communicate with one another using non optical electromagnetic waves. The RF links **120** could support data transfer at any suitable rate(s). For brevity, all non-optical communication links are referred to as RF links. In particular embodiments, the nodes **102-110** include RF phased array antennas to generate/receive multiple beams or to hop a single beam among multiple nodes. This provides for efficient usage of RF terminal hardware and a larger number of simultaneous RF links. In other embodiments, mechanically-steered RF directional antennas can be used. In still other embodiments, omnidirectional RF antennas can be used. In one embodiment, the RF overlay network **122** employs phased array antennas to either generate and receive multiple beams or hop a single beam among all the nodes. This has the advantage of efficient spectrum use and reduced probability of detection. Alternatively, omnidirectional antennas can be used, although this lacks the above advantages and may lack the capacity to support the control plane traffic. The RF overlay network **122** may be implemented especially to support the FSO network or may be an existing network whose primary purpose is to carry RF communication traffic.

The RF links **120** constitute a parallel or overlay network utilizing the same nodes **102-110**. The overlay network can be used to transport information at lower data rates relative to the optical communications network (such as control plane data), to transport certain data when optical communications links fails, or to transport data intended only to be carried on the RF network. RF may be used because of its higher availability in the atmosphere and the requirement that control information be delivered with higher assurance than user traffic. While the RF network provides logical connectivity between all nodes in the vicinity of the optical network, it does not need to be physically fully connected if it has sufficient capacity to relay information from distant nodes.

As discussed above, the RF overlay network **122** can be used to transmit control plane information between nodes. The control plane information can include a wide variety of information depending on the implementation. For example, the control plane information can include information for spatially and temporally coordinating transient reciprocal beam pointing between nodes, information that allows the nodes to repoint their optical systems at one another, and beacon signals or other signals. This information can be used to plan routes through the network for the traffic links. Because the optical state of potential links, node locations, and traffic patterns may change continuously, route calculations can be performed continuously. The RF overlay network **122** can also be used to transport a limited amount of priority traffic if optical traffic links (**112** in FIG. **1**B) are not available. The RF overlay network **122** can further be used to transport performance information about links **112** being monitored and to provide status information about nodes without tracking links **114** so that tracking links **114** can be rapidly established if needed.

In certain embodiments, the RF overlay network **122** comprises a MANET capable of discovering nodes and potential links. Therefore, it will be appreciated that RF overlay network **122** can provide the FSO mesh network **100** with a self-organizing capability based on RF discovery of nodes and traffic-based optical connectivity.

Referring now to FIG. **2**, optical terminals **200**, **202**, and **204**, each of which may be the same as or similar to any of optical terminals **102***a*, **104***a*, **106***a*, **108***a* and **110***a* in FIG. **1**A are shown. For simplicity of explanation, three nodes/terminals are shown in FIG. **2**, however it will be appreciated that the systems and methods described herein allow for networks with a generally arbitrary number of nodes. Each of the terminals **200**, **202**, **204** includes a respective one of optical communications apertures **206**, **208**, **210**, which transmit and/or receive communications beams **218-228**. Pairs of communications beams **218**, **220** and **222**, **224**, shown as dashed lines, form inactive traffic links and may correspond to any of links **114***a*-**114***d* in FIG. **1**A. Likewise, the pair of communication beams **226**, **228** form an active traffic link that may correspond to any links **112***a*-**112***d* in FIG. **1**A. For simplicity of explanation, pairs of counter-propagating communications beams may herein be interchangeably referred to as traffic links; although in some embodiments a traffic link may be unidirectional and consist of a single beam. Each terminal **200-204** further includes a respective plurality of acq/trk apertures **212***a*-**212***d*, **214***a*-**214***d*, and **216**-**216***d* that provide tracking beams (beacons) **230**, **232**, **234**, **236**, **238**, and **240**. Pairs of tracking beacons **230**, **232**, and **234**, **236**, and also **238**, **240** form respective tracking links. For simplicity of explanation, pairs of tracking beacons may herein be interchangeably referred to as tracking links.

Still referring to FIG. **2**, the operation and function of optical terminal **200** will now be described. It will be appreciated that, because optical terminals **200-204** have similar structures, this description also generally applies to terminals **202** and **204**. Optical terminal **200** uses precise electronic beam steering of transmit communication beams **218**, **228** and receive directions **220**, **226** to provide bidirectional network connectivity to neighboring node optical terminals **208** and **210** by way of STDM. Using a single optical communications aperture to connect a plurality of remote nodes lowers the cost and SWaP characteristics of using optical terminal **200** compared to the use of multiple optical terminals, each with a single beam, to provide the same number of beams.

