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(54) **SYSTEM AND METHOD FOR SPECTRALLY EFFICIENT TRANSMISSION OF DIGITAL DATA OVER OPTICAL FIBER**

SYSTEM UND VERFAHREN ZUR SPEKTRALEFFIZIENTEN ÜBERTRANGUNG VON DIGITALEN DATEN ÜBER EINE OPTISCHE FASER

SYSTEME ET PROCEDE DE TRANSMISSION SPECTRALE EFFICACE DE DONNEES NUMERIQUES VIA UNE FIBRE OPTIQUE

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(56) References cited:

EP-A- 0 756 393	**US-A- 4 061 577**
US-A- 5 351 148	**US-A- 5 387 927**
US-A- 5 559 561	**US-A- 5 680 238**

- **MOHSEN KAVEHRAD ET AL: "FIBER-OPTIC TRANSMISSION OF MICROWAVE 64-QAM SIGNALS" IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, vol. 8, no. 7, 1 September 1990, pages 1320-1326, XP000179199**
- **WILSON G: "Capacity of QAM SCM systems utilising optically linearised Mach-Zehnder modulator as transmitter" ELECTRONICS LETTERS, 10 DEC. 1998, IEE, UK, vol. 34, no. 25, pages 2372-2374, XP002104230 ISSN 0013-5194**
- **LU X ET AL: "BROAD-BAND AM-VSB/64 QAM CABLE TV SYSTEM OVER HYBRID FIBER/COAX NETWORK" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 7, no. 3, 1 March 1995, pages 330-332, XP000510280**

EP 1 060 603 B9

- EGON DOUVERNE ET AL: "EIN 64-QAM-MODEM FUR SDH-RICHTFUNKGERATE MIT INTEGRIERTEN KREUZPOLARISATIONSENTKOPPLER" NACHRICHTENTECHNISCHE BERICHTE, vol. 40, no. 11, 1 March 1994, pages 89-100, XP000520855
- YASUHISA NAKAMURA ET AL: "ADVANCED TECHNIQUES FOR SUPER MULTI-CARRIER DIGITAL MICROWAVE RADIOWITH TRELLIS-CODED 256QAM MODULATION" COMMUNICATIONS TECHNOLOGY FOR THE 1990'S AND BEYOND, DALLAS, NOV. 27 - 30, 1989, vol. 1, 27 November 1989, pages 389-394, XP000091133 INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS
- HIROYUKI OHTSUKA ET AL: "256-QAM SUBCARRIER TRANSMISSION FOR BROADBAND DISTRIBUTION NETWORKS" COUNTDOWN TO THE NEW MILENNIUM, PHOENIX, DEC. 2 - 5, 1991, vol. 3, 2 December 1991, pages 1817-1822, XP000313712 INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS
- KEANG-PO HO ET AL: "Hybrid WDM digital trunking system for both HFC and FTTC access networks" DIGEST. IEEE/LEOS 1996 SUMMER TOPICAL MEETINGS. ADVANCED APPLICATIONS OF LASERS IN MATERIALS PROCESSING;BROADBAND OPTICAL NETWORKS - ENABLING TECHNOLOGIES AND APPLICATIONS; SMART PIXELS; OPTICAL MEMS AND THEIR APPLICATIONS (CAT. NO. 96TH8164), DIGEST , pages 37-38, XP002104231 ISBN 0-7803-3175-3, 1996, New York, NY, USA, IEEE, USA
- GREEN, PAUL E.: "Fiber Optic Networks" 1993 , PRENTICE - HALL, INC. , ENGLEWOOD CLIFFS, NEW JERSEY 07632 XP002104589 236330 see page 331, line 4 - line 7; figures 9-1

Description

BACKGROUND OF THE INVENTION

1. **Field of the Invention**

[0001] This invention relates generally to the transmission of digital data over optical fibers, and more particularly, to transmission based on quadrature amplitude modulation (QAM) and frequency division multiplexing.

2. Description of the Related Art

[0002] As the result of continuous advances in technology, particularly in the areas of networking including the Internet, telecommunications, and application areas which rely on networking or telecommunications, there is an increasing demand for capacity for the transmission of digital data. For example, the transmission of digital data over a network's trunk lines (such as the trunk lines for telephone companies or for the Internet), the transmission of images or video over the Internet, the distribution of software, the transfer of large amounts of data as might be required in transaction processing, or videoconferencing implemented over a public telephone network typically requires the high speed transmission of large amounts of digital data. Typical protocols which are intended to support such transmissions include the OC, STM, and STS protocols. As applications such as the ones mentioned above become more prevalent, the use of these and similar protocols and the corresponding demand for transmission capacity will only increase.

[0003] Optical fiber is a transmission medium which is well-suited for the high speed transmission of digital data. Optical fiber has an inherent bandwidth which is much greater than metal-based conductors, such as twisted pair or coaxial cable, and protocols such as the OC protocol have been developed for the transmission of digital data over optical fibers. However, increasing the data throughput of an optical fiber simply by increasing the clock speed of these protocols, such as moving from 155 million bits per second (Mbps) OC-3 to 625 Mbps OC-12, is not straightforward.

[0004] For example, existing optical fiber communication systems typically use simple modulation schemes which result in low bandwidth efficiencies of approximately 1 bit per sec per Herz (bps/Hz). As an example, the OC protocol is based on on-off keying (OOK), which is a bandwidth inefficient modulation scheme, and the transmission of OC signals across optical fiber results in a bandwidth efficiency of approximately 1 bps/Hz. The useable bandwidth of current optical fibers is limited in part by dispersion and non-linearities which increase with bandwidth. The low bandwidth efficiency means that, for a given digital data rate, the transmitted signal will occupy a larger bandwidth. This results in larger dispersion and non-linear effects, which limit the useful transmission range of the system.

[0005] In addition, even if the optical fiber supports the higher data rates, the corresponding electronics and electro-optics might not be able to. For example, moving from OC-3 to OC-12 quadruples the bit rate but also requires the associated electronics to operate approximately four times faster. Electronics at these speeds simply may not be available or, if available, may have significant other drawbacks, such as larger power consumption, unwieldy size, high cost, or unacceptable fragility.

[0006] In theory, the bandwidth efficiency problem could be addressed partly by the use of more bandwidth-efficient modulation schemes, such as quadrature amplitude modulation (QAM). These modulation schemes have been used previously in radio-wave and coaxial systems. However, optical fiber systems are based on an entirely different technology base and many of the technologies, techniques, and design tradeoffs which were developed in order to implement more advanced modulation schemes in radio-wave and coaxial systems would have only minimal application to optical fiber systems. In addition, optical fiber systems present their own difficulties, such as fiber dispersion and non-linearities causing unwanted interference. Even if bandwidth-efficient modulation schemes could be easily applied to optical fiber systems, their use does not fully address the high-speed electronics problem described above. For example, if OC data streams were QAM-modulated rather than OOK-modulated, a move from OC-3 to OC-12 would still require a four-fold increase in the speed of the corresponding electronics.

[0007] As a result, the application of sophisticated modulation schemes to optical fiber systems has been limited. For example. QAM has recently been applied to an optical fiber system for the transmission of compressed video for the cable TV industry. However these communications systems run at low speeds with an aggregate data rate of less 1 billion bits per second (Gbps). Hence, they are not suited for high speed optical network operation.

[0008] Wavelength division multiplexing (WDM) is an alternate approach to increasing the data throughput of optical fiber systems. This approach, however, increases the aggregate bit rate simply by increasing the overall bandwidth utilized. It still suffers from bandwidth inefficiency. For example, a typical implementation of WDM might optically combine four OC-3 data streams, each at a different wavelength, to form an optical signal which has the same capacity as a single OC-12 data stream. The receiver would then optically separate the four OC-3 data streams, based on their wavelengths, in this approach, however, each OC-3 still has a bandwidth efficiency of approximately 1 bps/Hz, so the wavelength division multipiexed signal will also have a bandwidth efficiency of no more than 1 bps/Hz.

[0009] Thus, there is a need for systems and methods which transmit digital data over optical fibers at high aggregate data rates and with high bandwidth efficiencies, but without unnecessarily increasing the speed requirements on the corresponding electronics.

[0010] "Fiber-Optic Transmission of Microwave 64-QAM Signals" by Mohsen Kavehrad et al in the IEEE Journal On Selected Areas In Communications, Volume 8, No. 7, 1 September 1990, pages 1320 to 1326, describes experimental results on fiber-optic transmission of microwave 64-level quadrature amplitude modulated (QAM) signals at a 1.3 micrometer wavelength at 90Mb/s transmission rate. Two important methods of improving the system performance are discussed and demonstrated: laser intensity noise minimization and error-correction coding using a self-orthogonal convolutional code. The applicability of this transmission technique to the distribution of digital TV services is assessed.

[0011] US Patent No. 5,387,927 describes a method of transmitting broadband video services from a broadband digital signal source which includes forming the digital signal from said source into a plurality of channels of digital signals and modulating a plurality of carrier signals with respective channels of the digital signals. The resultant modulated channels are multiplexed to form a combined signal which is then used to modulate light from a laser light source. The modulated light signal is transmitted along a light fibre to a local distribution box where it is converted to electrical signals and broadcast to a number of subscriber set top terminals. Each set top terminal detects the modulated signal of a channel pre-assigned to that set top terminal. User control information is also received by that set top terminal and transmitted to the central office.

[0012] US Patent No. 5,351,148 describes an optical transmission system that provides digital signals which have added bits for error correction by an encoder which are converted into 16-QAM signals with a predetermined carrier frequency by a modulator, and then frequency division multiplexed with an AM signal so as to be inputted to an optical-electric converter. When the total sum of the light modulation indices of signals to be transmitted is over 1, a light modulation index of an M-QAM signal is set by calculating the light modulation index that marks the onset of diverging from the error rate given by a ratio between receiver noise power and the M-QAM signal power while considering a light modulation index corresponding to a usable transmission margin. The multiplexed signals are transmitted via optical fiber and converted into electric signals by a photo receiver, demodulated by a demodulator, and then outputted after having their errors corrected by an error corrector.

SUMMARY OF THE INVENTION

[0013] The present invention provides a system and method for transmitting digital data over an optical fiber according to claims I and 25, and a system and method for receiving digital data over an optical fiber according to claims 13 and 38.

[0014] In accordance with the present invention, a system for transmitting digital data over an optical fiber includes a modulation stage, a frequency division multiplexer, and an optical modulator. The modulation stage receives a plurality of digital data channels and applies QAM modulation to produce a plurality of QAM-modulated signals. The frequency division multiplexer combines the QAM-modulated signals by frequency division multiplexing them into an RF signal. The RF signal is input to the optical modulator, which generates an optical signal modulated by the RF signal, for transmission over an optical fiber.

[0015] In a preferred embodiment, the modulation stage individually scrambles, forward error encodes and then QAM modulates, using 64 QAM modulation, each of 64 incoming OC-3 digital data channels to produce 64 QAM-modulated signals. The frequency division multiplexer combines the 64 resulting QAM-modulated signals in two steps, first frequency division multiplexing the QAM-modulated signals eight signals at a time to produce a total of eight signals at an intermediate frequency, and then frequency division multiplexing the eight intermediate signals to produce the RF signal. The optical modulator includes an optical source and an external modulator. The RF signal is applied to the external modulator to modulate the optical carrier produced by the optical source. The resulting optical signal is suitable for transmission across an optical fiber.

[0016] In accordance with another aspect of the invention, a system for receiving digital data over an optical fiber includes a detector, a frequency division multiplexer, and a demodulation stage. The detector detects the optical signal produced by the transmitter system described previously, producing an RF signal. The frequency division demultiplexer separates the RF signal into its constituent QAM-modulated signals by frequency division demultiplexing. The demodulation stage converts the QAM-modulated signals into the original digital data channels.

[0017] The present invention is particularly advantageous because the combination of QAM modulation and frequency division multiplexing allows the transmission of digital data over optical fibers at high aggregate data rates and with high bandwidth efficiencies while using lower speed electronics. For example, the preferred embodiment described above has an aggregate data rate of approximately 10 Gbps and a bandwidth efficiency of approximately 4 bps/Hz, but the associated electronics need only support the 155 Mbps OC-3 data rate rather than the 10 Gbps aggregate rate.

BRIEF DESCRIPTION OF THE DRAWING

[0018] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a diagram of a system 100 in accordance with the present invention;

FIG. 2 is a block diagram of one embodiment of the transmitter 102 of FIG. 1;

FIG. 3 is a block diagram of a preferred embodiment of the modulation stage 200 of FIG. 2;

FIG. 4 is a block diagram of a preferred embodiment of the modulation substage 300A of FIG. 3;

FIG. 5 is a block diagram of one embodiment of the frequency division multiplexer 202 of FIG. 2;

FIGS. 6A and 6B are block diagrams of a second embodiment of the frequency division multiplexer 202 of FIG. 2;

FIG. 7 is a block diagram of one embodiment of the receiver 106 of FIG. 1;

FIG. 8 is a block diagram of one embodiment of the frequency division demultiplexer 702 of FIG. 7;

FIGS. 9A and 9B are block diagrams of a second embodiment of the frequency division demultiplexer 702 of FIG. 7;

FIG. 10 is a block diagram of a preferred embodiment of the demodulation stage 704 of FIG. 7; and

FIG. 11 is a block diagram of a preferred embodiment of the demodulation substage 1000A of FIG. 10.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0019] FIG. 1 is a diagram of a system 100 in accordance with the present invention. The system 100 includes a transmitter 102, an optical fiber 104, and a receiver 106. The transmitter 102 is coupled to the receiver 106 by optical fiber 104.

[0020] The system 100 operates as follows. The transmitter 102 receives N digital data channels 110A-N (collectively, digital data channels 110) and combines them into a single optical signal for transmission over fiber 104. The transmitter 102 accomplishes this by using a combination of quadrature amplitude modulation (QAM) and frequency division multiplexing (FDM). The optical signal created by transmitter 102 is transmitted across fiber 104 to receiver 106. Receiver 106 then reverses the functionality of transmitter 102, converting the optical signal into N digital data channels 120A-N.

[0021] In a preferred embodiment which shall be referred to as the "N = 64" or "K = 64" embodiment, the digital data channels 110 include 64 STS-3 channels, each providing digital data at a rate of 155 million bits per second (Mbps) for an aggregate rate of approximately 10 billion bits per second (Gbps). In addition, the use of QAM modulation typically results in a bandwidth efficiency in the range of 2-5 bps/Hz, which is a significant increase over the typical 1 bps/Hz for conventional optical fiber systems; while the use of FDM allows the corresponding electronics to operate at 155 Mbps speeds, which is significantly lower than the 10 Gbps aggregate data rate. In alternate embodiments, the digital data channels 110 may be high speed channels which provide digital data at a predetermined, fixed rate, typically greater than 100 million bits per second (Mbps). For example, the digital data channels 110 may be OC-3 or STM-1 channels. Other protocols may also be supported, including, for example, higher data rate channels such as OC-12, OC-48, etc. The number N of digital data channels 110 may also vary. For example, in a variant of the N = 64 embodiment, there are N = 128 digital data channels 110 for an aggregate bit rate of approximately 20 Gbps. Digital data channels 110 which are in optical form, such as OC-3, may be converted to electrical form by an O/E converter stage coupled to the modulation stage 200.

[0022] FIG. 2 is a block diagram of one embodiment of the transmitter 102 of FIG 1. The transmitter 102 includes a modulation stage 200, a frequency division multiplexer 202, and an optical modulator 204. These components form a data pipeline from the digital data channels 110 to the optical fiber 104. Specifically, the modulation stage 200 receives the digital data channels 110. The modulation stage 200 is coupled to the frequency division multiplexer 202, which is coupled to the optical modulator 204. The optical modulator 204 transmits the optical signal to optical fiber 104.

[0023] The transmitter 102 operates as follows. The modulation stage 200 receives the N digital data channels 110 and converts them into K QAM-modulated signals 210A-K. Frequency division multiplexer 202 receives the QAM-modulated signals 210 and frequency division multiplexes these signals into a single RF signal 212, which is then transmitted to the optical modulator 204. The optical modulator 204 produces an optical signal modulated by the RF signal and then transmits this resulting optical signal to optical fiber 104.

[0024] Various design tradeoffs are inherent in the design of a specific embodiment of transmitter 102 for use in a particular application. For example, in QAM, the signal lattice is evenly spaced in complex signal space but the total number of states in the QAM constellation is a design parameter which may be varied. The carrier frequencies for the QAM-modulated signals 210 are also design parameters which may be varied. The optimal choices of number of states, carrier frequencies, and other design parameters for modulation stage 200 will depend on the particular application. Some examples of modulation stage 200 will be described in further detail below. The frequency division multiplexer 202 also involves a number of design tradeoffs, such as the choices of intermediate frequencies, whether to implement components in the digital or in the analog domain, and whether to use multiple stages to achieve the multiplexing. As another example, an optical modulator 206 with better linearity will reduce unwanted harmonics and interference, thus increasing the transmission range of transmitter 102. However, optical modulators with better linearity are also more difficult to design and to produce. Hence, the optimal linearity will depend on the particular application. An example of a system-level tradeoff is the allocation of signal power and gain between the various components. Accordingly, many aspects of the invention will be described in the context of the N = 64 embodiment introduced earlier. However, it is to be understood that the invention is not limited to this specific embodiment.

