

METHODS AND APPARATUSES FOR BEAMFORMING IN A SATELLITE COMMUNICATIONS SYSTEM

TECHNICAL FIELD

[0001] Disclosed methods and apparatuses relate to satellite communications, and particularly relate to beamforming in a satellite communications system.

BACKGROUND

[0002] Radio Frequency (RF) beamforming is an advanced signal processing technique used in wireless communications systems to control the directionality of signal transmission and reception. This technology allows for the focusing of radio signals in specific directions, effectively increasing the signal strength and range while reducing interference. Beamforming achieves this by manipulating the phase and amplitude of signals from an array of antennas, causing constructive interference in desired directions and destructive interference in others.

[0003] In satellite communications systems, beamforming plays a critical role in directing signals to and from specific regions on Earth. Satellites typically transmit signals across wide areas, but RF beamforming allows for the creation of narrow, focused beams, enhancing signal strength in specific geographic areas or targeting individual users. This is particularly advantageous for systems where limited spectrum resources are shared among many users.

[0004] Ground-based beamforming (GBBF) is an approach where the beamforming process is handled by ground stations of the satellite communications network rather than by the satellite. This method involves the ground station transmitting multiple signals with precise phase and amplitude control to create the desired beam in space. Performing the beamforming operations on the ground reduces the complexity and power requirements of the satellite itself. GBBF also offers improved flexibility, because ground stations can be upgraded or reconfigured more easily than satellites, which are typically more difficult or impossible to modify once in orbit. However, ground-based beamforming introduces challenges such as the need for large amounts of feeder link bandwidth, which in turn may require synchronization and coordination between multiple ground stations.

SUMMARY

[0005] Disclosed methods and apparatuses embody an advantageous beamforming technique applied in a satellite communications system (SCS). A ground segment of the SCS computes beam weights for use by a beamformer onboard a satellite. Beam weight computation depends on the satellite providing the ground segment with per element sounding signals corresponding to reception by a phased array antenna onboard the satellite of channel sounding signals from

one or more user terminals (UTs) located in a user beam coverage area. Having access to these per element sounding signals supports ground-based estimation of the propagation channels between the phased array antenna and the UT(s), with the beam weights calculated from the channel estimates and output for uplink transmission to the satellite. In one or more embodiments, the onboard beamformer operates in a digital domain, with the beam weights being digital values.

[0006] An example embodiment comprises a method of operation in a SCS. The method includes performing a beam weight calculation procedure in a ground segment of the SCS. Operations of the procedure include obtaining per element sounding signal samples corresponding to respective antenna elements of a phased array antenna onboard a satellite of the SCS, for a time during which a channel sounding signal is transmitted by a reference UT located in a user beam coverage area served by the satellite and received via the respective antenna elements of the phased array antenna; generating channel estimates from the per element sounding signal samples; calculating a beam weight set from the channel estimates, the beam weight set comprising a corresponding beam weight for each of the respective antenna elements and calculated for formation of a radio frequency (RF) user beam via the phased array antenna, for illumination of the user beam coverage area; and sending the beam weight set to the satellite for application to per element communication signals carrying transport data associated with UTs located in the user beam coverage area and corresponding formation of the RF user beam.

[0007] Another embodiment comprises a method of operation in a SCS, where the method includes a satellite of the SCS receiving a channel sounding signal from a reference UT located in a user beam coverage area served by the satellite. The satellite receives the channel sounding signal via a phased array antenna that comprises respective antenna elements, each respective antenna element outputting a per element sounding signal corresponding to reception of the channel sounding signal via the phased array antenna. Further, the method includes providing the per element sounding signals to a ground segment of the SCS, receiving a beam weight set calculated by the ground segment in dependence on the per element sounding signals, each beam weight in the beam weight set corresponding to one of the respective antenna elements; and applying the beam weight set for transmission or reception of a RF user beam via the phased array antenna. The RF user beam carries multiplexed transport data associated with respective ones among a plurality of UTs located in the user beam coverage area.

[0008] Another example embodiment comprises a method of operation by a SCS, where the method includes a satellite of the SCS forming a radio frequency (RF) user beam via beamformer circuitry onboard a satellite of the SCS applying corresponding beam weights from a beam weight set to respective per element signals of a phased array antenna onboard the

satellite. The RF user beam illuminates a corresponding user beam coverage area that is served by the satellite and the method further includes calculating the beam weight set in a ground segment of the SCS, based on the satellite providing the ground segment with per element signals from the phased array antenna corresponding to a time or times during which channel sounding signals are transmitted by one or more reference UTs located in the corresponding user beam coverage area and received via the phased array antenna of the satellite. Still further, the method includes sending the beam weight set from the ground segment to the satellite.

[0009] Yet another example embodiment comprises a SCS that includes a ground segment having a ground station configured for transmitting feeder uplink signals to and receiving feeder downlink signals from a satellite of the SCS. Here, the satellite performs beamforming with respect to a user beam coverage area served by the satellite and the ground segment includes a communications processing system (CPS) that is communicatively coupled with the satellite via the ground station. The CPS is operative to perform a beam weight calculation procedure, based on one or more processors of the CPS being configured to: obtain per element sounding signal samples corresponding to respective antenna elements of a phased array antenna onboard the satellite, for a time during which a channel sounding signal is transmitted by a reference UT located in the user beam coverage area and received via the respective antenna elements of the phased array antenna; generate channel estimates from the per element sounding signal samples; calculate a beam weight set from the channel estimates, the beam weight set comprising a corresponding beam weight for each of the respective antenna elements and calculated for formation of a RF user beam via the phased array antenna, for illumination of the user beam coverage area; and send the beam weight set to the satellite via the ground station, for application by a beamformer onboard the satellite to per element communication signals carrying transport data associated with UTs located in the user beam coverage area and corresponding formation of the RF user beam.