As will become apparent from the description hereinbelow, space division multiplexing is provided by using high-speed, agile, precise electronic beam steering to hop communications beam **218**, **228** and receive direction **220**, **226** among remote terminals **202** and **204**. Time division multiplexing is provided by assigning each remote terminal **202** and **210** a time slot coincident with the dwell time of the transmit beam **218**, **228** and receive direction **220**, **226** on that remote terminal. Thus, a combination of space and time division multiplexing (i.e. STDM) enable optical terminal **200** to operate such that bidirectional communications are possible with the appropriate one of the plurality of remote terminals **202**, **204** as a result of transmit beam **218**, **228** and receive direction **220**, **226** being pointing at that remote terminal at the correct time.

Accordingly, at any given instant in time, terminal **200** (e.g., via a beam steering mechanism) directs a transmit beam and a receive direction at one of the remote terminals **202**, **204** and is able to transmit to and receive from that remote terminal. The time that terminal **200** dwells on a specific one of the remote terminals **202**, **204** coincides with the time slot allocated to that terminal and may be specified by a beam hopping sequence. The terminal **200** can support a variable number of neighbors, up to the maximum that is determined by several factors, including the number of communications apertures, the number of acq/trk apertures, the aggregate bandwidth capacity of the terminal **200**, and the service requirements of the network. As mentioned above, in certain embodiments, there is one acq/trk aperture for each neighboring node and one communications aperture shared among the neighboring nodes. In other embodiments, the number of acq/trk apertures may be fewer or greater than the number of neighbors. It will be appreciated that, by using STDM, the largest and most expensive components of terminal **200** can be shared among all its neighbors.

In the exemplary network show in FIG. **2**, a single optical communications terminal **200** communicates with neighboring terminals **200**, **204** through transmit beam **218**, **228** and receive direction **220**, **226** controlled using the single communications aperture **206**. The optical terminal **200** steers transmit beam **218**, **228** and receive direction **220**, **226** to each of the neighboring terminals **202**, **204** at a desired time and for a desired time period. Transmit beam **228** and receive direction **226** represent the state of the illustrative HO network at the current instant in time, where transmit beam **218** and receive direction **220** represent the state of the FSO network at an earlier or later instant in time. Thus, as shown, an actual traffic link is currently established between terminals **200** and **204**, whereas an inactive traffic link is established between nodes **200** and **202**.

To enable fast hopping without spatial re-acquisition, neighboring node terminal **202** provides a tracking beacon **232** to acq/trk aperture **212***b* and, likewise, neighboring node terminal **204** provides a tracking beacon **238** to acq/trk aperture **212***d*. In embodiments wherein the number of acq/trk apertures is the same as or greater than the number of neighbors, remote terminals **202**, **204** provide a respective one of tracking beacons **232**, **238** to a corresponding one of the tracking apertures **212***a*-**212***d*. Thus, each tracking apertures **212***a*-**212***d* continuously receives a respective one of the plurality of tracking beacons **232**, **238**. This enables each terminal to track neighboring terminals with the same precision whether or not an active traffic link exists between them. Further, the transmit beam and receive direction of a pair of terminals can be immediately (i.e. with no delay for re-acquisition) pointed to the appropriate one of the plurality of remote terminal **202**, **204** when a traffic link is required between them. The beacons **232**, **238** can also be modulated to transmit low-bandwidth control and order wire information between the remote terminals **202**, **204** and terminal **200**. Such control and order wire information may be exchanged through low-bit-rate encoding of the tracking beacons.

As shown, the terminal **200** includes four acq/trk apertures **212***a*, **212***b*, **212***c*, and **212***d* for tracking two neighboring node terminals **202**, **204**. It is desirable to have at least one dedicated acq/trk aperture for each neighbor in order to maximize bandwidth efficiency by avoiding the need for re-acquisition, and for the timely communication of control information that enables dynamic bandwidth allocation. It should be noted, however, that continuous control and tracking may not be required in every application. Thus, in some embodiments, the number of acq/trk apertures may less than the number of neighboring nodes.