[0025] FIG. 3 is a block diagram of a preferred embodiment of the modulation stage 200 of FIG. 2. The modulation stage 200 includes K modulation substages 300A-K. Each modulation substage 300 receives M of the digital data channels 110, where M = N/K, and converts them into a single QAM-modulated signal 210. In this embodiment, the modulation substages 300 are identical. For clarity, FIG. 3 shows a detail of a single modulation substage 300A.

[0026] Modulation substage 300A includes M encoders 302A-M, a combiner 303, and a QAM modulator 304. Each of the encoders 302 is coupled to receive one of the digital data channels 110. The QAM modulator 304 is coupled to the outputs of the encoders 302 via combiner 303.

[0027] The modulation substage 300A operates as follows. Each of the encoders 302 receives one of the digital data channels 110 and encodes the digital data. The encoded digital data channels from the encoders 302 are received by combiner 303, which combines the M data streams into a single input for QAM modulator 304. QAM modulator 304 converts the received data stream into the QAM-modulated signal 210. Various types of encoding and QAM modulation schemes are possible, one of which will be discussed in FIG. 4.

[0028] In a preferred embodiment, encoder 302 includes a forward error correction (FEC) encoder. This allows errors which occur during the subsequent processing stages and transmission to be corrected by the receiver. This is particularly relevant for optical fiber systems because they generally requires low bit error rates (BER) and any slight increase of the interference or noise level will cause the BER to exceed the threshold. FEC coding can compensate for these unwanted effects. Any variety of FEC techniques can be used, depending on the system margin requirements. For short transmission distances, FEC coding may not result in any significant advantages.

[0029] FIG. 4 is a block diagram of the modulation substage 300A used in the N = 64 embodiment. In this embodiment, K = N = 64 and M = 1. In other words, there is one modulation substage 300 for each incoming digital data channel 110 and each individual digital data channel 110 results in a separate QAM-modulated signal 210.

[0030] The modulation substage 300A includes a scrambler 400, a Reed-Solomon encoder 402, an interleaver 404, a trellis encoder 406, and QAM modulator 304. The scrambler 400, Reed-Solomon encoder 402, interleaver 404, and trellis encoder 406 are part of encoder 302. Combiner 303 of FIG. 3 is not required since M = 1. These components are coupled to form a pipeline in which digital data flows from the scrambler 400 to the Reed-Solomon encoder 402 to the interleaver 404 to the trellis encoder 406 to QAM modulator 304, thus being converted from digital data channel 110 to QAM-modulated signal 210.

[0031] The modulation substage 300A operates as follows. The digital data channel 110 is received by scrambler 400 which scrambles the incoming digital data, thus randomizing the data string.

[0032] Reed-Solomon encoder 402 encodes the scrambled digital data channel according to a Reed-Solomon code. Programmable Reed-Solomon codes are preferred for maintaining very low BER (typ. 10^{-12}) with low overhead (typ. less than 20%). For example, a Reed-Solomon code of (204,188) can be applied for an error correction capability of 8 error bits per every 188 data bits.

[0033] The interleaver 404 interleaves the digital data string output by the Reed-Solomon encoder 402. The interleaving results in more robust error recovery due to the nature of trellis encoder 406. Specifically, FEC codes are able to correct only a limited number of mistakes in a given block of data, but convolutional encoders such as trellis encoder 406 tend to cluster errors together. Hence, without interleaving, a block of data which contained a large cluster of errors would be difficult to recover. However, with interleaving, the cluster of errors is distributed over several blocks of data, each of which may be recovered by the FEC code. Convolution interleaving of depth 10 is preferred.

[0034] The trellis encoder 406 applies a QAM modulation, preferably 64 state QAM modulation, to the digital data stream output by the interleaver 404. The result typically is a complex baseband signal, representing the in-phase and quadrature (I and Q) components of the eventual QAM-modulated signal 210. The use of 64 QAM yields a modulation bandwidth efficiency of 6 bps/Hz, thus increasing the overall transmission capacity by a significant factor over conventional OOK systems. QAM with a different number of states may be used and varying the number of states from 16 to 1024 will generally improve the modulation bandwidth efficiency by a factor of 4 to 10.

[0035] QAM modulator 304 typically uses the I and Q components to modulate a carrier, resulting in QAM modulated signal 210 characterized by a carrier frequency. In a preferred embodiment, QAM modulator 304 implements the QAM modulation digitally and the sampled QAM modulated signals 210 are then converted to the analog domain by A/D converters for subsequent processing. In alternate embodiments, the QAM modulation may be implemented using analog techniques.

[0036] FIG. 5 is a block diagram of one embodiment of the frequency division multiplexer 202 of FIG. 2. The frequency division 202 includes K frequency shifters 500A-K and a combiner 502. Various devices may be used as frequency shifters 500, including both analog and digital designs. A common design is based on mixing the incoming signal with a local oscillator and then selecting the component at the desired frequency by means of a frequency filter. Each of the frequency shifters 500 is coupled to receive one of the QAM-modulated signals 210. The combiner 502 is coupled to receive the outputs of the frequency shifters 500.

[0037] The frequency division multiplexer 202 operates as follows. Each frequency shifter 500 frequency shifts its incoming QAM-modulated signal 210 to a carrier frequency which is different from the carrier frequencies used by all the other frequency shifters 500. Hence, the output of the frequency shifters 500 is the QAM-modulated signals 210 but each at a different carrier frequency. The combiner 502 then combines these signals into the RF signal 212. In other words, each QAM-modulated signal 210 is a different tone in the RF signal 212.

[0038] In a variant of the frequency division multiplexer 202 of FIG. 5, the modulation stage 200 may produce QAM-modulated signals 210 at carrier frequencies which are suitable for direct combination into RF signal 212. In this case, the frequency division multiplexer 202 does not require the frequency shifters 500 and combiner 502 directly combines the QAM-modulated signals 210 into RF signal 212.

[0039] FIGS. 6A and 6B are block diagrams of a second embodiment of the frequency division multiplexer 202 of FIG. 2. In this approach, the frequency division multiplexing occurs in two stages: first stage 622 shown in FIG. 6A and second stage 624 shown in FIG. 6B. For convenience, the frequency division multiplexer 202 will be explained in reference to the K = 64 embodiment.

[0040] In stage 622 of FIG. 6A, stage 622 is subdivided into the J substages 620A-J, with J = 8 in this embodiment. The 64 QAM-modulated signals 210 are also subdivided into J groups of H signals each, with J = H = 8 in this embodiment. Each substage 620 frequency division multiplexes one group of eight signals to form a single signal 607A-J, which is fed to the next stage 624. The processing of a single group of eight signals is shown in FIG. 6A. Other combinations of J and H may be used in alternate embodiments.

[0041] Substage 620A includes eight frequency shifters 604A-H, and a combiner 606. These components are coupled so that each incoming QAM-modulated signal 210 flows through a frequency shifter 604 to combiner 606.

[0042] Substage 620A operate as follows. In this embodiment, the QAM-modulated signals 210 are frequency shifted by frequency shifter 604 to a first carrier frequency. At this point, the first carrier frequencies for each of the eight signals within a substage 620 is different, but each substage 620 uses the same set of eight carrier frequencies. For example, in a preferred embodiment, the QAM-modulated signals 210 are frequency shifted to eight different carrier frequencies in the 1.0-1.6 GHz range. The combiner 606 combines the eight signals, all at different first carrier frequencies, into a single intermediate signal 607A which is input to stage 624 of FIG. 6B. Hence, at the output of stage 622 for the entire device, there are a total of eight intermediate signals 607, one for each substage 620. Furthermore, each intermediate signal 607 contains eight tones, one for each of the incoming QAM-modulated signal 210 within the substage 620.

[0043] Stage 624 of FIG. 6B then repeats the function of stage 622 to form the RF signal 212. Specifically, the stage 624 includes eight frequency shifters 608A-J and a combiner 610, which are coupled in the same fashion as the frequency shifters 604 and combiner 606 of stage 622. Each frequency shifter 608 receives one of the intermediate signals 607 from the previous stage 622 and frequency shifts it to a second carrier frequency. Each frequency shifter 608 uses a different second carrier frequency so that there is no overlap between the various signals. For example, continuing the previous example, the intermediate signals 607 were in the 1.0-1.6 GHz range. Frequency shifter 608A may shift the intermediate signal 607A to the 0.4-1.0 GHz range, frequency shifter 608B to the 1.0-1.6 GHz range; frequency shifter 608C to the 1.6-2.2 GHz range, and so forth. Note that, in this example, shifter 608A down-shifts, shifter 608B is not required since no shift is necessary, and the other shifters 608C-J up-shift. The combiner 610 then combines these outputs into the RF signal 212, which occupies the spectral band from 0.4-5.2 GHz in this example.

[0044] Referring again to FIG. 2, the optical modulator 204 receives the RF signal 212 and produces an optical beam modulated by the RF signal 212. Various techniques may be used to achieve this function. In a preferred embodiment, the modulator 204 includes an optical source and an external optical modulator. Examples of optical sources include solid state lasers and semiconductor lasers. Example external optical modulators include Mach Zehnder modulators, electro-optic modulators, and electro-absorptive modulators. The optical source produces an optical carrier, which is modulated by the RF signal 212 as the carrier passes through the external optical modulator. The RF signal may be predistorted in order to increase the linearity of the overall system.

[0045] Alternatively, the modulator 204 may be an internally modulated laser. In this case, the RF signal 212 drives the laser, the output of which will be an optical beam modulated by the RF signal.

[0046] Current optical fibers have two spectral regions which are commonly used for communications: the 1.3 and 1.55 micron regions. At a wavelength of 1.3 micron, transmission of the optical signal is primarily limited by attenuation in the fiber 104; dispersion is less of a factor. Conversely, at a wavelength of 1.55 micron, the optical signal will experience more dispersion but less attenuation. Hence, the optical signal preferably has a wavelength either in the 1.3 micron region or the 1.55 micron region and, for long distance communications systems, the 1.55 micron region is generally preferred.

[0047] FIG. 7 is a block diagram of one embodiment of the receiver 106 of FIG. 1, which in large part, is the reverse of transmitter 102. The receiver 106 includes a detector 700 such as an avalanche photo-diode or PIN-diode, a frequency division demultiplexer 702, and a demodulation stage 704. These elements are coupled to form a data pipeline which transforms the optical signal from optical fiber 104 into the digital data channels 120. More specifically, the detector 700 is coupled to the optical fiber 104; the frequency division demultiplexer 702 is coupled to the detector 700; and the demodulation stage 704 is coupled to the frequency division demultiplexer 702. The demodulation stage 704 outputs the digital data channels 120.

[0048] The receiver 106 operates as follows. The detector 700 detects the optical signal transmitted over optical fiber 104 to produce an RF signal 710, which includes K QAM-modulated signals 712A-K, each characterized by a different carrier frequency. Frequency division demultiplexer 702 frequency division demultiplexes the RF signal 710 into the K QAM-modulated signals 712. Demodulation stage 704 then converts the QAM-modulated signals 712 into the N digital data channels 120. This is essentially the reverse of transmitter 102, as shown in FIG. 2. RF signal 710, QAM-modulated signals 712, and digital data channels 120 are the counterparts to RF signal 212, QAM-modulated signals 210, and digital data channels 110.

[0049] FIG. 8 is a block diagram of one embodiment of the frequency division multiplexer 702 of FIG. 7. This embodiment includes a splitter 800, K frequency shifters 802A-K, and K bandpass filters 804A-K. The splitter 800 is coupled to receive the RF signal 710 and each frequency shifter 802 is coupled to receive an output of splitter 800. The output of each frequency shifter 802 is coupled to an input of a bandpass filter 804.

[0050] The frequency division multiplexer 702 operates as follows. The splitter 800 splits the RF signal 710 into K signals, each of which is input into a frequency shifter 802 - bandpass filter 804 combination. For example, one of the split RF signals is input into frequency shifter 802A. As described previously, the RF signal includes K different QAM-modulated signals each at a different carrier frequency. The frequency shifter 802A shifts the incoming RF signal by an amount such that one of these QAM-modulated signals is shifted to the pass band of filter 804A. This signal is filtered from the other signals by bandpass filter 804A, thus producing QAM-modulated signal 712A. Each of the frequency shifters 802 shifts by a different frequency amount so that each bandpass filter 804 will select a different one of the K QAM-modulated signals contained in the RF signal 710. In a preferred embodiment, the pass bands of the filters 804A-K are the same so that QAM-modulated signals 712 are characterized by the same carrier frequency.

[0051] FIGS. 9A and 9B are block diagrams of a second embodiment of the frequency division multiplexer 702 of FIG. 7. This embodiment achieves the frequency division demultiplexing in multiple stages. FIG. 9A shows a first stage 920; while FIG. 9B shows second stages 922. The multi-stage frequency division demultiplexer 702 will be explained in the context of the K = 64 embodiment.

[0052] In this embodiment, the first stage 920 of FIG. 9A includes a splitter 900, eight bandpass filters 902A-J and eight frequency shifters 904A-J. The splitter 900 splits the incoming RF signal 710 into eight signals, each of which is fed to a bandpass filter 902-frequency shifter 904 combination. As discussed in connection with FIGS. 6A and 6B, the RF signal in this particular embodiment contains eight groups of eight signals each. The purpose of stage 920 is to frequency division demultiplex the RF signal 710 into the eight groups.

[0053] Stage 920 operates as follows. Each of the bandpass filters 902 has a different pass band and therefore selects a different one of the eight groups contained in RF signal 710. Continuing the example of FIGS. 6A and 6B, the various pass bands would be 0.4-1.0 GHz, 1.0-1.6 GHz, etc. The frequency shifters 904 then frequency shift each of these groups to the same carrier frequency, the 1.0-1.6 GHz band in this example. Since each group was originally characterized by a different carrier frequency, each of the frequency shifters 904 must frequency shift by a different amount. The output of stage 920 is eight signals 905A-J, each at the same carrier frequency and each containing one group of eight QAM-modulated signals. Each of these signals is then input into stage 922 of FIG. 9B.

[0054] For convenience, FIG. 9B only shows the processing of signal 905A of the eight signals 905 from stage 920. Stage 922 of FIG. 9B includes a splitter 910, eight frequency shifters 912A-H, eight bandpass filters 914A-H, eight frequency shifters 916A-H, and eight A/D converters 918A-H. The incoming signal 905A contains eight QAM-modulated signals, each at a different frequency. The splitter 910 splits the incoming signal into eight different signals, each of which will be converted to a digital QAM-modulated signal 712A-H.

[0055] This is accomplished as follows. Each of the frequency shifters 912 frequency shifts one of the QAM-modulated signals in the incoming signal to a common carrier frequency. Bandpass filters 914 filter out the signal at the common carrier frequency. As with FIG. 9A, since each of the incoming signals is characterized by a different carrier frequency, each of the frequency shifters 912 must frequency shift by a different amount in order to shift the desired QAM-modulated signal to the proper bandpass region. Frequency shifter 916 then shifts these signals to a lower common carrier frequency. This is advantageous because bandpass filter 914 may operate at a higher frequency, permitting the use of filters with better performance. A/D converters 918 sample the output of frequency shifters 916, converting the QAM-modulated signals from analog to digital form in preparation for digital QAM demodulation.

[0056] FIG. 10 is a block diagram of a preferred embodiment of the demodulation stage 704 of FIG. 7. The demodulation stage 704 includes K demodulation substages 1000A-K. FIG. 10 shows the details of one of these demodulation substages 1000A. Each demodulation substage 1000 converts one of the QAM-modulated signals 712 into M digital data channels 120A-M, where M = N/K. The demodulation substage 1000A includes a QAM demodulator 1002 coupled to M decoders 1004A-M by splitter 1003. The demodulation substage 1000A generally performs the reverse function of the modulation substage 300A. Specifically, the QAM demodulator 1002 removes the QAM modulation from the incoming QAM-modulated signal 712. Splitter 1003 separates the demodulated signals into its constituent M data streams, which are then decoded by decoders 1004 to form the digital data channels 120.

[0057] FIG. 11 is a block diagram of the demodulation substage 1000A of FIG. 10 used in the N = 64 embodiment. In this case, M = 1 so splitter 1003 is not required. Decoder 1004 includes trellis decoder 1100, de-interleaver 1102, Reed-Solomon decoder 1104 and descrambler 1106. These components are coupled in the reverse order of their counterparts shown in FIG. 4. Specifically, following the direction of data flow, the QAM demodulator 1002 is coupled to the trellis decoder 1100 to the de-interleaver 1102 to the Reed-Solomon decoder 1104 to the descrambler 1106.