[0010] A further example embodiment comprises a SCS having a satellite that includes an onboard beamformer and a phased array antenna. The satellite is configured to receive a channel sounding signal from a reference UT located in a user beam coverage area served by the satellite, where the channel sounding signal is received via the phased array antenna, which comprises respective antenna elements, and where each respective antenna element outputs a per element sounding signal corresponding to reception of the channel sounding signal via the phased array antenna. The satellite is further configured to: provide the per element sounding signals to a ground segment of the SCS; receive a beam weight set calculated by the ground segment in dependence on the per element sounding signals, each beam weight in the beam weight set corresponding to one of the respective antenna elements; and apply the beam weight set via the

onboard beamformer, for transmission or reception of a RF user beam via the phased array antenna. The RF user beam carries multiplexed transport data associated with respective ones among a plurality of UTs located in the user beam coverage area.

[0011] Another example embodiment comprises a SCS that includes a satellite in a space segment of the SCS, and a processing node in a ground segment of the SCS. The satellite is configured to form a RF user beam via beamformer circuitry onboard the satellite applying corresponding beam weights from a beam weight set to respective per element signals of a phased array antenna onboard the satellite. The RF user beam illuminates a corresponding user beam coverage area that is served by the satellite, and the processing node is configured to: calculate the beam weight set, based on the satellite providing the ground segment with per element signals from the phased array antenna corresponding to a time or times during which channel sounding signals are transmitted by one or more reference UTs located in the corresponding user beam coverage area and received via the phased array antenna of the satellite; and output the beam weight set for transmission to the satellite.

[0012] 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

[0013] Figure 1 is a block diagram of a satellite communications system (SCS), according to an example embodiment.

[0014] Figures 2 and 3 are block diagrams of example details for the SCS.

[0015] Figures 4-6 are logic flow diagrams of methods of operation of the SCS, according to example embodiments.

DETAILED DESCRIPTION

[0016] Figure 1 illustrates an example satellite communications system (SCS) 10 that implements an advantageous technique for forming one or more forward user beams 12 in the forward link direction and/or return user beams 14 in the return link direction. Although Figure 1 suggests a scenario involving the same numbers of forward user beams 12 and return user beams 14, beamforming may be performed in only one direction or return beamforming may differ from forward beamforming in terms of beam count and/or beam orientation.

[0017] Regardless, the disclosed technique exploits the power and computational resources that are more practically implemented in a ground segment 16 of the SCS 10, as compared to the space segment 18, while at the same time avoiding the complexities that attend application of beam weights in the ground segment 16. Namely, the ground segment 16 of the SCS 10

generates beam weights—forward beam weight sets 20 and/or return beam weight sets 22—for use by a beamformer 24 onboard a satellite 26.

[0018] For each beam to be formed, the satellite 26 receives channel sounding signals 32 from one or more “reference” user terminals (UTs) 34 located within a corresponding user beam coverage area 36—a geographic area. The channel sounding signals 32 also may be referred to as sounding reference signals or SRS.

[0019] These reference UTs 34 may be the same or different than other UTs 38 within the respective user beam coverage areas 36 and they may be designated dynamically or statically. That is, a given UT 38 may operate as a reference UT 38. In an example scenario, each reference UT 34 is located at or near the geographic location on which the corresponding beam is to be centered. Thus, each of the reference UTs 34 shown by way of example in the diagram are at or near the centers of the respective user beam coverage areas 36, which may be forward and/or return user beam coverage areas in dependence on whether the satellite 26 performs one or both of forward and return beamforming.

[0020] The reference UTs 34 may be of the same type or class as other UTs 38 located in respective ones of the user beam coverage areas 36. The beam 12 or 14 that illuminates each user beam coverage area 36 carries transport data for all of the UTs 34/38 located in the coverage area, e.g., using time-division multiplexing (TDM). The satellite 26 receives channel sounding signals transmitted by a given reference UT 34 located in a given user beam coverage area 36 via its phased array antenna 35. More particularly, assuming that a plurality of individual antenna elements 40 of the phased array antenna are used in the beamforming at issue, the channel sounding signals 32 are received on those same antenna elements 40, thereby providing a basis for estimating the (propagation) channels between the reference UT 34 and the respective antenna elements 40.

[0021] In operation, a channel sounding signal 32 impinging on the phased array antenna 35 results in the phased array antenna 35 outputting a plurality of per element sounding signals, each one being the channel sounding signal 32 as received on a respective one among the plurality of antenna elements 40. The satellite 26 provides these per element sounding signals to the ground segment 16 via transmission over a feeder downlink 50, which together with a feeder uplink 52 forms a feeder link 54 that communicatively couples the satellite 26 with a ground station 60 in the ground segment 16 of the SCS 10. In cases where more than one ground station 60 simultaneously supports the satellite 26, a respective feeder link 54 communicatively couples the satellite 26 to each such ground station 60. Feeder links 54 may be RF based or optically based.

[0022] One or more network nodes 62 of the ground segment 16 operate as a communications processing system (CPS) 64. For example, one or more computer servers execute computer program instructions that configure the processor(s) residing therein to carry out CPS operations and functions. These functions include a communications traffic processing function 66, a sounding based channel estimation function 68, and a beam weight calculation and adaptation function 70. Although referred to as “functions,” it shall be appreciated that the CPS 64 comprises physical circuitry carrying communications signal processing and associated operations. Nonetheless, such circuitry may be part of a cloud processing or data-center installation and may involve host virtualization.

[0023] Interface circuitry 72 couples the processing elements of the CPS 64 to the ground station(s) 60. Such circuitry comprise physical layer and associated control and timing circuitry for wired or wireless communications with the ground station(s) 60. A further payload command link interface 74 provides for communication of beam weight signaling 76 to the satellite 26. The beam weight signaling 76 indicates the forward beam weight sets 20 and/or the return beam weight sets 22 to the satellite 26. The CPS 64 may recompute such beam weight sets periodically, e.g., based on recurring channel estimations, based on receiving the sounding-signal feedback from the satellite 26 on a recurring basis.

