

PROCESSED BROADBAND SATELLITE COMMUNICATION SYSTEM WITH SPATIALLY MULTIPLEXED OPTICAL FEEDER LINKS

TECHNICAL FIELD

[0001] A satellite communication system employs multiple free space optical links supported by respective ground stations, to provide spatial multiplexing of user data streams in one or both of the forward-link and return-link directions.

BACKGROUND

[0002] Multiple challenges arise in the context of designing, deploying, and operating satellite communication networks, with capacity limitations and spectrum efficiency representing recurring issues with no simple solutions. Increasing data rates needed for delivery of richer media and the desire to reduce latency exacerbate such issues.

[0003] One approach taken in addressing bandwidth limitations involves the use of free space optical “feeder links” between a satellite and the terrestrial gateways stations that send forward traffic to the satellite and receive return traffic from the satellite. Certain satellite communication systems also use optical links for inter-satellite communications, with these inter-satellite links improving overall capacity or providing additional coverage and traffic routing flexibility.

[0004] Despite offering significant bandwidth gains and concomitant improvements in feeder-link capacity as compared to radio frequency (RF) feeder links, optical feeder links are prone to impairment as a consequence of cloud cover and atmospheric effects such as beam wandering and scintillation. Scintillation arises from fluctuation of the index of refraction due to small variations of temperature in the propagation medium, resulting in variation of the received optical power. Due to these impairments, an optical feeder link is more prone to severe signal degradation or complete signal loss than a RF feeder link.

[0005] Using diverse optical links ameliorates the problems arising with use of a single optical link, but diversity transmission over multiple optical links brings its own challenges in terms of how to use the multiple links for transmitting the information in question. Further challenges arise in the context of underlying technologies, such as ground-based beamforming, where the ground segment of a satellite communication system performs or controls the signal weightings used to form forward or return beams used to serve user terminals in different locations.

SUMMARY

[0006] Disclosed techniques apply to forward-link and/or reverse-link transmissions between a satellite and a ground segment of a satellite communications system (SCS). For at least some user data streams conveyed over the optical feeder link between the satellite and the ground segment, individual user data streams are divided into two or more user data sub-streams. A different optical signal carries each user data sub-stream associated with the same user data stream, with each optical signal associated with a different optical ground station (OGS) of the SCS. Spatial diversity results because the OGSs are geographically separated, meaning that fading events are not correlated across the respective optical signals. Each user data sub-stream carries a different encoded data from the corresponding user data stream, such that the full user data stream may be recovered at the receiving end even with the instantaneous loss of one or more of the user data sub-streams.

[0007] One embodiment comprises a method of operation in a SCS, with the method performed by a satellite. The method includes the satellite receiving two or more forward optical signals that convey a set of forward user data sub-streams collectively comprising a forward user data stream targeted to a user terminal served by the satellite. Each forward user data sub-stream comprises a different subset of data from the forward user data stream and is conveyed in a respective one of the two or more forward optical signals. Each forward optical signal is transmitted by a respective one among a plurality of geographically distributed OGSs of the SCS. The method further includes the satellite reassembling the forward user data stream from the set of forward user data sub-streams and transmitting the forward user data stream for reception by the targeted user terminal.

[0008] A related embodiment comprises a satellite configured for operation in a SCS. The satellite includes two or more optical receivers, each configured to receive a respective one among two or more forward optical signals transmitted from respective ones among a plurality of geographically distributed OGSs of the SCS. The two or more forward optical signals convey a set of forward user data sub-streams collectively comprising a corresponding forward user data stream targeted to a UT served by the SCS. There are at least two forward user data sub-streams in the set, with each forward user data sub-stream comprising a different subset of data from the forward user data stream and conveyed via a respective one of the two or more forward optical signals. The satellite further includes communications circuitry that is configured to: (a) receive the set of forward user data sub-streams, as output from the two or more optical receivers; (b) reassemble the forward user data stream from the set of forward user data sub-streams; and (c) transmit the forward user data stream for reception by the targeted UT.

[0009] Another embodiment comprises a method of operation in a SCS, where the method is performed by a satellite and includes the satellite receiving a radio frequency (RF) return uplink signal from a UT served by the SCS. Here, the return uplink signal conveys a return user data stream. The satellite divides the return user data stream into a set of return user data sub-streams, the set of return user data sub-streams comprising two or more return user data sub-streams, each conveying a different subset of data from the return user data stream. Further, the method includes the satellite impressing each return user data sub-stream into a respective one among two or more return optical signals. Each return optical signal is transmitted by the satellite via a corresponding optical transmitter onboard the satellite and targets a respective one among a plurality of geographically distributed OGS.

[0010] A related embodiment comprises a satellite configured for operation in a SCS. The satellite includes a user link antenna system, communications circuitry, and two or more optical transmitters. The user link antenna system is configured to receive a RF return uplink signal from a UT served by the SCS, where the return uplink signal conveys a return user data stream. The communications circuitry is configured to: (a) divide the return user data stream into a set of return user data sub-streams, the set of return user data sub-streams comprising two or more return user data sub-streams, and each return user data sub-stream conveying a different subset of data from the return user data stream; and (b) impress each return user data sub-stream into a respective one among a plurality of return optical signals. Each return optical signal is transmitted via a corresponding one of the optical transmitters onboard the satellite and it targets a respective one among a plurality of geographically distributed OGSs.

[0011] Of course, the present invention is not limited to the above features and advantages. Indeed, those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 is a block diagram of a satellite communications system (SCS), according to one embodiment.

[0013] Figure 2 is a diagram of an example satellite service area and the subdivision thereof into a plurality of forward user beam coverage areas.

[0014] Figure 3 is a diagram of an example arrangement of optical channel signals in respective forward optical signals used in a feeder link between a satellite and respective optical ground stations (OGSs).

- [0015] Figure 4 is a block diagram of an optical transmitter such as may be used in an OGS or onboard a satellite, according to one embodiment.
- [0016] Figure 5 is a block diagram of a satellite, according to an example embodiment.
- [0017] Figure 6 is a block diagram of a user link antenna system and associated transmit circuitry, such as may be implemented onboard a satellite according to one embodiment.
- [0018] Figure 7 is a block diagram of a user link antenna system and associated transmit circuitry, such as may be implemented onboard a satellite according to another embodiment.
- [0019] Figure 8 is a block diagram of example circuitry configured to form a set of user data sub-streams from a corresponding user data stream, such as may be used in a ground segment of a SCS for forward spatial multiplexing via an optical feeder link to a satellite or used onboard a satellite for return spatial multiplexing to the ground segment via the optical feeder link.
- [0020] Figure 9 is a block diagram of example circuitry configured to reassemble a user data stream from a corresponding set of user data sub-streams, such as may be used in a ground segment of a SCS to reassemble return user data streams transmitted over the optical feeder link using return spatial multiplexing or used onboard a satellite to reassemble forward user data streams transmitted over the optical feeder link using forward spatial multiplexing.
- [0021] Figure 10 is a block diagram of an optical receiver, according to one embodiment, such as may be used in an OGS to receive a return optical signal from a satellite or used in a satellite to receive a forward optical signal from an OGS.
- [0022] Figure 11 is a diagram of an example satellite service area and the subdivision thereof into a plurality of forward user beam coverage areas.
- [0023] Figure 12 is a block diagram of a SCS, according to one embodiment.
- [0024] Figure 13 is a block diagram of a user link antenna system and associated receiver circuitry, according to one embodiment.
- [0025] Figure 14 is a block diagram of a user link antenna system and associated receiver circuitry, according to another embodiment.
- [0026] Figure 15 is a block diagram of a satellite, according to one embodiment.
- [0027] Figure 16 is a logic flow diagram of a method of operation by a satellite.
- [0028] Figure 17 is a logic flow diagram of another method of operation by a satellite.

DETAILED DESCRIPTION

- [0029] Figure 1 illustrates an example satellite communications system (SCS) 10 according to one embodiment. A communications and control subsystem (CCS) 12 of the SCS 10 receives an incoming user data stream 14 via a communications link 16 with one or more external

networks 18, such as the Internet or a telecommunications network. The CCS 12 forms a forward user data stream 20 corresponding to the incoming user data stream 14, such as by applying block encoding or other processing associated with the transport and transmission of data via the SCS 10, and spatial diversity processing circuitry 22 divides the forward user data stream 20 into a set of two or more forward user data sub-streams 26.

[0030] The subdivision of the forward user data stream 20 provides the basis for forward spatial multiplexing, as described herein, which also may be referred to as forward “spatial transmit diversity.” In the non-limiting example of Figure 1, the forward user data stream 20 is divided into a set of three forward user data sub-streams 26, which are denoted individually as forward user data sub-streams 26-1, 26-2, and 26-3. Here, and elsewhere, suffixing is used only where helpful to the explanation. Thus, the reference number “26” without suffixing may be used to refer to any given forward user data sub-stream(s).