[0058] The demodulation substage 1000A operates as FIG. 11 would suggest. The QAM demodulator 1002 demodulates the incoming QAM-modulated signal 712A, typically extracting baseband I and Q signals from the modulated carrier. Trellis decoder 1100 converts the I and Q signals to a digital stream. De-interleaver 1102 reverses the interleaving process. Reed-Solomon decoder 1104 reverses the Reed-Solomon encoding, correcting any errors which have occurred. Descrambler 1106 descrambles the resulting decoded signal to produce the digital data channels 120. The resulting digital data channels may be converted from electrical to optical form by a subsequent E/O conversion stage.

[0059] Although the invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments are possible. Therefore, the scope of the appended claims should not be limited to the description of the preferred embodiments contained herein.

Claims

1. A system for transmitting digital data over an optical fiber (104) comprising:

> a modulation stage (200) for converting a plurality N of high-speed digital data channels into a plurality K of QAM-modulated signals, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second;
> a frequency division multiplexer (202) coupled to the modulation stage for frequency division multiplexing the QAM-modulated signals into an RF signal; and
> an optical modulator (204) coupled to the frequency division multiplexer for producing an optical signal modulated by the RF signal, the optical signal suitable for transmission over an optical fiber (104);

wherein the modulation stage (200) includes an encoder unit (302) that is for encoding one of the plurality of digital data channels to form an encoded digital data channel, wherein the encoder unit (302) includes;
a scrambler (400) for scrambling a digital data channel;
a feed forward error correction encoder (402) coupled to the scrambler for encoding the scrambled digital data channel;
an interleaver (404) coupled to the first encoder for interleaving the encoded digital data channel; and
a Trellis encoder (406) coupled to the interleaver for converting the interleaved digital data channel to a QAM constellation.

2. The system of claim 1 wherein the modulation stage (200) includes:

> a plurality K of modulation substages (300) each modulation substage for converting M of the plurality of digital data channels into one of the plurality of QAM-modulated signals, with M = N/K.

3. The system of claim 2 wherein each modulation substage (300) further includes:

M encoders (302), each encoder (302) for encoding one of the M digital data channels to form an encoded digital data channel; and
a QAM modulator (304) coupled to the M encoders for converting the M encoded digital data channels into the QAM-modulated signal.

4. The system of claim 3 wherein each encoder (302) further includes:

a forward error correction encoder for encoding one of the M digital data channels according to a forward error correction code.

5. The system of claim 3 wherein:

K = N and M = 1; and
each encoder (302) includes:

a scrambler (400) for scrambling one of the plurality of digital data channels;
a Reed-Solomon encoder (402) coupled to the scrambler for encoding the scrambled digital data channel according to a Reed-Solomon code;
an interleaver (404) coupled to the Reed-Solomon encoder for interleaving the encoded digital data channel; and
a trellis encoder (406) coupled to the interleaver for converting the interleaved digital data channel to a QAM constellation.

6. The system of claim 1 wherein:

each QAM-modulated signal is **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and
the frequency division multiplexer (202) includes:

a combiner (502) for combining the plurality of QAM-modulated signals into the RF signal,

7. The system of claim 1 wherein:

each QAM-modulated signal is **characterized by** a first carrier frequency, all of the first carrier frequencies the same; and
the frequency division multiplexer (202) includes:

a plurality of frequency shifters (500) for frequency shifting the QAM-modulated signals from the first carrier frequencies to second carrier frequencies, each of the second carrier-frequencies different from the other second carrier frequencies; and
a combiner (502) for combining the plurality of QAM-modulated signals **characterized by** the second carrier frequencies into the RF signal.

8. The system of claim 1 wherein the frequency division multiplexer (202) comprises:

a multi-stage frequency division multiplexer.

9. The system of claim 1 wherein the optical modulator (204) comprises:

an internally modulated laser for producing an output optical beam modulated by the RF signal.

10. The system of claim 1 wherein the optical modulator (204) comprises:

an optical source for producing an optical carrier; and
an external optical modulator coupled to the optical source and the frequency division multiplexer for modulating the optical carrier with the RF signal.

11. The system of claim 1 wherein:

the optical signal is **characterized by** a wavelength in either one of the 1.3 micron region and the 1.55 micron region.

12. The system of claim 1 further comprising:

an O/E converter stage coupled to the modulation stage for converting the digital data channels from optical to electrical form.

13. A system for receiving digital data over an optical fiber (104) comprising:

a detector (700) for detecting an optical signal transmitted over an optical fiber to produce an RF signal;
a frequency division demultiplexer (702) coupled to the detector for frequency division demultiplexing the RF signal into a plurality K of QAM-modulated signals; and
a demodulation stage (704) for converting the plurality K of QAM-modulated signals into a plurality N of high-speed digital data channels, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second;

wherein the demodulation stage (704) includes a decoder unit (1004) that is for decoding one of a plurality of demodulation signals to form a digital data channel, wherein the decoder unit includes;
a Trellis decoder (1100) for decoding a demodulated signal according to a QAM constellation;
a de-interleaver (1102) coupled to the first decoder for de-interleaving the decoded signal,
a feed forward error correction decoder (1104) coupled to the de-interleaver for decoding the de-interleaved signal, and;
a descrambler (1106) coupled to the second decoder for descrambling the decoded signal.

14. The system of claim 1 or claim 13 wherein:

at least one of the digital data channels is capable of transmitting digital data at a predetermined, fixed rate greater than 100 million bits per second.

15. The system of claim 14 wherein:

at least one digital data channel is based on one of the protocols selected from the list comprising the OC protocol, the STM protocol, and the STS protocol.

16. The system of claim 1 or claim 13 wherein:

the plurality of digital data channels are capable of transmitting digital data at an aggregate rate greater than 2.5 billion bits per second.

17. The system of claim 13 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and the frequency division demultiplexer (702) includes:

a splitter (800) for splitting the RF signal into a plurality of RF signals;
a plurality of frequency shifters (802) coupled to the splitter, each frequency shifter for frequency shifting one of the split RF signals from one of the first carrier frequencies to a second carrier frequency, all.of the second carrier frequencies the same; and
a plurality of bandpass (804) filters coupled to the plurality of frequency shifters for filtering the split RF signals frequency shifted to the second carrier frequencies.

18. The system of claim 13 wherein the frequency division demultiplexer (702) comprises:

a multi-stage frequency division demultiplexer.

19. The system of claim 13 wherein the demodulation stage (704) includes:

a plurality of K of demodulation substages (1000) each demodulation substage for converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels, with M = N/K.

20. The system of claim 19 wherein each demodulation substage (1000) further includes:

a QAM demodulator (1002) for converting the QAM-modulated signal into M demodulated signals; and
M decoders (1004) coupled to the QAM demodulator, each decoder for decoding one of the M demodulated signals to form a digital data channel.

21. The system of claim 20 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and
each QAM demodulator (1002) is further for converting the QAM-modulated signals **characterized by** the first carrier frequencies into the M demodulated signals.

22. The system of claim 20 wherein each decoder (1004) further includes:

a forward error correction decoder for decoding one of the M demodulated signals according to a forward error correction code.

23. The system of claim 20 wherein:

K = N and M = 1; and
each decoder (1004) includes:

a trellis decoder (1100) coupled-to the QAM demodulator (1002) for decoding the demodulated signal according to a QAM constellation;
a de-interleaver (1102) coupled to the trellis decoder for de-interleaving the decoded signal;
a Reed-Solomon decoder (1104) coupled to the de-interleaver for decoding the de-interleaved signal according to a Reed-Solomon code; and
a descrambler (1106) coupled to the Reed-Solomon decoder for descrambling the decoded signal.

24. The system of claim 13 further comprising:

an E/O conversion stage coupled to the demodulation stage for converting the digital data channels from electrical to optical form.

25. A method for transmitting digital data over an optical fiber (104) comprising:

receiving a plurality N of digital data channels, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second;
converting the plurality of digital data channels into a plurality K of QAM-modulated signals;
frequency division multiplexing the QAM-modulated signals into an RF signal; and
producing an optical signal modulated by the RF signal, the optical signal suitable for transmission over an optical fiber (104);

wherein said converting the plurality of digital data channels into a plurality K of QAM-modulated signals includes encoding one of the plurality of digital data channels to form an encoded digital data channel, wherein said encoding one of the plurality of digital data channels to form an encoded digital data channel includes:

scrambling a digital data channel;
feed forward error correction encoding the scrambled digital data channel;
interleaving the encoded digital data channel; and
Trellis encoding the interleaved digital data channel to convert the interleaved digital data channel to a QAM constellation.

26. The method of claim 25 wherein:

receiving the plurality of digital data channels includes receiving the digital data channels at a predetermined, fixed rate.

27. The method of claim 25 wherein:

receiving the plurality of digital data channels includes receiving the plurality of digital data channels at an aggregate rate greater than 2.5 billion bits per second.

28. The method of claim 25 wherein converting the plurality N of digital data channels into the plurality K of QAM-modulated signals includes:

for K times in parallel, converting M of the plurality of digital data channels into one of the plurality of QAM-modulated signals, with M = N/K.

29. The method of claim 28 wherein converting M of the plurality of digital data channels into one of the plurality of QAM-modulated signals includes:

in parallel, encoding each of the M digital data channels to form an encoded digital data channel; and
converting the M encoded digital data channels into the QAM-modulated signal.

30. The method of claim 29 wherein encoding each of the M digital data channels includes:

encoding each of the M digital data channels according to a forward error correction code.

31. The method of claim 29 wherein:

K = N and M = 1; and
encoding each of the M digital data channels to form an encoded digital data channel includes:

scrambling the digital data channel;
encoding the scrambled digital data channel according to a Reed-Solomon code;
interleaving the encoded digital data channel; and
applying a QAM modulation to the interleaved digital data channels.

32. The method of claim 25 wherein:

each QAM-modulated signal is **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and
frequency division multiplexing the QAM-modulated signals into the RF signal includes:

combining the plurality of QAM-modulated signals into the RF signal.

33. The method of claim 25 wherein:

each QAM-modulated signal is **characterized by** a first carrier frequency, all of the first carrier frequencies the same; and
frequency division multiplexing the QAM-modulated signals into the RF signal includes:

frequency shifting the QAM-modulated signals from the first carrier frequencies to second carrier frequencies, each of the second carrier frequencies different from the other second carrier frequencies; and
combining the plurality of QAM-modulated signals **characterized by** the second carrier frequencies into the RF signal.

34. The method of claim 25 wherein frequency division multiplexing the QAM-modulated signals into an RF signal comprises:

frequency division multiplexing the QAM-modulated signals in at least two stages.

35. The method of claim 25 wherein producing the optical signal modulated by the RF signal comprises:

producing an optical carrier; and
modulating the optical carrier with the RF signal.

36. The method of claim 25 wherein:

the optical signal is **characterized by** a wavelength in either one of the 1,3 micron region and the 1.55 micron region.

37. The method of claim 25 further comprising:

converting the digital data channels from optical to electrical form.

38. A method for receiving digital data over an optical fiber (104) comprising:

detecting an optical signal transmitted over an optical fiber (104) to produce an RF signal;
frequency division demultiplexing the RF signal into a plurality K of QAM-modulated signals; and
converting the plurality K of QAM-modulated signals into a plurality N of digital data channels, at least one of the digital data channels capable of transmitting digital data at a rate greater than 100 million bits per second;

wherein said converting the plurality K of QAM-modulated signals into a plurality N of digital data channels includes decoding one of a plurality of demodulated signals to form a digital data channel, wherein said decoding one of a plurality of demodulated signals to form a digital data channel includes:

Trellis decoding a demodulated signal according to a QAM constellation;
de-interleaving the decoded signal;
feed forward error correction decoding the de-interleaved signal; and
descrambling the decoded signal.

39. The method of claim 38 wherein:

the digital data channels transmit digital data at a predetermined, fixed rate.

40. The method of claim 26 or claim 39 wherein:

at least one digital data channel is based on one of the protocols selected from the list comprising the OC protocol, the STM protocol, and the STS protocol.

41. The method of claim 38 wherein:

the plurality of digital data channels transmit digital data at an aggregate rate greater than 2.5 billion bits per second.

42. The method of claim 38 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and
frequency division demultiplexing the RF signal includes:

splitting the RF signal into a plurality of RF signals;
frequency shifting the split RF signals from the first carrier frequencies to second carrier frequencies, all of the second carrier frequencies the same; and
bandpass filtering the split RF signals frequency shifted to the second carrier frequencies.

43. The method of claim 38 wherein frequency division demultiplexing the RF signal comprises:

frequency division demultiplexing the RF signal in multiple stages.

44. the method of claim 38 wherein converting the plurality K of QAM-modulated signals into a plurality N of digital data channels includes:

for K times in parallel, converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels, with M = N/K.

45. The method of claim 44 wherein converting one of the plurality of QAM-modulated signals into M of the plurality of digital data channels includes:

converting the QAM-modulated signal into M demodulated signals; and
decoding each of the M demodulated signals to form the digital data channels.

46. The method of claim 45 wherein:

the RF signal includes the plurality of QAM-modulated signals, each QAM-modulated signal **characterized by** a first carrier frequency, each of the first carrier frequencies different from the other first carrier frequencies; and
converting the QAM-modulated signal into M demodulated signals includes converting the QAM-modulated signal **characterized by** the first carrier frequency into the M demodulated signals.

47. The method of claim 45 wherein decoding each of the M demodulated signals includes:

decoding the demodulated signal according to a forward error correction code.

48. The method of claim 45 wherein:

K = N and M = 1; and
decoding each of the M demodulated signals includes:

decoding the demodulated signal according to a QAM constellation;
de-interleaving the decoded signal;
decoding the de-interleaved signal according to a Reed-Solomon code; and
descrambling the decoded signal.

49. The method of claim 38 further comprising:

converting the digital data channels from electrical to optical form.

Patentansprüche

1. System zum Senden digitaler Daten über eine Lichtleitfaser (104), umfassend:

eine Modulationsstufe (200) zum Umsetzen mehrerer N Hochgeschwindigkeits-Digitaldaten-Kanäle in mehrere K QAM-modulierte Signale, wobei wenigstens einer der digitalen Datenkanäle fähig ist, digitale Daten mit einer Rate von mehr als 100 Millionen Bits pro Sekunde zu übertragen;
einen Frequenzbereich-Multiplexer (202), der mit der Modulationsstufe gekoppelt ist, um die QAM-modulierten Signale in ein HF-Signal zu multiplexieren; und
einen optischen Modulator (204), der mit dem Frequenzbereich-Multiplexer gekoppelt ist, um ein mittels des HF-Signals moduliertes Lichtsignal zu erzeugen, wobei das Lichtsignal für die Übertragung über eine Lichtleitfaser (104) geeignet ist;
wobei die Modulationsstufe (200) eine Codierereinheit (302) enthält, die zum Codieren eines der mehreren digitalen Datenkanäle dient, um einen codierten digitalen Datenkanal zu bilden, wobei die Codierereinheit (302) enthält:

einen Verwürfler (400) zum Verwürfeln eines digitalen Datenkanals;
einen Vorwärtsfehlerkorrektur-Codierer (402), der mit dem Verwürfler gekoppelt ist, um den verwürfelten digitalen Datenkanal zu codieren;
einen Verschachtler (404), der mit dem ersten Codierer gekoppelt ist, um den codierten digitalen Datenkanal

zu verschachteln; und
einen Gittercodierer (406), der mit dem Verschachtler gekoppelt ist, um den verschachtelten digitalen Datenkanal in eine QAM-Konstellation umzusetzen.

2. System nach Anspruch 1, wobei die Modulationsstufe (200) enthält:

mehrere K Modulationsunterstufen (300), wobei jede Modulationsunterstufe zum Umsetzen von M der mehreren digitalen Datenkanäle in eines der mehreren QAM-modulierten Signale dient, wobei M = N/K gilt.

3. System nach Anspruch 2, wobei jede Modulationsunterstufe (300) ferner enthält:

M Codierer (302), wobei jeder Codierer (302) zum Codieren eines der M digitalen Datenkanäle dient, um einen codierten digitalen Datenkanal zu bilden; und
einen QAM-Modulator (304), der mit dem M Codierern gekoppelt ist, um die M codierten digitalen Datenkanäle in das QAM-modulierte Signal umzusetzen.

4. System nach Anspruch 3, wobei jeder Codierer (302) ferner enthält:

einen Codierer mit Vorwärtsfehlerkorrektur zum Codieren eines der M digitalen Datenkanäle entsprechend einem Vorwärtsfehlerkorrekturcode.