[0024] Although the payload command link interface 74 may be distinct, other alternatives are possible. For example, the payload command link interface 74 may be a logical interface, e.g., with the beam weight signaling 76 being sent “in band” or on some logical channel conveyed on the feeder link 54. In other words, the payload command link interface 74 and the associated beam weight signaling 76 may be subsumed or otherwise provided for via the ground-to-satellite communications path provided by the ground links 78 coupling the CPS 64 to the ground station(s) 60 and the associated feeder link(s) 54.

[0025] Regarding feeder link communications, for reception of forward link transport data targeting respective UTs 34 or 38, the satellite 26 includes a feeder link receive (RX) antenna 80 and one or more receivers 82. The one or more receivers 82 include one or more frequency down converters 84, and one or more demodulators 86.

[0026] For transmission of return link transport data from respective UTs 34 or 38, the satellite 26 includes a feeder link transmit (TX) antenna 90 and one or more transmitters 92. The one or more transmitters 92 include one or more frequency up-converters 94 and one or more modulators 96. In an example arrangement, there is a frequency downconverter 84 and a demodulator 86 for each forward beam signal to be transmitted on a respective one of the forward user beams 12, and a frequency up-converter 84 and a modulator 96 for each return beam signal recovered from a respective one of the return user beams 14.

[0027] In an example embodiment, the feeder link RX and TX antennas 80 and 90 are E-band receive and transmit antennas, and the phased array antenna 35 is a L/S-band digital array. In its digital array implementation, for a signal impinging on the array, i.e., a signal being received via the array, the array outputs a plurality of per element digital signals, each corresponding to the impinging signal as received on a respective one of the antenna elements 40. Correspondingly, return beam weight application circuitry 30 operates in the digital domain, meaning that the return beam weight sets 22 comprise sets of digital weight values applied in the digital domain to the per element digital signals.

[0028] Similarly, for digital implementations of the phased array antenna 35 in the transmit case, forward beam weight application circuitry 28 operates in the digital domain using forward beam weight sets 20 that comprise respective sets of digital values, and outputs per element digital signals that are input to the phased array antenna 35 for conversion to the analog domain, power amplification, and transmission from respective antenna elements 40 of the array.

[0029] Of course, while implementation of the beamformer 24 onboard the satellite 26 as a digital beamformer offers certain advantages, the disclosed technique of using the ground segment 16 for channel estimation and corresponding beam weight calculation, to support beamforming onboard the satellite 26 is not limited to digital beamforming embodiments. Thus, in one or more other embodiments, the beamformer 24 onboard the satellite 26 is configured for beamforming in the analog domain.

[0030] Figure 2 illustrates details for forward link beamforming according to an example embodiment. The CPS 64 receives incoming packet data streams 100, e.g., a plurality of streams representing forward user traffic for individual UTs 34, 38. (Note that, hereafter, the reference number “38” is used to refer to any given UT, unless making specific reference to a UT that is operating as a reference UT 34.)

[0031] The CPS 64 forms forward beam signals 102, with each forward beam signal 102 aggregating the forward user traffic for all active UTs 38 that are located within a respective one among a plurality of user beam coverage areas 36. As such, each forward beam signal 102 multiplexes forward user traffic for a group or set of UTs 38 located in a particular user beam coverage area 36.

[0032] These forward beam signals 102 flow from the CPS 64 to one or more ground stations 60, with one ground station 60 shown by way of example in the diagram. In an example embodiment, for each forward beam signal 102 to be transmitted by a ground station 60, it modulates the forward beam signal 102 onto an uplink carrier at a defined uplink carrier frequency, for transmission via an included transmitter 106 and antenna system 108. In such an embodiment, then, the feeder uplink 52 comprises a plurality of forward uplink signals 110 or,

viewed another way, a composite or multiplexed forward uplink signal that comprises the plurality of forward uplink signals 110. For example, each forward uplink signal 110 is conveyed as modulations of a respective RF carrier at a particular uplink carrier frequency, such that the feeder uplink 52 is a composite of these modulated RF carriers.

[0033] The feeder link receive antenna 80 onboard the satellite 26 receives these forward uplink signals 110 and outputs them as antenna received signals 112. The one or more frequency down-converters 84 down-convert each signal 112, e.g., to an intermediate frequency (IF) for demodulation. Correspondingly, one or more demodulators 86 operate on resulting down-converted signals 114 to recover the respective forward beam signals 102. That is, the signals output from the demodulator(s) 86 are recovered forward beam signals 116.

[0034] In an example scenario, the SCS 10 operates as a non-terrestrial network (NTN) supporting wireless (cellular) communications. As a specific example, each forward beam signal 102 is a digitally-modulated RF communications signal, e.g., a Fifth Generation (5G) wireless communications signal structured according to the applicable Third Generation Partnership Project (3GPP) specifications. In this capacity, the satellite 26 operates as a radio network node in a larger wireless communications network, which also includes terrestrial links, and it should be noted that the CPS 64 may receive such signals in digital form for satellite transmission, rather than forming them from incoming packet data traffic.

[0035] According to this wireless network example, modulator(s) 104 in the ground station 60 uses digital or analog modulation to impress the RF communication signals on respective RF uplink carriers, with the demodulator(s) 86 onboard the satellite 26 recovering the 5G communications signals as the depicted recovered forward beam signals 116. For example, the modulator(s) 104 in the ground station digitally sample each RF communication signal and correspondingly digitally modulate a respective RF uplink carrier to form a respective one of the RF uplink signals. Forward error correction (FEC) may be added in the context of this digitization processor for error-corrected recovery of the recovered forward beam signals 116 onboard the satellite 26 via appropriate configuration of the demodulator(s) 86. Alternatively, each RF uplink carrier may be modulated in the analog domain by a respective one of the RF communication signals. In this case, the modulator(s) 86 onboard the satellite 26 may be quite simple. For example, assuming that the beamformer 24 onboard the satellite 26 is a digital beamformer, the modulator(s) 86 may simply comprise analog-to-digital converters (ADCs) configured to output the recovered forward beam signals 116 as a stream of digital samples.