[0031] In one or more embodiments, the spatial diversity processing circuitry 22 forms the forward user data stream 20 by block encoding the incoming user data stream 14, and it forms the set of forward user data sub-streams 26 by dividing each encoded block of the forward user data stream 20 into a respective set of sub-blocks, with each sub-block corresponding to a respective one of the forward user data sub-streams 26. With this encoding and sub-dividing, each forward user data sub-stream 26 carries a different portion of the data comprised in the forward user data stream 20, and the receiver may be able to recover the forward user data stream 20 despite instantaneous loss of any given one(s) of the forward user data sub-streams 26.

[0032] The CCS 12 sends each forward user data sub-stream 26 in the set to a different optical ground station (OGS) 28, with each OGS 28 coupled to the CCS 12 via a respective terrestrial communication link 30. Each OGS 28 transmits a forward optical signal 32 towards a satellite 34 of the SCS 10, with each forward optical signal 32 conveying a different one of the forward user data sub-streams 26 included in the set of forward user data sub-streams 26 formed by the spatial diversity processing circuitry 22 from the forward user data stream 20.

[0033] The satellite 34 includes a bus 36, which comprises power, telemetry, and control systems for operation and control of the satellite 34. Further, the satellite 34 includes a payload 38, which comprises communications circuitry 40, including spatial diversity processing circuitry 42 that is configured for sub-stream processing.

[0034] The satellite 34 includes an optical receiver—not shown in Figure 1—for each forward optical signal 32. In one example, the satellite 34 carries N optical receivers, where N is an integer number greater than or equal to two (2). With N optical receivers, the satellite 34 is

operative to receive up to N forward optical signals 32 simultaneously, although not all optical receivers need be used at the same time.

[0035] The communications circuitry 40 recovers the forward user data sub-stream 26 impressed in each forward optical signal 32—i.e., it recovers the complete set of forward user data sub-streams formed by the ground segment for the forward user data stream 20, and it reassembles the set to recover the forward user data stream 20. For example, in one embodiment, each forward optical signal 32 is a dense wavelength division multiplexed (DWDM) signal comprising a plurality of optical channel signals at respective optical wavelengths. Each such optical channel signal is an optical carrier at a respective optical wavelength and impressing a signal into the carrier, such as a forward user data stream 20 or forward user data sub-stream, refers to modulating the optical carrier according to the signal. One or more embodiments use digital modulation, while one or more other embodiments use radio frequency (RF) modulation. Regardless, the receiving satellite 34 demodulates each optical channel signal to recover the modulated information—i.e., to recover the signal(s) impressed into each optical channel signal. With this arrangement, transmitting a set of forward user data sub-streams 26 to the satellite 34 comprises transmitting each forward user data sub-stream 26 on a different forward optical signal 32 via a respective one of the optical channel signals comprised in that forward optical signal 32.

[0036] After demodulating and decoding the set of forward user data sub-streams 26, the communications circuitry 40 reassembles the forward user data stream 20 and transmits it to a targeted user terminal (UT) 44. In one or more embodiments, the transmission is a beamformed transmission, where the satellite 34 transmits a forward user beam 46 that illuminates a forward user beam coverage area 48 in which the targeted UT 44 is located. While not shown in Figure 1, the targeted UT 44 may be configured as a communications gateway or access point, such that it communicatively couples one or more downstream devices, such as TVs, laptops, phones, etc., to the external network(s) 18 via the SCS 10.

[0037] Figure 2 illustrates an example scenario where a satellite service area 50 is logically subdivided into a plurality of forward user beam coverage areas 48, where the satellite service area 50 comprises a potentially large geographic area, such as the continental United States. The SCS 10 may illuminate each forward user beam coverage area 48 with a corresponding forward user beam 46—e.g., a corresponding spot beam—with each forward user beam 46 being a directional radio beam carrying forward user data streams 20 for the UTs 44 assigned to the forward user beam 46.

[0038] The SCS 10 may reuse communications resources across the satellite service area 50 according to a color reuse pattern, where “color” refers to radio frequencies, signal polarizations, or combinations of frequency and polarization. For example, adjacent forward user beam coverage areas 48 are served using forward user beams 46 at different radio frequencies and/or different signal polarizations, to avoid inter-beam interference.

[0039] With all of the above in mind, it shall be appreciated that the SCS 10 in one or more embodiments is configured to receive a potentially large plurality of incoming user data streams 14, with each incoming user data stream 14 targeting a different UT 44, and with the SCS 10 applying spatial diversity transmission in the forward direction to one, some, or all of the incoming user data streams 14. That is, as used herein, the phrase “forward spatial diversity transmission” refers to the use of spatial multiplexing in the forward direction via the optical feeder link between two or more OGSs 28 and the satellite 34. In like manner, subsequent examples involve “return spatial multiplexing,” which refers to the use of spatial transmit diversity in the return direction via the optical feeder link between the satellite 34 and two or more OGSs 28.

[0040] The number of user data streams 14 incoming to the SCS 10 varies over time and the SCS 10 in one or more embodiments decides which ones and/or how many of the incoming user data streams 14 to transmit using forward spatial multiplexing based on any one or any combination of: the number of operational OGSs 28 available in the SCS 10, weather conditions affecting respective ones of the OGSs 28, the type(s) of communications service(s) associated with respective ones of the incoming user data streams 14, overall forward communication needs of the UTs 44 served by the SCS 10, and/or priorities or service agreements associated with respective ones of the UTs 44.

[0041] In one or more embodiments, the ground segment of the SCS 10 includes a potentially large population of geographically distributed OGSs 28, and different subsets among the population of OGSs 28 may be operated as respective forward diversity sets, each such set of OGSs 28 responsible for forward spatial multiplexing of different sets of forward user data sub-streams 26. These different subsets of OGSs 28 may transmit to the same satellite 34 or to different satellites 34 in the SCS 10, e.g., the satellite 34 depicted in Figure 1 may be one in a constellation of satellites 34.

[0042] Further, the SCS 10 in one or more embodiments may be configured to use different “degrees” of forward spatial multiplexing for different UTs 44 or for different groups of UTs 44. Thus, the forward user data stream 20 targeted to a given first UT 44 may be subdivided into only two forward user data sub-streams 26 for forward spatial multiplexing over the optical

feeder link to the satellite 34, while the forward user data stream 20 targeted to a given second UT 44 is subdivided into three, four, or more forward user data sub-streams 26 for forward spatial multiplexing over the optical feeder link to the satellite 34. Here, the forward optical signal(s) 32 represent the optical feeder link.

[0043] For each incoming user data stream 14 to which the SCS 10 applies forward spatial multiplexing, the SCS 10 forms a forward user data stream 20, divides the forward user data stream 20 into a corresponding set of two or more forward user data sub-streams 26, and transmits each forward user data sub-stream 26 on a different one among two or more forward optical signals 32. In this way, it shall be understood that two or more forward optical signals 32 collectively convey the forward user data stream 20, based on each one of those forward optical signals 32 conveying a respective forward user data sub-stream 26 from the corresponding set of forward user data sub-streams 26.

[0044] In turn, the satellite 34 recovers each forward user data stream 20 from the correspondingly received set of forward user data sub-streams 26 and transmits each recovered forward user data stream 20 via the forward user beam 46 that illuminates the forward user beam coverage area 48 that contains the UT 44 targeted by the forward user data stream 20. As such, the satellite 34 may support simultaneous formation of a plurality of forward user beams 46, each illuminating a respective one among the plurality of forward user beam coverage areas 48 that subdivide a larger satellite service area 50.

[0045] Figure 3 illustrates an example arrangement for the forward optical signals 32, with three shown as forward optical signals 32-1, 32-2, and 32-3. A first OGS 28-1 transmits the first optical signal 32-1, a second OGS 28-2 transmits the second forward optical signal 32-2, and a third OGS 28-3 transmits the third forward optical signal 32-3. Assuming that the OGSs 28-1, 28-2, and 28-3 are operated as a forward spatial multiplexing set for one or more forward user data streams 20, each such forward user data stream 20 is subdivided across the three forward optical signals 32-1, 32-2, and 32-3.

[0046] For example, each forward optical signal 32 is a multiplexed collection of individual optical channel signals 60, each optical channel signal 60 being at a respective optical wavelength, e.g., f_1 , f_2 , and so on. Figure 3 suggests N optical channel signals 60 per forward optical signal 32, where N is an integer number greater than one. N may be sixty-four (64), for example. To transmit a given incoming user data stream 14 using forward spatial multiplexing, the CCS 12 forms the corresponding forward user data stream 20, e.g., based on block encoding the incoming user data stream 14, and then divides the corresponding forward user data stream 20 into a set of two or more forward user data sub-streams 26, e.g., based on subdividing the

encoded data blocks such that each forward user data sub-stream 26 carries a different portion of the data contained in the forward user data stream 20.

[0047] Each such forward user data sub-stream 26 is conveyed to the satellite 34 on a respective optical channel signal 60 in a respective one of the three forward optical signals 32-1, 32-2, and 32-3. The same-frequency optical channel signal 60 may be used on each forward optical signal 32-1, 32-2, and 32-3, to carry the respective three forward user data sub-streams 26 divided out from the corresponding forward user data stream 20, or different-frequency optical channel signals 60 may be used across the set of forward optical signals 32 to carry the set of forward user data sub-streams 26 to the satellite 34.

