

(19) World Intellectual Property
Organization
International Bureau



(43) International Publication Date
10 February 2005 (10.02.2005)

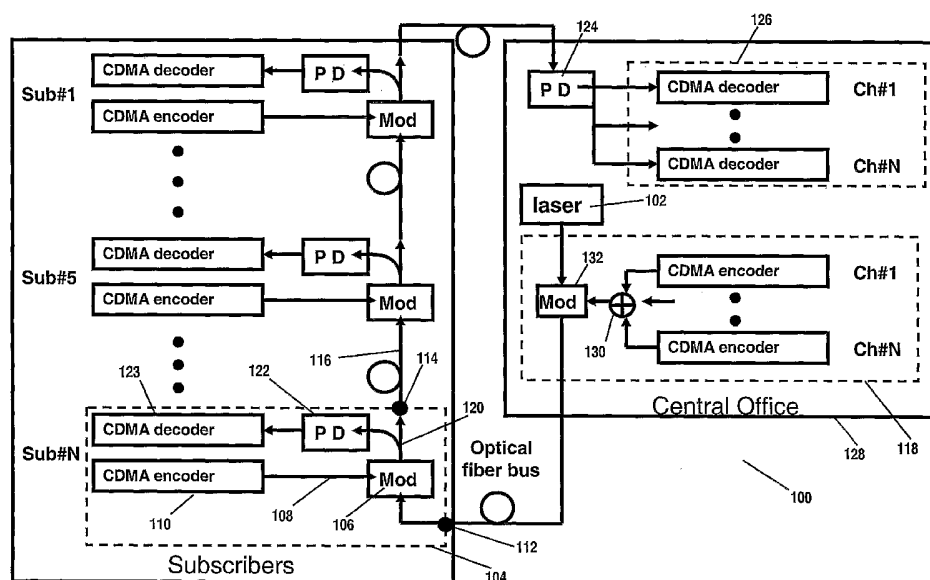
PCT

(10) International Publication Number
WO 2005/013526 A1

- (51) International Patent Classification⁷: **H04J 13/02**, 14/00
- (21) International Application Number: PCT/AU2004/001003
- (22) International Filing Date: 28 July 2004 (28.07.2004)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
2003903960 29 July 2003 (29.07.2003) AU
2003905518 9 October 2003 (09.10.2003) AU
- (71) Applicants (for all designated States except US): **UNIVERSITY OF MELBOURNE** [AU/AU]; Grattan Street, Parkville, VIC 3052 (AU). **UNIVERSITY OF SYDNEY** [AU/AU]; Paramatta Road, Sydney, NSW 2006 (AU).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **HEWITT, Donald, Francis** [AU/AU]; 8 Malcolm Street, Blackburn, VIC 3130 (AU). **SCEATS, Mark, Geoffrey** [AU/AU]; 102/38 Refinery Drive, Pymont, NSW 2006 (AU).
- (74) Agent: **WATERMARK PATENT & TRADEMARK ATTORNEYS**; 290 Burwood Road, Hawthorn, VIC 3122 (AU).
- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: OPTICAL NETWORK UTILISING SPREAD SPECTRUM TRANSMISSION



(57) Abstract: An optical network structure (100) includes an optical source (102) and a plurality of network access nodes (Sub#1 to Sub#N). Each access node includes an optical modulator (106) arranged to be driven by an electrical signal including a subscriber data channel encoded in accordance with an electrical spread-spectrum coding method (110,123). The plurality of network access nodes are optically interconnected such that, in use, light from the optical source passes successively through the optical modulators of at least two of the network access nodes. Light from the optical source is thereby successively modulated in response to the electrical signals driving the optical modulators of said at least two network nodes. An optical network access node, and corresponding methods of modulating an optical carrier are also provided.



Published:

— with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

OPTICAL NETWORK UTILISING SPREAD SPECTRUM TRANSMISSION

FIELD OF THE INVENTION

The present invention related broadly to an optical communications network, and more particularly to an apparatus and method for distributing data
5 over an optical communications network using an optical source shared amongst a number of subscribers.

BACKGROUND OF THE INVENTION

In optical communications networks a number of multiple-access techniques are known in the art for providing to multiple subscribers shared
10 access to a passive optical transmission medium such as, for example, an optical fibre, where in this context the word "subscriber" is used to refer to any user having access to the network to send and/or receive information. The known multiple-access techniques include time division multiple access (TDMA) and wavelength division multiple access (WDMA).

15 In TDMA methods, access to the transmission medium is shared amongst subscribers by allocating to each subscriber having data to send one or more distinct time slots during which the data may be transmitted without interference by the transmissions of other subscribers. Although TDMA techniques have been very popular and successful in networks employing active electronic transceivers
20 and switching at the subscriber access nodes, their implementation in passive optical networks presents a particular problem. Specifically, since optical signals are combined optically within the transmission medium, the access nodes are unable to rely upon electronic switching and buffering to multiplex the transmissions. Accordingly, it is necessary to employ relatively complex protocols
25 to achieve synchronisation and regulate the timing of transmissions within the network in order to avoid interference, or collisions, between transmissions originating from different subscribers.

Known WDMA methods avoid this drawback of TDMA techniques by employing multiple wavelengths of light to separate transmissions from different
30 subscribers. For example, a common plan employs a set of optical wavelengths contained within the low-loss window of standard optical fibre at around 1550 nm, wherein the allocated wavelengths are typically separated in frequency by a multiple of 100 GHz. Light of differing wavelengths can be combined into a

common transmission medium, and separated again, by using wavelength division multiplexing and demultiplexing methods and devices that are well-known in the art.

However, WDMA methods have a number of disadvantages. The number
5 of wavelengths that are available for use is limited by the wavelength stability and discrimination capability of the available components, including transmitters, filters, multiplexers and demultiplexers. Thus, unless WDMA methods are combined with other multiplexing methods such as TDMA, the number of simultaneous subscriber access nodes that can be supported is limited.
10 Furthermore, quality components that enable reasonably large numbers of wavelengths to be supported are relatively expensive. In addition, each subscriber access node requires at least one precision transmitter, and in some implementations each node may require multiple transmitters corresponding to different wavelengths.

15 Since shared medium access techniques are generally most advantageous in highly cost sensitive applications such as local area networks and access networks, the high costs associated with WDMA methods are often prohibitive.

Attempts have therefore been made to develop alternative optical shared
20 medium access techniques that do not suffer from these disadvantages. One approach known in the art is to attempt to employ spread spectrum techniques, such as code division multiple access (CDMA), which have proven successful in the electrical domain.

However, problems exist in translating CDMA methods to the optical
25 domain. Electrical transmissions, including wired and wireless transmissions, are based on variations in the voltage and current of an electromagnetic field. These properties of the field may take on both positive and negative values, enabling bipolar codes to be used such that at the receiver undesired and uncorrelated transmissions may be substantially nullified. Optical transmissions are typically
30 based on variations in the power or intensity of light, which cannot be negative. Accordingly, unipolar codes must be used, which cannot be effectively nullified at the receiver. As a result, despite a great deal of research investigating so-called

optical orthogonal codes in attempts to overcome this difficulty, such optical CDMA systems have been found to have severely limited capacity.

Accordingly, alternative optical spread spectrum methods have been investigated that rely instead upon the coherence properties of broadband light sources. Although these techniques enable the optical field corresponding to undesired channels to be substantially nullified at the receiver, they rely upon the use of expensive precision optical interference devices for their operation. Furthermore, they suffer from a fundamental flaw in that they are limited by quantum noise processes arising in the detection process.

It has more recently been recognised that electrical CDMA signals can be transported over an optical network as analog signals using known analog modulation and transmission techniques and technologies. In one known implementation of this approach due to Woodward and Ariyavisitakul, and described in *IEEE Transactions on Vehicular Technology*, vol. 48, no. 4, July 1999, pp. 1033-1038, multiple CDMA signals are combined in the electrical domain, over a radio link, and the optical transmission link only provides transport for the combined signal. There is accordingly no provision for shared access to the optical medium directly.

Other researchers have investigated an implementation in which shared access to the optical medium is enabled by providing a number of separate subscriber access nodes, each having its own transmitter which may be modulated with an electrical CDMA signal. Such systems are described, for example, by Yamamoto and Sugie in *IEEE Photonics Technology Letters*, vol. 12, no. 12, December 2000, pp. 1710-1712, by Ahn and Park in *IEEE Photonics Technology Letters*, vol. 14, no. 9, September 2002, pp. 1381-1383 and by Hsaio, Wang and Way in *IEEE Photonics Technology Letters*, vol. 9, no. 8, August 1997, pp. 1173-1175. However, as each of these documents reveals, such systems suffer from a problem in that when the combined optical signals are received, beating arises between the various optical carriers which results in distortion and interference between the signals transmitted from the different subscriber access nodes. Furthermore, these systems still require that each access node includes its own transmitter, which increases the cost of the node.

Accordingly, there is a need for a method and corresponding network structure that enables multiple subscriber access nodes to share a single optical transmission medium, and which mitigates the above-described problems of the prior art.

5 Any discussion of documents, devices, acts or knowledge in this specification is included to explain the context of the invention. It should not be taken as an admission that any of the material formed part of the prior art base or the common general knowledge in the relevant art on or before the priority date of the claims herein.

10 SUMMARY OF THE INVENTION

In one aspect, the present invention provides an optical network structure including:

an optical source; and

15 a plurality of network access nodes, each of which includes an optical modulator arranged in use to be driven by an electrical signal including a subscriber data channel encoded in accordance with an electrical spread-spectrum coding method,

wherein the plurality of network access nodes are optically interconnected such that, in use, light from the optical source passes successively through the optical modulators of at least two of the network access nodes, whereby the light from the optical source is successively modulated in response to the electrical signals driving the optical modulators of said at least two network nodes.

25 Accordingly, the invention provides the advantage that a number of network nodes share the use of a single optical source, reducing the overall cost of each node. A further advantage provided by the invention is that in embodiments in which the optical source is a coherent source, such as a laser, the use of a common source avoids the production of interference and distortion that may otherwise arise from beating between different optical carriers at a receiver.

30 In embodiments of the invention there may be additional optical sources, the aforementioned advantages being realised so long as at least one of the optical sources is shared amongst a number of network nodes. The optical sources may be of the same or differing wavelength, and may transmit light over

common or distinct optical links in the network. For example, two sources having different wavelengths may be transmitted in either the same or opposing directions over a single set of optical interconnections. It will be apparent that if sources directed in opposing directions are used, light from one source would
5 pass successively through the network access nodes in the reverse order to light from the other source. In this way, increased capacity may be realised using either unidirectional or bidirectional transmission over the single set of optical interconnections.

The optical source may be a coherent optical source, such as a laser diode
10 or other laser source. Alternatively, the optical source may be an incoherent optical source, such as a light emitting diode or other source of substantially broadband light.

Preferably the plurality of network access nodes are optically interconnected using optical fibres. Alternatively or additionally, optical
15 interconnection may be achieved using free-space optical links. However, other forms of optical interconnection may alternatively or additionally be used.

The wavelength emitted by the optical source may be within the 1550 nm transmission window. Alternatively, another wavelength may be employed, for example at around 1300 nm or 780 nm.

20 The optical network structure may include optical amplifiers, such as semiconductor optical amplifiers or erbium-doped fibre amplifiers.

The data channel may be a digital data channel.

Preferably the electrical spread-spectrum coding method is a direct sequence (DS) digital coding method employing orthogonal bipolar multiplicative
25 binary codes. In one embodiment, the network employs clock synchronisation and the binary code may be a relatively short code such as a Walsh code.

Clock synchronization may be achieved by transmitting through the optical network a synchronization signal receivable by the network access nodes, which are thereby able to synchronize their transmissions with the received
30 synchronization signal.

The synchronization signal may include a channel encoded in accordance with an electrical spread spectrum encoding method that modulates the light from the optical source along with the signals including subscriber data channels.

In a preferred embodiment, clock synchronization is achieved by modulating the light from the optical source with a direct sequence code, and in particular with a pseudo noise (PN) code having good autocorrelation properties. Accordingly, each node in the network is able to receive the PN code, and
5 synchronize its transmissions with the received code sequence, whereas the presence of the PN code synchronization signal causes minimal interference to subscriber data channels.

In an alternative embodiment, the network is asynchronous, and the binary code may be a relatively longer code such as a Gold code. Alternatively or
10 additionally, the electrical spread-spectrum coding method may be a frequency hopping coding method.

In some embodiments of the invention the electrical signal includes a baseband signal. Alternatively or additionally, the electrical signal may include a signal modulated onto a radio frequency carrier.

15 In preferred embodiments the modulator is arranged to be driven by the electrical signal such that the light from the optical source is modulated with a low modulation depth. Advantageously, the use of a low optical modulation depth may reduce the drive voltage required to the modulator which in turn results in reduced power requirements in the network nodes, and may additionally or
20 alternatively enable lower cost modulators to be used, further reducing the overall cost of each node. As an example, an optical modulation depth of 8% per modulator may be used. However, it will be appreciated by those skilled in the art that a different modulation depth may be chosen, and that this example is not limiting.

25 While any suitable optical modulator known in the art may be used, in preferred embodiments the optical modulator is a nonlinear optical modulator, such as a Mach-Zehnder modulator, which provides inherent limiting of modulation peaks. Advantageously, such limiting of peaks in the modulating signal enables the use of a relatively higher optically modulation depth per
30 channel while reducing the impact of clipping distortion upon the modulated optical signal, thereby providing for an overall improvement in power budget.

Alternatively, the modulator may be an electroabsorption modulator.

The modulator preferably has a low insertion loss, and relatively low optical modulation depth capability.

In some embodiments, the electrical signal provided at one or more of the network access nodes may include additional subscriber data channels. Advantageously, this enables channels from multiple subscribers to be multiplexed in the electrical domain using known spread-spectrum methods prior to transmission within the optical network. The possibility also exists to perform multiplexing of subscriber data channels within one or more of the network access nodes through the provision of one or more further optical modulators within the access node.

In preferred embodiments, the plurality of network access nodes are interconnected to form a bus network topology. Alternatively, the plurality of network access nodes may be interconnected to form a ring network topology. In some embodiments, parallel optical paths may be provided within the network structure. It will, however, be appreciated that many other applicable topologies are known in the art, and that accordingly these alternatives should not be understood as limiting the scope of the invention.

Transmissions within the network structure may be unidirectional. Alternatively, transmissions may be bidirectional.

In a particularly preferred embodiment, the plurality of network access nodes are interconnected to form a bus network topology in which the optical source is located at a head-end of the bus and the plurality of network access nodes are distributed at intervals along the length of the bus. The head-end of the bus may be located at a central office. The central office may therefore include the optical source. Preferably, the central office also includes one of the plurality of network access nodes to enable subscriber data channels to be transmitted in the direction of the further network access nodes distributed along the bus. It is particularly advantageous to arrange the bus in a folded or looped configuration such that the tail-end of the bus is also located at the central office. Accordingly, the optical signal may be received back at the central office, and all subscriber data channels modulated onto the optical carrier at the network access nodes may be extracted from the received signal at the central office. The

extracted subscriber data channels may then be routed within the central office towards their intended destinations.

In other embodiments, the optical network structure may include at least one set of two or more parallel optical paths disposed between an optical splitter and an optical combiner, each one of said parallel optical paths including zero or more network access nodes. Advantageously, the use of an electrical spread spectrum coding method to encode subscriber channels provides the optical network with an enhanced tolerance to interferometric noise resulting from the recombination of signals in the parallel optical paths, when compared with conventional optical access network technologies.

In another aspect, the present invention provides a network access node including:

- an optical input port;
- an optical output port; and
- an optical modulator arranged to receive light entering the network access node at the optical input port and transmit said light to the optical output port, wherein the optical modulator is further arranged in use to be driven by an electrical signal including a subscriber data channel encoded in accordance with an electrical spread-spectrum coding method, such that the light transmitted to the optical output port includes the light received at the optical input port after having been modulated in response to the electrical signal driving the optical modulator.

Preferably, the network access node further includes an optical tap arranged to couple out of the transmission path between the optical input port and the optical output port a fraction of the light passing through the network access node, and an optical receiver for receiving the light coupled out by the optical tap. Accordingly, any desired channel modulated onto the light entering the network access node prior to reaching the node may be extracted from the signal received by the optical receiver using a suitable spread spectrum decoding circuit. In this way, the network access node is able to receive signals transmitted to it by prior modulation of the light entering the node at the optical input port.