5. System nach Anspruch 3, wobei:

K = N und M = 1 gilt; und
jeder Codierer (302) enthält:

einen Verwürfler (400) zum Verwürfeln eines der mehreren digitalen Datenkanäle;
einen Reed-Solomon-Codierer (402), der mit dem Verwürfler gekoppelt ist, um den verwürfelten digitalen Datenkanal gemäß einem Reed-Solomon-Code zu codieren;
einen Verschachtler (400), der mit dem Reed-Solomon-Codierer gekoppelt ist, um den codierten digitalen Datenkanal zu verschachteln; und
einen Gittercodierer (406), der mit dem Verschachtler gekoppelt ist, um den verschachtelten digitalen Datenkanal in eine QAM-Konstellation umzusetzen.

6. System nach Anspruch 1, wobei:

jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, wobei jede der ersten Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
der Frequenzbereich-Multiplexer (202) enthält:

einen Kombinierer (502) zum Kombinieren der mehreren QAM-modulierten Signale in das HF-Signal.

7. System nach Anspruch 1, wobei:

jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, wobei alle ersten Trägerfrequenzen gleich sind; und
der Frequenzbereich-Multiplexer (202) enthält:

mehrere Frequenzverschieber (500) zum Frequenzverschieben der QAM-modulierten Signale von den ersten Trägerfrequenzen zu zweiten Trägerfrequenzen, wobei jede der zweiten Trägerfrequenzen von den anderen zweiten Trägerfrequenzen verschieden ist; und
einen Kombinierer (502) zum Kombinieren der mehreren QAM-modulierten Signale, die durch die zweiten Trägerfrequenzen **gekennzeichnet** sind, in das HF-Signal.

8. System nach Anspruch 1, wobei der Frequenzbereich-Multiplexer (202) umfasst:

einen mehrstufigen Frequenzbereich-Multiplexer.

9. System nach Anspruch 1, wobei der optische Modulator (204) umfasst:

einen intern modulierten Laser zum Erzeugen eines durch das HF-Signal modulierten Lichtstrahls.

10. System nach Anspruch 1, wobei der optische Modulator (204) umfasst:

eine Lichtquelle zum Erzeugen eines optischen Trägers; und
einen externen optischen Modulator, der mit der Lichtquelle und dem Frequenzbereich-Multiplexer gekoppelt ist, um den optischen Träger mit dem HF-Signal zu modulieren.

11. System nach Anspruch 1, wobei:

das Lichtsignal durch eine Wellenlänge entweder im 1,3μm-Bereich oder im 1,55μm-Bereich **gekennzeichnet** ist.

12. System nach Anspruch 1, ferner umfassend:

eine O/E-Umsetzerstufe, die mit der Modulationsstufe gekoppelt ist, um die digitalen Datenkanäle von einer optischen Form in eine elektrische Form umzusetzen.

13. System zum Empfangen digitaler Daten über eine Lichtleitfaser (104), umfassend:

einen Detektor (700) zum Erfassen eines Lichtsignals, das über eine Lichtleitfaser übermittelt worden ist, um ein HF-Signal zu erzeugen;
einen Frequenzbereich-Demultiplexer (700), der mit dem Detektor gekoppelt ist, zum Frequenzbereich-Demultiplexieren des HF-Signals in mehrere K QAM-modulierte Signale; und
eine Demodulationsstufe (704) zum Umsetzen der mehreren K QAM-modulierten Signale in mehrere N Hochgeschwindigkeits-Digitaldaten-Kanäle, wobei wenigstens einer der digitalen Datenkanäle fähig ist, digitale Daten mit einer Rate von mehr als 100 Millionen Bits pro Sekunde zu übertragen;

wobei die Demodulationsstufe (704) eine Decodierereinheit (1004) enthält, die zum Decodieren eines mehrerer Demodulationssignale dient, um einen digitalen Datenkanal zu bilden, wobei die Decodierereinheit enthält:

einen Gitterdecodierer (1100) zum Decodieren eines demodulierten Signals gemäß einer QAM-Konstellation;
einen Entschachtler (1102), der mit dem ersten Decodierer gekoppelt ist, um das decodierte Signal zu entschachteln,
einen Vorwärtsfehlerkorrektur-Decodierer (1104), der mit dem Entschachtler gekoppelt ist, um das entschachtelte Signal zu decodieren, und
einen Entwürfler (1106), der mit dem zweiten Decodierer gekoppelt ist, um das decodierte Signal zu entwürfeln.

14. System nach Anspruch 1 oder Anspruch 13, wobei:

wenigstens einer der digitalen Datenkanäle fähig ist, digitale Daten mit einer vorgegebenen festen Rate von mehr als 100 Millionen Bits pro Sekunde zu übertragen.

15. System nach Anspruch 14, wobei:

wenigstens ein digitaler Datenkanal auf einem Protokoll beruht, das aus der Liste ausgewählt wird, die das OC-Protokoll, das STM-Protokoll und das STS-Protokoll umfasst.

16. System nach Anspruch 1 oder Anspruch 13, wobei:

die mehreren digitalen Datenkanäle fähig sind, digitale Daten mit einer Gesamtrate von mehr als 2,5 Milliarden Bits pro Sekunde zu übertragen.

17. System nach Anspruch 13, wobei:

das HF-Signal mehrere QAM-modulierte Signale enthält, wobei jedes QAM-modulierte Signal durch eine erste

Trägerfrequenz **gekennzeichnet** ist, und wobei jede der ersten Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
der Frequenzbereich-Demultiplexer (702) enthält:

einen Teiler (800) zum Aufteilen des HF-Signals in mehrere HF-Signale;
mehrere Frequenzverschieber (802), die mit dem Teiler gekoppelt sind, wobei jeder Frequenzverschieber zum Frequenzverschieben eines der aufgeteilten HF-Signale von einer der ersten Trägerfrequenzen zu einer zweiten Trägerfrequenz dient, wobei alle zweiten Trägerfrequenzen gleich sind; und
mehrere Bandpass-Filter (804), die mit den mehreren Frequenzverschiebern gekoppelt sind, um die aufgeteilten HF-Signale zu filtern, die zu den zweiten Trägerfrequenzen in der Frequenz zu verschoben worden sind.

18. System nach Anspruch 13, wobei der Frequenzbereich-Demultiplexer (702) umfasst:

einen mehrstufigen Frequenzbereich-Demultiplexer.

19. System nach Anspruch 13, wobei die Demodulationsstufe (704) enthält:

mehrere K Demodulationsunterstufen (1000), wobei jede Demodulationsunterstufe zum Umsetzen eines der mehreren QAM-modulierten Signale in M der mehreren digitalen Datenkanäle dient, wobei M = N/K gilt.

20. System nach Anspruch 19, wobei jede Demodulationsunterstufe (1000) ferner enthält:

einen QAM-Demodulator (1002) zum Umsetzen des QAM-modulierten Signals in M demodulierte Signale; und
M Decodierer (1004), die mit dem QAM-Demodulator gekoppelt sind, wobei jeder Decodierer zum Decodieren eines der M-demodulierten Signale dient, um einen digitalen Datenkanal zu bilden.

21. System nach Anspruch 20, wobei:

das HF-Signal mehrere QAM-modulierte Signale enthält, wobei jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, und wobei jede der ersten Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
jeder QAM-Demodulator (1002) ferner zum Umsetzen der QAM-modulierten Signale, die durch die ersten Trägerfrequenzen **gekennzeichnet** sind, in M demodulierte Signale dient.

22. System nach Anspruch 20, wobei jeder Decodierer (1004) ferner enthält:

einen Vorwärtsfehlerkorrektur-Decodierer zum Decodieren eines der M demodulierten Signale gemäß einem Vorwärtsfehlerkorrekturcode.

23. System nach Anspruch 20, wobei:

K = N und M = 1 gilt; und
jeder Decodierer (1004) enthält:

einen Gitterdecodierer (1100), der mit dem QAM-Demodulator (1002) gekoppelt ist, um das demodulierte Signal gemäß einer QAM-Konstellation zu decodieren;
einen Entschachtler (1102), der mit dem Gitterdecodierer gekoppelt ist, um das decodierte Signal zu entschachteln;
einen Reed-Solomon-Decodierer (1104), der mit dem Entschachtler gekoppelt ist, um das entschachtelte Signal gemäß einem Reed-Solomon-Code zu decodieren; und
einen Entwürfler (1106), der mit dem Reed-Solomon-Decodierer gekoppelt ist, um das decodierte Signal zu entwürfeln.

24. System nach Anspruch 13, ferner umfassend:

eine E/O-Umsetzungsstufe, die mit der Demodulationsstufe gekoppelt ist, um die digitalen Datenkanäle von einer elektrischen Form in eine optische Form umzusetzen.

25. Verfahren zum Senden digitaler Daten über eine Lichtleitfaser (104), umfassend:

Empfangen mehrerer N digitaler Datenkanäle, wobei wenigstens einer der digitalen Datenkanäle fähig ist, digitale Daten mit einer Rate von mehr als 100 Millionen Bits pro Sekunde zu übertragen;
Umsetzen der mehreren digitalen Datenkanäle in mehrere K QAM-modulierte Signale;
Frequenzbereich-Multiplexieren der QAM-modulierten Signale in ein HF-Signal; und
Erzeugen eines Lichtsignals, das mittels des HF-Signals moduliert ist, wobei das Lichtsignal für die Übertragung über eine Lichtleitfaser (104) geeignet ist;

wobei das Umsetzen der mehreren digitalen Datenkanäle in mehrere K QAM-modulierte Signale das Codieren eines der mehreren digitalen Datenkanäle enthält, um einen codierten digitalen Datenkanal zu erhalten, wobei das Codieren eines der mehreren digitalen Datenkanäle zum Bilden eines codierten digitalen Datenkanals enthält:

Verwürfeln eines digitalen Datenkanals;
Vorwärtsfehlerkorrektur-Codieren des verwürfelten digitalen Datenkanals;
Verschachteln des codierten digitalen Datenkanals; und
Gittercodieren des verschachtelten digitalen Datenkanals, um den verschachtelten digitalen Datenkanal in eine QAM-Konstellation umzusetzen.

26. Verfahren nach Anspruch 25, wobei:

das Empfangen der mehreren digitalen Datenkanäle das Empfangen der digitalen Datenkanäle mit einer vorgegebenen festen Rate enthält.

27. Verfahren nach Anspruch 25, wobei:

das Empfangen der mehreren digitalen Datenkanäle das Empfangen der mehreren digitalen Datenkanäle mit einer Gesamtrate von mehr als 2,5 Milliarden Bits pro Sekunde enthält.

28. Verfahren nach Anspruch 25, wobei das Umsetzen der mehreren N digitalen Datenkanäle in die mehreren K QAM-modulierten Signale enthält:

K-fach paralleles Umsetzen von M der mehreren digitalen Datenkanäle in eines der mehreren QAM-modulierten Signale, wobei M = N/K gilt.

29. Verfahren nach Anspruch 28, wobei das Umsetzen von M der mehreren digitalen Datenkanäle in eines der mehreren QAM-modulierten Signale enthält:

paralleles Codieren jedes der M digitalen Datenkanäle, um einen codierten digitalen Datenkanal zu bilden; und
Umsetzen der M codierten digitalen Datenkanäle in das QAM-modulierte Signal.

30. Verfahren nach Anspruch 29, wobei das Codieren jedes der M digitalen Datenkanäle enthält:

Codieren jedes der M digitalen Datenkanäle gemäß einem Vorwärtsfehlerkorrekturcode.

31. Verfahren nach Anspruch 29, wobei:

K = N und M = 1 gilt; und
das Codieren jedes der M digitalen Datenkanäle zum Bilden eines codierten digitalen Datenkanals enthält:

Verwürfeln des digitalen Datenkanals;
Codieren des verwürfelten digitalen Datenkanals gemäß einem Reed-Solomon-Code;
Verschachteln des codierten digitalen Datenkanals; und
Anwenden einer QAM-Modulation auf die verschachtelten digitalen Datenkanäle.

32. Verfahren nach Anspruch 25, wobei:

jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, wobei jede der ersten

Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
das Frequenzbereich-Multiplexieren der QAM-modulierten Signale in das HF-Signal enthält:

Kombinieren der mehreren QAM-modulierte Signale in das HF-Signal.

33. Verfahren nach Anspruch 25, wobei:

jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, wobei alle erste Trägerfrequenzen gleich sind; und
das Frequenzbereich-Multiplexieren der QAM-modulierte Signale in die HF-Signale enthält:

Frequenzverschieben der QAM-modulierten Signale von den ersten Trägerfrequenzen zu zweiten Trägerfrequenzen, wobei jede der zweiten Trägerfrequenzen von den anderen zweiten Trägerfrequenzen verschieden ist; und
Kombinieren der mehreren QAM-modulierten Signale, die durch die zweiten Trägerfrequenzen **gekennzeichnet** sind, in das HF-Signal.

34. Verfahren nach Anspruch 25, wobei das Frequenzbereich-Multiplexieren der QAM-modulierten Signale in ein HF-Signal umfasst:

Frequenzbereich-Multiplexieren der QAM-modulierten Signale in wenigstens zwei Stufen.

35. Verfahren nach Anspruch 25, wobei das Erzeugen des mittels des HF-Signals modulierten Lichtsignals umfasst:

Erzeugen eines optischen Trägers; und
Modulieren des optischen Trägers mit dem HF-Signal.

36. Verfahren nach Anspruch 25, wobei:

das Lichtsignal durch eine Wellenlänge entweder im 1,3μm-Bereich oder im 1,55μm-Bereich **gekennzeichnet** ist.

37. Verfahren nach Anspruch 25, ferner umfassend:

Umsetzen der digitalen Datenkanäle von einer optischen Form in eine elektrische Form.

38. Verfahren zum Empfangen digitaler Daten über eine Lichtleitfaser (104), umfassend:

Erfassen eines über eine Lichtleitfaser (104) übertragenen Lichtsignals, um ein HF-Signal zu erzeugen;
Frequenzbereich-Demultiplexieren des HF-Signals in mehrere K QAM-modulierte Signale; und
Umsetzen der mehreren K QAM-modulierten Signale in mehrere N digitale Datenkanäle, wobei wenigstens einer der digitalen Datenkanäle fähig ist, digitale Daten mit einer Rate von mehr als 100 Millionen Bits pro Sekunde zu übertragen;

wobei das Umsetzen der mehreren K QAM-modulierten Signale in mehrere N digitale Datenkanäle das Decodieren eines von mehreren demodulierten Signale enthält, um einen digitalen Datenkanal zu bilden, wobei das Decodieren eines der mehreren demodulierten Signale zum Bilden eines digitalen Datenkanals enthält:

Gitterdecodieren eines demodulierten Signals entsprechend einer QAM-Konstellation;
Entschachteln des decodierten Signals;
Vorwärtsfehlerkorrektur-Decodieren des entschachtelten Signals; und
Entwürfeln des decodierten Signals.

39. Verfahren nach Anspruch 38, wobei:

die digitalen Datenkanäle digitale Daten mit einer vorgegebenen festen Rate übertragen.

40. Verfahren nach Anspruch 26 oder Anspruch 39, wobei:

wenigstens ein digitaler Datenkanal auf einem Protokoll beruht, das aus der Liste ausgewählt worden ist, die das OC-Protokoll, das STM-Protokoll und das STS-Protokoll umfasst.

41. Verfahren nach Anspruch 38, wobei:

die mehreren digitalen Datenkanäle digitale Daten mit einer Gesamtrate von mehr als 2,5 Milliarden Bits pro Sekunde übertragen.

42. Verfahren nach Anspruch 38, wobei:

das HF-Signal mehrere QAM-modulierte Signale enthält, wobei jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, und wobei jede der ersten Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
das Frequenzbereich-Demultiplexieren des HF-Signals enthält:

Teilen des HF-Signals in mehrere HF-Signale;
Frequenzverschieben der geteilten HF-Signale von den ersten Trägerfrequenzen zu zweiten Trägerfrequenzen, wobei alle zweiten Trägerfrequenzen gleich sind; und
Bandpassfiltern der geteilten HF-Signale, die zu den zweiten Trägerfrequenzen in der Frequenz verschoben worden sind.

43. Verfahren nach Anspruch 38, wobei das Frequenzbereich-Demultiplexieren des HF-Signals umfasst:

Frequenzbereich-Demultiplexieren des HF-Signals in mehreren Stufen.

44. Verfahren nach Anspruch 38, wobei das Umsetzen der mehreren K QAM-modulierten Signale in mehrere N digitale Datenkanäle enthält:

K-fach paralleles Umsetzen eines der mehreren QAM-modulierten Signale in M der mehreren digitalen Datenkanäle, wobei M = N/K gilt.

45. Verfahren nach Anspruch 44, wobei das Umsetzen eines der mehreren QAM-modulierten Signale in M der mehreren digitalen Datenkanäle enthält:

Umsetzen des QAM-modulierten Signals in M demodulierte Signale; und
Decodieren jedes der M demodulierten Signale, um die digitalen Datenkanäle zu bilden.