In one embodiment in which the number of acq/trk apertures is less than the number of remote terminals, the acq/trk apertures **212** are cycled such that each remote terminal does not necessarily have an acq/trk tracking aperture associated with it at all times. In this case, the terminal **200** manages the acq/trk apertures as a resource pool and assigns an acq/trk aperture to each remote terminal well before the time the terminal **200** points the communications transmit beam **218**, **228** and receive direction **220**, **226** at the remote terminal. In this way the spatial re-acquisition process is completed before the assigned communications time slot for the remote terminal is reached in the hopping sequence. Thus, each remote terminal may receive a different tracking beacon during different time slots in a hopping sequence. Because the remote terminal will have no beacon to track at certain times during the hopping cycle, it must also re-acquire the terminal **200** node when a new tracking beacon is assigned to it. It should be appreciated that the re-acquisition time depends upon the regularity of the relative motion of the nodes as well as the duration of the time interval during which no beacon and/or acq/trk aperture is available. However, accurate target trajectory prediction algorithms exist to reduce the re-acquisition time. Just as all terminals must be aware of the hopping sequence for the traffic links, there must be a re-acquisition sequence shared by all terminals when this "just in time" re-acquisition technique is employed.

Retelling now to FIG. **3**, an illustrative network node with both FSO and RF capabilities is shown. In particular, FIG. **3** illustrates a hybrid "optical plus RF" optical terminal **300** that may be located at any node **102**-**110** of FSO mesh network **100** in FIG. **1**A. In the embodiment shown, the terminal **300** includes a network node controller **302**, an RF system or terminal **304**, one or more optical systems or terminals **306**, and a network processor **308**. In other embodiments, a node may have an optical-only terminal.

The controller **302** controls the overall operation of the hybrid terminal. For example, the controller **302** may manage the operation of the RF terminal **304** and the optical terminal **306** to control the transmission or reception of data by the terminal **300**. The controller **302** is responsible for functions such as startup and shutdown of terminals, monitoring and reporting of terminal and link status, configuring the terminals, redirecting traffic and acq/trk links, and executing the primary and backup routing plans calculated and stored in the network processor **308** when instructed by the network processor **308**. The controller **302** includes any suitable structure for controlling a communication terminal, such as a processing system that includes at least one microprocessor, microcontroller, digital signal processor, field programmable gate array, or application-specific integrated circuit (ASIC).

The network processor **308** operates to maintain the topology of a network and the states of the nodes and links. The network processor **308** also participates in the distributed calculation of routes and hopping sequences based on traffic loads and link states, and stores the results. The calculation of routes could represent a distributed process performed amongst multiple nodes **300** using collaboration and information exchange amongst the nodes. The network processor **308** further decides on the mitigation procedure to be implemented in case of an outage, which may be local or remote. The processor **308** includes any suitable structure for supporting network organization, such as a processing system that includes at least one microprocessor, microcontroller, digital signal processor, field programmable gate array, or ASIC.

The RF terminal **304** may provide communication with other nodes using RF communications. The RF terminal **304** may be specifically designed to support the operation of an FSO mesh network, or it may also be part of an RF communication network that is used to incidentally provide support to the FSO mesh network. In this example, the RF terminal **304** includes RF electronics **310**, an RF antenna **312**, and a discovery antenna **314**. The RF electronics **310** perform various functions for generating signals for wireless transmission or for processing signals received wirelessly. For example, the RF electronics **310** could include filters, amplifiers, mixers, modems, or other components used to generate and receive RF signals. Other functions could also be supported, such as signal combining to combat multipath fading or to support the use of phased array antennas. The RF electronics **310** could further include MANET and Common Data Link (CDL) functionality, which supports the exchange of data with multiple other nodes. The RF electronics **310** include any suitable structure facilitating communication with other nodes using RF or other wireless non-optical electromagnetic signals.

The RF antenna **312** and the discovery antenna **314** support the transmission and receipt of RF signals to and from other nodes. In some embodiments, the RF antenna **312** is used to communicate with other nodes and exchange data, such as control plane information, and the discovery antenna **314** is used to locate and identify new nodes that come into RF range of the antenna **314** for the purpose of establishing RF communications. The RF antenna **312** includes any suitable structure for communicating data to and from other nodes, such as a phased array antenna. The discovery antenna **314** includes any suitable structure for receiving signals from new nodes, such as an omnidirectional radiator structure. Note that the use of antennas such as phased array antennas can support other functions, such as beam forming to simultaneously transmit a plurality of RF beams in different directions.