The optical tap may be an asymmetric optical fibre coupler. The optical receiver is preferably a photodiode, and may include further electrical circuitry for

performing such functions as filtering and amplification of the received optical signal.

The optical modulator may be any suitable type of modulator known in the art of optical communications, however it is preferably a modulator having a nonlinear transfer characteristic, such as a Mach-Zehnder modulator or electro-absorption modulator. It is particularly preferred that the modulator have a low insertion loss, and it may also have a relatively low optical modulation depth capability.

In embodiments of the invention, a low loss, small optical modulation depth modulator may be used, said modulator including:

- an asymmetric optical splitter having an optical input port;
- an asymmetric optical combiner having an optical output port; and
- an electrical input port for receiving a driving electrical signal,

the asymmetric optical splitter having a high power output port connected via a first optical path to a corresponding high power input port of the asymmetric optical combiner, and a low power output port connected via a second optical path to a corresponding low power input port of the asymmetric optical combiner,

wherein at least one of said first and second optical paths is arranged such that a change is induced in the relative optical path lengths of the optical paths in response to said driving electrical signal, whereby interference occurs at the asymmetric optical combiner resulting in modulation of the intensity of light emitted at the optical output port over a limited optical modulation depth.

Accordingly, it will be appreciated that said optical modulator is a modification of a conventional Mach-Zehnder modulator, optimized for low insertion loss and restricted optical modulation depth. For example, the ratio between the respective high power and low power ports of the asymmetric optical splitter and combiner may be 15dB.

In a preferred embodiment of the low loss, small optical modulation depth optical modulator, a change in the relative effective path lengths of the optical paths is achieved by including a phase shifting element responsive to the driving electrical signal in the second optical path. Accordingly, assuming a splitting and coupling ratio of 15dB, even if the phase shifting element result in high optical

losses, such as, for example, 6dB loss, the overall insertion loss of the modulator will be only 0.26dB, and the optical modulation depth will be 3.2%.

In yet another aspect, the present invention provides, in an optical network including an optical source and a plurality of network access nodes
5 interconnected such that light from the optical source passes successively through the network access nodes, a method of modulating an optical carrier with a plurality of subscriber data channels including the step of, in at least two of the network access nodes, modulating light from the optical source with subscriber data channels encoded in accordance with an electrical spread spectrum coding
10 method.

Advantageously, following photodetection of the modulated optical carrier produced by the method of the present invention, the individual subscriber data channels may be extracted from the received signal using electrical despread-
15 ing methods and circuits known in the art. In some embodiments of the invention, the known electrical despread- ing methods may include multi-user despread- ing methods employing co-channel interference cancellation. Such methods are known in, for example, wireless CDMA systems, however it is a particular benefit of the method of the invention that the stability of transmission within the optical interconnections is superior to that of wireless transmission which may suffer from
20 variable multipath interference effects. Accordingly, the performance of co-channel interference cancellation may be enhanced when used with the method of the invention in comparison to the performance achieved in wireless systems.

In a further aspect, the present invention provides in an optical network access node including an optical input port and an optical output port, a method
25 of modulating an optical carrier with a subscriber data channel including the steps of:

- receiving light at the optical input port;
- modulating the received light with a subscriber data channel encoded in accordance with an electrical spread spectrum coding method; and
30 transmitting the modulated light to the optical output port.

It will be appreciated from the above summary that the essence of the invention lies in the discovery by the inventor that electrical spread-spectrum channels that are successively modulated onto a single optical carrier can be

successfully and reliably demodulated in the electrical domain using standard electrical decoding methods after detection by an optical receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

Further benefits and advantages of the network structure, network access
5 node and modulation method of the present invention will become apparent in the following description of preferred embodiments of the invention, which should not, however, be considered to limit the scope of the invention or any of the preceding statements. Preferred embodiments are described with reference to the accompanying drawings in which:

10 Figure 1 is a block diagram of an optical fibre access network structure according to a preferred embodiment of the present invention;

Figure 2 shows a schematic setup of a computer simulation of an optical fibre access network according to a preferred embodiment of the invention;

15 Figure 3 shows results of a computer simulation of the optical fibre access network shown in Figure 2;

Figure 4 shows a schematic setup of a computer simulation of a bidirectional optical fibre access network in accordance with a preferred embodiment of the invention in which multiple subscriber data channels are multiplexed in the electrical domain on a coaxial cable bus;

20 Figure 5 shows results of a computer simulation of the bidirectional optical fibre access network of Figure 4;

Figure 6 shows a schematic setup of a computer simulation of a coaxial cable bus on which a baseband CDMA signal is multiplexed with CDMA signals modulated onto radio frequency carriers;

25 Figure 7 shows results of a computer simulation of the coaxial cable bus of Figure 6;

Figure 8 shows a schematic setup of a computer simulation of an optical fibre access network in accordance with a preferred embodiment of the invention employing asynchronous transmission of upstream channels;

30 Figure 9 shows results of a computer simulation of the optical fibre access network of Figure 8;

Figure 10 is a block diagram of a co-channel interference cancellation circuit for use with an optical fibre access network according to a preferred embodiment of the invention the present invention;

Figure 11 shows a schematic setup of a computer simulation of an optical fibre access network according to a preferred embodiment of the present invention employing co-channel interference cancellation at a receiving node;

Figure 12 shows results of computer simulations of the optical access network of Figure 11 both without and with the use of co-channel interference cancellation;

Figure 13 shows an embodiment of an optical network including free space optical links according to the present invention;

Figure 14 shows an alternative embodiment of an optical network including free space optical links according to the present invention;

Figure 15 shows a schematic set up of a computer simulation of an optical fibre access network including a clock synchronization signal in accordance with a preferred embodiment of the invention;

Figure 16 illustrates a specialised optical modulator having low insertion loss and restricted optical modulation depth in accordance with a preferred embodiment of the invention;

Figure 17 shows a schematic setup of a computer simulation of an optical fibre access network including parallel optical paths, in accordance with an embodiment of the invention; and

Figure 18 shows results of a computer simulation of the optical fibre access network of Figure 17.

DESCRIPTION OF PREFERRED EMBODIMENTS

A block diagram of a preferred embodiment of an optical fibre access network structure 100 according to the present invention is shown in Figure 1.

The network 100 includes an optical source 102, and a plurality of network access nodes, eg. 104, each of which includes an optical modulator 106 which is driven by an electrical signal 108 including a subscriber data channel encoded by encoding circuitry 110 in accordance with an electrical spread-spectrum coding method.

Each network access node further includes an optical input port 112 and an optical output port 114. Light entering the node at the optical input port 112 is transmitted to the optical output port 114 via the optical modulator 106. As a result, the light transmitted to the optical output port includes the light received at the optical input port after having been modulated in response to the electrical signal driving the optical modulator.

The network access nodes are connected using optical interconnecting links, eg. 116. Accordingly, light from the optical source 102 passes successively through the optical modulators 106 of each of the network access nodes. As a result, the light from the optical source 102 is successively modulated in response to the electrical signals 108 driving the optical modulators 106 of the network nodes.

In the embodiment of Figure 1, the network access nodes, eg. 104, are interconnected to form a bus network topology. The optical source 102 is located at a head-end of the bus and the network access nodes are distributed at intervals along the length of the bus. The head-end of the bus, including the optical source 102, is located at a central office 128.

The central office also includes its own network access node 118. The central office access node includes a number N of spread-spectrum encoding circuits that are combined in the electrical domain as represented by the summing junction 130. The combined signal drives the optical modulator 132 such that the light from the optical source is modulated in response to the electrical signal and accordingly carries the spread-spectrum encoded subscriber data channels from the central office.

In the embodiment shown in Figure 1, the number of channels transmitted from the central office 128 is equal to the number of further subscriber network access nodes, eg 104. Advantageously, this arrangement enables each subscriber access node to receive different data from the central office 128 according to subscriber requirements. However, it will be appreciated that there need not be one channel per subscriber transmitted from the central office 128, and that, for example, provision of broadcast services may be achieved by sending a channel that is subsequently received at multiple subscriber access nodes.

It is particularly advantageous to arrange the bus in a folded or looped configuration, as shown in the embodiment of Figure 1. According to this arrangement, the tail-end of the bus is also located at the central office 128. Accordingly, the optical signal may be received using a photodiode 124 or other
5 form of optical receiver back at the central office. All subscriber data channels modulated onto the optical carrier at the network access nodes may be extracted from the received signal at the central office using a bank 126 of spread-spectrum decoding circuits.

Each subscriber access node, eg. 104, further includes an optical tap 120
10 to remove a small fraction of the passing light from the network. The optical tap 120 may be, for example, an asymmetric optical fibre coupler. A photodiode 122 or other form of optical receiver is then used to detect the light tapped from the network. Any desired channel modulated onto the optical carrier prior to it reaching the node 104 may be extracted from the received signal using a spread-
15 spectrum decoding circuit 123. In this way, each subscriber node is able to receive at least any signal transmitted to it from the central office 128.

Accordingly, the embodiment of Figure 1 is suitable for use as an optical fibre access network for applications such as fibre to the home (FTTH), fibre to the office (FTTO) or fibre to the curb (FTTC) systems. Downstream channels are
20 transmitted to subscribers from the central office 128 along the fibre bus, and upstream channels are successively added to the optical signal at each subscriber access node eg. 104. At the tail end of the bus, back in the central office 128, all of the upstream channels may be received and decoded. These may then be routed via switching equipment within the central office (not shown)
25 towards the intended destinations, which may be either within the access network 100 or elsewhere within the regional, national or global telecommunications networks.

In preferred embodiments, the spread-spectrum encoding method is a direct-sequence (DS) CDMA method known in the art, in which each data bit is
30 multiplied by a bipolar sequence of code chips in the encoding circuit. A different code sequence is employed in each encoding circuit, and accordingly a decoding circuit is able to select any desired channel from a number of multiplexed channels by applying the same code sequence as was used at the corresponding

encoding circuit. A number of suitable codes are known in the art, such as Walsh codes and Gold codes.

The optical modulators, eg 106, 132, should be configured to employ a low modulation depth to enable a large number of channels to be successively modulated onto the optical carrier generated by the source 102. For example, by using a modulation depth of 8% at each network access node, it is possible to support at least 16 channels on a single optical carrier. A further advantage arising from the use of a low modulation depth is that the drive voltage required to the modulator is accordingly reduced, which in turn results in reduced power requirements in the network nodes, and may enable lower cost modulators to be employed.

While any suitable type of optical modulator known in the art of optical communications may be used, a particular benefit is obtained in preferred embodiments of the present invention by the use of a nonlinear optical modulator that provides inherent limiting of peaks in the modulating signals derived from the subscriber data channels. Such inherent limiting mitigates the impact of clipping distortion that arises when peaks of the multiple modulating signals having the same polarity coincide, resulting in a relatively large total depth of optical modulation. If a linear, or linearised, optical modulator is employed, then if the combined level of optical modulation exceeds unity, the optical signal will be clipped, resulting in a loss of information regarding the total level of modulation. However, when nonlinear modulators are used, abrupt clipping of this kind will not occur, and instead as the total level of modulation increases, a more gradual compression of the overall optical signal amplitude will occur. While this process still results in some distortion of the signal, the effect of this compression distortion is not as harmful as the effect of clipping distortion, and accordingly a higher peak optical modulation depth may be achieved which results in an overall improvement in power budget for the network.

While Figure 1 illustrates a unidirectional access network structure utilising a single optical source, it will be appreciated that the folded bus configuration may readily be adapted to provide a unidirectional or bidirectional structure having increased capacity using two or more optical sources. For example, a second set of optical links may be provided in parallel with the first set of interconnecting fibre

links e.g. 116. The optical and electronic components may then be duplicated at the central office 128, and in each of the access nodes, e.g. 104.

Alternatively, an access network having increased capacity may be provided over a single set of interconnecting links e.g. 116, by using two optical
5 sources at the central office 128 having differing wavelengths. The first optical source may be optical source 102 as shown in Figure 1, arranged to provide a downstream optical communication link. A second optical source (not shown in the figures) having a different wavelength from source 102 may be arranged to transmit light through the links e.g. 116 in the same direction, or in the opposite
10 direction, i.e. from the tail-end of the folded bus, to provide an upstream link. By employing suitable filtering and/or wavelength division multiplexing devices at the access nodes, the upstream and downstream signals may be readily separated and recombined.

By using widely-separated wavelengths for the upstream and downstream
15 sources, e.g. 1550nm for downstream and 1300 nm for upstream, a relatively low-cost unidirectional or bidirectional system having increased capacity as compared with a single wavelength system may be provided using coarse wavelength division multiplexing (CWDM) technologies and components. In some embodiments, the access nodes may transmit and receive on both the
20 upstream and downstream channels, however it is preferred that the downstream channel be used for transmissions from the central office to the access nodes, while the upstream channel may be used for transmissions from the access nodes to the central office. In this way, overall capacity is increased, without the need for duplication of all components in every node of the network.

It will also be understood that the upstream and downstream channels may
25 have different characteristics. For example, the upstream and downstream data rates may be different. Downstream transmissions may be synchronous, while upstream transmissions may be asynchronous. Accordingly, such an arrangement is particularly well-suited for asymmetric access networks, in which
30 higher capacity is required in the downstream direction than in the upstream direction.

It will be appreciated that in unidirectional or bidirectional arrangements as hereinbefore described, the upstream and downstream channels are substantially

independent of one another. Accordingly, the further description of embodiments of the invention relates primarily to unidirectional arrangements employing a single wavelength channel. It will be understood, however, that various equivalent arrangements employing multiple wavelength channels and/or
5 bidirectional transmission are possible.

In order to demonstrate the practical application of the present invention, as well as further benefits and advantages of the invention in various preferred embodiments, a number of computer simulations have been carried out. All simulations have been created and executed using the commercially available
10 photonic system simulation software tool *VPItransmissionMaker*TM from VPIphotonics.

Turning now to Figure 2, there is shown a schematic setup 200 of an optical fibre access network in accordance with the invention. The simulation model of the central office 204 is shown at the right hand side of the schematic.
15 The central office 204 includes a laser optical source 202 for the network. The central office further includes four downstream channel generators 206 including random data sources and DS-CDMA encoders. Also included in the central office are four DS-CDMA decoders 208 for receiving upstream channels from each of four subscriber access nodes eg. 210.

20 Further parameters of the simulation are as follows. Each simulated channel operates at a bit rate of 156.25 Mb/s. The DS-CDMA encoding is carried out using an eight chip Walsh code, resulting in an overall transmission rate per channel of 1.25 Gb/s. Transmission from all subscriber access nodes is synchronised such that at the central office DS-CDMA decoders the received bits
25 on each channel are aligned. There is a total of 5 km of fibre in the access loop.

In Figure 3 there is shown representative results of the simulation. Figure 3a shows a graph of the combined DS-CDMA waveform received back at the central office, which clearly shows the substantially additive nature of the successive modulation of the optical carrier at each of the access nodes. Figure
30 3b shows the transmitted 302 and received 303 digital data waveforms for the upstream channel 1, from node 1 to the central office, while Figure 3c shows the transmitted 304 and received 305 digital data waveforms for the downstream

channel 4, from the central office to node 4. Both of these pairs of graphs show that the data is successfully transmitted with no errors.

Turning now to Figure 4, there is shown a schematic setup 400 of a computer simulation of an alternative embodiment of a network according to the present invention. In the simulated embodiment 400 there is a bidirectional fibre bus, represented by the two fibre connections 402, 404 upon which signals are transmitted in opposing directions. Furthermore, there are shown two simulated coaxial cable busses, an upper bus 406 and a lower bus 408. Each bus supports five subscribers, labelled A to E on the upper bus 406 and F to J on the lower bus 408. Accordingly, DS-CDMA encoded transmissions from each of the subscriber access points on each bus are electrically combined on the coaxial busses, and the combined signals are transferred between the two busses via the bidirectional optical bus. The overall result of this arrangement is that all DS-CDMA transmissions by subscribers on both busses are available to be received and decoded by any subscriber on either bus.

Figure 5 shows representative results of the simulation. In particular, there is shown the digital data waveform as transmitted 502 by subscriber G on the lower bus 408, and as received 503 by the subscriber I also on the lower bus 408 as well as received 504 by subscriber B on the upper bus 406. At the same time, there is shown the digital data waveform transmitted 505 by the subscriber D and received 506 by the subscriber C. It is apparent that the data is successfully transmitted in each case without errors.

