signal input ports 1512, and the cross-talk compensated feed signals at feed signal output ports 1514 can be provided to the gateways as the beamweighted forward input signals; for crosstalk compensation of the return link, the return signal output from the gateways can be provide to the feed signal input ports 1512, and the cross-talk compensated feed signals at feed signal output ports 1514 can be provided to the return beamformer as the return signal outputs. Alternatively, the order of crosstalk compensation and beamforming can be reversed.

[0047] Another category of approaches to impairment compensation involves limited beamforming. As described herein, feeder beams are produced using focused antenna elements, and some embodiments of the focused antenna elements are implemented according to a multiple feed per beam (MFPB) architecture. In MFPB architectures, each antenna feed can be associated with a weighted and combined set of multiple feed signals. To form each weighted and combined set, multiple feed signals can be passed through phase shifters, summers, and/or other hardware that can adjust amplitude weights, phase, and/or other characteristics of the resulting combined feed signal according to applied coefficients. The applied coefficients can be stored in a beamforming coefficient memory on the satellite 140. The coefficients can be pre-computed and/or adaptively updated (e.g., using feedback to the satellite from the gateways), so that the resulting combined feed signals can generated statically or adaptively. Applying the coefficients effectively applies some beamforming to the feeder signals, which can be used to compensate for impairments in the feeder antenna pattern. For example, crosstalk can be predetermined (e.g., estimated or pre-computed) or measured using any of the approaches described above. Rather than using equalization or cancelation to remove the measured crosstalk, coefficients in the MFPB architecture can be used to apply limited beamforming to at least partially correct for the antenna impairments causing the crosstalk (e.g., in a predefined or adaptive manner). Some embodiments can use a hybrid of the categories of approaches. For example, equalization or cancelation can be used to remove measured crosstalk on one of the feeder uplink or downlink, and limited beamforming can be used to remove crosstalk on the other of the feeder uplink or downlink.

[0048] Effective implementation of MSSMFL can rely on proper mutual synchronization of signals among the spatially separated feeder links. A number of approaches can be used to implement such mutual synchronization, and those approaches can depend on characteristics (e.g., overlap, etc.) of the user and feeder coverage areas. For example, in the forward direction, the gateway terminals 130 transmit forward uplink signals to the satellite 140, which are received by antenna elements of the feeder antenna subsystem 230, communicated through forward-link pathways of the forward repeater subsystem 240 to the user antenna subsystem 250, and transmitted as forward downlink signals by antenna elements of the user antenna subsystem 250. To enable the transmitted forward downlink signals to spatially combine to form forward user beams, embodiments use feeder-side ground segment components to generate the feeder signals 135 as mutually synchronized, beam-weighted

CLAIMS:

1. A satellite (140) comprising:

a feeder antenna subsystem (230) comprising a plurality of focused-beam antenna elements "FAEs" (243), each having a forward-link FAE port;

a user antenna subsystem (250) comprising an array of de-focused beamforming antenna elements "BAEs" (247), each having a forward-link BAE port; and

a forward repeater subsystem (240) having a forward uplink frequency range and a forward downlink frequency range, the forward repeater subsystem comprising a plurality of forward-link pathways (245), each of the plurality of forward-link pathways being coupled between one of the forward-link FAE ports and one of the forward-link BAE ports, and each of the plurality of forward-link pathways having an input in the forward uplink frequency range and an output in the forward downlink frequency range,

wherein the forward-link pathways are configured to generate a plurality of beam-weighted, mutually phase-synchronized forward downlink signals (255) from beam-weighted, mutually phase-synchronized forward uplink signals (235) that are each received via a same carrier frequency at a respective one of the FAEs from a corresponding one of a plurality of geographically distributed gateway terminals (130), and

wherein the BAEs are configured to transmit the forward downlink signals to cause the forward downlink signals from multiple of the plurality of forward-link pathways to spatially superpose to form at least one forward user beam (260).

2. The satellite of claim 1, further comprising a return repeater subsystem (340) having a return uplink frequency range and a return downlink frequency range, wherein:

each FAE of the feeder antenna subsystem further has a return-link FAE port;

each BAE of the user antenna subsystem further has a return-link BAE port; and

the return repeater subsystem comprises a plurality of return-link pathways (345), each coupled between one of the return-link BAE ports and one of the return-link FAE port, and each having an input in the return uplink frequency range and an output in the return downlink frequency range,

wherein the return-link pathways are configured to generate a plurality of return downlink signals (335) for transmission by the FAEs, the return downlink signals generable from return uplink signals (355) received at the BAEs from at least one user terminal (165), thereby forming at least one return user beam (360) for communications with the at least one user terminal.