46. Verfahren nach Anspruch 45, wobei:

das HF-Signal die mehreren QAM-modulierten Signale enthält, wobei jedes QAM-modulierte Signal durch eine erste Trägerfrequenz **gekennzeichnet** ist, und wobei jede der ersten Trägerfrequenzen von den anderen ersten Trägerfrequenzen verschieden ist; und
das Umsetzen des QAM-modulierten Signals in M demodulierte Signale das Umsetzen des QAM-modulierten Signals, das durch die erste Trägerfrequenz **gekennzeichnet** ist, in die M demodulierten Signale enthält.

47. Verfahren nach Anspruch 45, wobei das Decodieren jedes der M demodulierten Signale enthält:

Decodieren des demodulierten Signals gemäß einem Vorwärtsfehlerkorrekturcode.

48. Verfahren nach Anspruch 45, wobei:

K = N und M = 1 gilt; und
das Decodieren jedes der M demodulierten Signale enthält:

Decodieren des demodulierten Signals gemäß einer QAM-Konstellation;
Entschachteln des decodierten Signals;
Decodieren des entschachtelten Signals gemäß einem Reed-Solomon-Code; und
Entwürfeln des decodierten Signals.

49. Verfahren nach Anspruch 38, ferner umfassend:

Umsetzen der digitalen Datenkanäle von einer elektrischen Form in eine optische Form.

Revendications

1. Système de transmission de données numériques sur une fibre optique (104) comprenant :

un étage de modulation (200) pour convertir une pluralité N de canaux de données numériques à grand débit en une pluralité K de signaux à amplitude modulée en quadrature (ou QAM pour Quadrature Amplitude Modulation), au moins un des canaux de données numériques étant en mesure de transmettre des données numériques à un débit supérieur à 100 millions de bits par seconde ;
un multiplexeur à répartition de fréquence (202) couplé à l'étage de modulation pour le multiplexage par répartition de fréquence des signaux à amplitude modulée en quadrature en un signal RF ; et
un modulateur optique (204) couplé au multiplexeur à répartition de fréquence pour produire un signal optique modulé par le signal RF, le signal optique convenant pour une transmission sur une fibre optique (104) ;

dans lequel l'étage de modulation (200) comprend une unité de codage (302) qui est destinée à coder un parmi la pluralité des canaux de données numériques pour former un canal de données numériques codé, dans lequel l'unité de codage (302) comprend :

un embrouilleur (400) pour embrouiller un canal de données numériques ;
un codeur à correction d'erreur en aval (402) couplé à l'embrouilleur pour coder le canal de données numériques embrouillé ;
un entrelaceur (404) couplé au premier codeur pour entrelacer le canal de données numériques codé ; et
un codeur trellis (406) couplé à l'entrelaceur pour convertir le canal de données numériques entrelacé en une constellation.

2. Système selon la revendication 1, dans lequel l'étage de modulation (200) comprend :

une pluralité K de sous-étages de modulation (300), chaque sous-étage de modulation servant à convertir M parmi la pluralité de canaux de données numériques en un parmi la pluralité K de signaux à amplitude modulée en quadrature, avec M = N/K.

3. Système selon la revendication 2, dans lequel chaque sous-étage de modulation (300) comprend de plus :

M codeurs (302), chaque codeur (302) servant à coder un des M canaux de données numériques pour former un canal de données numériques codé ; et
un modulateur QAM (304) couplé aux M codeurs pour convertir les M canaux de données numériques codés en un signal à amplitude modulée en quadrature.

4. Système selon la revendication 3, dans lequel chaque codeur (302) comprend de plus :

un codeur à correction d'erreur en aval servant à coder un des M canaux de données numériques en un code correcteur d'erreur en aval.

5. Système selon la revendication 3, dans lequel :

K = N et M = 1 ; et
chaque codeur (302) comprend :

un embrouilleur (400) pour embrouiller un parmi la pluralité de canaux de données numériques ;
un codeur Reed-Solomon (402) couplé à l'embrouilleur pour coder le canal de données numériques embrouillé selon un code Reed-Solomon ;
un entrelaceur (404) couplé au codeur Reed-Solomon pour entrelacer le canal de données numériques codé ; et
un codeur trellis (406) couplé à l'entrelaceur pour convertir le canal de données numériques entrelacé en

une constellation QAM.

6. Système selon la revendication 1, dans lequel :

chaque signal à amplitude modulée en quadrature est **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et le multiplexeur à répartition de fréquence (202) comprend :

un combinateur (502) servant à combiner la pluralité des signaux à amplitude modulée en quadrature en le signal RF.

7. Système selon la revendication 1, dans lequel :

chaque signal à amplitude modulée en quadrature est **caractérisé par** une première fréquence porteuse, toutes les premières fréquences porteuses étant les mêmes ; et
le multiplexeur à répartition de fréquence (202) comprend :

une pluralité de décaleurs de fréquence (500) servant à décaler en fréquence les signaux à amplitude modulée en quadrature des premières fréquences porteuses sur des deuxièmes fréquences porteuses, chacune des deuxièmes fréquences porteuses étant différente des autres deuxièmes fréquences porteuses ; et
un combinateur (502) servant à combiner la pluralité des signaux à amplitude modulée en quadrature **caractérisés par** les deuxièmes fréquences porteuses en un signal RF.

8. Système selon la revendication 1, dans lequel le multiplexeur à répartition de fréquence (202) comprend :

un multiplexeur à répartition de fréquence multi-étagé.

9. Système selon la revendication 1, dans lequel le modulateur optique (204) comprend :

un laser modulé en interne servant à produire un faisceau optique de sortie modulé par le signal RF.

10. Système selon la revendication 1, dans lequel le modulateur optique (204) comprend :

une source optique servant à produire une porteuse optique ; et
un modulateur optique externe couplé à la source optique et au multiplexeur à répartition de fréquence pour moduler la porteuse optique avec le signal RF.

11. Système selon la revendication 1, dans lequel :

le signal optique est **caractérisé par** une longueur d'onde dans l'une des régions de 1,3 micron et de 1,55 micron.

12. Système selon la revendication 1, comprenant de plus :

un étage de conversion O/E couplé à l'étage de modulation servant à convertir les canaux de données numériques de la forme optique à la forme électrique.

13. Système pour recevoir des données numériques sur une fibre optique (104) comprenant :

un détecteur (700) pour détecter un signal optique transmis sur une fibre optique pour produire un signal RF ;
un démultiplexeur à répartition de fréquence (702) couplé au détecteur pour démultiplexer par répartition de fréquence le signal RF en une pluralité K de signaux à amplitude modulée en quadrature ; et
un étage de démodulation (704) pour convertir la pluralité K de signaux à amplitude modulée en quadrature en une pluralité N de canaux de données numériques à grand débit, au moins un des canaux de données numériques étant en mesure de transmettre des données numériques à un débit supérieur à 100 millions de bits par seconde ;

dans lequel l'étage de démodulation (704) comprend une unité de décodage (1004) qui est destinée à décoder un parmi une pluralité de signaux de démodulation pour former un canal de données numériques, dans lequel l'unité de décodage comprend :

un décodeur trellis (1100) pour décoder un signal démodulé selon une constellation QAM ;
un désentrelaceur (1102) couplé au premier décodeur pour désentrelacer le signal décodé ;
un décodeur à correction d'erreur en aval (1104) couplé au désentrelaceur pour décoder le signal désentrelacé ; et
un désembrouilleur (1106) couplé au deuxième décodeur pour désembrouiller le signal décodé.

14. Système selon la revendication 1 ou la revendication 13, dans lequel :

au moins un des canaux de données numériques est en mesure de transmettre des données numériques à un débit fixe prédéterminé supérieur à 100 millions de bits par seconde.

15. Système selon la revendication 14, dans lequel :

au moins un canal de données numériques est basé sur un des protocoles sélectionnés sur la liste comprenant le protocole OC, le protocole STM et le protocole STS.

16. Système selon la revendication 1 ou la revendication 13, dans lequel :

la pluralité des canaux de données numériques sont en mesure de transmettre des données numériques à un débit total supérieur à 2,5 milliards de bits par seconde.

17. Système selon la revendication 13, dans lequel :

le signal RF comprend la pluralité de signaux à amplitude modulée en quadrature, chaque signal à amplitude modulée en quadrature étant **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et
le démultiplexeur à répartition de fréquence (702) comprend :

un diviseur (800) servant à diviser le signal RF en une pluralité des signaux RF ;
une pluralité de décaleurs de fréquence (802) couplés au diviseur, chaque décaleur de fréquence servant à décaler en fréquence un des signaux RF divisés de l'une des premières fréquences porteuses sur une deuxième fréquence porteuse, toutes les deuxièmes fréquences porteuses étant les mêmes ; et
une pluralité de filtres passe-bande (804) couplés à la pluralité de décaleurs de fréquence pour filtrer les signaux RF divisés décalés en fréquence sur les deuxièmes fréquences porteuses.

18. Système selon la revendication 13, dans lequel le démultiplexeur à répartition de fréquence (702) comprend :

un démultiplexeur à répartition de fréquence multi-étagé.

19. Système selon la revendication 13, dans lequel l'étage de démodulation (704) comprend :

une pluralité de K de sous-étages de démodulation (1000), chaque sous-étage de démodulation servant à convertir un parmi la pluralité de signaux à amplitude modulée en quadrature en M parmi la pluralité de canaux de données numériques, avec M = N/K.

20. Système selon la revendication 19, dans lequel chaque sous-étage de démodulation (1000) comprend de plus :

un démodulateur QAM (1002) pour convertir les signaux à amplitude modulée en quadrature en M signaux démodulés ; et
M décodeurs (1004) couplés au démodulateur QAM, chaque décodeur servant à décoder un des M signaux démodulés pour former un canal de données numériques.

21. Système selon la revendication 20, dans lequel :

le signal RF comprend la pluralité de signaux à amplitude modulée en quadrature, chaque signal à amplitude

modulée en quadrature étant **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et
chaque démodulateur QAM (1002) est également destiné à convertir les signaux à amplitude modulée en quadrature **caractérisés par** les premières fréquences porteuses en M signaux démodulés.

22. Système selon la revendication 20, dans lequel chaque décodeur (1004) comprend de plus :

un décodeur à correction d'erreur en aval servant à décoder un des M signaux démodulés selon un code correcteur d'erreur en aval.

23. Système selon la revendication 20, dans lequel :

K = N et M = 1 ; et
chaque décodeur (1004) comprend :

un décodeur trellis (1100) couplé au démodulateur QAM (1002) pour décoder le signal démodulé selon une constellation QAM ;
un désentrelaceur (1102) couplé au décodeur trellis pour désentrelacer le signal décodé ;
un décodeur Reed-Solomon (1104) couplé au désentrelaceur pour décoder le signal désentrelacé selon un code Reed-Solomon ; et
un désembrouilleur (1106) couplé au décodeur Reed-Solomon pour désembrouiller le signal décodé.

24. Système selon la revendication 13, comprenant de plus :

un étage de conversion E/O couplé à l'étage de démodulation servant à convertir les canaux de données numériques de la forme électrique à la forme optique.

25. Procédé pour transmettre des données numériques sur une fibre optique (104) comprenant les étapes qui consistent à :

recevoir une pluralité N de canaux de données numériques, au moins un des canaux de données numériques étant en mesure de transmettre des données numériques à un débit supérieur à 100 millions de bits par seconde ;
convertir la pluralité de canaux de données numériques en une pluralité K de signaux à amplitude modulée en quadrature ;
multiplexer par répartition de fréquence les signaux à amplitude modulée en quadrature en un signal RF ;
produire un signal optique modulé par le signal RF, le signal optique convenant pour une transmission sur une fibre optique (104) ;

dans lequel ladite conversion de la pluralité des canaux de données numériques en une pluralité K de signaux à amplitude modulée en quadrature comprend le codage d'un parmi la pluralité de canaux de données numériques pour former un canal de données numériques codé, dans lequel ledit codage d'un parmi la pluralité de canaux de données numériques pour former un canal de données numériques codé comprend les étapes qui consistent à :

embrouiller un canal de données numériques ;
coder le canal de données numériques embrouillé avec une correction d'erreur en aval ;
entrelacer le canal de données numériques codé ; et
procéder à un codage en trellis du canal de données numériques entrelacé pour convertir le canal de données numériques entrelacé en une constellation QAM.

26. Procédé selon la revendication 25, dans lequel :

la réception de la pluralité de canaux de données numériques comprend la réception des canaux de données numériques à un débit fixe prédéterminé.

27. Procédé selon la revendication 25, dans lequel :

la réception de la pluralité de canaux de données numériques comprend la réception de la pluralité de canaux de données numériques à un débit total supérieur à 2,5 milliards de bits par seconde.

28. Procédé selon la revendication 25, dans lequel la conversion de la pluralité N de canaux de données numériques en la pluralité K de signaux à amplitude modulée en quadrature comprend :

la conversion, pendant K fois en parallèle, de M parmi la pluralité de canaux de données numériques en un parmi la pluralité de signaux à amplitude modulée en quadrature, avec M = N/K.

29. Procédé selon la revendication 28, dans lequel la conversion de M parmi la pluralité de canaux de données numériques en un parmi la pluralité de signaux à amplitude modulée en quadrature comprend les étapes qui consistent à :

coder, en parallèle, chacun des M canaux de données numériques pour former un canal de données numériques codé ; et
convertir les M canaux de données numériques codés en un signal à amplitude modulée en quadrature.

30. Procédé selon la revendication 29, dans lequel le codage de chacun des M canaux de données numériques comprend :

le codage de chacun des M canaux de données numériques selon un code correcteur d'erreur en aval.

31. Procédé selon la revendication 29, dans lequel :

K = N et M = 1 ; et
le codage de chacun des M canaux de données numériques pour former un canal de données numériques codé comprend les étapes qui consistent à :

embrouiller le canal de données numériques ;
coder le canal de données numériques embrouillé selon un code Reed-Solomon ;
entrelacer le canal de données numériques codé ; et
appliquer une modulation QAM aux canaux de données numériques entrelacés.

32. Procédé selon la revendication 25, dans lequel :

chaque signal à amplitude modulée en quadrature est **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et
le multiplexage par répartition de fréquence des signaux à amplitude modulée en quadrature en un signal RF comprend l'étape qui consiste à :

combiner la pluralité des signaux à amplitude modulée en quadrature en un signal RF.

33. Procédé selon la revendication 25, dans lequel :

chaque signal à amplitude modulée en quadrature est **caractérisé par** une première fréquence porteuse, toutes les premières fréquences porteuses étant les mêmes ; et
le multiplexage par répartition de fréquence des signaux à amplitude modulée en quadrature en un signal RF comprend les étapes qui consistent à :

décaler en fréquence les signaux à amplitude modulée en quadrature des premières fréquences porteuses sur des deuxièmes fréquences porteuses, chacune des deuxièmes fréquences porteuses étant différente des autres deuxièmes fréquences porteuses ; et
combiner la pluralité des signaux à amplitude modulée en quadrature **caractérisés par** les deuxièmes fréquences porteuses en un signal RF.

34. Procédé selon la revendication 25, dans lequel le multiplexage par répartition de fréquence des signaux à amplitude modulée en quadrature en un signal RF comprend l'étape qui consiste à :

multiplexer par répartition de fréquence des signaux à amplitude modulée en quadrature dans au moins deux étages.

35. Procédé selon la revendication 25, dans lequel la production du signal optique modulé par le signal RF comprend les étapes qui consistent à :

produire une porteuse optique ; et
moduler la porteuse optique avec le signal RF.

36. Procédé selon la revendication 25, dans lequel le signal optique est **caractérisé par** une longueur d'onde dans l'une des régions de 1,3 micron et de 1,55 micron.

37. Procédé selon la revendication 25, comprenant de plus l'étape qui consiste à :

convertir les canaux de données numériques de la forme optique à la forme électrique.

38. Procédé pour recevoir des données numériques sur une fibre optique (104) comprenant les étapes qui consistent à :

détecter un signal optique transmis sur une fibre optique (104) pour produire un signal RF ;
démultiplexer par répartition de fréquence le signal RF en une pluralité K de signaux à amplitude modulée en quadrature ; et
convertir la pluralité K de signaux à amplitude modulée en quadrature en une pluralité N de canaux de données numériques, au moins un des canaux de données numériques étant en mesure de transmettre des données numériques à un débit supérieur à 100 millions de bits par seconde ;

dans lequel ladite conversion de la pluralité K de signaux à amplitude modulée en quadrature en une pluralité N de canaux de données numériques comprend le décodage d'un parmi une pluralité de signaux démodulés pour former un canal de données numériques, dans lequel ledit décodage d'un parmi une pluralité de signaux démodulés pour former un canal de données numériques comprend les étapes qui consistent à :

décoder en trellis le signal démodulé selon une constellation QAM ***[suppression(s)]*** ;
désentrelacer le signal décodé ;
procéder à un décodage ***[suppression(s)]*** du signal désentrelacé avec une correction d'erreur en aval ; et
désembrouiller le signal décodé.

39. Procédé selon la revendication 38, dans lequel les canaux de données numériques transmettent des données numériques à un débit fixe prédéterminé.