[0048] Figure 4 illustrates an optical transmitter 70 that is configured for the transmission arrangement suggested in Figure 3, with Figure 3 assuming N optical channel signals 60. There are N RF modulators 72, each receiving a respective transmit (TX) signal 74. Each TX signal 74 is, for example, one of a respective forward user data stream 20, a forward user data sub-stream 26, or control signaling conveying configuration or control signaling from the ground segment to the satellite 34.

[0049] In the case that the TX signal 74 fed into one of the N RF modulators 72 is a forward user data stream 20, it shall be understood that that forward user data stream 20 is being transmitted to the satellite 34 without the use of forward spatial multiplexing—i.e., the undivided forward user data stream 20 is conveyed via a single forward optical signal 32. In the case that the TX signal 74 fed into one of the N RF modulators 72 is a forward user data sub-stream 26, it will be understood that each of the remaining forward user data sub-streams 26 in the corresponding set is transmitted from a respective one among the set of OGSs 28 providing the forward spatial multiplexing. That is, for forward spatial multiplexing, a forward user data stream 20 is divided into a set of forward user data sub-streams 26, with each forward user data sub-stream 26 conveyed via a different forward optical signal 32.

[0050] Each RF modulator 72 outputs a corresponding modulated signal 76 at a RF or intermediate frequency (IF). Indeed, because each modulated signal 76 will be carried via a respective one among the plurality of optical channel signals 60, all modulated signals 76 may be at the same frequency. In any case, each modulated signal 76 is input to a respective one among N optical modulators 78, with each optical modulator 78 outputting a respective one of the N optical channel signals 60.

[0051] To do so, each optical modulator 78 applies the input modulated signal 76 to a DC bias signal via a summing circuit 80, and the resulting biased signal is input to a Mach-Zender modulator (MZM) 82 or other suitable optical modulation circuit. Each MZM 82 operates on a

respective optical carrier signal output by a laser source 84, with each laser source 84 outputting light at a respective optical wavelength, e.g., see the frequencies f_1 , f_2 , and so on, as depicted in Figure 3. Thus, each optical channel signal 60 is at a different optical wavelength and an optical combiner 90 combines them via DWDM to form the corresponding forward optical signal 32, which may be transmitted from the OGS 28 towards the satellite 34 via transmission optics 92, such as a lens or prism.

[0052] Figure 5 illustrates corresponding details at the satellite 34, according to an example embodiment. The satellite 34 includes two or more optical receivers 100. In at least one embodiment, each optical receiver 100 includes an optical beam steering assembly 102, such as a steerable lens or prism that is rotatable about two or more axes, or a mirror-based pointing system, to align reception with a selected OGS 28 from among a plurality of geographically distributed OGSs 28. Such operation allows a given optical receiver 100 to be “repointed” as needed, to allow for the use of different OGSs 28. Note, too, that the satellite 34 may not necessarily use all its optical receivers 100 at the same time. For example, forward spatial multiplexing to the satellite 34 may involve fewer than the maximum number of forward optical signals 32 that the satellite 34 can receive simultaneously.

[0053] Each optical receiver 100 outputs a plurality of recovered TX signals 104. Here, each recovered TX signal 104 is recovered from a respective one of the optical channel signals 60 multiplexed in the forward optical signal 32, and it corresponds to the TX signal 74 conveyed by the respective optical channel signal 60. Thus, the plurality of recovered TX signals 104 output from each optical receiver 100 corresponds to the plurality of TX signals 74 conveyed by the respective forward optical signal 32 received by the optical receiver 100. At any given time, then, the plurality of recovered TX signals 104 output from each optical receiver 100 may convey any one or more of a plurality of forward user data streams 20, a plurality of forward user data sub-streams 26 (each associated with a different forward user data stream 20), and/or configuration/control signaling.

[0054] The communications circuitry 40 onboard the satellite 34 includes a plurality of demodulators 106 configured to demodulate the plurality of recovered TX signals 104 output from each optical receiver 100. The demodulators 106 output corresponding pluralities of demodulated signals 108—i.e., a plurality of demodulated signals 108 for each forward optical signal 32 received by the satellite 34.

[0055] Further included in the communications circuitry 40 is baseband processing circuitry 110, which is configured to decode the respective pluralities of demodulated signals 108 and output a corresponding plurality of baseband downlink signals 112 comprising streams of user

traffic to be transmitted by the satellite 34. The baseband processing circuitry 110 also outputs one or more control/configuration signals to the extent that the forward optical signals 32 convey such signaling.

[0056] Each baseband downlink signal 112 is a digital-domain signal carrying the user traffic targeted for transmission in a given forward user beam 46, e.g., time-multiplexed data for serving respective ones of the UTs 44 that are assigned to the given forward user beam 46. Thus, there is a baseband downlink signal 112 for each forward user beam 46 provided by the satellite 34. Transmit circuitry 114 performs, among other things, digital-to-analog conversion, modulation, up-conversion, filtering, and amplification, for outputting a plurality of RF transmit signals 116 that are transmitted via a user link antenna system 120 that is onboard the satellite 34. The number and nature of the RF transmit signals 116 depends on the mechanism used to form the forward user beams 46.

[0057] For example, Figure 6 illustrates one embodiment of the user link antenna system 120, where the user link antenna system 120 comprises a plurality of feed horns or other radiating elements 122 that output each RF transmit signal 116 as a corresponding forward user beam 46. That is, the user link antenna system 120 transmits the RF transmit signals 116 as respective spot beams, each spot beam oriented to illuminate a respective one of the forward user beam coverage areas 48 comprised within the overall satellite service area 50. In such embodiments, there may be a one-to-one correspondence between baseband downlink signals 112 and the RF transmit signals 116—i.e., each baseband downlink signal 112 is used to form a corresponding one of the RF transmit signals 116, and each RF transmit signal 116 is radiated as a spot beam via a corresponding one of the feed horns 122 of the user link antenna system 120.

[0058] The transmit circuitry 114 can be understood as providing transmit signal paths 130 for processing the baseband downlink signals 112, to form the RF transmit signals 116. In the example embodiment of Figure 6, each transmit signal path 130 includes a digital-to-analog converter (DAC) 132, to output an analog signal corresponding to a respective one of the baseband downlink signals 112, a modulator 134 responsive to the analog signal and operative to output a RF or IF analog signal, a mixer 136 to upconvert the RF/IF signal to the desired RF downlink signal frequency, and a power amplifier (PA) 138 to amplify the upconverted signal for transmission.

[0059] Figure 7 illustrates another embodiment of the SCS 10/satellite 34, which relies on phase-array beamforming to produce the plurality of forward user beams 46. The communications circuitry 40 of the satellite 34 includes beamforming circuitry comprising splitter circuitry 140, which may operate on the baseband downlink signals 112 in the digital

domain, or which may include DACs for conversion of them to the analog domain. As with Figure 6, each baseband downlink signal 112 may be understood as carrying the user traffic for UTs 44 served by a particular forward user beam 46 provided by the satellite 34, e.g., according to a time-multiplexing arrangement.

[0060] The splitter circuitry 140 creates M copies of each baseband downlink signal 112, where M equals the number of antenna elements being used for forward link beamforming. Thus, the splitter circuitry 40 outputs a set of M duplicate signals 142 for each baseband downlink signal 112 input to it. Weighting circuitry 144 applies a respective set of forward beam weights 146 to each set of M duplicate signals 142, such that the weighting circuitry 144 outputs a set of M weighted signals 148, with each such set corresponding to a respective one of the baseband downlink signals 112.

[0061] With each baseband downlink signal 112 carrying user traffic corresponding to one forward user beam 46, the set of forward beam weights 146 used to form the corresponding set of M weighted signals 148 is calculated such that simultaneous transmission of the set of M weighted signals 148 from respective antenna elements of the involved antenna array result in far-field signal superpositions that form the corresponding forward user beam 46. In this regard, it shall be understood that each duplicate signal 142 in each set of M duplicate signals 142 maps to a respective antenna element, with each beam weight in the corresponding set of forward beam weights 146 being a complex value that controls the relative signal attenuation and phase of the duplicate signal 142, as transmitted from the respective antenna element.

[0062] Combining circuitry 150 performs combining of the respective sets of M weighted signals 148, and outputs a corresponding set of M combined signals 152. Each combined signal 152 in the set of M combined signals 152 is a summation across the sets of M weighted signals 148 on a per antenna element basis—that is, there is one combined signal 152 for each of the M antenna elements, formed as a combination of the weighted signals 148 that map to that element. Each of the M combined signals 152 passes through a respective transmit signal path 154, which provides, for example, modulation, mixing, and power amplification, resulting in the output of M antenna element signals 156. Each of the M antenna element signals 156 is applied to an antenna array 158 for transmission from a respective antenna element 160 of the antenna array 158. The antenna array 158 comprises the user link antenna system 120, or at least a portion thereof.

[0063] Particularly, there are M antenna elements 160 used in the forward beamforming and each one of the M antenna element signals 156 corresponds to a respective one of the M antenna elements 160. Simultaneous transmission of the M antenna element signals 156, which may be an ongoing operation, yields the above-described far-field signal superpositions, resulting in the

formation of a plurality of forward user beams 46, each forward user beam 46 being a radio beam conveying the user traffic of UTs 44 assigned to it. In this regard, it shall be understood that the respective sets of forward beam weights 146 may be updated, e.g., on a recurring basis.