[0036] Whether implemented in the digital or analog domains, each recovered forward beam signal 116 flows into the forward beam weight application circuitry 28 onboard the satellite 26. That circuitry 28 includes per beam signal splitters 118, which are configured to split

each recovered forward beam signal 116 into a plurality of signal copies 120. Assuming that there are N forward user beams 12 being transmitted simultaneously and that there are M antenna elements 40 of the phased array antenna 35 of the satellite 26 used in forming the N forward user beams 12, then there are N forward beam signals 102, each one to be transmitted on a respective one of the N forward user beams 12, N recovered forward beam signals 116, and N sets of signal copies 120.

[0037] Each one of the N sets of signal copies 120 includes M copies, with each copy mapped or corresponding to a respective one of the M antenna elements 40 used in forward link beamforming. For each forward user beam 12, there is a corresponding forward beam weight set 20 that is calculated for formation of the corresponding forward user beam 12, with the set 20 containing a beam weight for each one of the M antenna elements 40. Thus, each one of the N sets of signal copies 120 has M signal copies, with each one of those copies being weighted by the corresponding beam weight from the corresponding forward beam weight set 20. This weighting occurs in corresponding per element signal weighting circuitry 122.

[0038] The per element signal weighting circuitry 122 outputs N sets of weighted signal copies 124, where each one of the N sets of weighted signal copies 124 corresponds with a respective one of the forward user beams 12 and contains M signal copies, each weighted for transmission from a particular one of the M antenna elements 40. Per element combining circuitry 126 forms one or more sets of combined weighted signals 128, based on performing per element combining of the weighted signal copies 124 across the N sets of weighted signal copies 124 or, more particularly, across those particular sets of weighted signal copies 124 all corresponding to the same downlink frequency. For example, the SCS 10 may be configured such that adjacent beams among the plurality of forward user beams 12 are at different frequencies in order to avoid inter-beam interference, with a set of downlink beam frequencies reused across the plurality of forward user beams 12 according to a defined reuse pattern.

[0039] For example, assume that 20 MHz of spectrum is available and is divided into four 5 MHz channels, and that adjacent beams use different 5 MHz channels. Such an arrangement may be referred to as a “four color” frequency reuse scheme. As a more general example applicable to at least one embodiment of the SCS 10, assume that there are R beam frequencies reused among N forward user beams 12 according to a frequency reuse pattern, where $N \gg R$. The per element combining circuitry 126 in such cases performs combining on beam frequency basis, meaning that combining is performed for all forward user beams 12 that use the same downlink carrier frequency. In an example embodiment, for all forward user beams 12 on the same downlink carrier frequency, the per element combining circuitry 126 forms a corresponding set of combined weighted signal copies 128. Each such set contains M weighted signal copies 128,

with each such copy formed from the corresponding per element weighted signal copies 124 in the sets of weighted signal copies 124 corresponding to that downlink carrier frequency.

[0040] In the example digital implementation, the set(s) of combined weighted signals 128 comprise streams of digital samples, with these sample streams flowing into the phased array antenna 35, which, in this digital-domain example, includes digital-to-analog converters (DACs) 130, to obtain set(s) of analog per element signals 132 corresponding to the set(s) of combined weighted signals 128. The phased array antenna 35 in the example embodiment includes frequency converters (FCs) 134 and power amplifiers (PAs) 136, to form a plurality of antenna element signals 138 to be transmitted from the M antenna elements 40 of the phased array antenna 35 as transmitted signals 140. Note that frequency conversion may be applied to each set of analog per element signals 132 according to the corresponding downlink carrier frequency, and analog combining and amplifying these frequency-converted signals to produce the M antenna element signals 138 applied element-wise to the M antenna elements 40. Because of the weightings, the transmitted signals 140, superpose in the far field to form the N forward user beam 12, with each forward user beam 12 illuminating (focused on) a respective one among the forward user beam coverage areas.

[0041] Figure 3 illustrates a return beam forming example, where M antenna elements 40 of the phased array antenna 35 receive an incoming signal 200. Note that the M antenna elements 40 used for return link beamforming may or may not be the same M antenna elements 40 used for forward link beamforming. However, in one embodiment, the phase array antenna 35 uses the same antenna elements 40 but with different feeds into and out of the phased array antenna 35 for reception and transmission, and UTs 38 transmitting uplink signals use user uplink frequencies that are different than the user downlink frequencies used to form the forward user beams 12.

[0042] In this sense, the incoming signal 200 can be understood as being a composite signal that, at any given time, is a composite of potentially many different user uplink signals being transmitted by respective UTs 38, according to scheduling by the CPS 64 of the SCS 10. More particularly, in at least one embodiment herein, the SCS 10 operates on a “slot” basis with respect to performing a beam update procedure that is used to update or otherwise adapt the forward and/or return beam weight sets 20 and 22. Here, a “slot” is a window in time, and slots may exist in a running succession during live operation of the SCS 10.

[0043] Using this slot arrangement, some slots—denoted as “first” slots—are used for exchanging traffic, while other slots—denoted as “second” slots—are used for channel sounding. During channel sounding, one or more reference UTs 34 transmit a channel sounding signal 32 that is used by the SCS 10 to perform channel estimation in support of calculating/re-calculating

the sets of beam weights 20 and/or 22. For forward beam weight adaptation, one or more reference UTs 34 in each forward user beam coverage area transmits a channel sounding signal 32; for return beam weight adaptation, one or more reference UTs 34 in each return user beam coverage area transmits a channel sounding signal 32. To the extent that the forward and return user beam coverage areas are the same or the reference UT locations are the same, the process may be performed in common for both forward and return beamforming.

[0044] Any one or more of time, frequency, space, or code multiplexing may be used to distinguish the channel sounding signal(s) 32 transmitted by the reference UT(s) 34 in one beam coverage area 36 from those transmitted in another beam coverage area. One or more embodiments allow for simultaneous channel sounding from multiple beam coverage areas 36 based on orthogonalizing the channel sounding signals 32 in the different areas. In any case, it shall be understood that the incoming signal 200 shown in Figure 3 is a generic representation and that, at certain times, the incoming signal 200 comprises a composite of UT uplink signals conveying return user traffic, while at certain other times, it comprises a channel sounding signal 32 from a particular reference UT 34, or a composite of multiple channel sounding signals 32 from multiple UTs 34.