3. The satellite of claim 1 or 2, further comprising:

a satellite synchronization subsystem (710) having a beacon transmitter,

wherein the forward uplink signals are synchronized prior to receipt at the FAEs in accordance with a synchronization signal transmitted by the beacon transmitter.

4. The satellite of any of claims 1 – 3, wherein:

each FAE has a first forward-link FAE port at a first polarization orientation, and a second forward-link FAE port at a second polarization orientation;

the plurality of forward-link pathways comprises:

a first plurality of forward-link pathways, each coupled between one of the first forward-link FAE ports and one of the forward-link BAE ports; and

a second plurality of forward-link pathways, each coupled between one of the second forward-link FAE ports and another of the forward-link BAE ports.

5. The satellite of claims 1 or 4, wherein:

each forward-link input is coupled with a frequency separator (1010) having a first frequency sub-range output and a second frequency sub-range output; and

the plurality of forward-link pathways comprises:

a first plurality of forward-link pathways, each coupled between the first frequency sub-range output of one of the frequency separators and one of the forward-link BAE ports; and

a second plurality of forward-link pathways, each coupled between the second frequency sub-range output of one of the frequency separators and another of the forward-link BAE ports.

6. The satellite of claim 2, wherein:

each FAE has a first return-link FAE port at a first polarization orientation and a second return-link FAE ports at a second polarization orientation;

each BAE has a first return-link BAE port at the first polarization orientation and a second return-link BAE ports at the second polarization orientation; and

the plurality of return-link pathways comprises:

a first plurality of return-link pathways, each coupled between one of the first return-link BAE ports and one of the first return-link FAE ports; and

a second plurality of return-link pathways, each coupled between one of the second return-link BAE ports and one of the second return-link FAE ports.

7. The satellite of claim 2 or 6, wherein:

each return-link FAE port is coupled with a frequency combiner (1020) having a first frequency sub-range input and a second frequency sub-range input; and

the plurality of return-link pathways comprises:

a first plurality of return-link pathways, each coupled between one of the return-link BAE ports and the first frequency sub-range input of one of the frequency combiners; and

a second plurality of return-link pathways, each coupled between another of the return-link BAE ports and the second frequency sub-range input of one of the frequency combiners.

8. The satellite of any of claims 2, 6 or 7, wherein:

the forward uplink frequency range overlaps the return uplink frequency range; and

the forward downlink frequency range overlaps the return downlink frequency range.

9. The satellite of any of claims 1 - 8, wherein:

the feeder antenna subsystem further comprises a feeder reflector (410); and

the user antenna subsystem further comprises a user reflector (430).

10. A satellite communications system (100, 200, 700, 800) comprising:

a forward beamformer (210);

a plurality of geographically distributed gateway terminals, each comprising:

a beam-weighted forward signal input in communication with the forward beamformer (210) via a distribution network (120);

a synchronization input coupled with a synchronization subsystem (125); and

a feeder uplink signal output that corresponds to a mutually synchronized version of the beam-weighted forward signal input in accordance with the synchronization input; and

the satellite of any of claims 1 – 9, wherein each forward-link FAE port is communicatively coupled with the feeder uplink signal output of a corresponding one of the gateway terminals.

11. The satellite communications system of claim 10, wherein:

each geographically distributed gateway terminal further comprises:

a return signal output in communication with a return beamformer via the distribution network; and

a feeder downlink signal input; and

each FAE of the feeder antenna subsystem further has a return-link FAE port;

each BAE of the user antenna subsystem further has a return-link BAE port; and

the satellite further comprises a return repeater subsystem (340) having a return uplink frequency range and a return downlink frequency range, wherein the return repeater subsystem comprises a plurality of return-link pathways, each coupled between one of the return-link BAE ports and one of the return-link FAE ports, and each having an input in the return uplink frequency range and an output in the return downlink frequency range,

wherein the return-link pathways are configured to generate a plurality of return downlink signals for transmission by the FAEs, the return downlink signals generable from return uplink signals received at the BAEs from at least one user terminal, thereby forming at least one return user beam for communications with the at least one user terminal.

12. The satellite communications system of claim 10, wherein:

surface distortions on the feeder reflector define feeder antenna impairment regions (1210); and

the plurality of geographically distributed gateway terminals are positioned away from the feeder antenna impairment regions.

13. The satellite communications system of claim 10, wherein:

surface distortions on the feeder reflector define feeder antenna impairment regions; and

the feeder antenna subsystem comprises a multiple feeds per beam antenna to apply limited beamforming to feeder beams to compensate for the feeder antenna impairment regions.

14. The satellite communications system of claim 13, wherein:

the multiple feed per beam antenna comprises a beamforming coefficient memory having pre-computed beamforming coefficients stored therein, the pre-computed beamforming coefficients used to apply the limited beamforming.