[0064] In one embodiment, the communications circuitry 40 of the satellite 34 includes channel estimation circuitry. Such circuitry uses channel state information (CSI) obtained for one or more UTs 44 operating in each forward user beam coverage area 48, which areas may be predefined. Particularly, the channel estimation circuitry uses the CSI to estimate the forward propagation channels between the antenna array 158 and each such UT 44. For example, there may be at least one UT 44 at or near a geographic location corresponding to the nominal beam center of each forward user beam 46, with each such UT 44 used as a reference UT (RUT) for determining the CSI. In another embodiment, the ground segment of the SCS 10 receives such CSI as feedback relayed via the satellite 34, and the CCS 12 is configured to compute the respective sets of forward beam weights 146 and transmit them to the satellite 34, for application onboard the satellite 34 via the weighting circuitry 144.

[0065] To better understand the handling of forward user data streams 20 and sets of forward user data sub-streams 26 onboard the satellite 34, Figure 8 illustrates example details for the spatial diversity processing circuitry 22 implemented in the CCS 12 of the ground segment. A block encoder circuit 170 receives a forward user data stream 20—e.g., data packets of a data packet flow targeting a particular UT 44. The block encoder circuit 170 outputs a corresponding stream of encoded blocks 172 and a divider circuit 174 divides each encoded data block 172 into a corresponding set of sub-blocks, with each sub-block in the set thus containing a different portion of encoded data from the encoded data block 172. Dividing each encoded block 172 in the stream of encoded blocks 172 thus creates respective streams of sub-blocks, with each sub-block stream being a respective forward user data sub-stream 26.

[0066] Figure 9 depicts corresponding example details for the spatial diversity processing circuitry 42 included in the communications circuitry 40 that is onboard the satellite 34. Such circuitry includes identification circuitry 180, which receives recovered forward user data sub-streams 182, where the term “recovered” refers to the fact that these forward user data sub-streams 182 are extracted from respective ones of the recovered optical channel signals 60 contained in the two or more forward optical signals 32 received by the satellite 34. Each such recovered forward user data sub-stream 182 may carry an explicit stream identification (ID), indicating the forward user data stream 20 to which it belongs. Alternatively, the order in which forward user data sub-streams 26 are impressed into the respective forward optical signals 32 provides for implicit stream identification, e.g., the satellite 34 may be configured to treat optical

channel signals 60 at the same optical wavelength as carrying respective forward user data sub-streams 26 all belonging to the same forward user data stream 20. For example, in the context of Figure 3, the “f1” optical channel signal 60 in each forward optical signal 32 may be implicitly understood as carrying a respective one among a set of forward user sub-stream 26 constituting one forward user data stream 20.

[0067] The CCS 12 and the satellite 34 may be configured with a common mapping or understanding of the use of the forward optical signals 32, e.g., with a particular pattern or range of optical channel signals 60 predesignated for carrying forward user data sub-streams 26, other predesignated for carrying undivided forward user data streams 20, and still others for carrying beam weights and/or other control or configuration signaling. Of course, these pre-designations may be updated from time to time, to reflect changing spatial multiplexing configurations adopted responsive to changing weather conditions or changing needs or conditions within the SCS 10.

[0068] Depending upon how sub-stream/stream affiliations are indicated, the identification circuitry 180 may or may not need to decode the recovered forward user data sub-streams 182. In any case, the identification circuitry 180 groups the recovered forward user data sub-streams 182 according to their corresponding forward user data streams 20—and reassembly circuitry 184 uses each such group to recover the corresponding forward user data stream 20. Figure 8 uses the reference number “186” to identify each recovered forward user data stream.

[0069] Baseband downlink signal generation circuitry 188 forms the aforementioned baseband downlink signals 112 based on processing the recovered forward user data streams 186, and further based on any recovered forward user data streams 190 corresponding to forward user data streams 20 that were transmitted without using forward spatial multiplexing. Such processing includes, for example, forming each forward downlink signal 112 as a data stream containing the user traffic for transmission via a respective one of the forward user beams 46.

[0070] Figure 10 illustrates an optical receiver 100 according to an example embodiment, with the understanding that the satellite 34 has two or more optical receivers 100 onboard, for receiving two or more respective forward optical signals 32, each transmitted from a different one among a plurality of geographically distributed OGSs 28. The optical receiver 100 includes an optical demultiplexer 200, which comprises a set of filters, for example, and is configured to demultiplex the plurality of optical channel signals 60 comprised in a forward optical signal 32 incoming to a lens or other optical receiving element 202 of the optical receiver 100.

[0071] For clarity, the optical channel signals 60 that are demultiplexed from the incoming forward optical signal 32 are referred to as “recovered optical channel signals 204.” A respective

focusing lens or other optical element 206 directs each recovered optical channel signal 204 to a corresponding photodetector 208, which may be implemented as a photodiode. The photodetectors 208 output the plurality of recovered TX signals 104, which correspond with the TX signals 104 shown in the example optical transmitter 70 of Figure 4.

[0072] The foregoing details focus on the use of forward spatial multiplexing on the optical feeder link between the ground segment of the SCS 10 and the satellite 34. However, one or more embodiments of the SCS 10 implement return spatial multiplexing on the optical feeder link, in addition to, or as an alternative to, forward spatial multiplexing. “Return spatial multiplexing” as used herein refers to the subdivision of a return user data stream into a set of two or more return user data sub-streams and the transmission of each such return user data sub-stream on a different return optical signal.

[0073] Figure 11 illustrates the logical subdivision of the overall satellite service area 50 into a plurality of return user beam coverage areas 220. The return user beam coverage areas 220 may or may not be coincident with the forward user beam coverage areas 48. That is, the SCS 10 may or may not use the same number and orientation of return user beams as used for the forward user beams 46. Moreover, in at least some embodiments, return user beams are realized in the digital domain rather than in the physical-layer transmission domain.

[0074] Consider Figure 12, which depicts a UT 44 operating in a given return user beam coverage area 220 that is associated with a return user beam 222 having a beam footprint that illuminates the return user beam coverage area 220. The UT 44 transmits a return uplink signal 224, which is a RF signal using a designated frequency and/or polarization, with the return uplink signal 224 conveying a return user data stream 226. For example, the return user data stream 226 comprises data packets of a data packet flow outgoing from the UT 44, such as where the UT 44 carries on IP-based communications with a computer server or other system accessible through the SCS 10, via connection of the SCS 10 with the external network(s) 18.

[0075] There may be a large plurality of return user beam coverage areas 220, and at any given instant in time, there may multiple UTs 44 transmitting return uplink signals 224 for reception by the satellite 34. As such, the satellite 34 may receive a large plurality of return user data streams 226 concurrently, for retransmission to the ground segment of the SCS 10.

[0076] The satellite 34 may be configured on a static, semi-static, or dynamic basis to apply return spatial multiplexing to none, one, some, or all of the return user data streams 226 being received by it. For example, there may be specific UTs 44 or specific groups of UTs 44 for which the satellite 34 applies return spatial multiplexing, or there may be specific UTs 44 or groups of UTs 44 for which the satellite 34 does not apply return spatial multiplexing.

Additionally, or alternatively, the decision about whether, when, and to what degree the satellite 34 applies return spatial multiplexing may be orchestrated by the ground segment of the SCS 10. Orchestration depends on, for example, any one or more of the availability of OGSs 28, overall loading of the SCS 10, weather conditions affecting respective OGSs 28, etc. Control signaling sent from the CCS 12 to the satellite 34 via one or more of the forward optical signals 32 may be used to configure use of return spatial multiplexing by the satellite 34.

[0077] Turning back to the details of Figure 12, the satellite 34 receives the return uplink signal 224 from the UT 44 via the user link antenna system 120, which may include separate transmit and receive antenna sub-systems, or which may use the same antenna arrangements for transmit and receive on the user link. Receive (RX) circuitry 228 includes RF reception circuitry, such as filters, Low Noise Amplifiers (LNAs), down-converters, demodulators, and analog-to-digital converters, for recovering digital streams corresponding to return uplink signals 224 impinging on the user link antenna system 120. The RX circuitry 228 shall be understood as comprising a portion of the communications circuitry 40.

[0078] For return spatial multiplexing operations, the diversity processing circuitry 42 of the communications circuitry 40 may include circuitry like that shown in Figure 8. That is, the diversity processing circuitry 42 in one or more embodiments is configured to divide given return user data streams 226 into corresponding sets of two or more return user data sub-streams. In the example context of Figure 12, the satellite 34 has three onboard optical transmitters 230, each outputting a return optical signal 232 for reception by a respective one among three OGSs 28 that are participating in the return spatial multiplexing.

[0079] Figure 12 illustrates the dividing of the return user data stream 226 into a set of three return user data sub-streams 234, denoted as 234-1, 234-2, and 234-3. Each return user data sub-stream 234 is carried on a respective one of the three return optical signals 232. Of course, the number three is not limiting and return spatial multiplexing may involve no more than two return optical signals 232 or may involve more than three return optical signals 232. Each OGS 28 includes an optical receiver for receiving a respective one of the return optical signals 232. For example, each OGS 28 includes an optical receiver configured like or similar to the one shown in Figure 10.