[0045] Regardless, the incoming signal 200 impinges on respective ones among the M antenna elements 40 used for receiving the incoming signal 200, with each such element outputting one of M antenna element signals 202. Each antenna element signal 202 has a relative phase and attenuation associated with its position within the phased array antenna 35.

[0046] The satellite 26 in one or more embodiments includes separate RF chains for each uplink signal polarization in use. Further, the RF signal paths may be further separated according to uplink frequency band, e.g., separate low-noise amplification and filtering, for each uplink frequency band in use by the population of UTs 38 served by the satellite 26. Alternatively, a single wideband low noise amplifier (LNA) may handle multiple uplink frequency bands.

[0047] The illustrated arrangement represents an example digital embodiment, where the phased array antenna 35 includes low noise amplifiers (LNAs) 204 and FCs 206, and possibly filters, etc., for outputting one or more sets of M conditioned antenna element signals 208, e.g., one such set per signal polarization in use on the user uplink.

[0048] Each set of conditioned antenna element signals 208 includes a conditioned antenna element signal 208 for each of the M antenna elements 40, for a given uplink signal polarization and/or frequency band. Analog-to-digital converters (ADCs) 210 output a corresponding set or sets of digitized element signals 212. Thus, in this example embodiment, there is a set of M digitized element signals 212, for each uplink signal polarization and/or frequency band used among the overall plurality of return user beams 14.

[0049] For each set of M digitized element signals 212, there is a corresponding beam weighting circuit 214, for each return user beam 14 that is associated with the corresponding uplink signal polarization and/or frequency band. Each such beam weighting circuit 214 uses the return beam weight set 22 corresponding to the return user beam 14 with which the beam weighting circuit 214 is associated. For an overall total of N return user beams 14, there are N beam weighting circuits 214, with each beam weighting circuit 214 outputting a corresponding plurality of M weighted signals 216. Each set of M weighted signals 216 corresponds with one of the N return user beams 14 and is formed by weighting the corresponding set of digitized element signals 212 input to the beam weighting circuit 214 with beam weights from the return beam weight set 22 corresponding to the return user beam 14 being formed.

[0050] For each set of M weighted signals 216, there is a corresponding combining circuit 218, which combines the set of M weighted signals to form a corresponding return beam signal 220. Each such return beam weight set 22 is calculated such that the combining operation “focuses” reception sensitivity in a direction that illuminates the corresponding return user beam coverage area, with each such return beam weight set 22 including M weights (which may be complex values) corresponding to the M antenna elements 40 used in return beamforming. Thus, each return beam signal 220 enhances the SINR for uplink return signals originating from UTs 38 located in a corresponding one among the return user beam coverage areas. In one or more example embodiments, the return beam signals 220 are, for example, 5G or other wireless communication signals.

[0051] The modulator(s) 96 of the satellite 26 form a modulated return signal 222 from each return beam signal 220. Such operations include, for example, converting from the digital domain to the analog domain. That is, each return beam signal 220 comprises, in one or more embodiments, samples of the RF spectrum of the incoming signal 200, or at least those RF components of the incoming signal 200 corresponding to the respective return user beam coverage area.

[0052] The resulting modulated return signals 222 flow from the modulator(s) 96 to the frequency up-converter(s) 94 of the satellite 26, which place the respective modulated return signals 222 onto respective feeder downlink carrier frequencies. The resulting frequency-converted (shifted) signals 224 are applied to the transmit antenna 90 of the satellite 26 for transmission on the feeder downlink 50 as feeder downlink signals 226. An antenna system 230 of the ground station 60 and receiver and demodulation circuitry 232 and 234 receives and demodulates the feeder downlink signals 226, to obtain recovered return user beam signals 236. Each recovered return user beam signal 236 corresponds to a respective one of the return beam signals 220 formed in the satellite 26—i.e., it carries signal samples from one or more of the UTs

38 located in the corresponding return user beam coverage area. The recovered return user beam signals 236 comprise, for example, recovered wireless communication signals, e.g., 5G communication signals received via the satellite 26. The CPS 64 recovers outgoing data packet streams 238 from the recovered return user beam signals 236.

[0053] Of course, as noted, the SCS 10 may be operated such that first time slots are used for conveying user traffic, while second time slots are used for channel sounding, in support of recurring or ongoing channel estimation and corresponding recalculation or adaptation of beam weights, to account for changing channel conditions. There may be many more first time slots than second time slots, and the second time slots may be interleaved with respect to the first time slots. Operation with respect to the first time slots may be referred to as “normal” operation, while operation during each second time slot may be referred to as “sounding” operation. Notably, with respect to each sounding operation, the channel estimation and beam weight updating may occur as part of sounding operation or may be performed as a background process during subsequent normal operation. Further, upon completing recalculation of a given forward or return beam weight set 20 or 22, the updates may be signaled to the satellite 26, for application. Changing from an “old” or “current” beam weight set to a “new” or “updated” beam weight set may be synchronized with the overall communication signal timing/structure, e.g., at subframe or frame boundaries, and the satellite 26 may be understood as containing buffers for holding old and updated beam weights at least temporarily for any given beam.

[0054] In more detail, during normal operation in one or more embodiments of the SCS 10, the ground station 60 transmits each forward beam signal 102 as sampled RF spectrum conveyed on the feeder uplink 52. Likewise, the satellite 26 transmits each return beam signal 220 as sampled RF spectrum conveyed on the feeder downlink 50. In the forward direction, the satellite 26 demodulates the sampled RF spectrum from feeder uplink 52, to obtain the recovered forward beam signals 116. In the return direction, the satellite 26 modulates the sample RF spectrum comprising the return beam signals 220, for feeder downlink transmission.