The simulated embodiment 400 demonstrates that a network according to the present invention is able to support a plurality of subscriber data channels at each network access node, wherein the subscriber data channels are multiplexed in the electrical domain using conventional methods known in the art. The embodiment 400 further demonstrates the use of bidirectional optical transmission in place of the unidirectional bus of the embodiments 100, 200.

The computer simulations described with reference to Figures 2 to 4 have been conducted using ideal, linear, modulator models. Further simulations have been conducted using nonlinear Mach-Zehnder modulator models, and these simulations have demonstrated that when such nonlinear modulators are used, it is possible to increase the optical modulation depth, or the total number of

channels in the system for a given optical modulation depth, thereby increasing the power budget of the system. Accordingly, the use of nonlinear optical modulators with a correspondingly increased optical modulation depth per channel enables a higher level of total optical loss in the network to be tolerated.

5 Turning now to Figure 6, there is shown a schematic setup 600 of a computer simulation demonstrating a further alternative means of multiplexing electrical DS-CDMA subscriber data channels for the purpose of modulating an optical carrier. In the setup 600 there is shown a coaxial cable bus with five ports, of which three ports are active. The active ports have attached transceivers 602,
10 603, 604 for transmitting and receiving subscriber data channels over the coaxial cable bus 601. As configured in the setup 600, the transceiver 602 includes a transmitter arranged to generate a DS-CDMA signal modulated onto a radio frequency carrier at 3 GHz, substantially as employed in known CDMA wireless telephony systems. The transceiver 602 further includes a receiver arranged to
15 demodulate and decode a DS-CDMA signal modulated onto a 3 GHz radio frequency carrier. The transceiver 603 includes a 3 GHz radio frequency DS-CDMA transmitter and a baseband DS-CDMA receiver. The transceiver 604 includes a baseband DS-CDMA transmitter and a 3 GHz DS-CDMA receiver.

Figure 7 shows representative results of executing the simulation setup
20 600. The graph 702 shows the radio frequency spectrum of the combined signal carried on the coaxial cable bus 601, whereas the graph 704 shows the combined signal time waveform. The effect of combining the baseband signal transmitted from the transceiver 604 with the radio frequency signals transmitted from the transceivers 602, 603 is clearly visible in these traces.

25 The graph 706 shows the digital data waveform transmitted by the transceiver 602, whereas the graph 708 shows the corresponding digital data waveform received by the transceiver 604. Similarly, the graph 710 shows the digital data waveform transmitted by the transceiver 603, whereas the graph 712 shows the corresponding digital data waveform received by the transceiver 602.
30 Finally, the graph 714 shows the digital data waveform transmitted by the transceiver 604, whereas the graph 716 shows the corresponding digital data waveform received by the transceiver 603. The arrows on the figure indicate the

part of the radio frequency spectrum in which each of these signals is carried over the coaxial cable bus.

It is apparent that in all cases, the digital data is successfully transmitted without errors.

5 The simulation setup 600 and corresponding results demonstrate that the encoded electrical signal used to drive the optical modulator may be a baseband signal, or a signal modulated onto a radio frequency carrier, and that channels from multiple subscribers may be multiplexed in the electrical domain at baseband or on radio frequency carriers, or using a combination of different types
10 of signals. A particular benefit offered by this flexibility is the ability to transport wireless CDMA signals directly over a network in accordance with the present invention without the necessity to demodulate and decode each wireless radio channel in the network access node.

Turning now to Figure 8, there is shown in part a schematic setup 800 of
15 another optical fibre access network in accordance with the invention. The setup 800 is similar to the setup 200 previously described with reference to Figure 2, and so details of the elements of the simulated network will not be repeated.

In the setup 800, the further parameters of the simulation are now as follows. Each simulated channel again operates at a bit rate of 156.25 Mb/s.
20 However, in this case the DS-CDMA encoding is carried out using a 32 chip Gold code, resulting in an overall transmission rate per channel of 5 Gb/s. There are in total in the simulation 15 upstream subscriber data channels transmitted from the network access nodes. Seven DS-CDMA receivers have been included in the central office, each of which may be configured to receive any one of the 15
25 upstream channels by selection of the corresponding Gold code for decoding.

However, in this case transmission from all subscriber access nodes is asynchronous, such that at the central office DS-CDMA decoders the received bits on each channel are not aligned. Use of Gold codes for encoding of the transmitted signal in place of the shorter Walsh codes used in the previously
30 described setup 200 improves the ability of the DS-CDMA decoders to reliably extract the desired channel in the presence of unsynchronised interfering channels. This is demonstrated in Figure 9, which shows on the left the transmitted digital data waveforms of four representative subscriber data

channels, and on the right the corresponding received channels after decoding at the central office. In all four cases, the digital data is successfully transmitted without errors.

5 This demonstration of the successful operation of an asynchronous embodiment of the invention is significant because synchronising the distributed network access nodes may add undesired complexity to the network. It is accordingly advantageous in some embodiments to implement the network without the requirement for synchronous operation.

10 On the other hand, synchronous DS-CDMA systems generally exhibit superior bit error rate (BER) performance to equivalent asynchronous systems. Accordingly, in applications in which it is desired to maximise BER performance the additional complexity involved in synchronizing the network may be justified. One possible technique for achieving synchronization is discussed below, with reference to Figure 15 of the accompanying drawings.

15 Turning now to Figure 10, there is shown a block diagram of a co-channel interference cancellation circuit 1000 for use with an optical fibre access network according to the present invention. Such circuits and variations thereto are known in the art, and their function is to improve the quality and reliability of reception and decoding of multiple CDMA channels, as at the central office in the
20 embodiment of the invention previously described with reference to Figure 1.

As shown in Figure 10, the combined CDMA channels modulated onto the optical carrier at the network access nodes are received from the optical network 1002. The received signal is input to a bank of CDMA decoders, eg 1004, 1006, 1008, there being one such decoder for each received subscriber data channel.
25 Bit errors may occasionally occur in the decoders, however in a practical implementation the majority of bits are correctly received and decoded. Estimated replicas of the originally transmitted CDMA signals are generated using duplicate CDMA encoders eg 1010, 1012, 1014. By subtracting the replicas of the undesired channels from the total received signal, a resulting signal is
30 produced that has reduced co-channel interference enabling the desired channel to be decoded more reliably.

Figure 11 shows in part a simulation setup 1100 in accordance with the present invention that is similar to the setup 800 previously described with

reference to Figure 8. However, in the setup 1100 co-channel interference cancellation has been included in accordance with the implementation described above with reference to Figure 10.

In Figure 12, representative results from execution of the simulation setup 1100 are shown. The waveform 1202 shows the output of the integrator in the receiver for one of the channels at the central office in the case that the co-channel interference cancellation is inactive. Over each bit period, the output of the integrator ideally either ramps upwards, in the case of a transmitted '1' symbol, or downwards, in the case of a transmitted '0' symbol. Accordingly, at the end of the bit period there should be no practical difficulty in discriminating between a received '1' or received '0' symbol. However, it is evident from the waveform 1202 that, due to the effects of co-channel interference from the undesired channels, there are a number of bits for which it is unclear whether the transmitted symbol was a '1' or a '0'.

The waveform 1204 shows the same integrator output with co-channel interference cancellation activated. In this case it is clear over each bit period whether the transmitted symbol was a '1' or a '0'. The simulation results thus demonstrate the effectiveness of co-channel interference cancellation when applied in a network according to the present invention. Indeed, co-channel interference cancellation is expected to be more beneficial in networks of this type than in wireless CDMA networks, because the optical fibre is a far more stable transmission medium than the radio environment, because signals in fibre are not subjected to the time-varying multipath fading effects that are an unavoidable characteristic of wireless systems.

The present invention is not limited to optical fibre networks, and may be employed in networks including other types of optical links. Figure 13 illustrates a further exemplary embodiment 1300 of a network according to the invention that includes a central office (CO) 1328 and a number of access nodes (AN) 1304a-g. The CO and AN's may be configured substantially as previously described with reference to Figure 1. As shown, a number of the links interconnecting adjacent AN's are optical fibre links e.g, 1302. However, two of the links shown, being those interconnecting AN's 1304c, 1304d and 1304e, include free space optical links.

Each free space optical link as shown in Figure 13 includes a first lens arrangement 1308 at the transmitting end of the link that collects and collimates the light emitted from an optical fibre. A substantially collimated beam 1306 is then directed toward a second lens arrangement 1309 at the receiving end of the link, which focuses the received beam back into an optical fibre or other optical waveguide structure. An optical amplifier 1307 is shown placed before the first lens arrangement 1308 to boost the optical power prior to transmission through free space, while a second optical amplifier 1310 is shown placed after the second lens arrangement 1309 to restore the optical power at the receiving end of the link. Each of the optical amplifiers 1307, 1310 is included to compensate for optical losses that may occur in the coupling of light into and out of optical fibres and other waveguide structures, and due to free space propagation losses as well as losses due to misalignment of the beam with the receiving lens arrangement 1309. The optical amplifiers 1307, 1310 are optional, and either one or both may be excluded if sufficient optical power is available in the absence of optical amplification.

Although not illustrated in the drawings, further simulations have been carried out using semiconductor optical amplifiers to provide amplification of optical signals in embodiments of the optical network structure of the present invention. These simulations demonstrated that such amplification can provide compensation for losses in the network while having negligible impact on the quality of received signals. Of course, other known amplification technologies, such as erbium-doped fibre amplifiers, would be equally applicable in embodiments of the invention.

Free space links may be included in the network 1300 in order to provide access for subscribers via access nodes e.g. 1304d that are not provided with optical fibre connections to the network. For example, in areas where optical fibre cabling has not yet been installed, the cost of providing access via free space optical links may be substantially lower than the cost of installation of fibre cabling.

A network 1300 including a combination of fibre and free space links implemented in accordance with the invention may use a light source in the central office 1328 having an emission wavelength in the vicinity of 1550 nm.

This provides the advantages of operation within the minimum attenuation transmission window of standard optical fibres, as well as compatibility with erbium doped optical amplifiers in cases where the amplifiers 1308, 1310 are required to overcome transmission losses. Furthermore, the use of a longer wavelength optical source, operating around 1550 nm, rather than, for example, a 780 nm or 1300 nm source, provides for the transmission of substantially higher power on free space links, while not compromising eye safety. Systems operating at 1550 nm are around 70 times more eye-safe, in terms of maximum permitted exposure, than systems operating below 1000 nm.

A potential disadvantage of the use of terrestrial free space links within the network 1300 is that the atmosphere is not an ideal optical communications channel. Fluctuations in collected optical power at the receiving end of an atmospheric free space link occur as a result of atmospheric turbulence, as well as meteorological impairments such as rain or fog. In order to mitigate such effects, the network may employ a technique such as a delayed diversity scheme, in which signals are transmitted twice, for example using different wavelengths, polarisations, or a pair of orthogonal CDMA codes, with a delay between the transmissions that is longer than the correlation times associated with the atmospheric fluctuations. Implementation of a delayed diversity scheme may require modifications to the CO and AN configurations, however by employing separate CDMA codes rather than additional wavelengths or polarisations of light, the additional cost and complexity of each node may be minimal.

It should be noted that in addition to terrestrial application, free space links may be advantageously employed in space-based communications, such as inter-satellite links, where the provision of fibre links is impractical, and atmospheric effects are not present.

An alternative embodiment 1400 of a network including a node 1404 having access via a free space link 1406 is shown in Figure 14. As with the embodiment 1300 described previously with reference to Figure 13, the free space link of the embodiment 1400 includes collimating lens arrangement e.g. 1408 for sending and receiving a substantially collimated optical beam over a free space transmission path. However, in the embodiment 1400 the free space link 1406 is bidirectional, providing access to the node 1404 from a single physical

location in the installed fibre network. As shown in the figure, transmission booster amplifiers 1407, 1410 are employed in the free space link, however in this example amplifiers are not required at the receiving end.

The access node 1404 may be a fixed node. Alternatively, it may be a mobile node if suitable tracking mechanisms are provided to aim the lens arrangements e.g. 1408 to maintain the appropriate beam direction during motion of the mobile node. A further potential benefit of the arrangement shown in Figure 14 is that by providing an optical switch (not shown) at the end of the free space link, it would be possible to directly connect the fixed optical fibre links in order to isolate the node 1404 from the network in the case of adverse weather conditions, failure of the node 1404, or other loss of contact with the node 1404.

As has been previously discussed, it may be desirable to synchronize all transmissions in the network in order to obtain improved bit error rate performance while using relatively short spreading codes, such as Walsh codes. In embodiments of the optical fibre access network of the present invention, clock synchronization may be achieved, for example, by transmitting through the optical network a synchronization signal that is receivable by the access nodes in the network. While a synchronization signal may be transmitted out of band, for example, using a dedicated RF subcarrier or a separate wavelength, it is preferable both from the point of view of cost and of avoiding potential problems due to fibre dispersion, to transmit a synchronization signal in band with the subscriber data channels.

Accordingly, a preferred method of transmitting a clock synchronization signal includes encoding a suitable synchronization channel in accordance with an electrical spread spectrum coding method. The synchronization signal may thereby be transmitted from a head-end of the fibre network, upstream of the network access nodes, and received by each of the network access nodes, which are thereby able to synchronize their transmissions with the received synchronization signal.

While it would be possible to use an orthogonal code, such as a Walsh code, to encode a synchronization channel so as to eliminate interference to the subscriber data channels, orthogonal codes do not have good autocorrelation characteristics, and accordingly the network access nodes may experience

difficulty in reliably synchronizing to a signal based on an orthogonal code. Accordingly, it is preferable to encode a synchronization channel using a long direct sequence code having good autocorrelation properties, such as a pseudo noise (PN) code. Accordingly, each node in the network is thereby able to
5 receive the PN code, and synchronize its transmissions with the received code sequence. However, since the PN code is not truly orthogonal to the codes used for spreading of the subscriber data channels, the synchronization signal will cause some degree of interference to the subscriber data channels.

In order to assess the impact of a non-orthogonal pseudo noise
10 synchronization channel on subscriber data channels, further simulation studies have been carried out. Figure 15 shows a schematic set up of a computer simulation of an optical fibre access network 1500 including a central office 1504 and a number of network access nodes, eg 1510. The central office includes downstream channel generators 1506, having random data sources and DS-
15 CDMA encoders. The central office also includes DS-CDMA decoders 1508 for receiving upstream channels from each of the access nodes, eg 1510.

The downstream channel generator 1512 is a pseudo noise generator that provides a synchronization signal that may be received and used by the access node 1510 to synchronize its own subscriber data channel transmissions. The
20 network access node 1510 includes first optical tap 1513 to remove a small fraction of the light entering the input port of the node. The decoding circuit 1514 is used to extract the pseudo noise sequence from the incoming signal. Once the PN code has been successfully detected and extracted from the optical signal, or transmitted subscriber data may be synchronized to the received PN sequence to
25 ensure that all channels transmitted in the network are synchronous. Access node 1510 includes data source and encoding circuitry 1516 representing a subscriber data channel that is synchronized to the received PN sequence and modulated onto the optical carrier along with other subscriber data channels.

Access node 1510 also includes a second tap 1517 and decoding circuitry
30 1518 for receiving a subscriber data channel directed to the node 1510.

Simulations of the configuration 1500 shown in Figure 15 have demonstrated that the presence of the PN code synchronization signal causes minimal interference to subscriber data channels. Furthermore, interference

cancellation techniques, such as iterative interference cancellation methods, are expected to be very effective in removing the effect of interference by a PN synchronizing code from the subscriber data channel encoded using orthogonal codes, such as Walsh codes.

5 As has been previously described, it is preferable in embodiments of the optical network to employ modulators having nonlinear transfer characteristics, low insertion loss, and low optical modulation depth. Accordingly, it may be beneficial to employ specialised modulators that are designed specifically to exhibit these desirable characteristics. Figure 16 illustrates the structure and
10 characteristics of such a specialised modulator that may be used in embodiments of the present invention.

In Figure 16, there is shown a simulation model of a specialised modulator 1600 that is based upon a Mach-Zehnder configuration. The modulator 1600 includes an asymmetric optical splitter 1602 having an optical input port 1603.
15 The modulator 1600 also includes an asymmetric optical combiner 1604 having an optical output port 1605. High power output port 1612 of the asymmetric splitter 1602 is connected via optical path 1606 to high power input port 1613 of asymmetric combiner 1604. Low power output port 1614 of asymmetric splitter 1602 is connected via phase modulator 1610 to low power input port 1615 of
20 asymmetric combiner 1604. The simulation model includes an attenuator 1608, to represent the optical loss that may be associated with the active material of the modulator 1600 that is used to provide the function of the phase modulator 1610.