As shown, the optical system **306** includes an optical transceiver **316**, an optical bench **318**, an electronic communications beam steering assembly **320**, and an electronic tracking and beacon steering assembly **322**. The optical transceiver **316** generally operates to convert electrical data into optical signals for transmission and to convert received optical signals into electrical data for processing. The optical transceiver **316** includes any suitable structure for converting electrical data to and from optical signals, such as an optical modem. Note that while an integrated optical transceiver is shown here, the optical transceiver **316** could be implemented using an optical transmitter and a separate optical receiver.

The optical bench **318** performs various functions to process the optical beams sent to and from the optical transceiver **316**. For example, the optical bench **318** could include components for collimating light and directing the light towards both the communications beam steering assembly **320** and the racking beam steering assembly **322**. The optical bench **318** includes any suitable structure for altering optical beams sent to and from an optical transceiver. The optical bench **318** also performs functions needed for acquisition and tracking. An example embodiment of the optical bench **318** is shown in FIG. **4**, which is described below.

The electronic communication beam steering assembly **320** is configured to steer an outgoing communication transmit beam and an incoming receive direction. The electronic beam steering assembly **320** can therefore change the transmit beam direction and the receive direction. The transmit beam direction represents the direction in which an outgoing beam is transmitted away from the terminal **300**. The receive direction represents the direction from which an incoming beam is received at the terminal **300**. Similarly, the acq/trk beam steering assembly **322** aims the tracking beacon toward a remote terminal and points the receive direction to collect light from the beacon sent by that terminal. The electronic beam steering assemblies **320** and **322** include any suitable structure for directing and redirecting incoming and outgoing optical beams, such as one or more optical phased arrays and one or more diffraction gratings. Possible designs for the electronic beam steering assembly are provided in U.S. Pat. No. 7,215,472; U.S. Pat. No. 7,428,100; and U.S. Patent Publication No. 2012/0081621 (which are hereby incorporated by reference). Any other beam steering apparatus that provides rapid, agile, and precise beam repointing can be used.

Referring to FIG. **4**, an illustrative FSO optical bench **318** for use in optical terminal **300** of FIG. **3** is shown. The optical bench **318** is optically coupled to one or more optical transmitters **402** and one or more optical receivers **404** in the optical transceiver **316** of FIG. **3**. Multiple optical transmitters and receivers can be employed if wavelength division multiplexing (WDM) is used to increase the data rate on a given traffic link. Each optical transmitter **402** generally operates to generate optical sisals for outgoing communication, and each optical receiver **404** generally operates to convert incoming optical signals into another form (such as electrical signals) for further processing. Additional components could be used in the optical transceiver **316**, such as a high-power optical amplifier between an optical transmitter **402** and the optical bench **318** or an Optical Automatic Gain Control (OAGC) amplifier or low-noise optical amplifier between an optical receiver **404** and the optical bench **318**.

FIG. **4** is an example of an optical bench **318** adapted to provide optical communications over a traffic link that occurs through a communication aperture, while the optical tracking links are operated through separate acq/trk apertures as described above. In this embodiment, an electronic beam steering assembly **320** is used only for the optical traffic links, and an electronic beam steering assembly **322** is used only for the tracking links. The electronic beam steering assemblies **320**, **322** may be of the same or different designs depending on, for example, cost and SWaP characteristics fir a particular application.

The optical bench **318** includes one or more transmit fiber collimators **406**. The collimator **406** converts light from the optical transmitter **402** propagating in an optical fiber to a collimated beam of light in free space. In some embodiments, one or more differential steering elements **408** direct the outgoing collimated beams in the appropriate direction(s) to an optical diplexer/multiplexer **410**. The purpose of the differential steering elements **408** is to compensate for offset in the pointing angles for transmission and reception. In other embodiments, the same function can be performed by placing the differential steering elements **408** in the receiver path. The differential steering elements **408** may include any type of precision steering components, such as fine steering mirrors or OPAs. The diplexer/multiplexer **410** separates the transmit and receive beams and, if WDM is used, separates (for receive) and combines (for transmit) the different wavelength channels. The diplexer/multiplexer **410** directs the outgoing beams to the electronic beam steering assemblies **320**, **322**.