[0055] During sounding operation, however, signal samples from each of the M antenna elements 40 used in beamforming are fed back from the satellite 26 to the ground segment 16. That is, during sounding operation, the incoming signal 200 impinging on the phased array antenna 35 comprise one or more channel sounding signals 32 from one or more reference UTs 34, located in one or more user beam coverage areas 36 (forward and/or return user beam coverage areas).

[0056] Turning back to Figures 2 and 3, momentarily, the satellite 26 is configured such that, for sounding operation, it bypasses its beamforming circuitry and instead returns per element sounding signals 150—which are digital samples in one or more embodiments. As such, the

ground segment 16 gains access to the phased array antenna 35 for purposes of channel estimation in support of beamforming from the phased array antenna 35. One form of “bypassing” is based on disabling or temporarily reconfiguring the beamforming circuitry onboard the satellite 26, such that it simply passes through the M antenna element signals 202, or digitized versions thereof, for times during which the satellite 26 operates in the sounding mode, such that the ground segment 16 receives per element sounding signals for channel estimation in support of beam weight calculation.

[0057] Figures 2 and 3 illustrate such bypassing. The example, satellite 26 includes mode control circuitry 152 that generates mode control signaling 154, to control whether the satellite 26 operates in normal mode for communications signal conveyance, including beamforming, or operates in sounding mode, wherein it bypasses beamforming and instead provides per element sounding signals 150 to the ground segment 16. In an example embodiment, channel sounding signals 32 are spread signals so that they are recoverable despite not benefitting from the beamforming gain applied to communication signals from the UTs 38.

[0058] The mode control circuitry 152 comprises, for example, one or more computer processors or other programmatically configured digital processing circuitry. As a specific example, the mode control circuitry 152 comprises a processor that is specially adapted for the described mode control, based on the execution of computer program instructions stored in computer readable media onboard the satellite 26. Of course, the satellite 26 at large may include multiple processors or processing systems, for overall control and operation as part of the SCS 10 and the mode control circuitry 152 may be implemented as a function within such larger processing systems.

[0059] Regardless of the particular arrangement by which the ground segment 16 is provided with the per element sounding signals 150, new beam weights—new beam weight sets 20 and/or 22—are calculated on a periodic or recurring basis, using newly returned per element sounding signals 150. In one embodiment, each updating is based on a recalculation from new channel estimations made from the per element sounding signals 150 new to each update. Of course, various approaches to beam weight adaptation may be used, and the relatively plentiful processing and power resources available in the ground segment 16 represent significant capabilities for high performance and high accuracy.

[0060] The beam recalculations need to happen often enough to effectively keep the beams formed in the proper directions, taking into account the motion of the satellite 26, the changing interference environment, and any other dynamically changing system parameters. Depending upon the design and circumstances, example intervals for updating beam weights are anywhere

from a few milliseconds to several seconds. Thus, new beam weight sets 20 and/or 22 are uploaded to the satellite 26 on a recurring basis.

[0061] In an example arrangement, the feeder link 54 has a feeder link bandwidth wide enough to accommodate the simultaneous transmission of a plurality of beam signals during normal operation, where each “beam signal” carries user traffic to or from the UTs 38 located in a particular one of the user beam coverage areas 36—i.e., each beam signal comprises the communications traffic exchanged on a particular one of the forward or return user beams 12 or 14.

[0062] During normal operation, simultaneous beam signal transmission on the feeder link 54 comprises, for example, stacking the beam signals in the frequency domain, based on modulating each beam signal onto a respective feeder link carrier, with the plurality of carriers occupying different frequencies within the overall feeder link bandwidth. The stacked-frequency arrangement may be used on the feeder uplink 52 operating in first feeder link spectrum for transmitting forward beam signals from the ground station 60 to the satellite 26 and may be used on the feeder downlink 50 operating in second feeder link spectrum for transmitting return beam signals from the satellite 26 to the ground station 60. Note that the user downlink and user uplink between the satellite 26 and the population of UTs 38 served by the satellite 26 may be in a frequency band distinct from the feeder link frequency band(s).

[0063] Regardless of the particular frequency bands involved, the feeder link bandwidth on the feeder downlink 50 is “reused” during sounding operation for conveying the per element sounding signals 150 from the satellite 26 to the ground station 60. The same frequency stacking arrangement used between the satellite 26 and the ground station 60 for conveying multiple return beam signals to the ground station 60 may be reused for conveying the plurality of per element sounding signals 150. That is, each per element sounding signal 150 is modulated onto a particular one among a plurality of feeder downlink carriers at different feeder downlink carrier frequencies. The mapping between particular ones of the antenna elements 40 and feeder downlink carriers may be predefined or dynamically configured and, in either case, the CPS 64 knows which antenna element 40 is represented by each per element sounding signal 150.

[0064] Figure 4 illustrates a method 400 of operation in a SCS 10, according to one embodiment. The method 400 includes performing a beam weight calculation procedure in a ground segment 16 of the SCS 10. The beam weight calculation procedure includes: obtaining (Block 402) per element sounding signal samples corresponding to respective antenna elements 40 of a phased array antenna 35 onboard a satellite 26 of the SCS 10, for a time during which a channel sounding signal 32 is transmitted by a reference UT 34 located in a user beam coverage area 36 served by the satellite 26 and received via the respective antenna elements 40 of the

phased array antenna 35; generating (Block 404) channel estimates from the per element sounding signal samples; calculating (Block 406) a beam weight set 20 or 22 from the channel estimates, the beam weight set 20 or 22 comprising a corresponding beam weight for each of the respective antenna elements 40 and calculated for formation of a RF user beam 12 or 14 via the phased array antenna 35, for illumination of the user beam coverage area 36; and sending (Block 408) the beam weight set 20 or 22 to the satellite 26 for application to per element communication signals carrying transport data associated with UTs 38 located in the user beam coverage area 36 and corresponding formation of the RF user beam 12 or 14.

[0065] In one or more embodiments, the method 400 includes performing the beam weight calculation procedure on a recurring basis, with each recurrence using new per element sounding signal samples. In at least one embodiment, the satellite 26 uses first time slots for exchanging transport data with the UTs 38 located in the user beam coverage area 36, and uses second time slots for channel sounding, and wherein each first time slot has corresponding per element communication signals and each second time slot has corresponding per element sounding signals 150. The second time slots are interleaved with the first time slots, for example.