15. The satellite communications system of claim 13, wherein:

the multiple feed per beam antenna comprises a beamforming coefficient memory having adaptively updated coefficients stored therein, the adaptively updated coefficients used to apply the limited beamforming.

16. The satellite communications system of claim 10, wherein:

the plurality of geographically distributed gateway terminals comprises M gateway terminals; and

the forward repeater subsystem comprises M forward-link pathways, each corresponding to a respective one of the M gateway terminals.

17. The satellite communications system of any of claims 10 - 16, wherein the feeder uplink signal output corresponds to a phase-synchronized version of the beam-weighted forward signal input responsive to the synchronization input.

18. The satellite communications system of any of claims 10 - 17, wherein:

the satellite further comprises a beacon transmitter; and

the synchronization subsystem comprises:

a loopback input; and

a synchronization output coupled with the synchronization input, the synchronization output responsive to phase-synchronization of a beacon signal and a loopback signal both received at the loopback input.

19. The satellite communications system of claim 18, wherein each gateway terminal further comprises a loopback transmitter.

20. The satellite communications system of any of claims 10 - 19, wherein each gateway terminal further comprises a local instance of the synchronization subsystem.

21. The satellite communications system of any of claims 10 - 19, further comprising:

the synchronization subsystem, wherein each of the plurality of geographically distributed gateway terminals is coupled with the synchronization subsystem via the distribution network.

22. The satellite communications system of any of claims 10 - 21, further comprising:

a crosstalk canceler (1510) having:

a plurality of feed input ports to receive feed input signals from the plurality of gateway terminals; and

a plurality of feed output ports to output crosstalk-compensated feed signals, the crosstalk-compensated feed signals generated as a function of the feed input signals and a stored crosstalk matrix.

23. The satellite communications system of claim 22, wherein:

the satellite further comprises a loopback pathway having a loopback antenna element that is coupled with the FAEs via a plurality of switches (1410),

such that, over a plurality of time slots, the loopback antenna element is sequentially coupled with the respective forward-link FAE port of each of the FAEs, thereby, in each of the time slots, transmitting a repeated loopback signal to the gateway terminals in response to receiving a loopback beacon signal from the gateway terminal associated with the FAE that is sequentially coupled in the time slot.

24. The satellite communications system of claim 22, wherein:

the satellite further comprises a loopback pathway (500) having a loopback antenna element that is coupled with the FAEs via a plurality of switches (1410),

such that, over a plurality of time slots, the loopback antenna element is sequentially coupled with the respective return-link FAE port of each of the FAEs, thereby, in each of the time slots, transmitting a repeated loopback signal to the gateway terminal associated with the FAE that is sequentially coupled in the time slot in response to receiving a loopback beacon signal from the gateway terminals.

25. The satellite communications system of any of claims 10 - 24, wherein:

the feeder antenna subsystem illuminates a plurality of forward feeder beams; and

the formed forward user beams do not spatially overlap with the forward feeder beams.

26. The satellite communications system of any of claims 10 - 25, wherein the forward beamformer comprises:

a plurality of forward data stream inputs;

a beam weight input indicating beam weights associated with each of the gateway terminals and forward data streams; and

a plurality of beam-weighted forward signal outputs, each coupled with the beam-weighted forward signal input of a respective one of the gateway terminals via the distribution network, and each being a weighted sum of the forward data stream inputs beam-weighted according to the beam weights associated with the respective one of the gateway terminals.

27. The satellite communications system of claim 26, wherein:

the forward data stream input comprises *K* forward data stream inputs, each corresponding to a respective one of *K* formed forward user beams;

the plurality of geographically distributed gateway terminals comprises *L* feeder uplink signal outputs; and

the beam weight input comprises *L* x *K* beam weights; and

the beam-weighted forward signal outputs correspond to *L* composites of the *K* forward data stream inputs beam-weighted according to the *L* x *K* beam weights.

28. The satellite of any of claims 1 – 9, or the satellite communications system of any of claims 10 - 27, wherein the satellite is a geostationary satellite.

29. A method for ground-based beamforming in a satellite communications system comprising a satellite (140), the method (1100) comprising:

receiving, by the satellite, a plurality of beam-weighted mutually phase-synchronized forward uplink signals (235), each received at a same carrier frequency via one of a plurality of focused feeder uplink antenna elements (243) from a corresponding one of a plurality of spatially separated gateways;

generating, by the satellite, each of a plurality of beam-weighted, mutually phase-synchronized forward downlink signals (255) by amplifying and frequency converting a corresponding one of the plurality of beam-weighted, mutually phase-synchronized forward uplink signals; and

transmitting, by the satellite, the plurality of forward downlink signals via a plurality of de-focused user downlink antenna elements (247), such that the forward downlink signals from multiple of the plurality of forward-link pathways spatially superpose to form a user beam (260).