40. Procédé selon la revendication 26 ou la revendication 39, dans lequel :

au moins un canal de données numériques est basé sur un des protocoles sélectionnés sur la liste comprenant le protocole OC, le protocole STM et le protocole STS.

41. Procédé selon la revendication 38, dans lequel :

la pluralité des canaux de données numériques transmettent des données numériques à un débit total supérieur à 2,5 milliards de bits par seconde.

42. Procédé selon la revendication 38, dans lequel :

le signal RF comprend la pluralité de signaux à amplitude modulée en quadrature, chaque signal à amplitude modulée en quadrature étant **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et
le démultiplexage par répartition de fréquence du signal RF comprend les étapes qui consistent à :

diviser le signal RF en une pluralité des signaux RF ;
décaler en fréquence les signaux RF divisés des premières fréquences porteuses sur des deuxièmes fréquences porteuses, toutes les deuxièmes fréquences porteuses étant les mêmes ; et
filtrer dans un filtre passe-bande les signaux RF divisés décalés en fréquence sur les deuxièmes fréquences porteuses.

43. Procédé selon la revendication 38, dans lequel :

le démultiplexage par répartition de fréquence du signal RF comprend l'étape qui consiste à :

démultiplexer le signal RF par répartition de fréquence dans plusieurs étages.

44. Procédé selon la revendication 38, dans lequel la conversion de la pluralité K de signaux à amplitude modulée en quadrature en une pluralité N de canaux de données numériques comprend l'étape qui consiste à :

convertir, pendant K fois en parallèle, un parmi la pluralité de signaux à amplitude modulée en quadrature en M parmi la pluralité de canaux de données numériques, avec M = N/K.

45. Procédé selon la revendication 44, dans lequel la conversion d'un parmi la pluralité de signaux à amplitude modulée en quadrature en M parmi la pluralité de canaux de données numériques comprend les étapes qui consistent à :

convertir le signal à amplitude modulée en quadrature en M signaux démodulés ; et
décoder chacun des M signaux démodulés pour former les canaux de données numériques.

46. Procédé selon la revendication 45, dans lequel le signal RF comprend la pluralité de signaux à amplitude modulée en quadrature, chaque signal à amplitude modulée en quadrature étant **caractérisé par** une première fréquence porteuse, chacune des premières fréquences porteuses étant différente des autres premières fréquences porteuses ; et
la conversion du signal à amplitude modulée en quadrature en M signaux démodulés comprend la conversion du signal à amplitude modulée en quadrature **caractérisé par** la première fréquence porteuse en les M signaux démodulés.

47. Procédé selon la revendication 45, dans lequel le décodage de chacun des M signaux démodulés comprend :

le décodage du signal démodulé selon un code de correction d'erreur en aval.

48. Procédé selon la revendication 45, dans lequel :

K = N et M = 1 ; et
le décodage de chacun des M signaux démodulés comprend les étapes qui consistent à :

décoder le signal démodulé selon une constellation QAM ;
désentrelacer le signal décodé ;
décoder le signal désentrelacé selon un code Reed-Solomon ; et
désembrouiller le signal décodé.

49. Procédé selon la revendication 38, comprenant de plus :

la conversion des canaux de données numériques de la forme électrique à la forme optique.

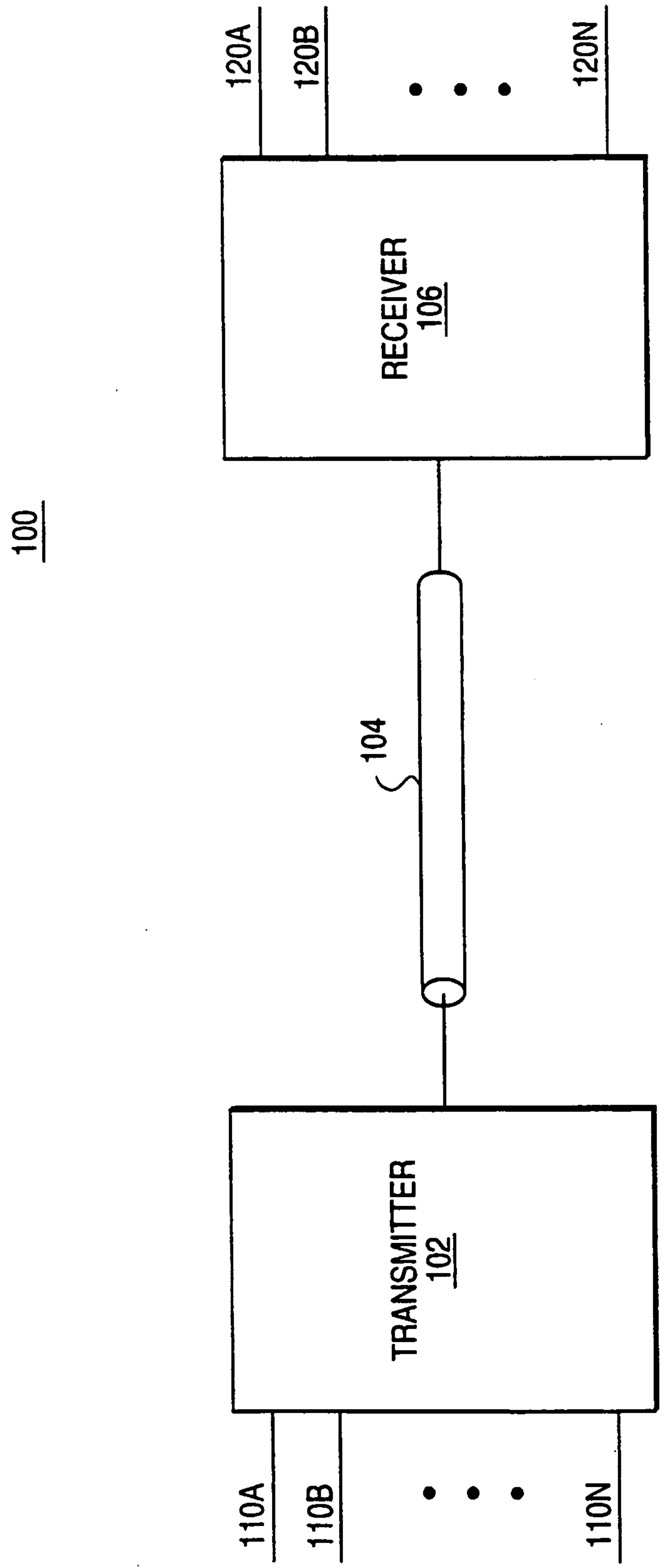
100
120A
120B
120N
RECEIVER
106
104
TRANSMITTER
102
110A
110B
110N

FIG. 1

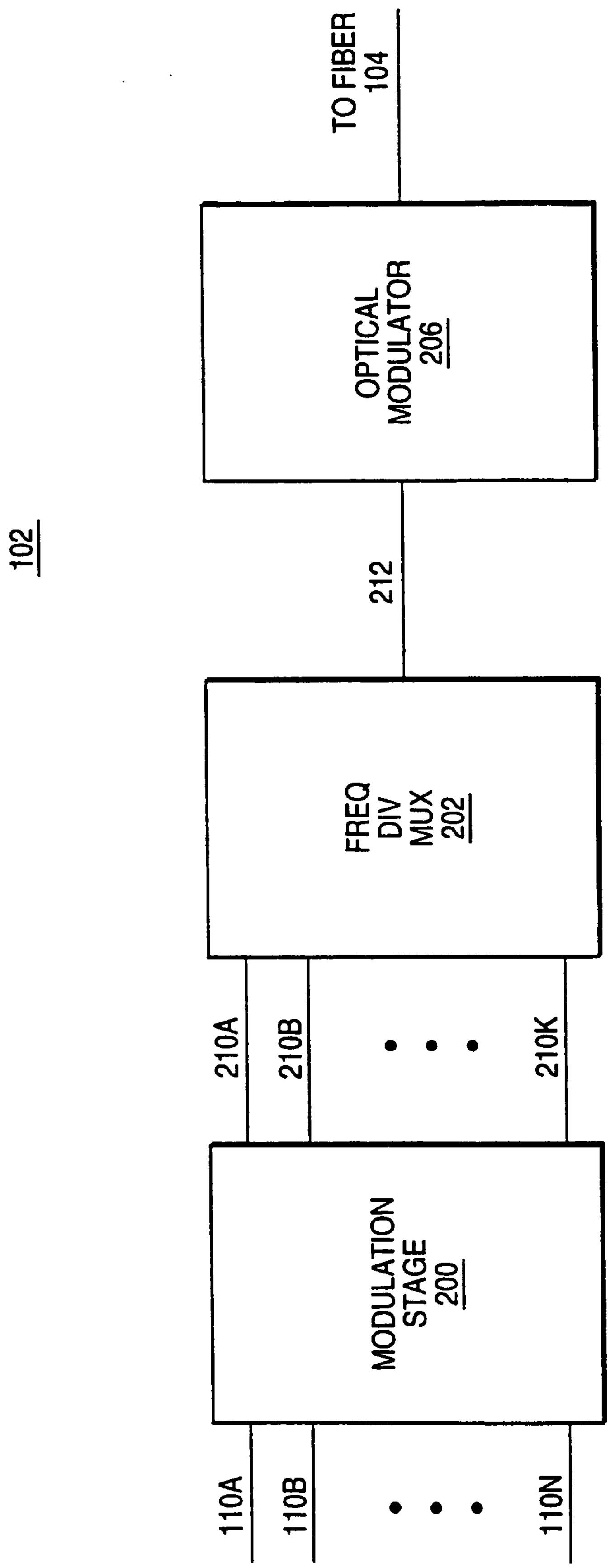
102
TO FIBER
104
OPTICAL
MODULATOR
206
212
FREQ
DIV
MUX
202
210A
210B
210K
MODULATION
STAGE
200
110A
110B
110N

FIG. 2

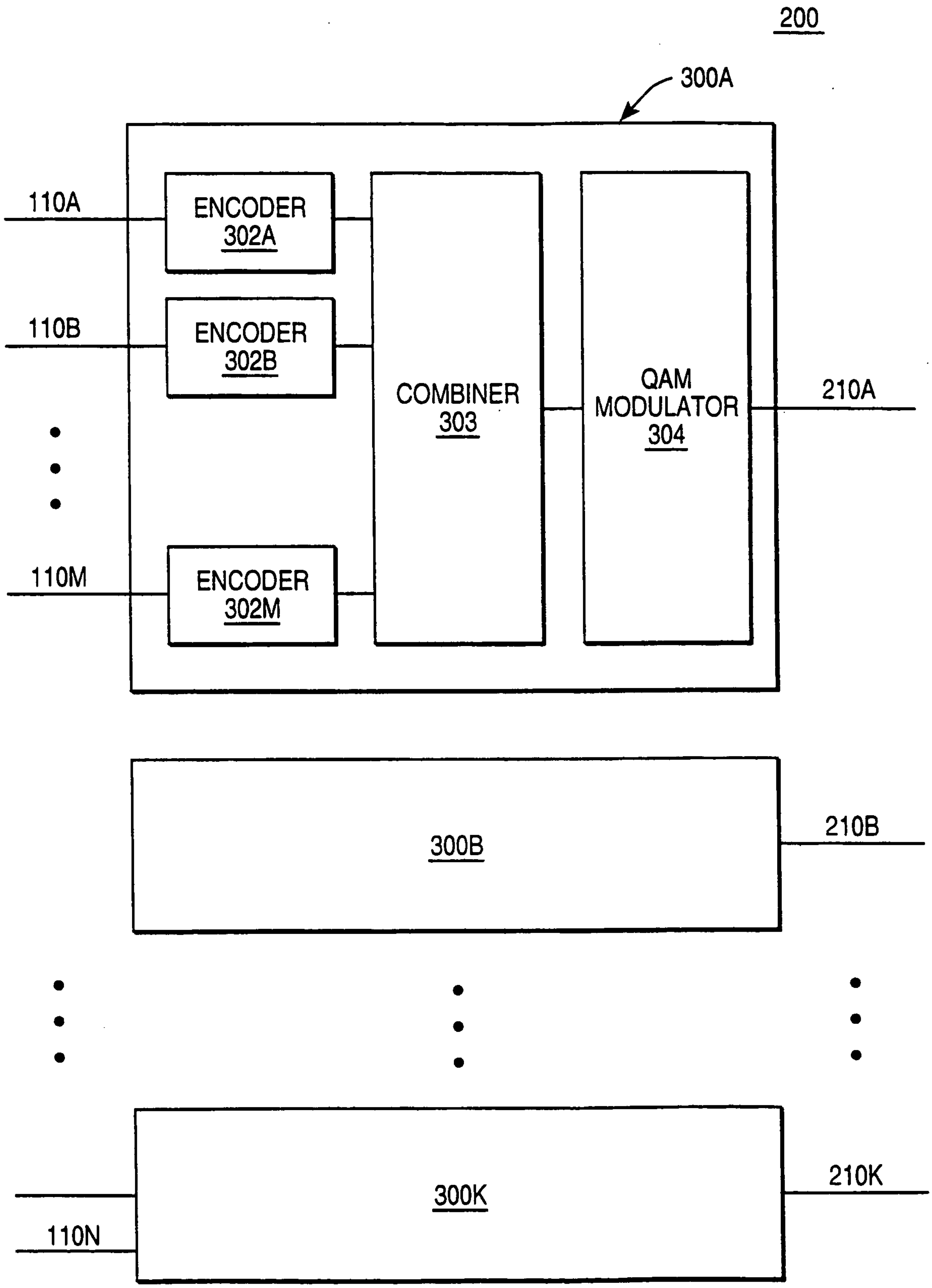
200
300A
110A
ENCODER
302A
110B
ENCODER
302B
COMBINER
303
QAM
MODULATOR
304
210A
110M
ENCODER
302M
300B
210B
300K
210K
110N

FIG. 3

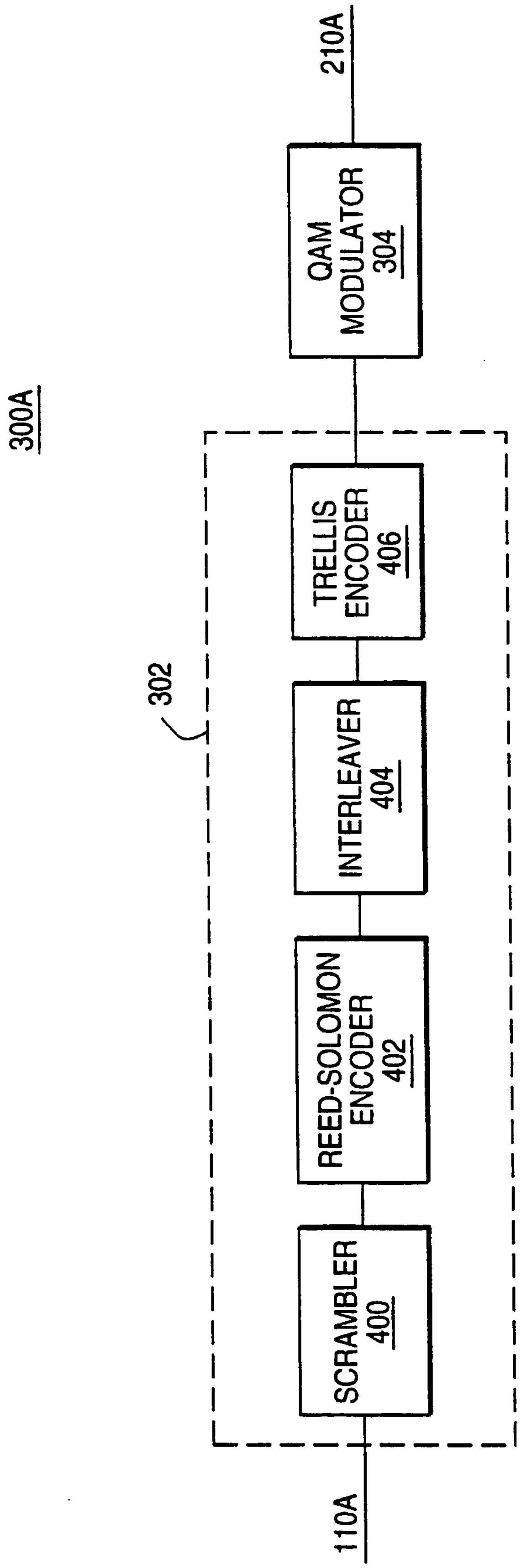
210A
QAM MODULATOR 304
300A
TRELLIS ENCODER 406
302
INTERLEAVER 404
REED-SOLOMON ENCODER 402
SCRAMBLER 400
110A