One or more incoming beams are received at the optical diplexer/multiplexer **410** from the electronic steering assembly **320**. The diplexer/multiplexer **410** directs the incoming beams to one or more receive fiber collimators **412**. The collimators **412** focus the light in the incoming beams into optical fibers, which conduct the beams to the optical receiver **404**. Each collimator **406**, **412** includes any suitable structure for collimating light. The differential steering elements **408** include any suitable structure for directing light in a desired direction. The diplexer/multiplexer **410** includes any suitable structure for providing different optical paths for different beams of light based on such properties as, for example, polarization, wavelength, and propagation direction. In this example, transmit beams are directed from the steering element **408** to the steering assembly **320**, while receive beams are directed from the steering assembly **320** to the collimators **412**. In embodiments, the diplexer/multiplexer **410** includes a WDM multiplexer/demultiplexer.

As shown in FIG. **4**, the optical bench **318** may also include an acq/trk sensor **414**, a beacon source **416**, and a beam/sensor diplexer **418**. Tracking beacons can be directed to other nodes using the electronic beam steering assembly **322**. The acq/trk sensor **414** is used to optically locate and establish a link with neighboring node based on a tracking beacon being received from that node. This typically proceeds through a mutual process (i.e. spatial acquisition) that transitions from approximate determination of direction through precise closed-loop tracking. Once tracking is established, it is maintained as a tracking link. Optionally, a tracking link can be established and maintained using the steering assembly **320**. The spatial acquisition and tracking functions can be performed by the same sensor **414** or by separate sensors **414**. Examples of such sensors **414** include quadrant detectors, focal plane arrays, or other optical position or angle sensors.

The beacon source **416** generates an optical beam to provide a beacon directed toward a distant node to enable the distant node to acquire and track the local node. The beacon source **416** may include any suitable optical beam source, such as a laser, and it may generate a modulated signal to provide low-data-rate information over a link to the distant node. An example of such information could include the status of the local node and its capability to carry additional traffic. The beacon/sensor diplexer **418** may be used to separate/combine the outgoing beacon from/with the incoming beacon in a manner similar to that of the optical diplexer/multiplexer **410**. In other embodiments, the beacon/sensor diplexer **418** is not needed, and the acq/trk sensor **414** and the beacon source **416** each have their own electronic beam steering assembly **322**.

Referring to FIGS. **5**A-**5**C, reconfiguration of traffic and tracking links in an illustrative FSO mesh network **526** having nodes **502**, **504**, **506**, and **508** is shown. Each node **502-508** includes an optical terminal, such as terminal **400** of FIG. **3**, capable of transmitting and receiving an optical communications beam suitable for high-rate data transfer. In addition, each optical terminal may be capable of acquiring and tracking at least two neighboring nodes, as shown. In FIG. **5**A, a first topology **500** is formed by a traffic link **510*a*** between nodes **502** and **504** and a traffic link **510*b*** between nodes **506** and **508**. In FIG. **5**B, a second topology **522** is formed by a traffic link **514*a*** between nodes **502** and **506** and a traffic link **514*b*** between nodes **504** and **508**. In FIG. **5**C, a third topology **524** is formed by a traffic link **518*a*** between nodes **502** and **508** and a traffic link **518*b*** between nodes **504** and **506**. It will be appreciated that the network topologies **500**, **522**, and **524** are defined by the respectively configuration of traffic links, as shown.

FIGS. **5**A-**5**C may collectively represent a coordinate hopping sequence among nodes **502-508**. The coordinated hopping sequence has three steps, as shown in FIGS. **5**A, **5**B, and **5**C respectively. At each step, the links are maintained for some planned period of time, referred to as a time slot or the dwell time. Each time slot may short, for example several milliseconds, to increase the node degree from its static value of 1 to a dynamic value of 3. Alternatively, each time slot may be long, for example several seconds, to allow burst mode transmission through the network. The dwell times associated with FIGS. **5**A-**5**C could be of equal or different durations. Where latency is an important consideration, short time slots are preferred.