[0080] Each OGS 28 transmits a return data signal 236 over its respective communication link 30 with the CCS 12, with each return data signal 236 conveying the return user data sub-stream 234 received by the OGS 28 via the respective return optical signal 232. Thus, in the example of Figure 12, the return data signal 236-1 carries the return user data sub-stream 234-1,

the return data signal 236-2 carries the return user data sub-stream 234-2, and the return data signal 236-3 carries the return user data sub-stream 234-3.

[0081] Thus, the CCS 12 receives all three return user data sub-streams 234 corresponding to the return user data stream 226 transmitted by the UT 44 and it includes identification and reassembly circuitry 240 that is configured like or similar to that shown for the satellite 34 in Figure 9. As such, the identification and reassembly circuitry 240 reforms the return user data stream 226 based on reassembling the set of return user data sub-streams 234. Finally, the CCS 12 outputs an outgoing user data stream 242 corresponding to the return user data stream 226, for transport to a remote device or system via the external network(s) 18. Of course, each return data signal 236 may carry pluralities of return user data sub-streams 234 and/or return user data streams 226 and the CCS 12 provides corresponding processing for all such streams and sub-streams.

[0082] Various embodiments take different approaches to “formation” of the return user beams 222. Figure 13 illustrates one embodiment where the user link antenna system 120 includes a number of spot-beam feeds 250, each outputting a RF receive signal 252 comprising return uplink signals 224 transmitted by respective UTs 44 operating within the return user beam coverage area 220 illuminated by the return user beam 222 provided by the spot-beam feed 250. Each such RF receive signal 252 passes through a corresponding RX signal path 254, which in such embodiments shall be understood as comprising part of the communications circuitry 40 onboard the satellite 34.

[0083] Each RX signal path 254 includes, for example, filter/LNA circuitry 256, a down-converter 258, a demodulator 260, and an analog-to-digital converter (ADC) 262. Each RX signal path 254 outputs a digital receive signal 264 in the digital domain, for processing by the baseband processing circuitry 110. Each digital receive signal 264 includes digital samples corresponding to the return uplink signal(s) 224 received via a respective one of the spot-beam feeds 250. In one example, the baseband processing circuitry 110 uses its knowledge of the scheduling by which respective UTs 44 in each return user beam coverage area 220 transmit return uplink signals 224, to determine which digital samples in the respective digital receive signals 264 correspond to which UTs 44.

[0084] In this manner, the baseband processing circuitry 110 recovers the respective return user data streams 226 being transmitted by the various UTs 44 served via the satellite 34. For each such return user data stream 226 transmitted using spatial multiplexing, the baseband processing circuitry 110 includes circuitry such as that shown for the CCS 12 in Figure 8—i.e., the baseband processing circuitry 110 is configured to divide each such return user data stream

226 into a set of two or more return user data sub-streams 234. Each such return user data sub-stream 234 in a given set of return user data sub-streams 234 is transmitted on a respective one of the return optical signals 232.

[0085] Figure 14 illustrates another embodiment in which the return user beams 222 are formed via reception beamforming onboard the satellite 34, where the user link antenna system 120 includes an antenna array 270 for reception beamforming. The antenna array 270 may be the same as or different than the antenna array 158 used in one or more embodiments of the satellite 34 for transmit beamforming.

[0086] The antenna array 270 includes a plurality of antenna elements 272. Each antenna element 272 outputs a corresponding antenna element signal 274, which is a RF signal that is a composite of the incoming RF signal(s) impinging on the respective antenna element 272 at any given instant in time. With M antenna elements 272, there are M antenna element signals 274. Note that the value of " M " for reception beamforming may or may not be the same as " M " in the context of transmit beamforming.

[0087] There are M receive signal paths 276 that output M RF signals 278, based on filtering, amplifying and/or frequency-converting the M antenna element signals 274. Splitter circuitry 280 creates respective sets of M duplicate signals 282, with each such set duplicating the M RF signals 278, albeit possibly at different signal levels or signal power. There is a set of M duplicate signals 282 for each return user beam 222. Each such set of M duplicate signals 282 is input into weighting circuitry 284. The weighting circuitry 284 applies a respective set of return beam weights 286 to each set of M duplicate signals 282. With each set of M duplicate signals 282 corresponding to a respective return user beam 222, each set of return beam weights 286 corresponds to a respective one of the return user beams 22.

[0088] Each set of M duplicate signals 282 is weighted by the corresponding set of return beam weights 286—each such set including a weight corresponding to each antenna element—to obtain a corresponding set of M weighted signals 290. Each such set of M weighted signals 290 is combined via combining circuitry 292, to form a corresponding return beam signal 294, which may be in the analog or digital domain. Each set of return beam weights 286 is computed to accentuate the signal-to-noise-and-interference ratio (SINR) of return uplink signals 224 originating from UTs 44 in the corresponding return user beam coverage area 220.

[0089] As with embodiments that use forward beamforming, the communications circuitry 40 of the satellite 34 may include channel estimation circuitry configured to compute the sets of return beam weights 286, or the satellite 34 may receive the sets of return beam weights 286 from the ground segment of the SCS 10—e.g., they may be computed by the CCS 12 and

forwarded to the satellite 34, on a recurring basis. CSI from one or more RUTs in each return user beam coverage area 220 may be used to compute the respective sets of return beam weights 286.

[0090] Additional functional logic in the communications circuitry 40 operates on the return beam signals 294, e.g., to assign return user data streams 226 to respective ones among the return optical signals 232 and/or to divide each of one or more of the return user data streams 226 into a corresponding set of two or more return user data sub-streams 234, with each such return user data sub-stream 234 conveyed on a respective return optical signal 232.

[0091] Figure 15 illustrates general details for the satellite 34 in a return-direction context and is applicable regardless of the particular mechanism used for forming the return user beams 222. In Figure 15, the user link antenna system 120 outputs antenna-received signals 300 corresponding to the return uplink signals 224 incoming to the user link antenna system 120 at any given time. These antenna-received signals 300 may be the signals 274 shown in Figure 14 or may be the signals 252 shown in Figure 13.

[0092] Receive circuitry 302 performs various receive-path operations on the antenna-received signals 300, e.g., filtering, amplification, down-conversion, demodulation, and digitization, for outputting digital RX signals 304 to the baseband processing circuitry 110. The baseband processing circuitry 110 forms baseband TX signals 306, each one targeting a respective optical channel signal in a respective one of the return optical signals 232. For reference, see the example case of Figure 3 where each forward optical signal 32 is DWDM signal that includes a plurality of optical channel signals 60 at respective optical wavelengths. Each baseband TX signal 306 at any given instant in time carries one of a return user data stream 226, a return user data sub-stream 234, or control signaling, and it shall be understood that the baseband processing circuitry 110 is configured, with respect to a set of return user data sub-streams 234 that collectively represent a return user data stream 226, to map each such return user data sub-stream 234 for transmission in a different one of the available return optical signals 232. The baseband TX signals 306 pass to modulation circuitry 308, which outputs analog TX signals 310, each such analog TX signal 310 being conveyed via a respective one of the optical channel signals in a respective one of the return optical signals 232.

[0093] Each return optical signal 232 is transmitted by a respective optical transmitter 312 onboard the satellite 34, and each optical transmitter 312 may include a steerable lens or other steerable optical element 314 for orienting the return optical signal 232 transmitted by it towards a selected OGS 28. For example, the CCS 12 may generate control signaling or scheduling information for the satellite 34 that determines how the satellite 34 orients or aims each return

optical signal 232. Each optical transmitter 312 may be configured like or similar to the optical transmitters used in the OGSs 28—see Figure 4.

[0094] Figure 16 illustrates a method 1600 of operation in a SCS 10, where the method 1600 is performed by a satellite 34 of the SCS 10 and includes: receiving (Block 1602) two or more forward optical signals 32 that convey a set of forward user data sub-streams 26 collectively comprising a forward user data stream 20 targeted to a UT 44 served by the satellite 34, each forward user data sub-stream 26 comprising a different subset of data from the forward user data stream 20 and conveyed in a respective one of the two or more forward optical signals 32, with each forward optical signal 32 transmitted by a respective one among a plurality of geographically distributed OGSs 28 of the SCS 10; reassembling (Block 1604) the forward user data stream 20 from the set of forward user data sub-streams 26; and transmitting (Block 1606) the forward user data stream 20 for reception by the targeted UT 44.

[0095] Reassembling the forward user data stream 20 from the set of forward user data sub-streams 26 comprises, for example, using header information included in one or more of the forward user data sub-streams 26, indicating a reassembly order for respective data blocks comprised in respective ones of the forward user data sub-streams 26 in the set. Reassembling the forward user data stream 20 in at least one embodiment comprises demodulating and decoding each forward user data sub-stream 26 in the set to recover corresponding encoded data sub-blocks, reassembling the encoded data sub-blocks in order, to obtain encoded data blocks, decoding the encoded data blocks to recover the forward user data stream 20, and generating a RF downlink signal modulated in dependence on the forward user data stream 20.