FIG. 4

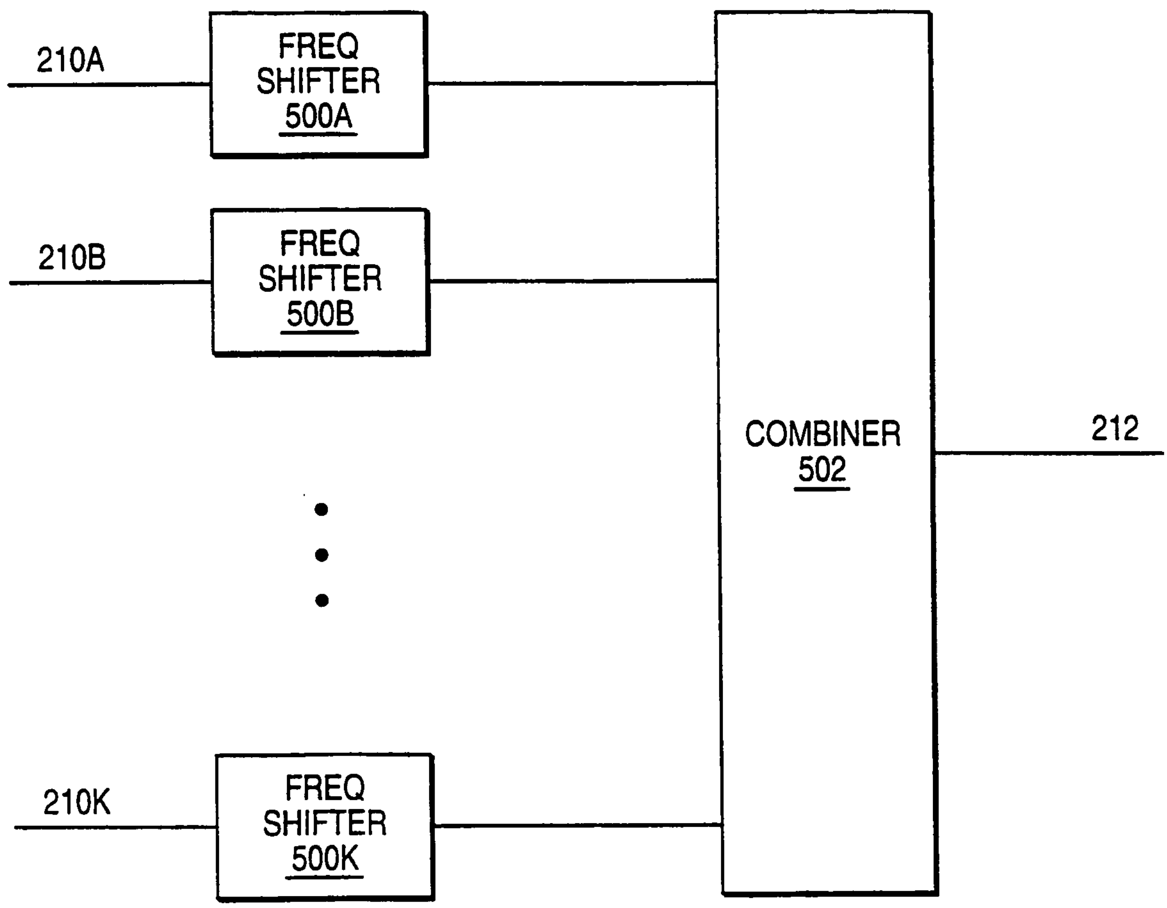
210A
FREQ
SHIFTER
500A
210B
FREQ
SHIFTER
500B
210K
FREQ
SHIFTER
500K
COMBINER
502
212

FIG. 5

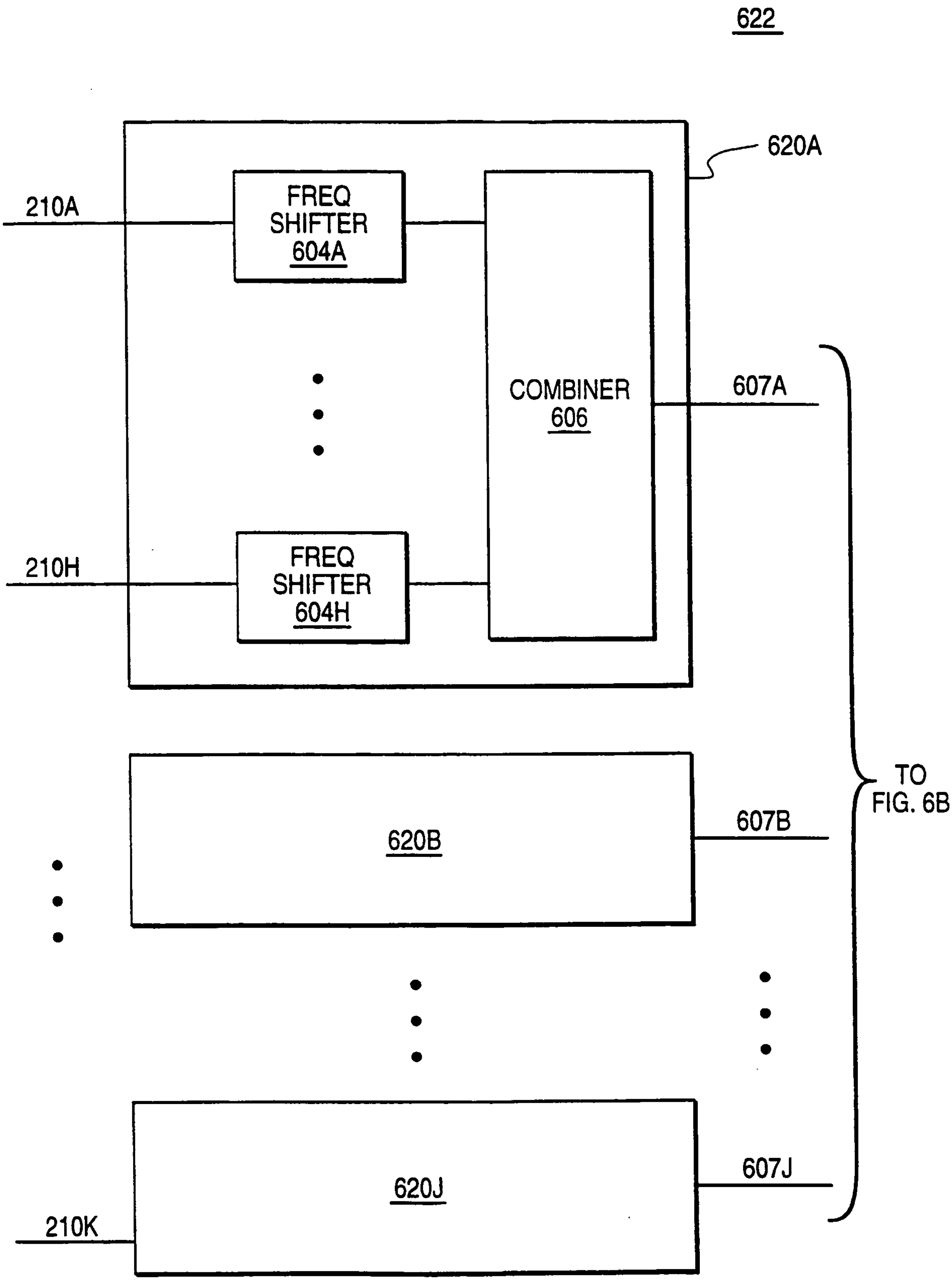
622
620A
210A
FREQ
SHIFTER
604A
COMBINER
606
607A
210H
FREQ
SHIFTER
604H
620B
607B
TO
FIG. 6B
620J
607J
210K

FIG. 6A

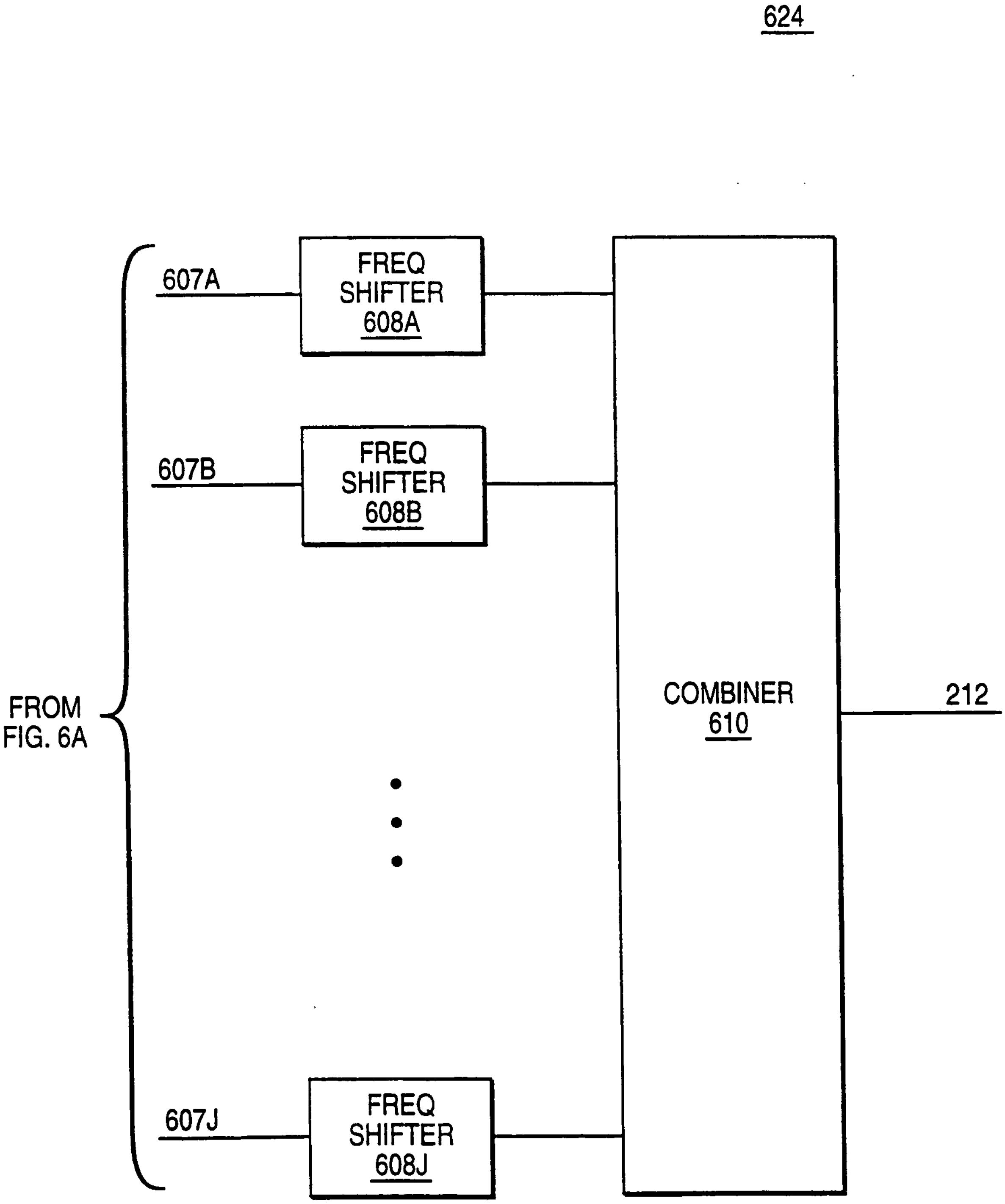
624
607A
FREQ
SHIFTER
608A
607B
FREQ
SHIFTER
608B
FROM
FIG. 6A
COMBINER
610
212
607J
FREQ
SHIFTER
608J

FIG. 6B

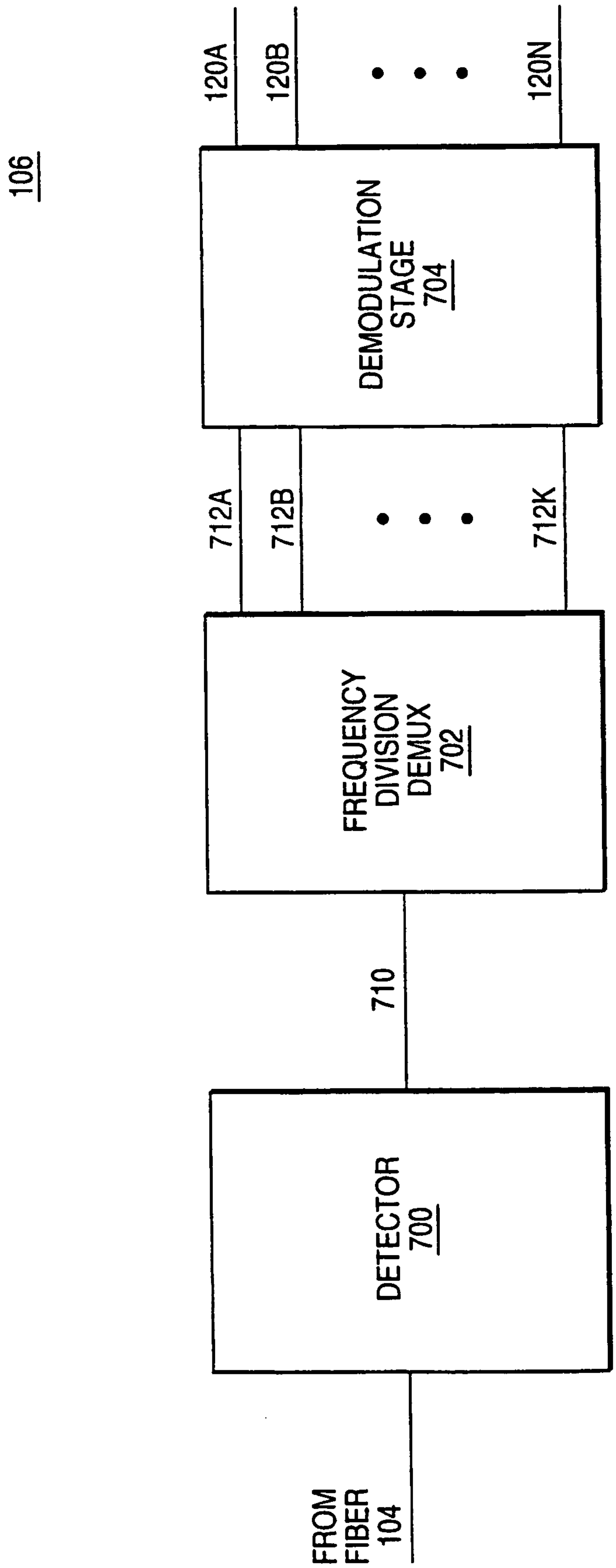
106
120A
120B
120N
DEMODULATION STAGE 704
712A
712B
712K
FREQUENCY DIVISION DEMUX 702
710
DETECTOR 700
FROM FIBER 104

FIG. 7

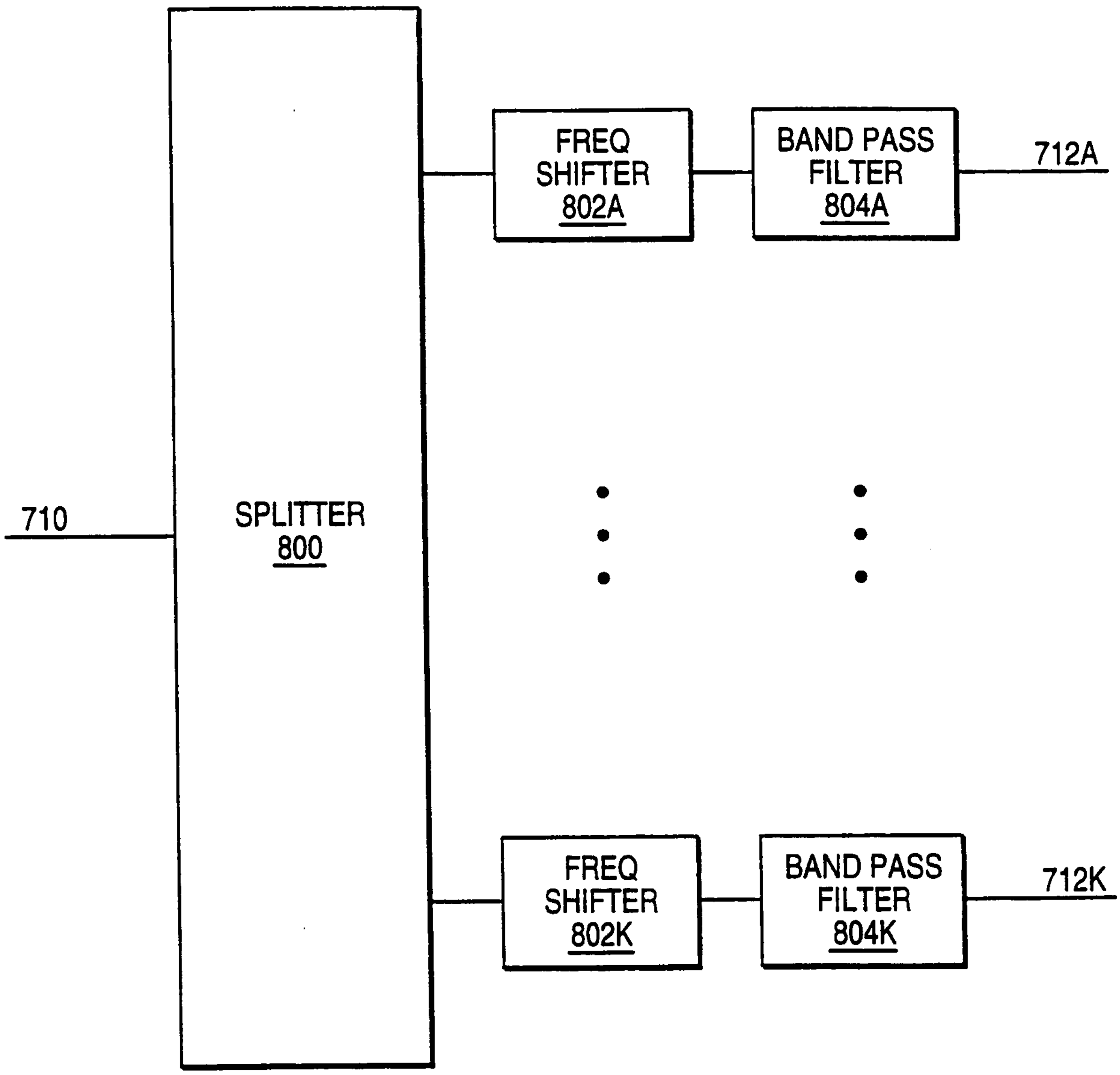
SPLITTER
800
710
FREQ
SHIFTER
802A
BAND PASS
FILTER
804A
712A
FREQ
SHIFTER
802K
BAND PASS
FILTER
804K
712K