FIG. **6** is a flowchart corresponding to the spatial acquisition (i.e., network organization) and hopping sequence processes shown in FIGS. **5**A-**4**C, from the perspective of node **502**. Each node of the example network of FIGS. **5**A-**5**C will execute similar procedure relative to its own perspective and, therefore, the node numbers shown in FIG. **6** are relative to representative node **502**. Moreover, the relative acquisition/hopping sequence shown in FIG. **6** must be coordinated in time and space with a similar sequence performed by or more other nodes in the network. It should be appreciated that the sequence shown in FIG. **6** can be implemented in hardware, such as the electronic beam steering assembly **320** (FIG. **3**) and/or computer systems, such as a network node controller **302** (FIG. **3**). Rectangular elements (typified by element **602**), herein denoted "activity blocks," represent combinations of hardware activities and computer software instructions or groups of instructions. Diamond shaped elements (typified by element **610**), herein denoted "decision blocks," represent computer software instructions, or groups of instructions, which affect the execution of the computer software instructions represented by the processing blocks.

Alternatively, the computer-system-related operations of the activity and decision blocks represent steps performed by functionally equivalent circuits such as a digital signal processor circuit ASICs, or FPGAs. The low diagram does not depict the syntax of any particular programming language. Rather, the flow diagram illustrates the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the operations required of the particular apparatus for its intended purpose. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of blocks described is illustrative only and can be varied without departing from the spirit of the disclosure. Thus, unless otherwise stated the blocks described below are unordered meaning that, when possible, the steps can be performed in any convenient or desirable order, for example, communicating with the other nodes in a different order than indicated or changing order in real time. From FIG. **6**, it should be obvious to one of ordinary skill in the art which additional steps are needed to reconfigure the network by adding or subtracting nodes, with the resultant modification to the hopping sequence.

Prior to **600** the particular nodes constituting the network are discovered by RF or some other mechanism are known to each other. In addition, the hopping order and timing have been established and are known to all participating nodes. At step **600** the connection of the network nodes is initiated. From the perspective of node **502**, this requires spatial acquisition followed by precision tracking of node **504** (step **602**), node **506** (step **604**), and node **508** (step **606**). Note that steps **602-606** can be performed in any order or in parallel. Once these activities are complete, node **502** points its transmit (Tx) beam and receive (Rx) direction at node **504** (step **608**), the first node with which it is to communicate in the example illustrated in FIG. **6**. Once this is done, node **502** begins exchanging traffic with node **504** while simultaneously maintaining precision tracking of nodes **504**, **506**, and **508** (step **610**). As indicated, by decision block **612**, this continues until the preset time slot for communication has ended, after which node **502** repoints its Tx beam and Rx direction at node **506** (step **614**). Then node **502** will exchange traffic with node **506** while maintaining precisions tracking of nodes **504**, **506**, and **508** (step **616**). When the time slot for exchanging traffic has ended (step **618**), node **502** repoints its Tx beam and Rx direction at node **508** (step **620**). Node **502** then exchanges traffic with node **508** while simultaneously tracking nodes **504**, **506** and **508** (step **622**). When the third time slot is completed (step **624**), node **502** restarts the sequence by repointing its Tx beam and Rx direction to node **504** (step **608**).

In certain embodiments, the hopping sequence may be repeated as shown in FIG. **6**, in other embodiments, the hopping sequence may be adaptive and change in response to network conditions, traffic demands, or other factors, as discussed further above. It should be appreciated that each of the other nodes in the network execute a complementary sequence of steps. For example, when node **502** points its Tx beam and Rx direction at node **504** (step **608**), node **504** will simultaneously point its Tx beam and Rx direction at node **502**. It should also be noted that the steps of FIG. **6** (or permutations of them) are executed while the network of FIGS. **5**A-**5**C is needed to transport traffic. When the network is no longer needed it can be dissolved by having the nodes disconnect from each other by terminating all optical links. Similarly, if changes in traffic patterns or locations of nodes require modification of the network, nodes can be added or subtracted from the network and a new hopping sequence implemented.

Having described certain embodiments, which serve to illustrate various concepts, structures and techniques, which are the subject of this patent, it will now become apparent to those of ordinary skill in the art that other embodiments incorporating these concepts, structures and techniques may be used. Accordingly, it is submitted that that scope of the patent should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed is:

1. A network comprising:

four or more nodes, each node having a plurality of optical data terminals to provide optical beam hopping capability to connect to at least two remote nodes using an optical link;

wherein each of the nodes includes:

a network node controller;

a network processor;

an RF system connected to the node controller and the network processor, establishing RF links with each of the other nodes, and monitoring spatial and temporal information of each of the other nodes; and

an optical system connected to the network node controller and including an optical bench and the optical data terminals;

wherein at least a first pair of nodes and a second pair of nodes connected in a first network topology during a first period of time, and

wherein at least a different first pair of nodes and a different second pair of nodes connected in a second network topology during a second period of time,

wherein a first data path is established among the connected nodes during the first period of time and a second data path is established among the connected nodes during a second period of time,

wherein adaptive routing and link switching are used to select the first and second network topology based upon the number of nodes in the network and based on the spatial and temporal information of the nodes in the network.