[0096] Transmitting the forward user data stream 20 for reception by the targeted UT 44 comprises forming a RF downlink signal modulated by the forward user data stream 20, and transmitting the RF downlink signal as per-element signals 156 from respective antenna elements 160 of an antenna array 158 onboard the satellite 34 according to a set of beam weights 146 calculated such that far-field superpositions of the per-element signals 156 form a forward user beam 46 that illuminates a forward user beam coverage area 48 associated with the targeted UT 44. In one embodiment, the method 1600 includes the satellite 34 receiving the set of beam weights 146 via one or more among the plurality of forward optical signals 32. In another embodiment, the method 1600 includes determining the set of beam weights 146 onboard the satellite 34, according to CSI obtained for one or more UTs 44 operating in the forward user beam coverage area 48.

[0097] In one or more embodiments, transmitting the forward user data stream 20 for reception by the targeted UT 44 comprises forming a RF downlink signal modulated by the

forward user data stream 20, and applying the RF downlink signal to a transmit feed horn 122 of a user link antenna system 120 onboard the satellite 34. Here, the transmit feed 122 is configured for spot-beam illumination of a corresponding forward user beam coverage area 48 associated with the satellite 34.

[0098] In one or more embodiments, the set of forward user data sub-streams 26 is one among a plurality of sets of forward user data sub-streams 26 received by the satellite 34 via the plurality of forward optical signals 32. Here, each forward optical signal 32 conveys a respective multiplexed plurality of forward user data sub-streams 26, with each forward user data sub-stream 26 in each respective multiplexed plurality of forward user data sub-streams 26 belonging to a respective one among a plurality of forward user data streams 20 being transmitted collectively by the plurality of forward optical signals 32. Correspondingly, the method 1600 includes the satellite 34 reassembling and transmitting the plurality of forward user data streams 20.

[0099] In at least one embodiment, the satellite 34 reassembling and transmitting the plurality of forward user data streams 20 comprises forming one or more RF forward downlink signals. Each RF forward downlink signal is associated with a corresponding forward user beam coverage area 48 and is modulated according to respective ones among the plurality of forward user data streams 20 targeted to respective UTs 44 in the corresponding forward user beam coverage area 48. Each forward optical signal 32 comprises, for example, a multiplexed plurality of optical channel signals 60, wherein each set of forward user data sub-streams 26 among the plurality of sets of forward user data sub-streams 26 is carried on a respective set of optical channel signals 60, with each one of the optical channel signals 60 in the respective set of optical channel signals 60 carried on a respective one of the forward optical signals 32. Correspondingly, the satellite 34 demultiplexes each forward optical signal 32 to recover the corresponding plurality of optical channel signals 60 and demodulates the corresponding pluralities of optical channel signals 60 to recover the plurality of sets of forward user data sub-streams 26.

[0100] In one or more embodiments, or at least during certain operating instants, at least one of the forward optical signals 32 conveys one or more further forward user data streams 20 that are transmitted without being subdivided into corresponding sets of forward user data sub-streams 26. For such further forward user data streams 20, the method 1600 includes the satellite 34 transmitting these further forward user data streams 20 for reception by the UTs 44 targeted by the further forward user data streams 20. Put simply, in some embodiments or at certain times, the two or more forward optical signals 32 being received by the satellite 34 may carry a

mix of forward user data streams 20, with some transmitted without use of forward spatial multiplexing and with others transmitted using forward spatial multiplexing.

[0101] In at least one embodiment, the method 1600 includes the satellite orienting optical beam steering assemblies 102 of the respective optical receivers 100 onboard the satellite 34, for receiving the forward optical signals 32 from respective OGSs 28 among a plurality of geographically distributed OGSs 28. The optical beam steering assemblies 102 are lenses in one embodiment, but they may be implemented as prisms, mirror-based pointing assemblies, etc.

[0102] For a given set of OGSs 28 that are transmitting a given forward user data stream 20 as a set of forward user data sub-streams, the given set of OGSs 28 may be referred to as a forward transmission diversity set and the method 1600 may include the satellite 34 reorienting the optical beam steering assembly 102 of one or more of its optical receivers 100, in response to the SCS 10 changing which OGSs 28 are included in the forward transmission diversity set.

[0103] The communications circuitry 40 of the satellite 34 may be configured to carry out the operations comprised in the method 1600, and any of the variations and extensions described above. For example, the communications circuitry 40 comprises fixed circuitry or programmatically configured circuitry, or a mix of both. In at least one embodiment, the communications circuitry 40 includes any one or more of: one or more microprocessors, one or more Field Programmable Gate Arrays (FPGAs), or one or more Application Specific Integrated Circuits (ASICs). For example, the communications circuitry 40 includes at least one microprocessor that is configured to perform the forward spatial multiplexing operations described herein, based on the execution of computer program instructions stored in a computer-readable media.

[0104] Whereas the method 1600 relates to satellite operations for forward spatial multiplexing, the method 1700 depicted in Figure 17 relates to satellite operations for return spatial multiplexing. The method 1700 includes the satellite 34: receiving (Block 1702) a return uplink signal 224 from a UT 44 served by the SCS 10, the return uplink signal 224 conveying a return user data stream 226; dividing (Block 1704) the return user data stream 226 into a set of return user data sub-streams 234, the set of return user data sub-streams 234 comprising two or more return user data sub-streams 234, each conveying a different subset of data from the return user data stream 226; and impressing (Block 1706) each return user data sub-stream 234 into a respective one among two or more return optical signals 232, each return optical signal 232 transmitted via a corresponding optical transmitter 312 onboard the satellite 34 and targeting a respective one among a plurality of geographically distributed OGSs 28.

[0105] In carrying out the method 1700 with respect to the return user data stream 226 received from the UT 44, the method includes demodulating and decoding the return uplink signal 224 to obtain the return user data stream 226.

[0106] Dividing the return user data stream 226 into the set of return user data sub-streams 234 comprises, for example, block encoding the return user data sub-stream 234 to obtain a corresponding stream of encoded data blocks and dividing each encoded data block into respective encoded sub-blocks to obtain corresponding streams of encoded sub-blocks, each return user data sub-stream 234 comprising one of the corresponding streams of encoded sub-blocks. In at least one embodiment, the method 1700 includes the communications circuitry 40 of the satellite 34 adding header information to one or more of the return user data sub-streams 234, indicating a reassembly order of the respective encoded sub-blocks, for reassembly of the return user data stream 226 by a ground network of the SCS 10, e.g., by the CCS 12 of the SCS 10.

[0107] In at least one embodiment, the method 1700 includes the satellite 34 orienting steerable optical elements—e.g., lenses, prisms, etc.—of the corresponding optical transmitters 312 onboard the satellite 34, for transmission of the return optical signals 232 to the respective ones among the plurality of geographically distributed OGSs 28. The respective OGSs 28 belong to a return transmission diversity set of OGSs 28, and the method 1700 may further include reorienting the steerable optical element 314 of one or more of the corresponding optical transmitters 312 in response to the SCS 10 changing which OGSs 28 are included in the return transmission diversity set.

[0108] In at least one embodiment or under at least some operation conditions, the satellite 34 receives a plurality of return uplink signals 224, which are RF signals. Each return uplink signal 224 conveys a corresponding return user data stream 226, such that the satellite 34 concurrently receives a plurality of return user data streams 226. In a corresponding embodiment of the method 1700, the satellite 34 provides return spatial multiplexing for at least some among the plurality of return user data streams 226. Such operation is based on, for each return user data stream 226 among the at least some return user data streams 226, forming a respective set of return user data sub-streams 234 and transmitting each return user data sub-stream 234 in the respective set on a different one of the return optical signals 232. Of course, at the same time, the method 1700 may include the satellite 34 transmitting at least one among the plurality of return user data streams 226 received by the satellite 34 without using return spatial multiplexing, by transmitting each such return user data stream 226 on a single one of the return optical signals 232.

[0109] For each return user data stream 226 that is transmitted using return spatial multiplexing, the method 1700 in one or more embodiments includes, for each return user data sub-stream 234 in the set of return user data sub-streams 234 corresponding to the return user data stream 226, modulating, according to the return user data sub-stream 234, a respective optical channel signal among a plurality of optical channel signals that are multiplexed together to form a corresponding one of the return optical signals 232.

[0110] The satellite 34 in one or more embodiments includes a user link antenna system 120 that provides spot-beam illumination of a plurality of return user beam coverage areas 220, the satellite 34 receives a return user data stream 226 from any given UT 44, based on receiving a RF return uplink signal 224 from the UT 44 via a spot-beam feed 250 corresponding to the return user beam coverage area 220 that contains the UT 44.

[0111] In one or more other embodiments, the user link antenna system 120 includes an antenna array 270 used for receive beamforming, and the satellite 34 receives a return user data stream 226 from any given UT 44 based on receiving a return uplink signal 224 from the given UT 44 via respective antenna elements 272 among a plurality of antenna elements 272 comprised in the antenna array 270. Each antenna element 272 outputs an antenna element signal 274 corresponding to reception of the RF return uplink signal 224, and the method 1700 in such embodiments includes applying return beam weights 286 to the plurality of antenna element signals 274 to produce a set of weighted signals 290. The method 1700 further includes combining the weighted signals 290 to form a return beam signal 294 corresponding to a return user beam coverage area 220 that contains the UT 44 and recovering the return user data stream 226 from the return beam signal 294. In one embodiment, the method 1700 includes the satellite 34 determining the return beam weights 286, e.g., the communications circuitry 40 includes logic configured for channel estimation and beam weight calculation. In another embodiment, the communications circuitry 40 is configured to receive the return beam weights 286 from the ground segment of the SCS 10, e.g., as calculated and sent from the CCS 12 via one of the OGSs 28.