30. The method of claim 29, further comprising:

applying beam-weighting to a plurality of forward data streams (205) to generate *L* beam-weighted forward signals (215);

communicating each of the *L* beam-weighted forward signals to a corresponding one of *M* spatially separated gateways; and

synchronizing the beam-weighted forward signals at the gateways to generate the *L* beam-weighted, mutually synchronized forward uplink signals.

31. The method of claim 30, wherein:

the forward downlink signals spatially superpose to form *K* user beams; and

the beam-weighting comprises applying *L* x *K* beam weights (213) to *K* forward data streams to generate the *L* beam-weighted forward signals.

32. The method of any of claims 29 - 31, wherein:

the receiving is at an uplink frequency range;

the transmitting is at a downlink frequency range; and

the frequency converting comprises converting from the uplink frequency range to the downlink frequency range.

33. The method of any of claims 29 - 32, further comprising:

receiving, by the satellite, a plurality of return uplink signals (355) via a plurality of de-focused user uplink antenna elements (247);

generating, by the satellite, each of a plurality of return downlink signals (335) from a corresponding one of the plurality of return uplink signals; and

transmitting, by the satellite, the plurality of return downlink signals via a plurality of focused feeder downlink antenna elements (243) to the spatially separated gateways,

the de-focused user uplinks originating in a beam coverage area formed by ground-based mutual phase-synchronizing and beam-weighting of the return downlink signals subsequent to transmitting the return downlink signals.

34. The method of claim 33, further comprising:

receiving the plurality of return downlink signals at the spatially separated gateways;

synchronizing the return downlink signals at the gateways to generate a plurality of mutually phase-synchronized return signals; and

beam-weighting the plurality of mutually phase-synchronized return signals to generate beam-weighted mutually phase-synchronized return signals.

35. The method of claim 34, wherein:

the beam-weighted mutually phase-synchronized return signals comprise *L* beam-weighted mutually phase-synchronized return signals;

the formed beam coverage area comprises *K* user beams; and

beam-weighting the plurality of mutually phase-synchronized return signals comprises applying *L* x *K* return beam weights (313) to the *L* beam-weighted mutually phase-synchronized return signals to recover *K* return data streams (305).

36. The method of any of claims 33 – 35, wherein:

the plurality of return uplink signals are received at a return uplink frequency range;

the plurality of return downlink signals are transmitted at a return downlink frequency range; and

the generating comprises converting from the return uplink frequency range to the return downlink frequency range.

37. The method of any of claims 30, 31, 34, or 35, wherein:

the synchronizing comprises:

receiving a beacon signal at the gateways, the beacon signal transmitted from the satellite;

receiving, at each gateway, a respective loopback signal transmitted from the gateway; and

phase-synchronizing, at each gateway, the received respective loopback signal with the received beacon signal.

38. The method of any of claims 30 - 37, further comprising:

receiving feed input signals (1512) from the gateways; and

generating crosstalk-corrected feed signals (1514) as a function of the feed input signals and a stored crosstalk matrix.

39. The method of claim 38, further comprising:

sequentially coupling a loopback antenna element, over a plurality of time slots, with each of the focused feeder uplink antenna elements, thereby, in each of the time slots, transmitting a repeated loopback signal to the gateways in response to receiving a loopback beacon signal from the gatewayassociated with the focused feeder uplink antenna element that is sequentially coupled in the time slot,

wherein, over the plurality of time slots, the feed input signals correspond to the repeated loopback signals as received at the gateways.

40. The method of claim 38, further comprising:

sequentially coupling a loopback antenna element, over a plurality of time slots, with each of a plurality of focused feeder downlink antenna elements, thereby, in each of the time slots, transmitting a repeated loopback signal to the gateway associated with the focused feeder downlink antenna elements that is sequentially coupled in the time slot in response to receiving a loopback beacon signal from the gateways,

wherein, in each of the time slots, at least one of the feed input signals corresponds to the repeated loopback signal as received by at least one of the gateways in the time slot.

41. The method of any of claims 30 - 37, further comprising:

receiving at least one probe signal by at least one of the gateways from at least one user terminal; and

generating at least one crosstalk-corrected feed signal as a function of comparing the at least one probe signal with an expected feed signal.

42. The method of any of claims 30 - 37, further comprising:

receiving at least one probe signal by at least one user terminal from at least one of the gateways; and

generating at least one crosstalk-corrected feed signal as a function of comparing the at least one probe signal with an expected user signal.