[0066] Obtaining the per element sounding signal samples comprises, for example, the satellite 26 providing per element sounding signals 150 via a feeder downlink signal received by the ground segment 16 from the satellite 26, for subsequent digital sampling in the ground segment. Alternatively, the satellite 26 provides the samples themselves.

[0067] Figure 5 illustrates a further method 500 of operation in a SCS 10, according to one embodiment. The method 500 includes a satellite 26 of the SCS 10 receiving (Block 502) a channel sounding signal 32 from a reference UT 34 located in a user beam coverage area 36 served by the satellite 26, the channel sounding signal 32 being received via a phased array antenna 35 comprising respective antenna elements 40, each respective antenna element 40 outputting a per element sounding signal 150 corresponding to reception of the channel sounding signal 32 via the phased array antenna 35. According to the method 500, the satellite 26 provides (Block 504) the per element sounding signals 150 to a ground segment 16 of the SCS 10.

[0068] Further, the method 500 includes the satellite 26 receiving (Block 506) a beam weight set 20 or 22 calculated by the ground segment 16 in dependence on the per element sounding signals 150, each beam weight in the set 20 or 22 corresponding to one of the respective antenna elements 40. Still further, the method 500 includes the satellite 26 applying (Block 508) the beam weight set 20 or 22 for transmission or reception of a RF user beam 12 or 14 via the phased array antenna 35, the RF user beam 12 or 14 carrying multiplexed transport data associated with respective ones among a plurality of UTs 38 located in the user beam coverage area 36.

[0069] Figure 6 illustrates another method 600 of operation by a SCS 10 according to one embodiment. The method 600 includes forming (Block 602) a user beam 12 or 14 via beamformer circuitry 24 onboard a satellite 26 of the SCS 10 applying corresponding beam weights from a beam weight set 20 or 22 to respective per element signals of a phased array antenna 35 onboard the satellite 26, where the user beam 12 or 14 illuminates a corresponding user beam coverage area 36 that is served by the satellite 26.

[0070] The method 600 further includes calculating (Block 604) the beam weight set 20 or 22 in a ground segment 16 of the SCS 10, based on the satellite 26 providing the ground segment 16 with per element signals 150 from the phased array antenna 35 corresponding to a time or times during which channel sounding signals 32 are transmitted by one or more reference UTs 34 located in the corresponding user beam coverage area 36 and received via the phased array antenna 35 of the satellite 26. Still further, the method 600 includes sending (Block 606) the beam weight set 20 or 22 from the ground segment 16 to the satellite 26.

[0071] 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 (SCS), the method comprising:
 - performing a beam weight calculation procedure in a ground segment of the SCS, the beam weight calculation procedure comprising:
 - obtaining per element sounding signal samples corresponding to respective antenna elements of a phased array antenna onboard a satellite of the SCS, for a time during which a channel sounding signal is transmitted by a reference user terminal (UT) located in a user beam coverage area served by the satellite and received via the respective antenna elements of the phased array antenna;
 - generating channel estimates from the per element sounding signal samples;
 - calculating a beam weight set from the channel estimates, the beam weight set comprising a corresponding beam weight for each of the respective antenna elements and calculated for formation of a radio frequency (RF) user beam via the phased array antenna, for illumination of the user beam coverage area; and
 - sending the beam weight set to the satellite for application to per element communication signals carrying transport data associated with UTs located in the user beam coverage area and corresponding formation of the RF user beam.
2. The method according to claim 1, further comprising performing the beam weight calculation procedure on a recurring basis, with each recurrence using new per element sounding signal samples.
3. The method according to claim 1 or 2, wherein the satellite uses first time slots for exchanging transport data with the UTs located in the user beam coverage area, and uses second time slots for channel sounding, and wherein each first time slot has corresponding per element communication signals and each second time slot has corresponding per element sounding signals.

4. The method according to claim 3, wherein the second time slots are interleaved with the first time slots.
5. The method according to claim 3 or 4, wherein, with respect to each first time slot, the per element communication signals correspond to a beam signal exchanged between the satellite and the ground segment, where the beam signal conveys multiplexed transport data associated with the UTs located in the user beam coverage area, and wherein, with respect to each second time slot, the ground segment receives corresponding per element sounding signals or samples thereof from the satellite.
6. The method according to any one of claims 1-5, wherein the user beam coverage area is one among a plurality of user beam coverage areas served by the satellite, and wherein the method further comprises the ground segment of the SCS performing the beam weight calculation procedure with respect to each user beam coverage area, for formation of a corresponding plurality of RF user beams via the phased array antenna of the satellite, each RF user beam illuminating a respective one among the plurality of user beam coverage areas.
7. The method according to any one of claims 1-6, wherein the user beam coverage area is a forward user beam coverage area and wherein the beam weight set comprises a set of forward beam weights, and wherein the RF user beam comprises a forward user beam.
8. The method according to any one of claims 1-6, wherein the user beam coverage area is a return user beam coverage area and wherein the beam weight set comprises a set of return beam weights, and wherein the RF user beam comprises a return user beam.
9. The method according to any one of claims 1-8, wherein obtaining the per element sounding signal samples comprises one of:
 - the satellite providing per element sounding signals via a feeder downlink signal received by the ground segment from the satellite, for subsequent digital sampling in the ground segment; or
 - the satellite providing the per element sounding signal samples via the feeder downlink signal.

10. The method according to claim 9, wherein the phased array antenna comprises a digital array that outputs the per element sounding signal samples, and the satellite provides the per element sounding signal samples via the feeder downlink signal.

11. The method according to any one of claims 1-10, wherein the satellite includes a digital beamformer that applies the beam weight set with respect to the phased array antenna, for formation of the RF user beam, and wherein the beam weight set comprises a set of digital weight values for application in a digital domain by the digital beamformer.