[0112] The communications circuitry 40 of the satellite 34 may be configured to carry out the operations comprised in the method 1700, and any of the variations and extensions described above.

[0113] Notably, modifications and other embodiments of the disclosed invention(s) will come to mind to one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention(s) is/are not to be limited to the specific embodiments disclosed and that modifications

and other embodiments are intended to be included within the scope of this disclosure. Although specific terms may be employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

CLAIMS

What is claimed is:

1. A method of operation in a satellite communications system, the method comprising, at a satellite of the satellite communications system:

receiving two or more forward optical signals that convey a set of forward user data sub-streams collectively comprising a forward user data stream targeted to a user terminal served by the satellite, each forward user data sub-stream comprising a different subset of data from the forward user data stream and conveyed in a respective one of the two or more forward optical signals, with each forward optical signal transmitted by a respective one among a plurality of geographically distributed ground stations of the satellite communications system;

reassembling the forward user data stream from the set of forward user data sub-streams;

and

transmitting the forward user data stream for reception by the targeted user terminal.

2. The method according to claim 1, wherein reassembling the forward user data stream from the set of forward user data sub-streams comprises using header information included in one or more of the forward user data sub-streams, indicating a reassembly order for respective data blocks comprised in respective ones of the forward user data sub-streams in the set.

3. The method according to claim 1 or 2, wherein reassembling the forward user data stream comprises demodulating and decoding each forward user data sub-stream in the set to recover corresponding encoded data sub-blocks, reassembling the encoded data sub-blocks in order, to obtain encoded data blocks, decoding the encoded data blocks to recover the forward user data stream, and generating a radiofrequency (RF) downlink signal modulated in dependence on the forward user data stream.

4. The method according to any one of claims 1-3, wherein transmitting the forward user data stream for reception by the targeted user terminal comprises forming a radiofrequency (RF) downlink signal modulated by the forward user data stream, and transmitting the RF downlink signal as per-element signals from respective antenna elements of an antenna array onboard the satellite according to a set of beam weights calculated such that far-field superpositions of the per-element signals form a forward user beam that illuminates a forward user beam coverage area associated with the targeted user terminal.

5. The method according to claim 4, further comprising receiving the set of beam weights via one or more among the plurality of forward optical signals.
6. The method according to claim 4, further comprising determining the set of beam weights onboard the satellite, according to channel state information obtained for one or more user terminals operating in the forward user beam coverage area.
7. The method according to claim 1, wherein transmitting the forward user data stream for reception by the targeted user terminal comprising forming a radiofrequency (RF) downlink signal modulated by the forward user data stream, and applying the RF downlink signal to a transmit feed of a user link antenna system onboard the satellite that is configured for spot-beam illumination of a forward user beam coverage area associated with the satellite.
8. The method according to any one of claims 1-7, wherein the set of forward user data sub-streams is one among a plurality of sets of forward user data sub-streams received by the satellite via the plurality of forward optical signals, each optical signal conveying a respective multiplexed plurality of forward user data sub-streams, with each forward user data sub-stream in each respective multiplexed plurality of forward user data sub-streams belonging to a respective one among a plurality of forward user data streams being transmitted collectively by the plurality of forward optical signals, and wherein the method includes reassembling and transmitting the plurality of forward user data streams .
9. The method according to claim 8, wherein reassembling and transmitting the plurality of forward user data streams comprises forming one or more radiofrequency (RF) forward downlink signals, each RF forward downlink signal associated with a corresponding forward user beam coverage area and modulated according to respective ones among the plurality of forward user data streams targeted to respective user terminals in the corresponding forward user beam coverage area.
10. The method according to claim 8 or 9, wherein each forward optical signal comprises a multiplexed plurality of optical channel signals, wherein each set of forward user data sub-streams among the plurality of sets of forward user data sub-streams is carried on a respective set of optical channel signals, with each one of the optical channel signals in the respective set of optical channel signals carried on a respective one of the forward optical signals, and wherein the

satellite demultiplexes each forward optical signal to recover the corresponding plurality of optical channel signals, and demodulates the corresponding pluralities of optical channel signals to recover the plurality of sets of forward user data sub-streams.

11. The method according to any one of claims 8-10, wherein at least one of the forward optical signals conveys one or more further forward user data streams that are transmitted without being subdivided into corresponding sets of forward user data sub-streams, and wherein the method includes the satellite transmitting these further forward user data streams.

12. The method according to any one of claims 1-11, further comprising orienting steerable lenses of respective optical receivers onboard the satellite, for receiving the forward optical signals from the respective ground stations among the plurality of geographically distributed ground stations.

13. The method according to claim 12, wherein the respective ground stations belong to a forward transmission diversity set of ground stations, and further comprising reorienting the steerable lens of one or more of the respective optical receivers in response to the satellite communications system changing which ground stations are included in the forward transmission diversity set.

14. A method of operation in a satellite communications system, the method comprising, at a satellite of the satellite communications system:

receiving a radiofrequency (RF) return uplink signal from a user terminal served by the satellite communications system, the RF return uplink signal conveying a return user data stream;

dividing the return user data stream into a set of return user data sub-streams, the set of return user data sub-streams comprising two or more return user data sub-streams, each conveying a different subset of data from the return user data stream; and

impressing each return user data sub-stream into a respective one among two or more return optical signals, each return optical signal transmitted via a corresponding optical transmitter onboard the satellite and targeting a respective one among a plurality of geographically distributed ground stations.

15. The method according to claim 14, further comprising demodulating and decoding the RF return uplink signal to obtain the return user data stream.

16. The method according to claim 15, wherein dividing the return user data stream into the set of return user data sub-streams comprises block encoding the return user data stream to obtain a corresponding stream of encoded data blocks and dividing each encoded data block into respective encoded sub-blocks to obtain corresponding streams of encoded sub-blocks, each return user data sub-stream comprising one of the corresponding streams of encoded sub-blocks.

17. The method according to claim 16, further comprising adding header information to one or more of the return user data sub-streams, indicating a reassembly order of the respective encoded sub-blocks, for reassembly of the return user data stream by a ground network of the satellite communications network.

18. The method according to any one of claims 14-17, further comprising orienting steerable lenses of the corresponding optical transmitters onboard the satellite, for transmission of the return optical signals to the respective ones among the plurality of geographically distributed ground stations.

19. The method according to claim 18, wherein the respective ground stations belong to a return transmission diversity set of ground stations, and further comprising reorienting the steerable lens of one or more of the corresponding optical transmitters in response to the satellite communications system changing which ground stations are included in the return transmission diversity set.

20. The method according to any one of claims 14-19, wherein the satellite receives a plurality of radiofrequency (RF) return uplink signals, each conveying a corresponding return user data stream, such that the return user data stream is one among a plurality of return user data streams received by the satellite, and wherein the method further comprises the satellite providing return spatial multiplexing for at least some among the plurality of return user data streams, based on, for each return user data stream among the at least some return user data streams, forming a respective set of return user data sub-streams and transmitting each return user data sub-stream in the respective set on a different one of the return optical signals.

21. The method according to claim 20, further comprising transmitting at least one among the plurality of return user data streams received by the satellite without using return spatial multiplexing, by transmitting each such return user data stream on a single one of the return optical signals.

22. The method according to 20, wherein, for each return user data stream that is transmitted using return spatial multiplexing, the method includes, for each return user data sub-stream in the set of return user data sub-streams corresponding to the return user data stream, modulating, according to the return user data sub-stream, a respective optical channel signal among a plurality of optical channel signals that are multiplexed together to form a corresponding one of the return optical signals.

23. The method according to any one of claims 14-22, wherein the satellite includes a user link antenna system that provides spot-beam illumination of a plurality of return user beam coverage areas, and wherein receiving the return user data stream from the user terminal comprises receiving a radiofrequency (RF) return uplink signal from the user terminal via an antenna feed corresponding to the return user beam coverage area that contains the user terminal.

24. The method according to any one of claims 14-22, wherein the satellite includes a user link antenna system comprising an antenna array used for receive beamforming, and wherein receiving the return user data stream from the user terminal comprises receiving a radiofrequency (RF) return uplink signal from the user terminal via respective antenna elements among a plurality of antenna elements comprised in the antenna array, each antenna element outputting an element signal corresponding to reception of the RF return uplink signal, and wherein the method includes applying beamforming weights to the plurality of element signals to produce a set of weighted signals, combining the weighted signals to form a return beam signal corresponding to a return user beam coverage area that contains the user terminal, and recovering the return user data stream from the return beam signal.

25. The method according to claim 24, further comprising one of: determining the beam weights onboard the satellite or receiving the beam weights from a ground network of the satellite communications system.