The modulator represented by simulation model 1600 may be implemented using any one of a number of technologies known in the art, such as
25 semi-conductor or lithium niobate technologies. Alternatively, optical fibre based couplers and phase modulation technologies may be employed.

The phase modulation section 1610 of the modulator 1600 is driven by an electrical input signal applied to electrical input port 1616. The application of an electrical driving signal to input port 1616 causes a phase shift in the light passing
30 through phase modulator 1610, which may be viewed as an induced change in the effective optical path length between low power ports 1614, 1615. Accordingly, the effect of the phase modulation is to change the relative effective optical path lengths between the two arms of the Mach-Zehnder interferometer

whereby interference will occur at the asymmetric optical combiner 1604 resulting in a corresponding modulation of the intensity of light emitted at the optical output port 1605. Because of the asymmetry in the interferometer, such modulation occurs over a limited optical modulation depth, and with low overall optical
5 insertion loss.

A typical transfer characteristic of the specialised modulator 1600 is shown in graph 1620. The output optical power as a function of the electrical drive voltage is a sinusoidal function 1622 that varies between a maximum 1624 (the “+1” level) and a minimum 1626 (the “-1” level). For example, if the ratio between
10 the high power and low power ports of the asymmetric splitter and combiner is 15dB, and the loss through the phase shifting arm of the interferometer is 6dB, the overall insertion loss will be 0.26dB, and the optical modulation depth will be 3.2%. These characteristics are shown in the output power graph 1630, which is the result of a simulation in which the input power to the modulator is 1mW. As
15 can be seen in the graph 1630, the output power is modulated between approximately 910 microwatts and 972 microwatts.

In the preceding description of preferred embodiments of the optical network structure of the present invention only a single optical path was provided between a head-end and a tail-end of an optical bus structure. In some
20 applications, however, it may be desirable to include parallel optical paths within an optical network in accordance with an embodiment of the invention. For example, if an optical fibre network is to be deployed within an office environment, or an apartment building, it may be desirable to provide separate, parallel, optical links, for example on separate floors of the office or apartment building.

25 It is a relatively straight forward matter to divide a signal from a shared optical source into a number of parallel paths, for example using a passive optical splitter. However, problems may be encountered in recombining such parallel paths into a single return fibre. Each of the parallel paths between the splitter and combiner will typically be of differing length, and accordingly light travelling
30 through each parallel path will experience corresponding differing propagation delays. Accordingly, when light from a shared narrow linewidth source, such as semiconductor laser, is recombined into the return fibre, interferometric noise will be introduced in the combined optical signal.

While such interferometric noise may cause unacceptable signal degradation in conventional fibre networks, a spread spectrum receiver integrates over the chip sequence corresponding to the duration of each individual data bit. Accordingly, such a receiver averages the effect of interferometric noise arising
5 due to the recombination of optical signals that have traversed parallel paths having different propagation delays. Accordingly, an optical access network including parallel optical paths in accordance with an embodiment of the present invention may provide advantages, and acceptable performance levels, that are not achievable using conventional optical access network technologies.

10 In order to assess the feasibility of using parallel optical paths in embodiments of the optical network, a preliminary simulation study has been conducted. Figure 17 shows a schematic setup of a computer simulation of an optical fibre access network 1700 including a shared optical source 1702, which is divided at power splitter 1704 into parallel optical paths 1706, 1708.

15 In the simulation setup of network 1700, first parallel path 1706 includes DS-CDMA data sources 1710, 1712, while second parallel optical path 1708 includes further DS-CDMA data sources 1714, 1716. The computer simulation setup further includes a one nanosecond optical delay 1718 in second optical path 1708 in order to simulate a possible difference in propagation delay between
20 the two parallel optical paths 1706, 1708.

Signals from the two parallel paths are recombined at optical combiner 1720, and are received at tail end node 1722. The tail end node 1722 includes DS-CDMA decoders 1724, 1726, 1728 and 1730 for receiving and decoding the four data channels added by sources 1710, 1712, 1714, 1716. It is expected that
25 interferometric noise will be present in the signal received at tail-end node 1722, due to the narrow linewidth, being 20 MHz in the simulation model, of the optical source laser 1702, in combination with the one nanosecond difference in propagation delay through the parallel optical paths 1706, 1708.

Figure 18 shows the results of simulation of the optical network 1700.
30 Graph 1800 shows the optical signal received at tail-end node 1722, which includes the modulated data generated by sources 1710, 1712, 1714, 1716, and the effect of interferometric noise resulting from recombination of the light that has propagated through the two parallel paths 1706, 1708.

Eye diagrams 1802, 1804, 1806, 1808 illustrate the decoded data signals received by decoders 1724, 1726, 1728, 1730. In each case, clear eye openings 1810, 1812, 1814, 1816 are visible in the eye diagrams. Accordingly, it may be concluded that an optical network structure including subscriber data channels
5 encoded in accordance with an electrical spread spectrum coding method, and including parallel optical paths in accordance with an embodiment of the present invention, exhibits a relatively high level of tolerance to interferometric noise resulting from differences in optical path lengths between the parallel optical paths. This tolerance to differences in propagation delay between parallel optical
10 paths is a further advantage provided by preferred embodiments of the present invention.

From the foregoing description, it will be readily apparent to those skilled in the art that many variations of the network structure, network access node, and modulating method are possible in accordance with the invention, which is not to
15 be limited to the embodiments described. A number of combinations of features have been described with reference to specific embodiments of the invention, or component parts thereof, however it will be apparent to the skilled person that these various features may be combined in other ways while still falling within the scope of the invention as defined by the appended claims. For example, in the
20 exemplary embodiments, the use of optical amplifiers has only been described in relation to networks including free space optical links, however it will be appreciated that optical amplifiers may be employed in networks in which all links are optical fibre links.

CLAIMS:

1. An optical network structure including:
an optical source; and
a plurality of network access nodes, each of which includes an optical modulator arranged in use to be driven by an electrical signal including a subscriber data channel encoded in accordance with an electrical spread-spectrum coding method, wherein the plurality of network access nodes are optically interconnected such that, in use, light from the optical source passes successively through the optical modulators of at least two of the network access nodes, whereby the light from the optical source is successively modulated in response to the electrical signals driving the optical modulators of said at least two network nodes.
2. The optical network structure of claim 1 wherein the electrical spread spectrum coding method is a direct sequence method employing orthogonal bipolar multiplicative codes.
3. The optical network structure of claim 2 wherein the bipolar multiplicative codes are Walsh codes or Gold codes.
4. The optical network structure of any one of the preceding claims, including multiple optical sources wherein at least one of said optical sources is shared amongst a plurality of network access nodes.
5. The optical network structure of any one of the preceding claims wherein the optical source is a laser source.
6. The optical network structure of any one of the preceding claims wherein the optical source emits light in one or more of the 1550 nm, 1300nm or 780nm transmission windows.
7. An optical network structure according to any one of the preceding claims, including at least two optical sources emitting light of different wavelengths and

arranged such that, in use, light from each of the optical sources passes successively through each of the network access nodes so as to provide increased data capacity as compared with a structure including only a single optical source.

8. An optical network structure according to claim 7 wherein each network access node receives a subscriber data channel modulated onto light at a first said wavelength, and transmits a subscriber data channel by modulating the light at a second said wavelength.

9. The optical network structure of any one of the preceding claims wherein the network access nodes are interconnected using optical fibres.

10. The optical network structure of any one of the preceding claims wherein the network access nodes are interconnected using free space links.

11. The optical network structure of any one of the preceding claims wherein the network access nodes are interconnected using a combination of optical fibres and free space links.

12. The optical network structure of any one of the preceding claims wherein the optical modulator in each of said network access nodes modulates the light from the optical source with a low modulation depth.

13. The optical network structure of claim 12 wherein the modulation depth is less than about 8%.

14. The optical network structure of any one of the preceding claims wherein the optical modulator in each of said network access nodes is a nonlinear optical modulator.

15. The optical network structure of any one of the preceding claims wherein the network access nodes are interconnected to form a bus network topology.

16. The optical network structure of claim 15 wherein the bus includes a head-end including the optical source and the plurality of access nodes are distributed along the length of the bus.
17. The optical network structure of claim 15 or claim 16, wherein the bus includes a tail-end including an optical receiver and spread spectrum decoding circuitry coupled to the receiver for extracting one or more of said subscriber data channels.
18. A network access node including:
an optical input port;
an optical output port; and
an optical modulator arranged to receive light entering the network access node at the optical input port and transmit said light to the optical output port, wherein the optical modulator is further arranged in use to be driven by an electrical signal including a subscriber data channel encoded in accordance with an electrical spread-spectrum coding method, such that the light transmitted to the optical output port includes the light received at the optical input port after having been modulated in response to the electrical signal driving the optical modulator.
19. The network access node of claim 18 wherein the optical modulator modulates the light received at the optical input port with a low modulation depth.
20. The network access node of claim 19 wherein the modulation depth is less than about 8%.
21. The network access node of any one of claims 18 to 20 wherein the optical modulator is a nonlinear optical modulator.
22. The network access node of claim 21, wherein the nonlinear optical modulator is Mach-Zehnder type modulator.

23. The network access node of any one of claims 18 to 22 wherein the modulator is a low loss, small optical modulation depth modulator including:

- an asymmetric optical splitter having an optical input port;
- an asymmetric optical combiner having an optical output port; and
- an electrical input port for receiving a driving electrical signal,

the asymmetric optical splitter having a high power output port connected via a first optical path to a corresponding high power input port of the asymmetric optical combiner, and a low power output port connected via second optical path to a corresponding low power input port of the asymmetric optical combiner,

wherein at least one of said first and second optical paths is arranged such that a change is induced in the relative optical path lengths of the optical paths in response to said driving electrical signal, whereby interference occurs at the asymmetric optical combiner resulting in modulation of the intensity of light emitted at the optical output port over a limited optical modulation depth.

24. The network access node of any one of claims 18 to 23, further including:

an optical tap arranged to couple out of the transmission path between the optical input port and the optical output port a fraction of the light passing through the network access node;

an optical receiver arranged to receive light coupled out of the transmission path by the optical tap; and

a spread spectrum decoding circuit for extracting an upstream subscriber data channel modulated onto the light entering the network access node at the optical input port.

25. The network access node of any one of claims 18 to 24 further including:

an optical tap arranged to couple out of the transmission path between the optical input port and the optical output port a fraction of the light passing through the network access node;

an optical receiver arranged to receive light coupled out of the transmission path by the optical tap; and

a decoding circuit for extracting a synchronization signal modulated onto the light entering the network access node at the optical input port,

wherein the node is configured to synchronize the encoded subscriber data channel modulated onto the light passing through the network access node with the received synchronization signal.

26. The network access node of claim 25 wherein the synchronization signal includes a pseudo noise code having good auto correlation properties.

27. In an optical network including an optical source and a plurality of network access nodes interconnected such that light from the optical source passes successively through the network access nodes, a method of modulating an optical carrier with a plurality of subscriber data channels including the step of, in at least two of the network access nodes, modulating light from the optical source with subscriber data channels encoded in accordance with an electrical spread spectrum coding method.

28. The method of claim 27 wherein the electrical spread spectrum coding method is a direct sequence method employing orthogonal bipolar multiplicative codes.

29. The method of claim 28 wherein the bipolar multiplicative codes are Walsh codes or Gold codes.

30. The method of any one of claims 27 to 29 wherein the step of modulating includes modulating the light from the optical source with a low modulation depth.

31. The method of claim 30 wherein the modulation depth is less than about 8%.

32. The method of any one of claims 27 to 31 wherein the step of modulating includes modulating the light in a manner that limits modulation peaks so as to reduce the impact of clipping distortion upon the modulated optical signal.

33. The method of any one of claims 27 to 32 further including the steps of:
providing a synchronization signal in the optical network;

receiving the synchronization signal at each of said network access nodes;
and

synchronizing the modulation of light from the optical source in each of said network access nodes with the received synchronization signal.

34. The method of claim 33 wherein the synchronization signal is provided by modulating the light from the optical source with a direct sequence code.

35. The method of claim 34 wherein the direct sequence code is a pseudo noise code having good autocorrelation properties.

36. In an optical network access node including an optical input port and an optical output port, a method of modulating an optical carrier with a subscriber data channel including the steps of:

receiving light at the optical input port;

modulating the received light with a subscriber data channel encoded in accordance with an electrical spread spectrum coding method; and

transmitting the modulated light to the optical output port.

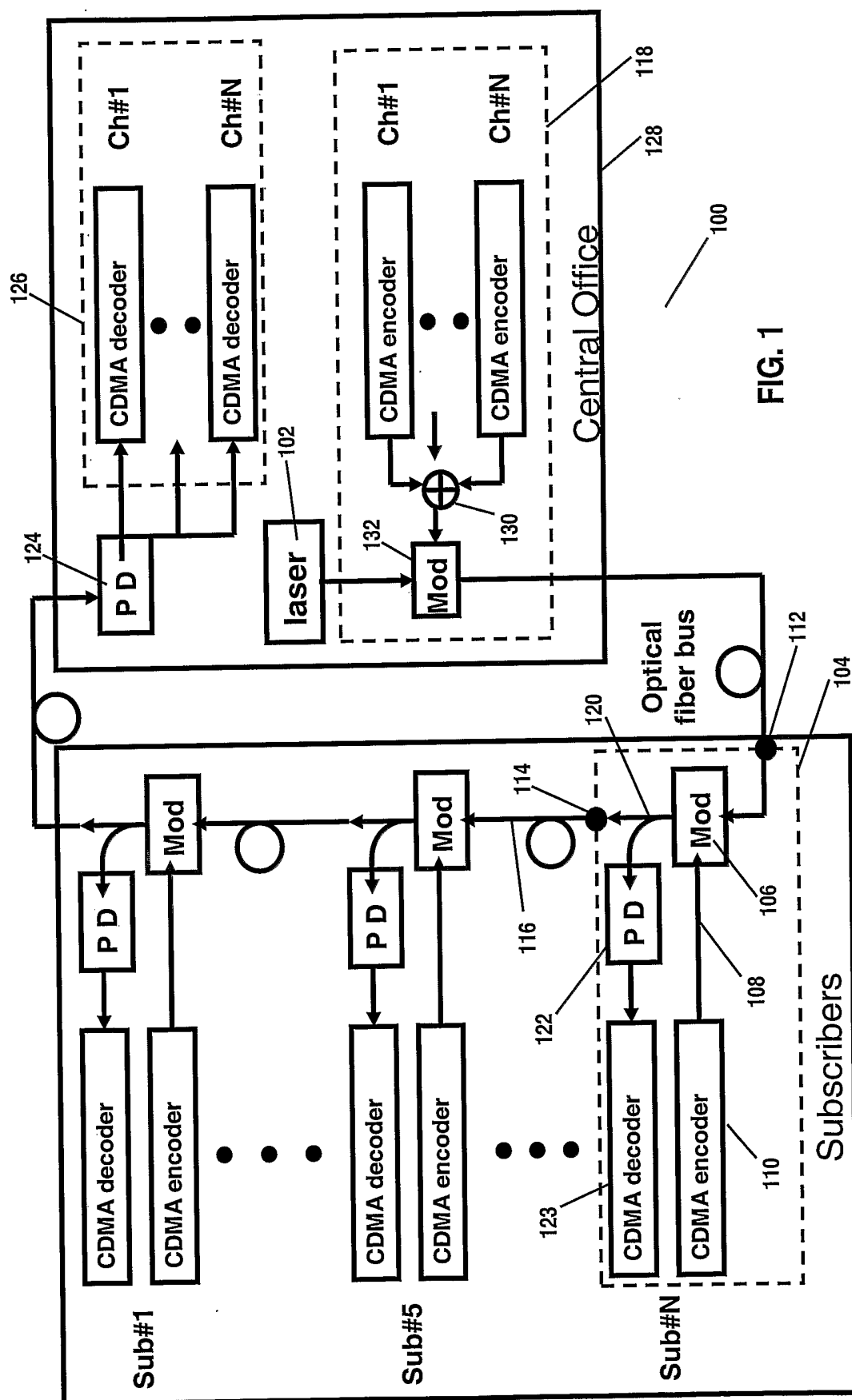
37. The method of claim 36 wherein the electrical spread spectrum coding method is a direct sequence method employing orthogonal bipolar multiplicative codes.