2. The network of claim **1** wherein each node is assigned a time slot to transmit data during the first period of time and each node is assigned a time slot to transmit data during the second period of time.

3. The network of claim **1** wherein each node is assigned a time slot to receive data during the first period of time and each node is assigned a time slot to receiving data during the second period of time.

4. The network of claim **1** wherein the time between the end of the first time period and the start of the second time period is 15 milliseconds or less.

5. The network of claim **1** wherein:

each node is assigned a time slot to transmit data during the first period of time;

each node is assigned a time slot to receive data during the first period of time, and the time slots to transmit data coincide with the time slots to receive data.

6. The network of claim **1** wherein the duration of the time slots can different for each network topology.

7. The network of claim **1** wherein the duration of either of the first or second periods of time is based upon a factor selected from the group consisting of:

real-time traffic demand;

environment conditions;

the status of at least one node; and

the status of at least one optical link.

8. The network of claim **1** wherein of either the first or second network topology is based upon a factor selected from the group consisting of:

real-time traffic demand;

environment conditions;

the status of at least one node; and

the status of at least one optical link.

9. The network of claim **1** wherein the optical data terminal includes an optical phased array.

10. The network of claim **1** wherein each node further includes a tracking assembly to spatially track a plurality of remote nodes and each node transmits tracking beacons to be tracked by a plurality of remote nodes.

11. The network of claim **10** wherein the tracking assembly has an attribute selected from the group consisting of:

smaller size compared to the optical data terminal;

a lower weight compared to the optical data terminal;

a lower power requirement compared to the optical data terminal; and

a lower cost compared to the optical data terminal.

12. The network of claim **1** wherein each node further includes an acquisition assembly providing capability to acquire the spatial position of a plurality of remote nodes.

13. The network of claim **12** where the acquisition assembly includes an RF antenna.

14. The network of claim **12** wherein the acquisition assembly includes an optical phased array.

15. The network of claim **12** wherein the acquisition assembly further provides capability to spatially track a plurality of remote nodes.

16. A method for transmitting data in a free-space optical network having four or more nodes, the method comprising:

establishing an RF overlay network including a first node, a second node, a third node, and a fourth node, wherein each of the nodes is connected with wireless RF links the other nodes;

each of the nodes monitoring spatial and temporal information of each of the other nodes using the wireless RF links;

selecting a first network topology to define a first data path between the first node and the second node and second data path between the third node and the fourth node;

pointing optical data beams, using the spatial and the temporal information from the RF overlay network, and connecting the first node and the second node and connecting the third node and the fourth node according to the first network topology;

transmitting data from the first node to the second node and from the third node to the fourth node during a first period of time;

using adaptive routing and link switching selecting a second network topology based upon a number of nodes in the network and locations of the nodes in the network, wherein the second network topology defines a third data path between the first node and the third node and a fourth data path between the second node and the fourth node;

pointing optical data beams, using the spatial and the temporal information from the RF overlay network, and connecting the first node and the third node and connecting the second node and the fourth node according to the second network topology; and

transmitting data from the first node to the third node and from the second node to the fourth node during a second period of time.

17. The method of claim **16** wherein the second node transmits data to the first node during the first time period.

18. The method of claim **16** wherein the time between the end of the first time period and the start of the second time period is 15 milliseconds or less.

19. The method of claim **16** wherein electronic steeling is used to point the optical data beams.

20. The method of claim **16** further comprising pointing tracking beacons from the first and second nodes.

21. The network of claim **1** wherein each of the nodes includes:

an RF system to send traffic load and link state information to one or more other nodes and to receive traffic load and link state information from one or more other nodes; and

a network processor coupled to the RF system and operable to maintain the topology of the network and to participate in the distributed calculation of primary and backup routes using traffic load and link state information received from one or more other nodes.

22. The method of claim **16** wherein using adaptive routing and link switching to select the second network topology comprises using traffic load and link state information shared via an RF overlay network.

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