26. A satellite configured for operation in a satellite communications system, the satellite comprising:

two or more optical receivers, each configured to receive a respective one among two or more forward optical signals transmitted from respective ones among a plurality of geographically distributed ground stations of the satellite communications network, the two or more forward optical signals conveying a set of forward user data sub-streams collectively comprising a corresponding forward user data stream targeted to a user terminal served by the satellite communications system, there being at least two forward user data sub-streams in the set, with each forward user data sub-stream comprising a different subset of data from the forward user data stream and conveyed via a respective one of the two or more forward optical signals; and

communications circuitry configured to:

receive the set of forward user data sub-streams, as output from the two or more optical receivers;

reassemble the forward user data stream from the set of forward user data sub-streams; and

transmit the forward user data stream for reception by the targeted user terminal.

27. The satellite according to claim 26, wherein, for reassembling the forward user data stream from the set of forward user data sub-streams, the communications circuitry is configured to use header information included in one or more of the forward user data sub-streams, indicating a reassembly order for respective data blocks comprised in respective ones of the forward user data sub-streams in the set.

28. The satellite according to claim 26 or 27, wherein, for reassembling the forward user data stream, the communications circuitry is configured to demodulate and decode each forward user data sub-stream in the set to recover corresponding encoded data sub-blocks, reassemble the encoded data sub-blocks in order, to obtain encoded data blocks, decode the encoded data blocks to recover the forward user data stream, and generate a radiofrequency (RF) downlink signal modulated in dependence on the forward user data stream.

29. The satellite according to any one of claims 26-28, wherein, for transmitting the forward user data stream for reception by the targeted user terminal, the communications circuitry is

configured to form an analog signal modulated by the forward user data stream, apply a set of beam weights to the analog signal to form a plurality of antenna element signals for transmission from respective antenna elements of an antenna array onboard the satellite, the set of beam weights calculated such that far-field superpositions of the antenna element signals form a forward user beam that illuminates a forward user beam coverage area associated with the targeted user terminal.

30. The satellite according to claim 29, wherein the communications circuitry is configured to receive the set of beam weights via one or more among the two or more forward optical signals.

31. The satellite according to claim 29, wherein the communications circuitry is configured to determine the set of beam weights, according to channel state information obtained for one or more user terminals operating in the forward user beam coverage area.

32. The satellite according to claim 26, wherein, for transmitting the forward user data stream for reception by the targeted user terminal, the communications circuitry is configured to form a radiofrequency (RF) downlink signal modulated by the forward user data stream and apply the RF downlink signal to a transmit feed of a user link antenna system onboard the satellite that is configured for spot-beam illumination of a forward user beam coverage area associated with the satellite.

33. The satellite according to any one of claims 26-32, wherein the set of forward user data sub-streams is one among a plurality of sets of forward user data sub-streams received by the satellite via the two or more forward optical signals, each optical signal conveying a respective multiplexed plurality of forward user data sub-streams, with each forward user data sub-stream in each respective multiplexed plurality of forward user data sub-streams belonging to a respective one among a plurality of forward user data streams, and wherein the communications circuitry is configured to reassemble and transmit the plurality of forward user data streams.

34. The satellite according to claim 33, wherein, for reassembling and transmitting the plurality of forward user data streams, the communications circuitry is configured to form one or more radiofrequency (RF) forward downlink signals, each RF forward downlink signal associated with a corresponding forward user beam coverage area and modulated according to

respective ones among the plurality of forward user data streams targeted to respective user terminals in the corresponding forward user beam coverage area.

35. The satellite according to claim 33 or 34, wherein each forward optical signal comprises a multiplexed plurality of optical channel signals, wherein each set of forward user data sub-streams among the plurality of sets of forward user data sub-streams is carried on a respective set of optical channel signals, with each one of the optical channel signals in the respective set of optical channel signals carried on a respective one of the forward optical signals, and wherein the communications circuitry is configured to demultiplex each forward optical signal to recover the corresponding plurality of optical channel signals, and demodulate the corresponding pluralities of optical channel signals to recover the plurality of sets of forward user data sub-streams.

36. The satellite according to any one of claims 33-35, wherein at least one of the forward optical signals conveys one or more further forward user data streams that are transmitted without being subdivided into corresponding sets of forward user data sub-streams, and wherein the communications circuitry is configured to transmit these further forward user data streams.

37. The satellite according to any one of claims 26-36, wherein each optical receiver has a steerable lens, and wherein the satellite further comprises control circuitry configured to orient the steerable lens of each optical receiver, for receiving a respective one among the two or more forward optical signals from a respective one among the plurality of geographically distributed ground stations.

38. The satellite according to claim 37, wherein the respective ground stations belong to a forward transmission diversity set of ground stations, and wherein the control circuitry is configured to reorient the steerable lens of one or more of the respective optical receivers in response to the satellite communications system changing which ground stations are used for transmitting the two or more forward optical signals.

39. A satellite configured for operation in a satellite communications system, the satellite comprising:

- a user link antenna system configured to receive a radiofrequency (RF) return uplink signal from a user terminal served by the satellite communications system, the RF return uplink signal conveying a return user data stream; and

communications circuitry configured to:

divide the return user data stream into a set of return user data sub-streams, the set of return user data sub-streams comprising two or more return user data sub-streams, and each return user data sub-stream conveying a different subset of data from the return user data stream; and

impress each return user data sub-stream into a respective one among a plurality of return optical signals, each return optical signal transmitted via a corresponding optical transmitter onboard the satellite and targeting a respective one among a plurality of geographically distributed ground stations.

40. The satellite according to claim 39, wherein the communications circuitry is configured to demodulate and decode the RF return uplink signal to obtain the return user data stream.

41. The satellite according to claim 40, wherein, for dividing the return user data stream into the set of return user data sub-streams, the communications circuitry is configured to block encode the return user data stream to obtain a corresponding stream of encoded data blocks, and divide each encoded data block into respective encoded sub-blocks to obtain corresponding streams of encoded sub-blocks, each return user data sub-stream comprising one of the corresponding streams of encoded sub-blocks.

42. The satellite according to claim 41, wherein the communications circuitry is configured to add header information to one or more of the return user data sub-streams, indicating a reassembly order of the respective encoded sub-blocks, for reassembly of the return user data stream by a ground network of the satellite communications network.

43. The satellite according to any one of claims 39-42, wherein control circuitry onboard the satellite is configured to orient steerable lenses of the corresponding optical transmitters, for transmission of the return optical signals to the respective ones among the plurality of geographically distributed ground stations.

44. The satellite according to claim 43, wherein the respective ground stations belong to a return transmission diversity set of ground stations, and wherein the control circuitry is configured to reorient the steerable lens of one or more of the corresponding optical transmitters

in response to the satellite communications system changing which ground stations are included in the return transmission diversity set.

45. The satellite according to any one of claims 39-44, wherein the satellite is configured to receive a plurality of radiofrequency (RF) return uplink signals, each conveying a corresponding return user data stream, such that the return user data stream is one among a plurality of return user data streams received by the satellite, and wherein the communication circuitry is configured to provide return spatial multiplexing for at least some among the plurality of return user data streams, based on, for each return user data stream among the at least some return user data streams, forming a respective set of return user data sub-streams and transmitting each return user data sub-stream in the respective set on a different one of the return optical signals.

46. The satellite according to claim 45, wherein the communications circuitry is configured to transmit at least one among the plurality of return user data streams received by the satellite without using return spatial multiplexing, by transmitting each such return user data stream on a single one of the return optical signals.

47. The satellite according to 45, wherein, for each return user data stream that is transmitted using return spatial multiplexing, the communications circuitry is configured to, for each return user data sub-stream in the set of return user data sub-streams corresponding to the return user data stream, modulate, according to the return user data sub-stream, a respective optical channel signal among a plurality of optical channel signals that are multiplexed together to form a corresponding one of the return optical signals.

48. The satellite according to any one of claims 39-47, wherein the satellite includes a user link antenna system that provides spot-beam illumination of a plurality of return user beam coverage areas, and wherein the satellite is configured to receive given RF return uplink signals from given user terminals in any given one of the return user beam coverage areas, and wherein the communications circuitry is configured to, for each given RF return uplink signal, recover a corresponding user data stream.

49. The satellite according to any one of claims 14-22, wherein the satellite includes a user link antenna system comprising an antenna array, the antenna array comprising a plurality of antenna elements, and wherein the satellite is configured to receive given RF return uplink

signals from given user terminals in given ones among a plurality of return user beam coverage areas, the antenna array outputting a plurality of antenna element signals, each antenna element signal being a composite of given RF return uplink signals then impinging on a corresponding one of the antenna elements, and wherein the communications circuitry includes beamforming circuitry that is configured to apply respective sets of beamforming weights to the plurality of antenna element signals to produce corresponding sets of weighted signals, each set of weighted signals combined to form a return beam signal corresponding to one of the return user beam coverage areas, and wherein the communications circuitry is configured to recover the return user data streams conveyed in each return beam signal.

50. The satellite according to claim 49, wherein the communications circuitry is configured for one of: receiving the beam weights from a ground network of the satellite communications system or calculating the beam weights based on channel state information corresponding to respective user terminals operating in respective ones among the plurality of return user beam coverage areas.