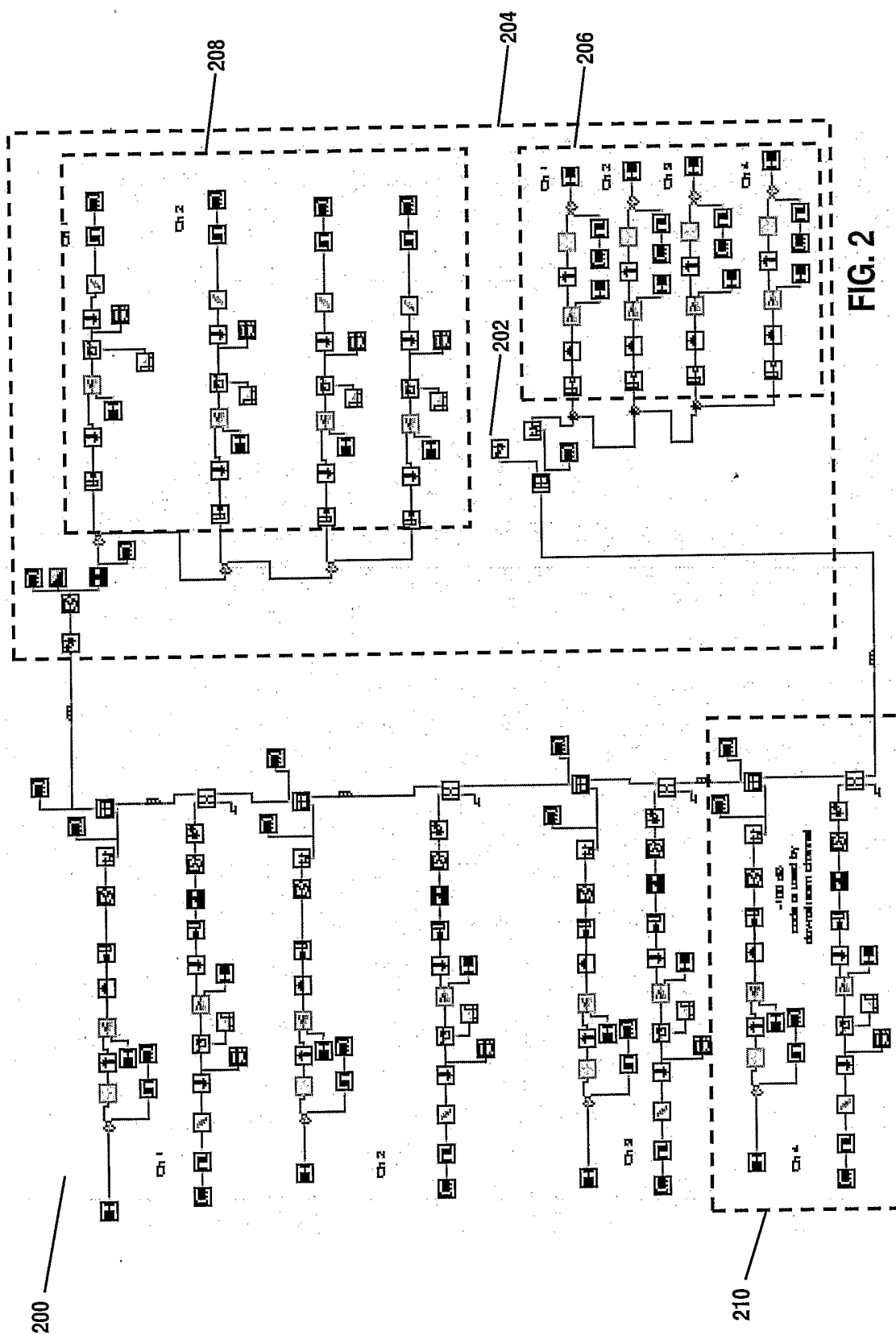
38. The method of claim 37 wherein the bipolar multiplicative codes are Walsh codes or Gold codes.

39. The method of claim 38 wherein the step of modulating includes modulating the light received at the optical input port with a low modulation depth.

40. The method of claim 39 wherein the modulation depth is less than about 8%.

41. The method of any one of claims 36 to 40 wherein the step of modulating includes modulating the light in a manner that limits modulation peaks so as to reduce the impact of clipping distortion upon the modulated optical signal.
42. The method of any one of claims 36 to 40 further including the steps of:
receiving a synchronization signal at the network access node; and
synchronizing the modulation of light received at the optical input port with the received synchronization signal.
43. The method of claim 42 wherein the synchronization signal includes a signal modulated onto the light received at the optical input port using a direct sequence code.
44. The method of claim 43 wherein the direct sequence code is a pseudo noise code having good autocorrelation properties.





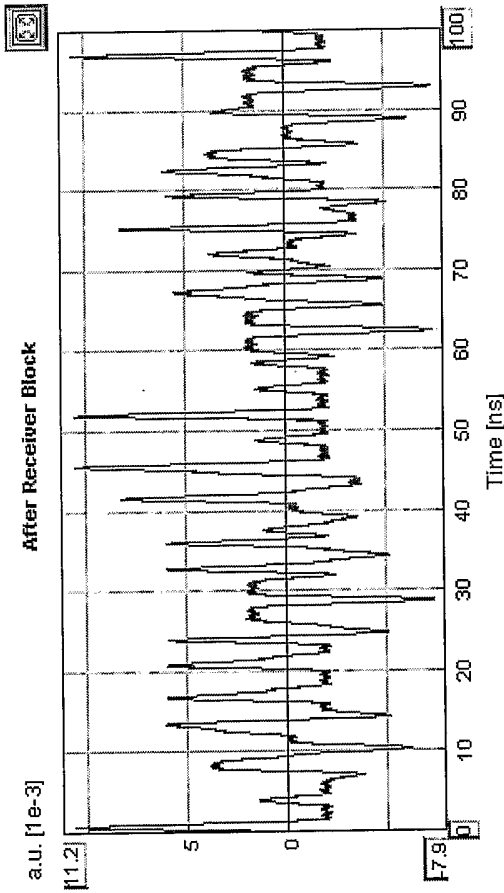


FIG. 3a

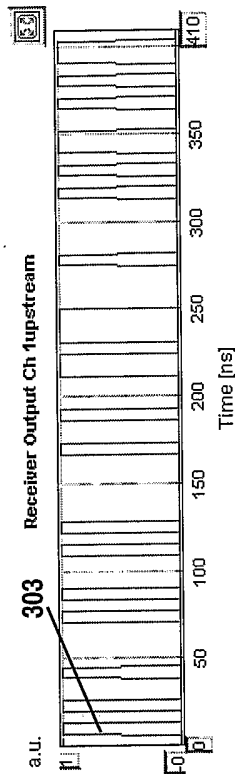


FIG. 3b

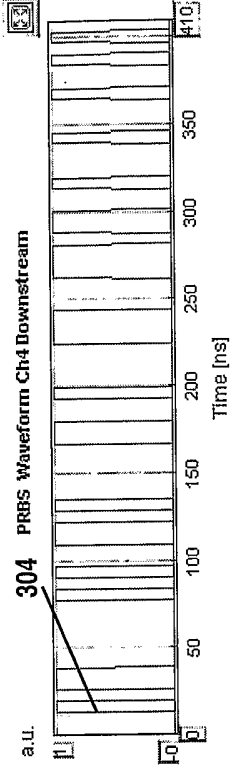
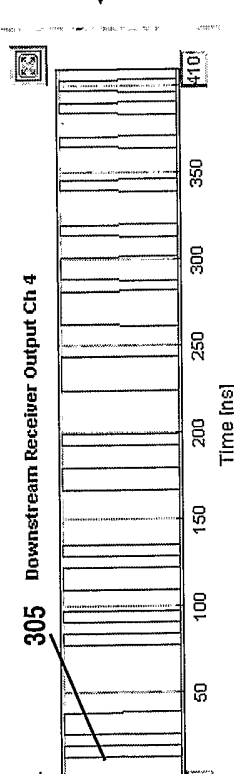
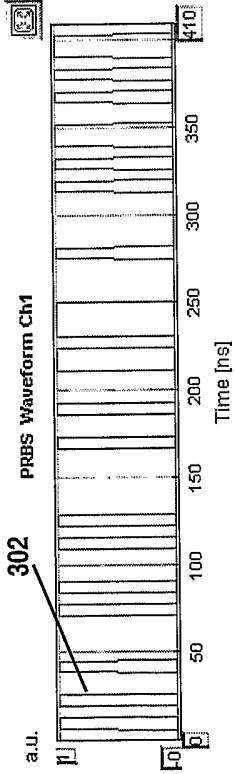
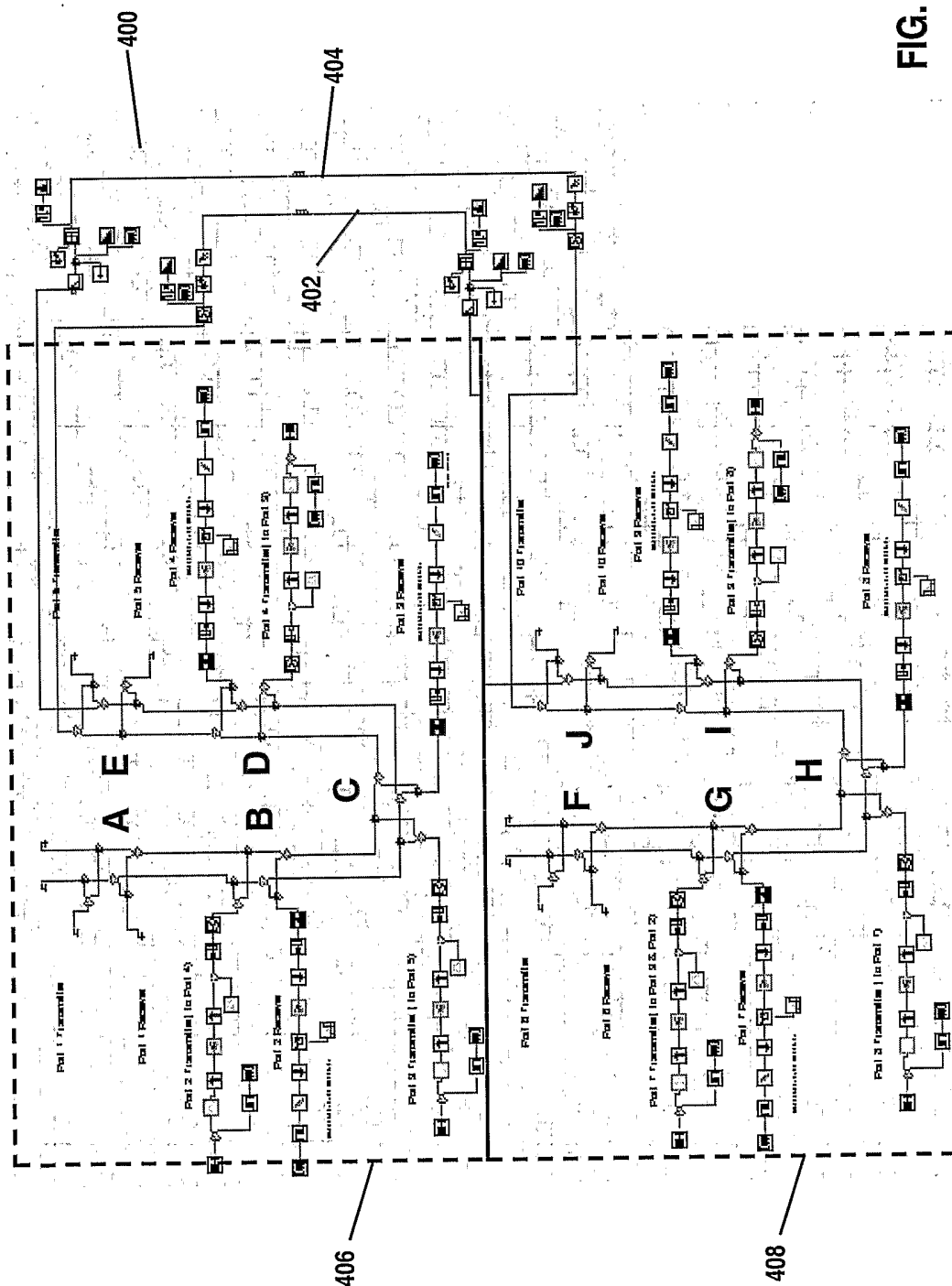