12. A method of operation in a satellite communications system (SCS), the method comprising:

a satellite of the SCS:

receiving a channel sounding signal from a reference user terminal (UT) located in a user beam coverage area served by the satellite, the channel sounding signal received via a phased array antenna comprising respective antenna elements, each respective antenna element outputting a per element sounding signal corresponding to reception of the channel sounding signal via the phased array antenna;

providing the per element sounding signals to a ground segment of the SCS;

receiving a beam weight set calculated by the ground segment in dependence on the per element sounding signals, each beam weight in the beam weight set corresponding to one of the respective antenna elements; and

applying the beam weight set for transmission or reception of a radio frequency (RF) user beam via the phased array antenna, the RF user beam carrying multiplexed transport data associated with respective ones among a plurality of UTs located in the user beam coverage area.

13. The method according to claim 12, wherein the RF user beam is a forward user beam, the user beam coverage area is a forward user beam coverage area, and the beam weight set is a set of forward beam weights, and wherein the ground segment modulates a forward user beam signal onto a feeder uplink carrier and the method further comprises the satellite recovering the forward user beam signal from the feeder uplink carrier, for weighted transmission from the phased array antenna according to the beam weight set and corresponding formation of the forward user beam.

14. The method according to claim 13, wherein applying the set of forward beam weights comprises beamformer circuitry onboard the satellite splitting recovered forward beam signal into a plurality of signal copies, each signal copy corresponding to one among the respective antenna elements and weighted by the corresponding forward beam weight to form a corresponding weighted signal copy, such that simultaneous transmission of the corresponding weighted signal copies from the respective antenna elements results in far field formation of the forward user beam.

15. The method according to claim 14, wherein the beamformer circuitry onboard the satellite comprises digital beamformer circuitry and wherein the method comprises the satellite obtaining the plurality of signal copies in a digital domain and converting the corresponding weighted signal copies from the digital domain to an analog domain, for transmission from the respective antenna elements.

16. The method according to claim 12, wherein the RF user beam is a return user beam, the user beam coverage area is a return user beam coverage area, and the beam weight set is a set of return beam weights, and wherein the method includes the satellite forming the return user beam by applying the set of return beam weights to per element communication signals to obtain corresponding weighted per element communication signals, which are combined to form a return user beam signal, and wherein the per element communication signals correspond to reception of a communication signal via the phased array antenna, and the method further includes the satellite modulating the return user beam signal onto a feeder downlink carrier, for reception by the ground segment.

17. The method according to claim 16, wherein beamformer circuitry onboard the satellite forms the return user beam.

18. The method according to claim 17, wherein the beamformer circuitry onboard the satellite comprises digital beamformer circuitry.

19. A method of operation by a satellite communications system (SCS), the method comprising:

forming a radio frequency (RF) user beam via beamformer circuitry onboard a satellite of the SCS applying corresponding beam weights from a beam weight set to respective per element signals of a phased array antenna onboard the satellite, the

RF user beam illuminating a corresponding user beam coverage area that is served by the satellite;

calculating the beam weight set in a ground segment of the SCS, based on the satellite providing the ground segment with per element signals from the phased array antenna corresponding to a time or times during which channel sounding signals are transmitted by one or more reference user terminals (UTs) located in the corresponding user beam coverage area and received via the phased array antenna of the satellite; and

sending the beam weight set from the ground segment to the satellite.

20. A satellite communications system (SCS), the SCS comprising a ground segment that includes:

a ground station configured for transmitting feeder uplink signals to and receiving feeder downlink signals from a satellite of the SCS that performs beamforming with respect to a user beam coverage area served by the satellite; and

a communications processing system (CPS) that is communicatively coupled with the satellite via the ground station, the CPS operative to perform a beam weight calculation procedure, based on one or more processors of the CPS being configured to:

obtain per element sounding signal samples corresponding to respective antenna elements of a phased array antenna onboard the satellite, for a time during which a channel sounding signal is transmitted by a reference user terminal (UT) located in the user beam coverage area and received via the respective antenna elements of the phased array antenna;

generate channel estimates from the per element sounding signal samples;

calculate a beam weight set from the channel estimates, the beam weight set comprising a corresponding beam weight for each of the respective antenna elements and calculated for formation of a radio frequency (RF) user beam via the phased array antenna, for illumination of the user beam coverage area; and

send the beam weight set to the satellite via the ground station, for application by a beamformer onboard the satellite to per element communication signals carrying transport data associated with UTs located in the user beam coverage area and corresponding formation of the RF user beam.

21. A satellite communications system (SCS), the SCS comprising a satellite having an onboard beamformer and a phased array antenna, wherein the satellite is configured to:
- receive a channel sounding signal from a reference user terminal (UT) located in a user beam coverage area served by the satellite, the channel sounding signal received via the phased array antenna, which comprises respective antenna elements, each respective antenna element outputting a per element sounding signal corresponding to reception of the channel sounding signal via the phased array antenna;
 - provide the per element sounding signals to a ground segment of the SCS;
 - receive a beam weight set calculated by the ground segment in dependence on the per element sounding signals, each beam weight in the beam weight set corresponding to one of the respective antenna elements; and
 - apply the beam weight set via the onboard beamformer, for transmission or reception of a radio frequency (RF) user beam via the phased array antenna, the RF user beam carrying multiplexed transport data associated with respective ones among a plurality of UTs located in the user beam coverage area.
22. A satellite communications system (SCS), the SCS comprising:
- a satellite configured to form a radio frequency (RF) user beam via beamformer circuitry onboard the satellite applying corresponding beam weights from a beam weight set to respective per element signals of a phased array antenna onboard the satellite, the RF user beam illuminating a corresponding user beam coverage area that is served by the satellite; and
 - a processing node in a ground segment of the SCS, the processing node configured to:
 - calculate the beam weight set, based on the satellite providing the ground segment with per element signals from the phased array antenna corresponding to a time or times during which channel sounding signals are transmitted by one or more reference user terminals (UTs) located in the corresponding user beam coverage area and received via the phased array antenna of the satellite; and
 - output the beam weight set for transmission to the satellite.