FIG. 8

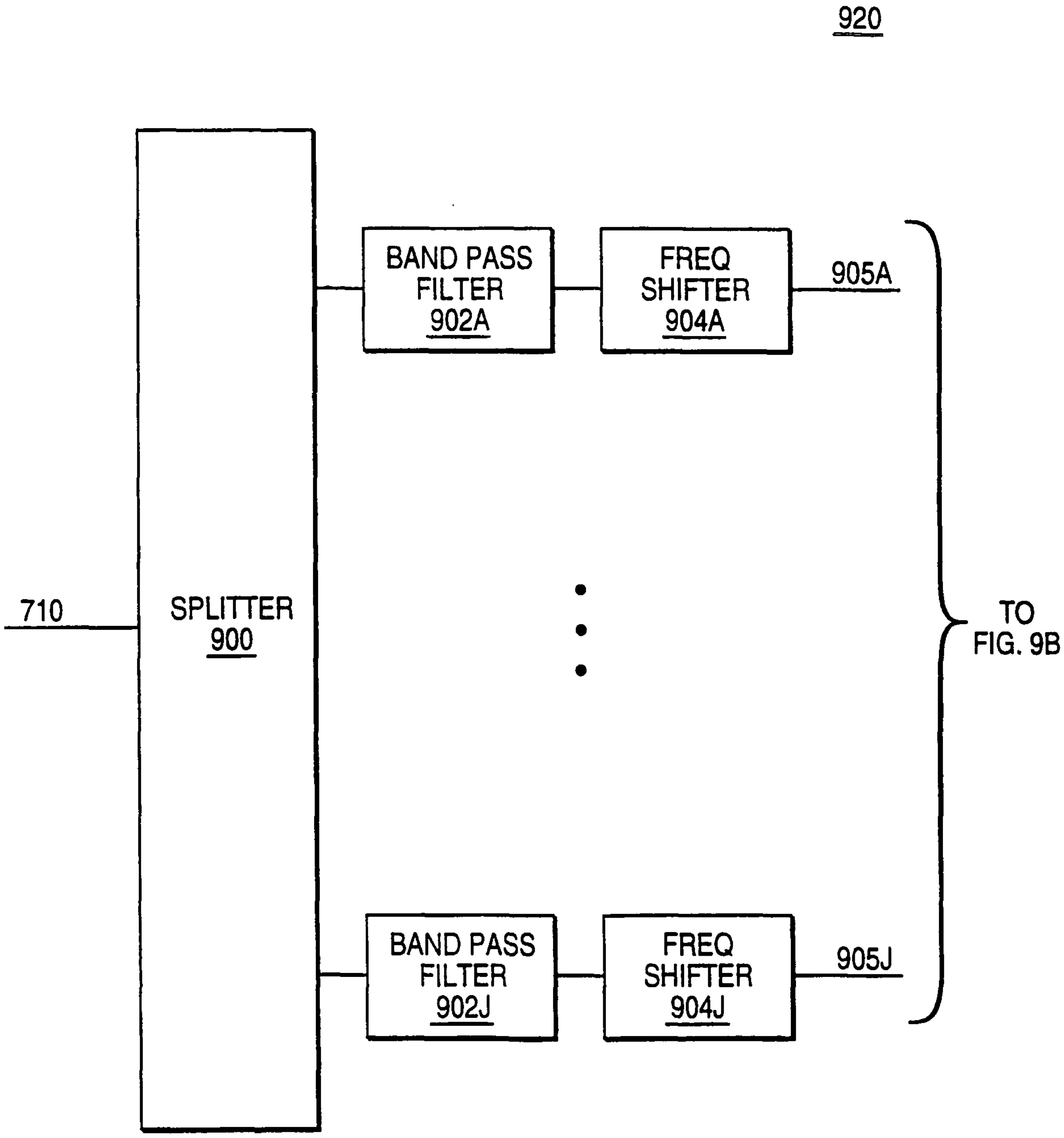
920
710
SPLITTER
900
BAND PASS
FILTER
902A
FREQ
SHIFTER
904A
905A
BAND PASS
FILTER
902J
FREQ
SHIFTER
904J
905J
TO
FIG. 9B

FIG. 9A

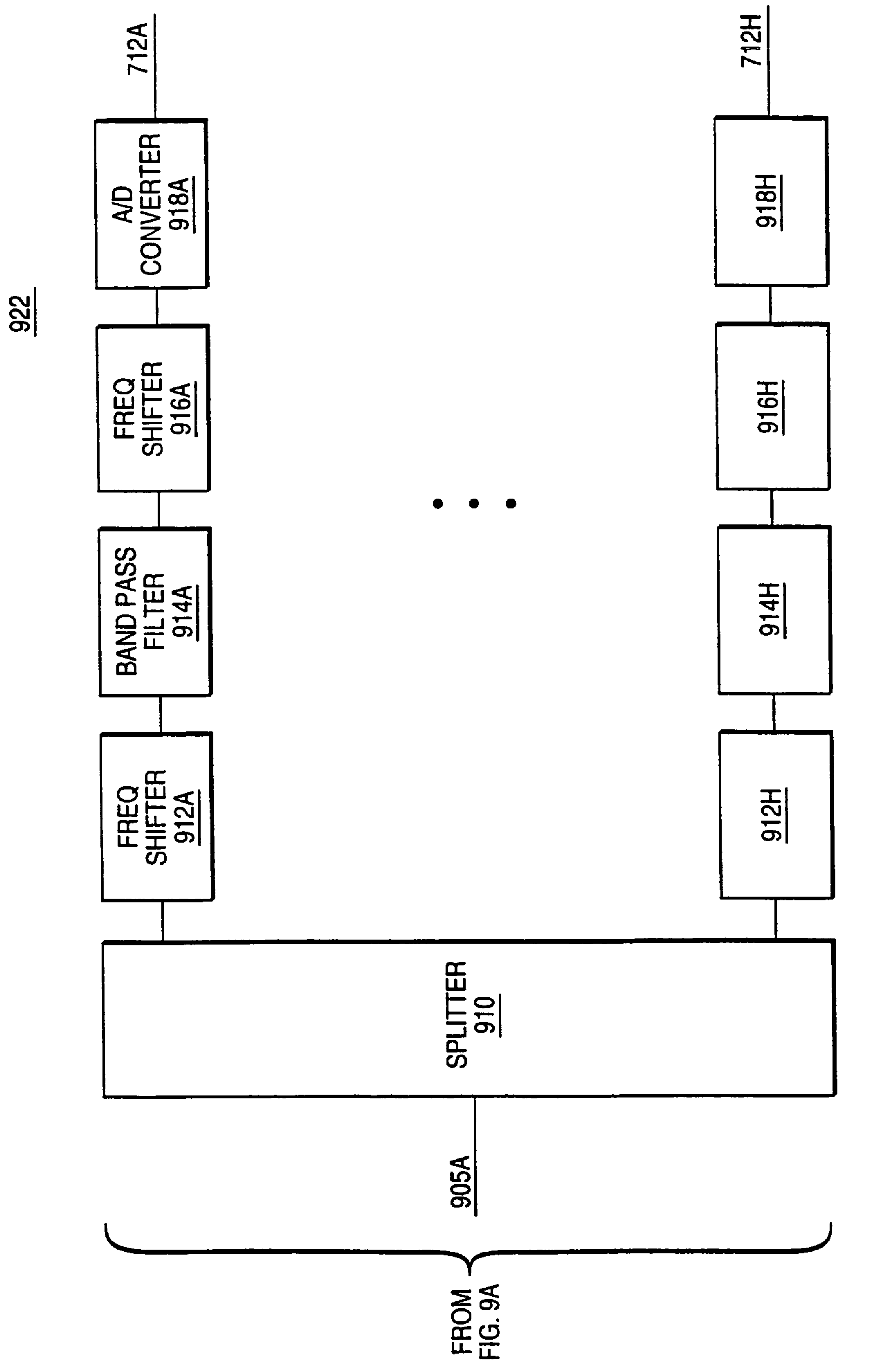
922
712A
A/D CONVERTER 918A
FREQ SHIFTER 916A
BAND PASS FILTER 914A
FREQ SHIFTER 912A
712H
918H
916H
914H
912H
SPLITTER 910
905A
FROM FIG. 9A

FIG. 9B

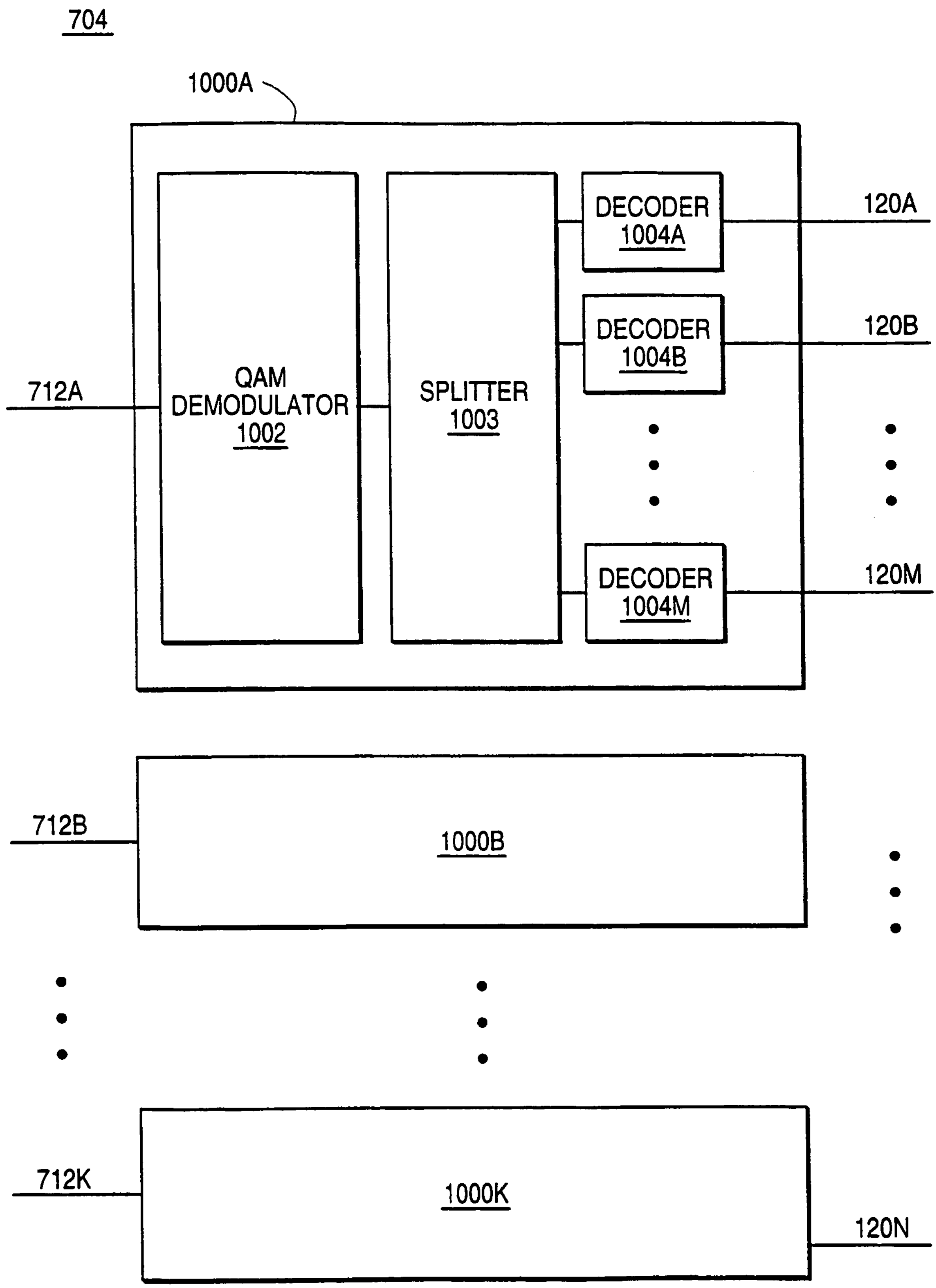
704
1000A
712A
QAM
DEMODULATOR
1002
SPLITTER
1003
DECODER
1004A
DECODER
1004B
DECODER
1004M
120A
120B
120M
712B
1000B
712K
1000K
120N

FIG. 10

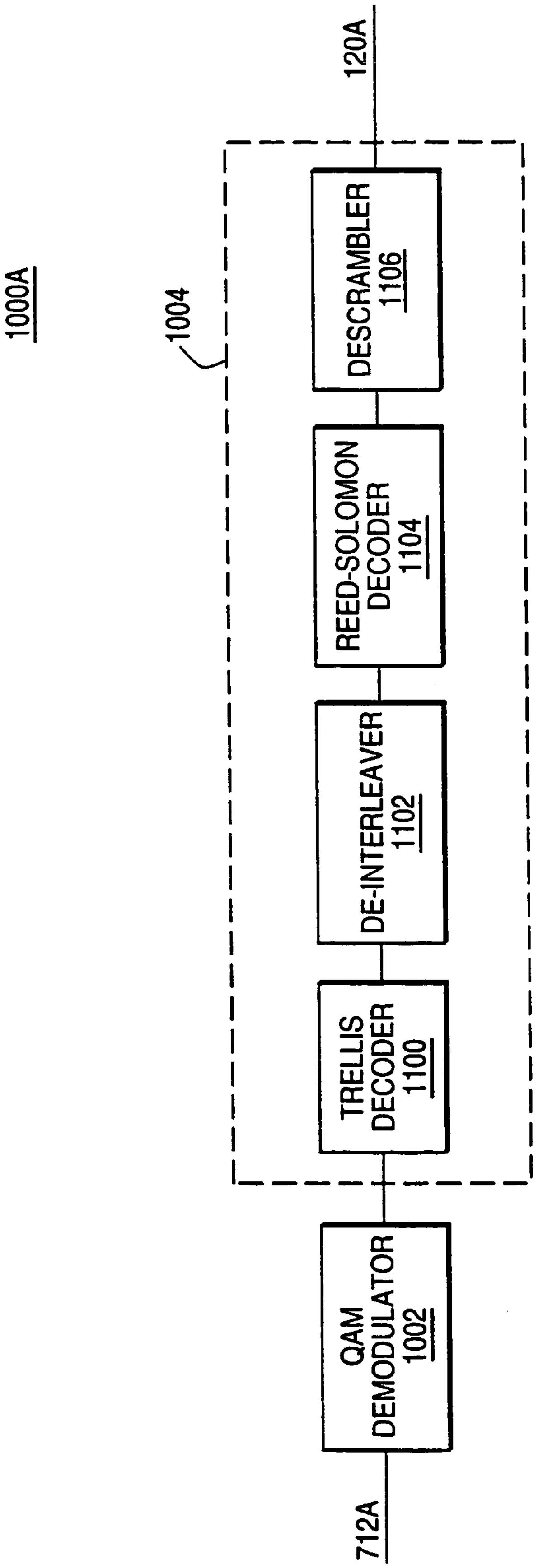
1000A
1004
712A
QAM DEMODULATOR 1002
TRELLIS DECODER 1100
DE-INTERLEAVER 1102
REED-SOLOMON DECODER 1104
DESCRAMBLER 1106
120A

FIG. 11