FIG. 3c





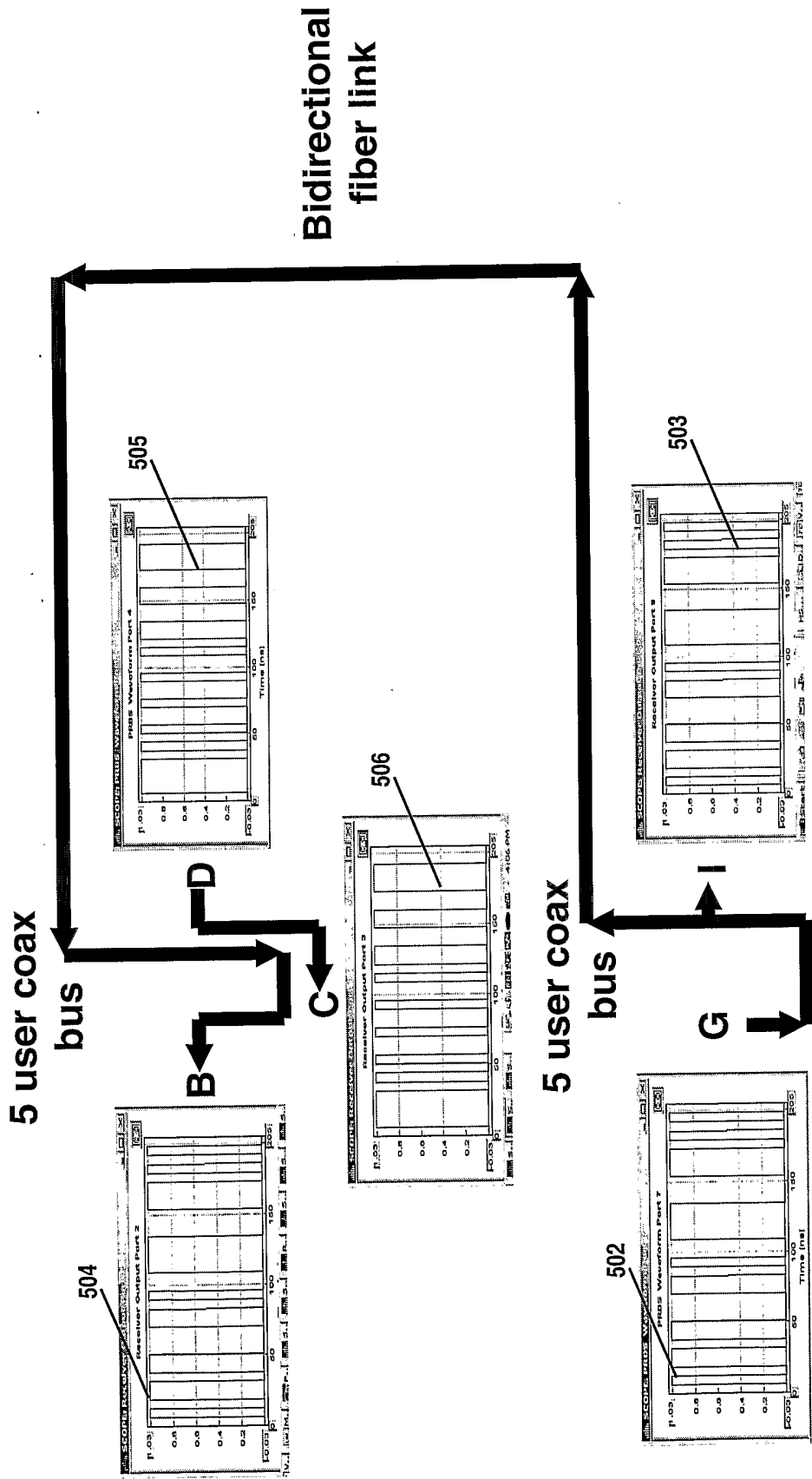


FIG. 5

Ultra-Wide Bandwidth DS-SS-CDMA Baseband and Carrier Coaxial System

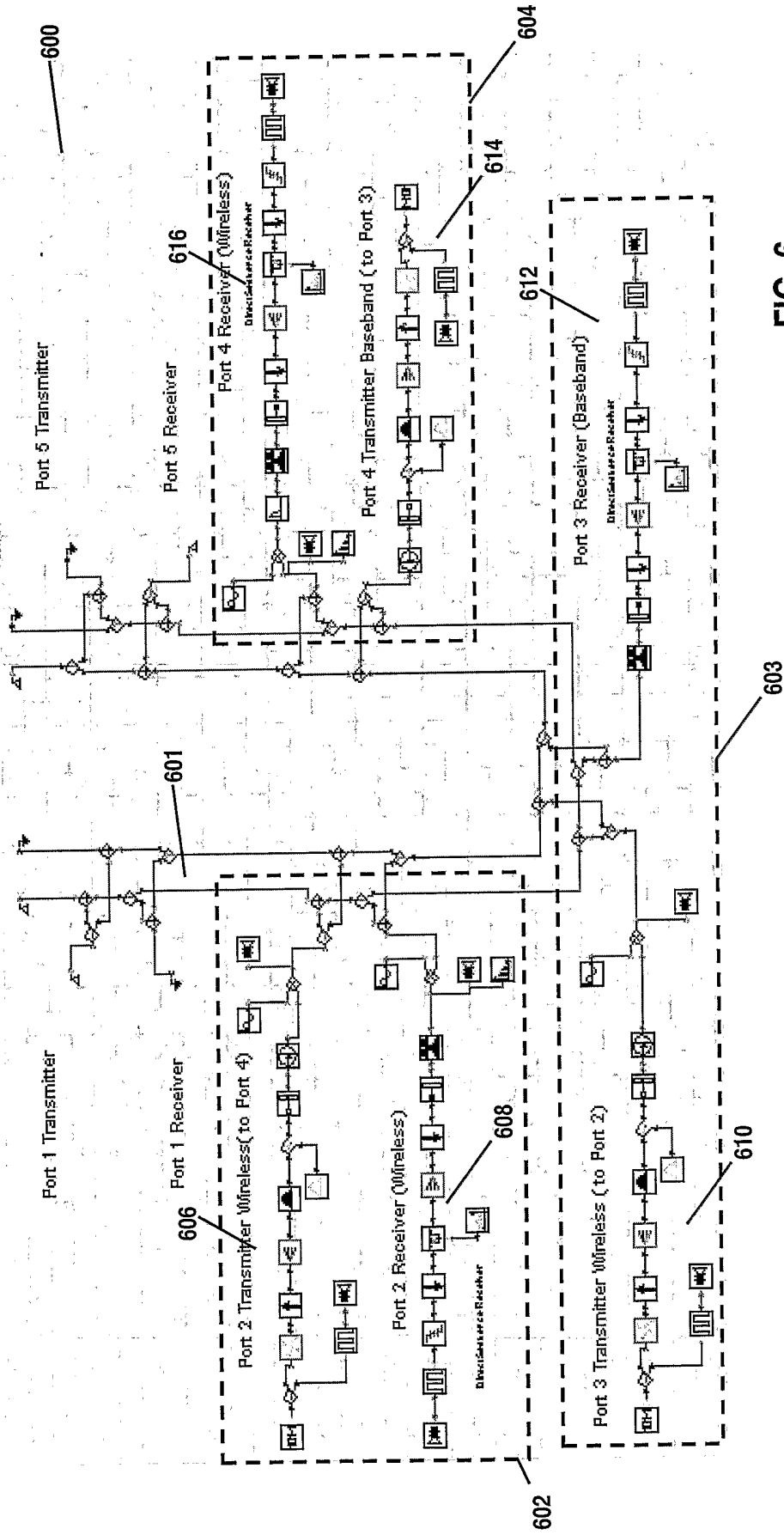


FIG. 6

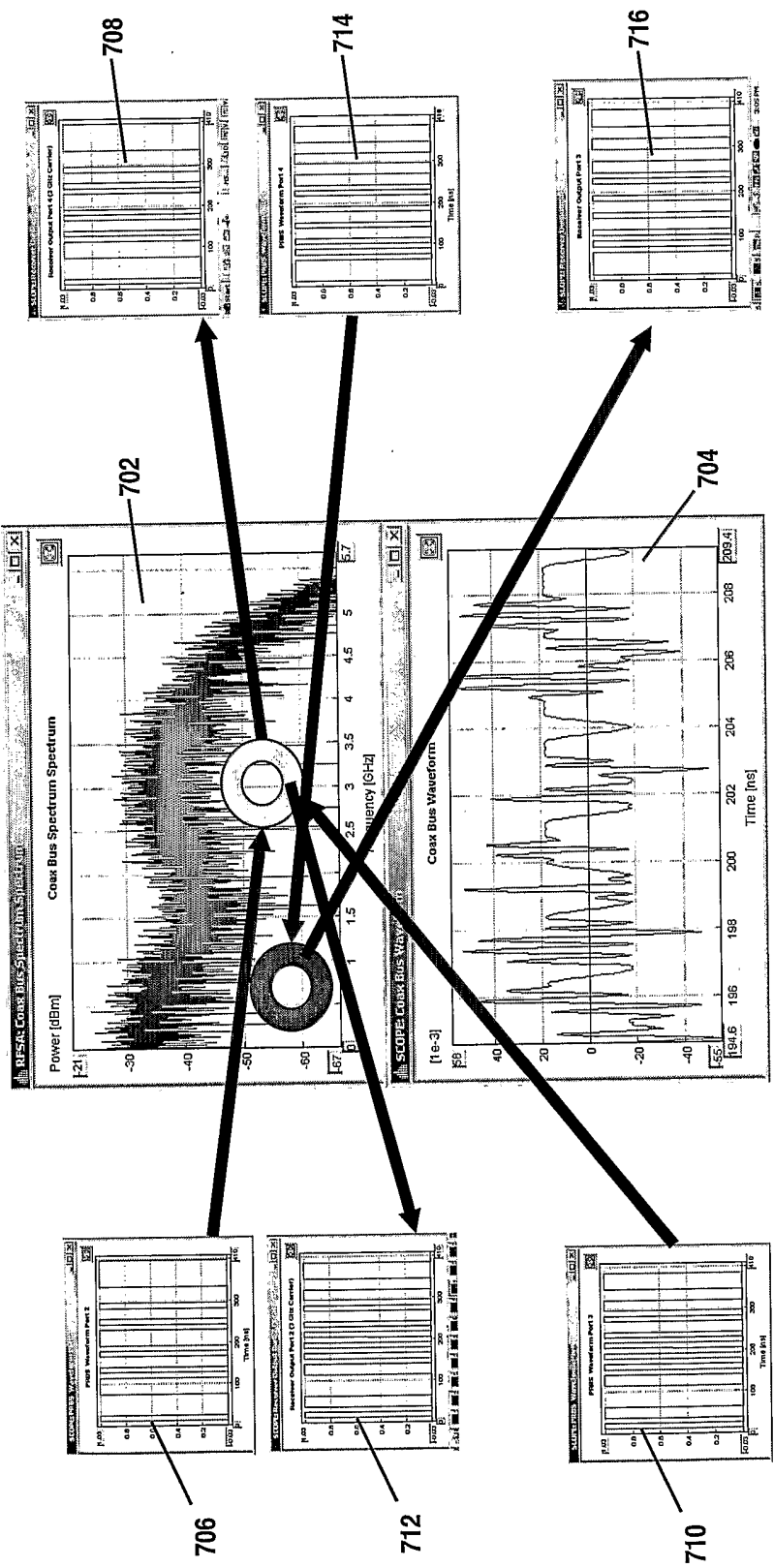


FIG. 7

800

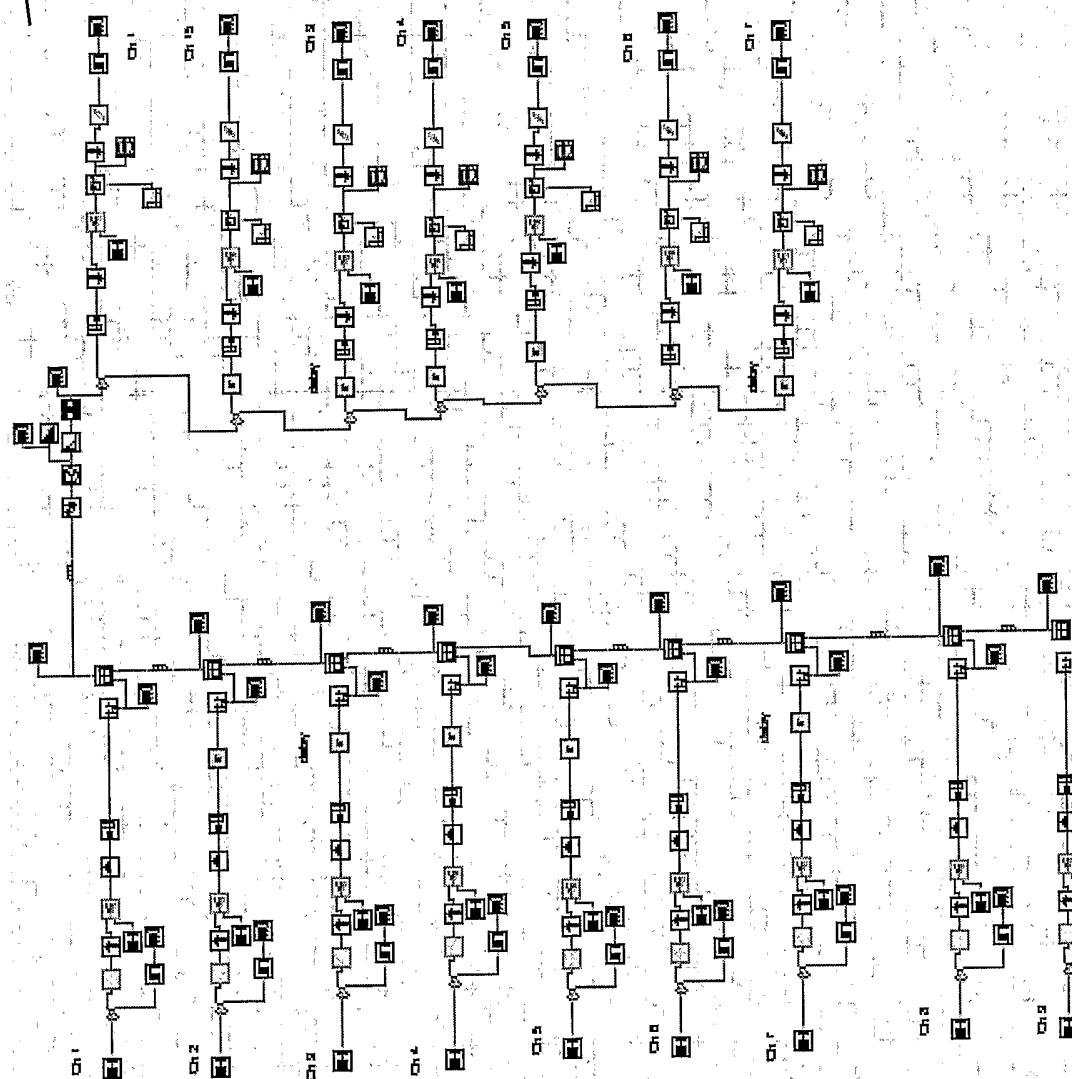


FIG. 8

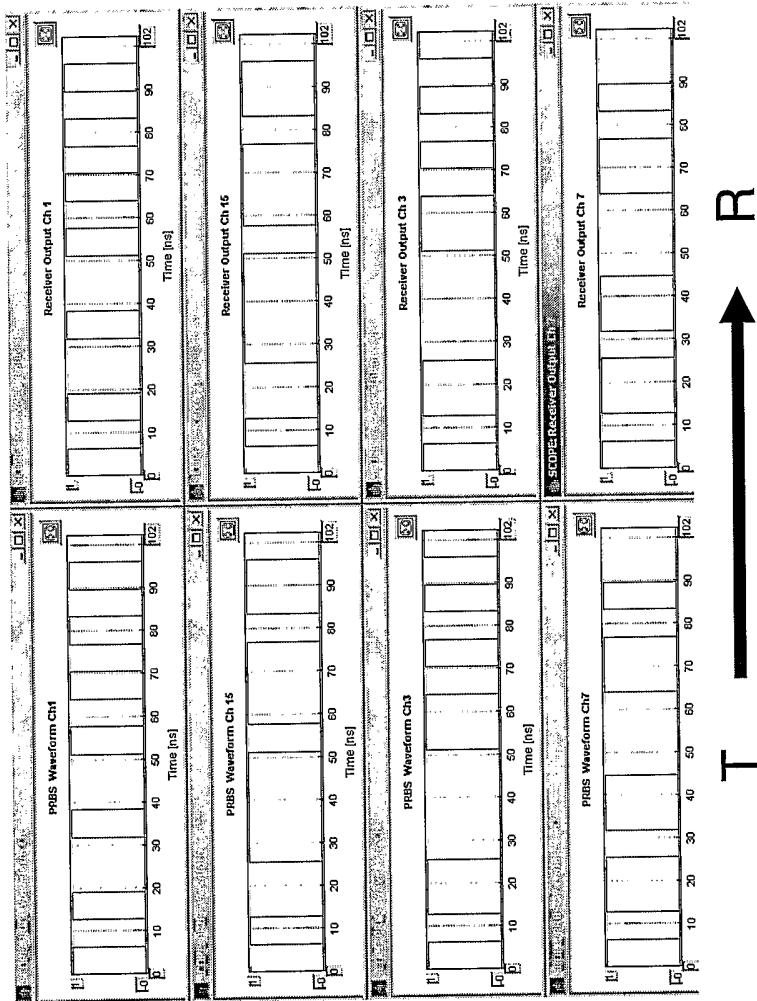


FIG. 9

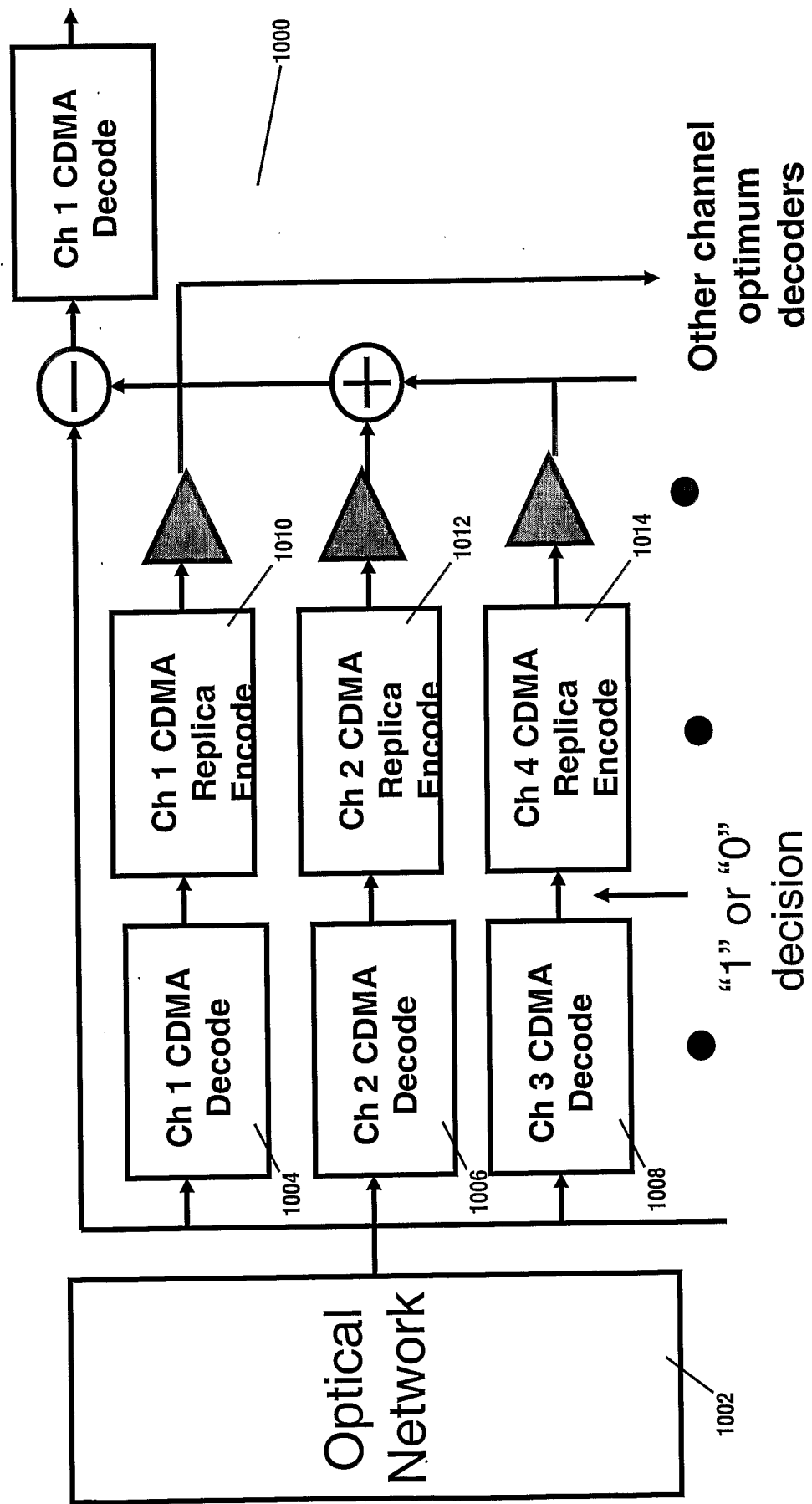


FIG. 10

11/18

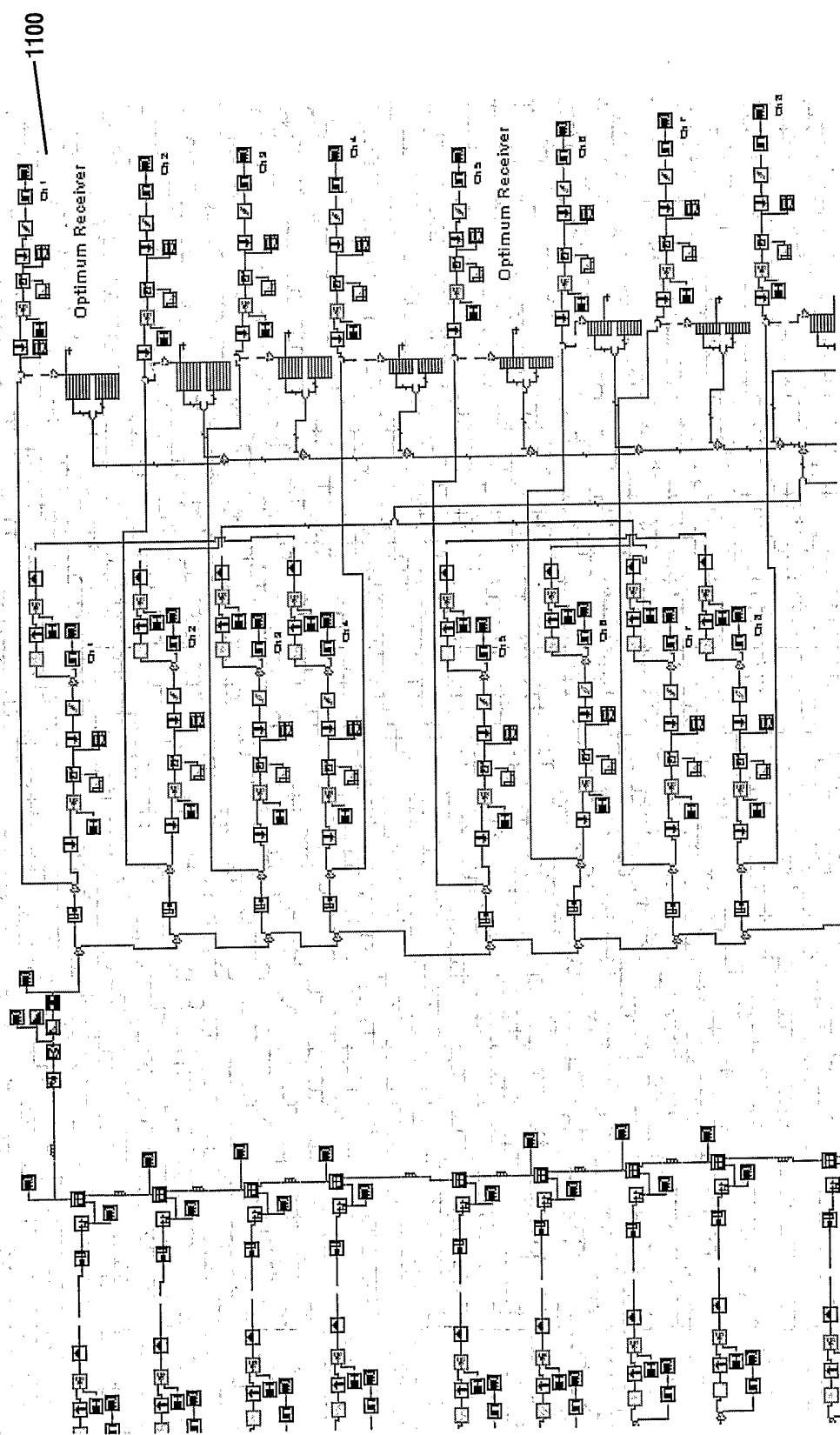


FIG. 11

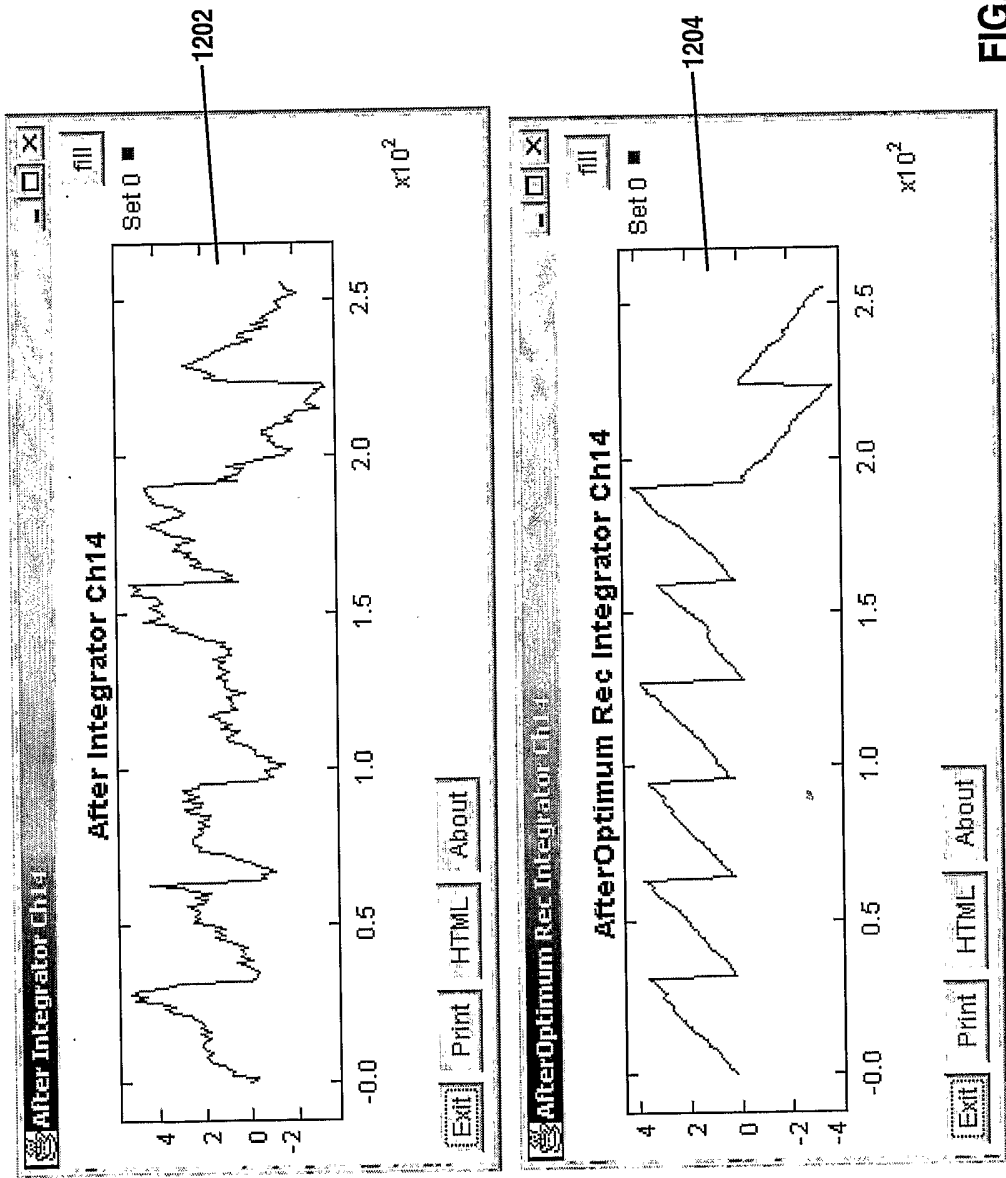


FIG. 12

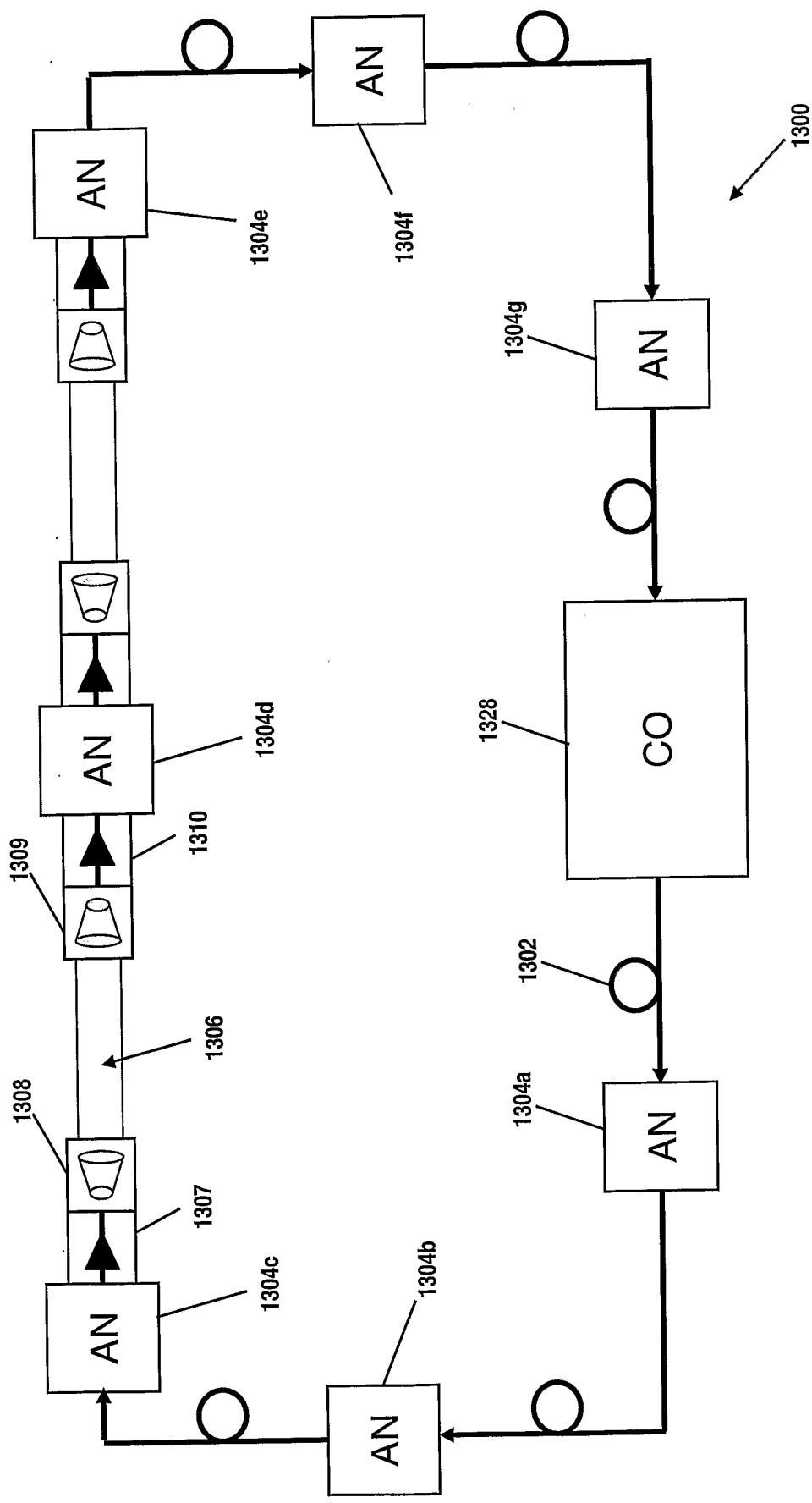


FIG. 13

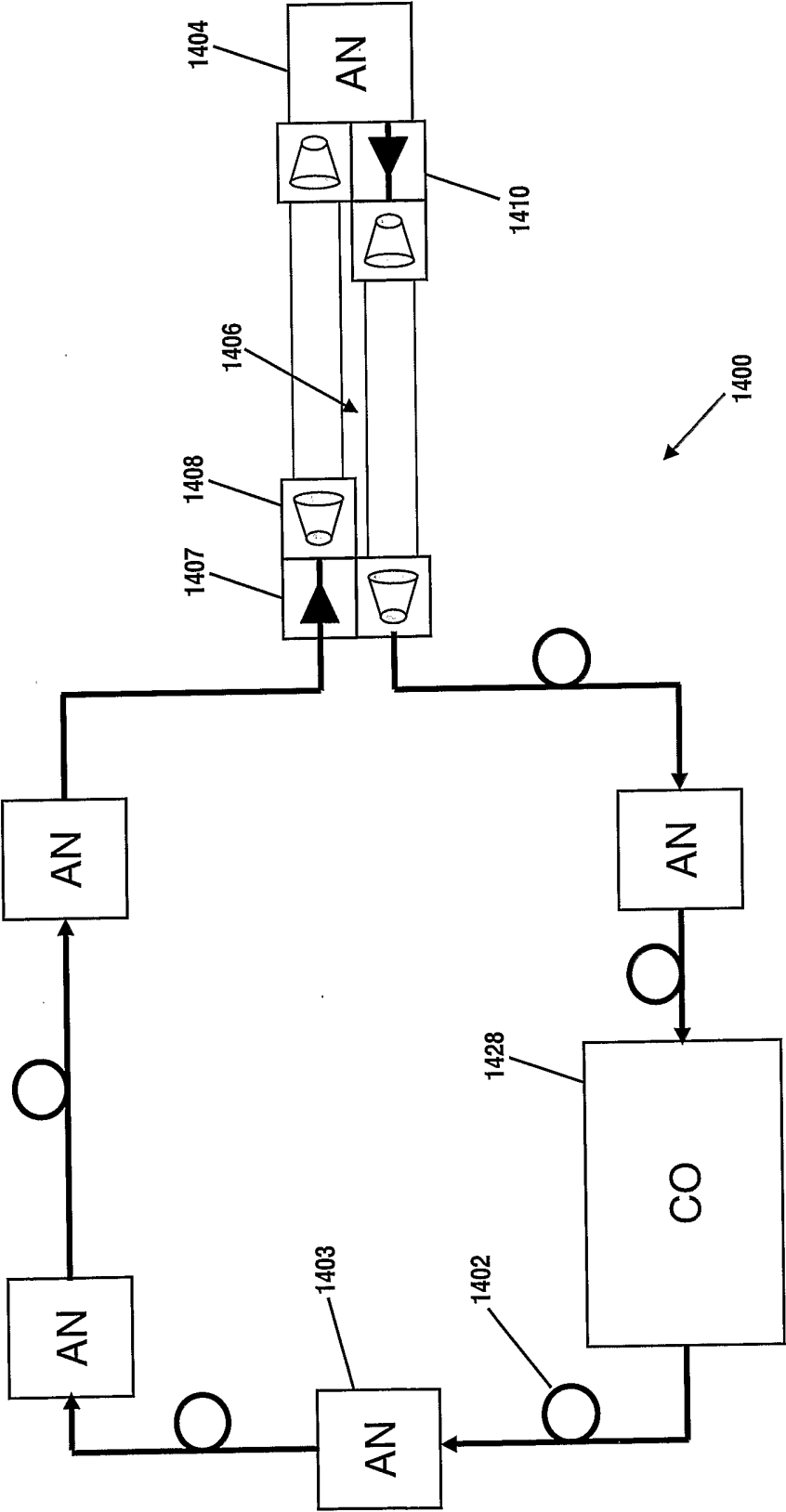


FIG. 14

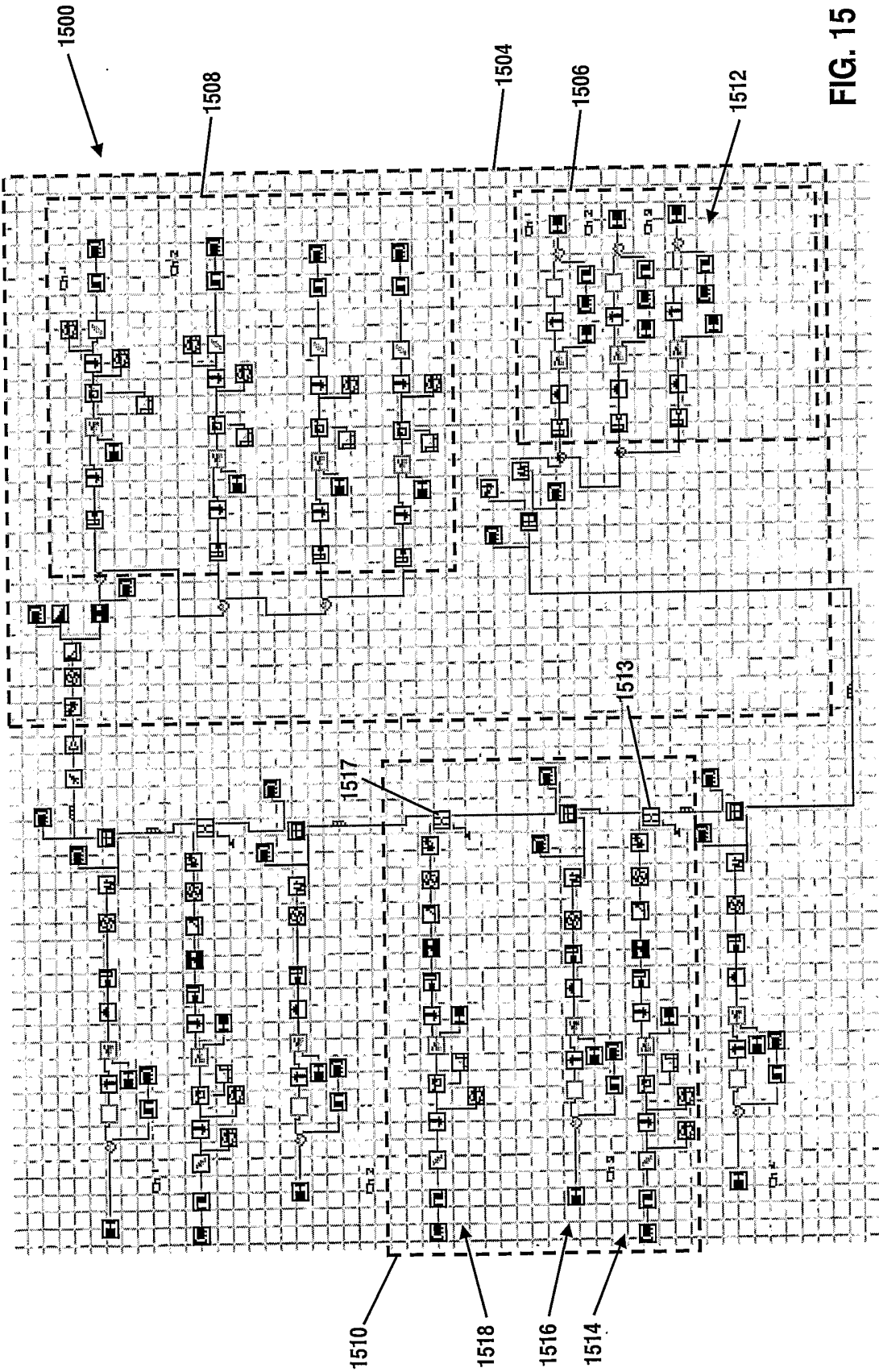
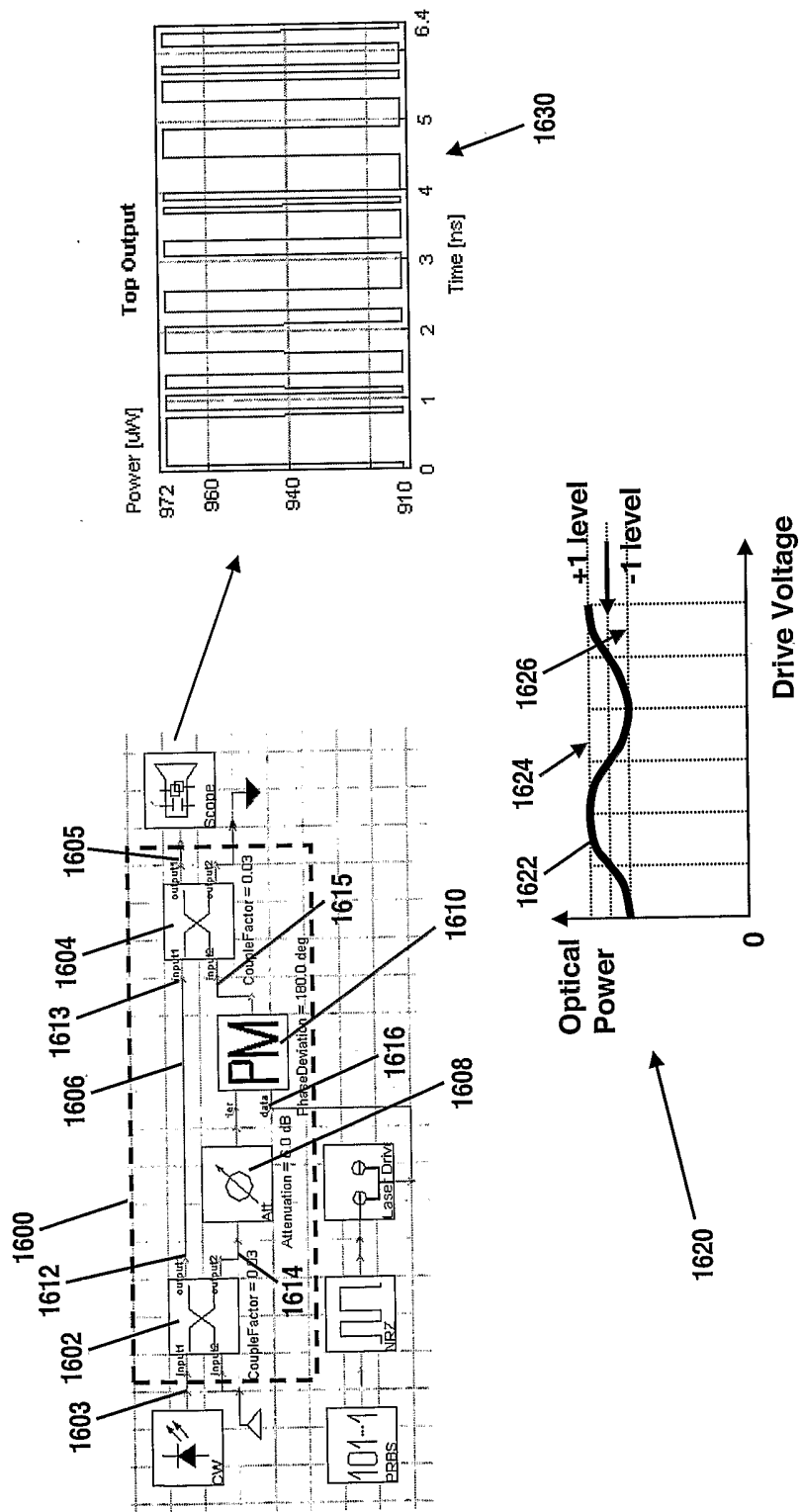


FIG. 15



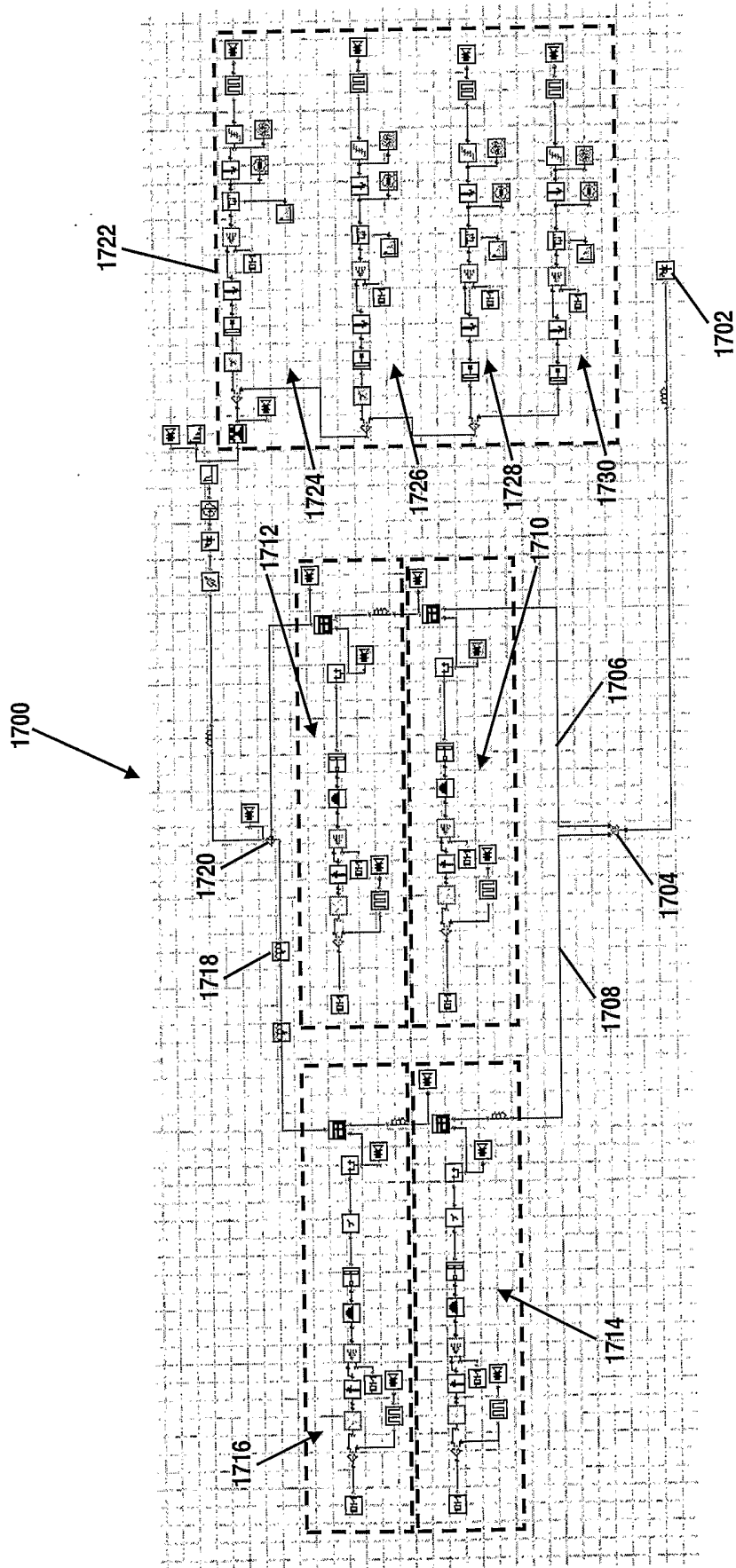


FIG. 17

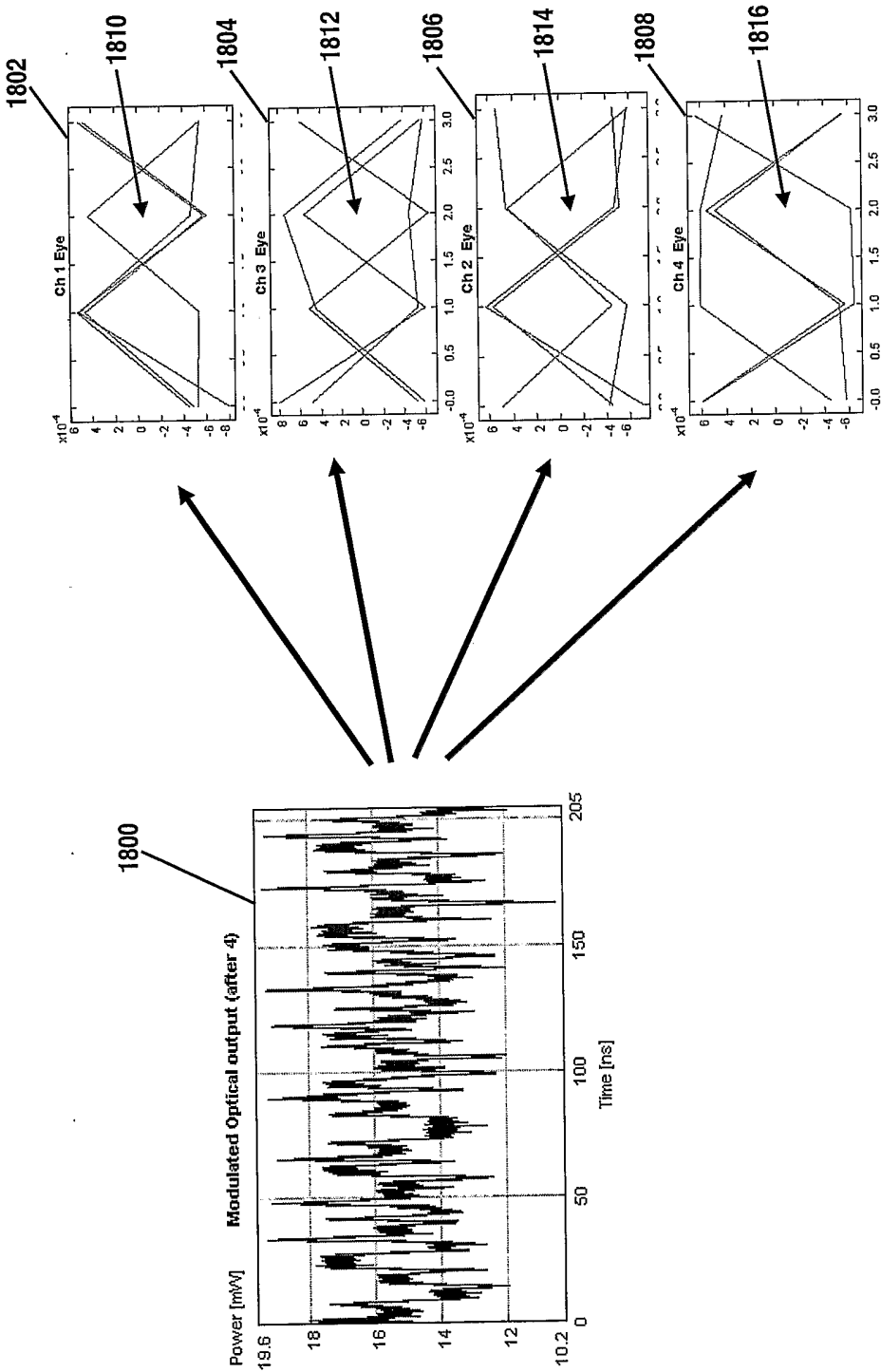


FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2004/001003

A. CLASSIFICATION OF SUBJECT MATTER Int. Cl. ⁷ : H04J 13/02, H04J 14/00 According to International Patent Classification (IPC) or to both national classification and IPC					
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPAT. KEYWORDS: OPTICAL, CDMA, SPREAD, LAN, NETWORK AND SIMILAR.					
C. DOCUMENTS CONSIDERED TO BE RELEVANT					
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.			
A	US 4866699 A (BRACKETT et al) 12 September 1989 Whole document.	1 to 44			
☐ Further documents are listed in the continuation of Box C ☒ See patent family annex					
<table style="width: 100%; border: none;"> <tr> <td style="width: 33%; vertical-align: top;"> * Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed </td> <td style="width: 33%; vertical-align: top;"> "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family </td> <td style="width: 33%;"></td> </tr> </table>			* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family	
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family				
Date of the actual completion of the international search 1 October 2004		Date of mailing of the international search report 12 OCT 2004			
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaaustralia.gov.au Facsimile No. (02) 6285 3929		Authorized officer RICHARD REED Telephone No : (02) 6283 7927			

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2004/001003

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report	Patent Family Member
US 4866699	
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.	
END OF ANNEX	