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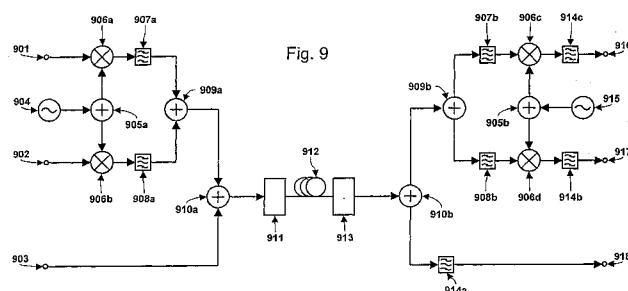
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(54) Title: APPARATUS AND METHOD FOR TRANSPORTING MULTIPLE SIGNALS OVER OPTICAL FIBER



(57) Abstract: A method and apparatus for transporting three or more radio signals of the same frequency, such as multiple input multiple output (MIMO) radio signals, over optical fiber on a single optical carrier by frequency mixing two such MIMO radio signals at a time with a single low-frequency local oscillator (LO) signal is disclosed.

Apparatus and Method for Transporting Multiple Signals Over Optical Fiber

The present invention relates to the field of telecommunications and more particularly, to transporting three or more radio signals of the same frequency, such
5 as multiple input, multiple output (MIMO) radio signals, over optical fiber.

A radio signal is defined as a signal whose carrier frequency corresponds to the part of the electromagnetic spectrum in the frequency range between 3 kHz and 300 GHz. This encompasses the part of the communications spectrum that may also be referred
10 to as microwave. Radio signals of the same frequency concerned are to be understood to have the same carrier frequency. Baseband signal has nonzero spectral amplitude between 0 Hz (DC) and an upper frequency which is dependent on the modulation rate. Optical signal is to be understood to be any electromagnetic radiation in the visible light and infrared regions with the wavelength range between
15 380 nm and 3000 nm which corresponds to the frequency range between 789 THz and 100 THz.

The rapid rise in information and telecommunication services has resulted in the need for ever more efficient and higher capacity wireless services to provide very
20 high speed wireless multimedia communication services. This is being achieved through the use of a combination of optical communication and wireless communication technologies where a wired communication technology is combined with a wireless communication technology to provide a high speed transmission system along with a mobile wireless technology – such a technology being called
25 Radio over Fiber (ROF).

Such an ROF technology uses an optical link apparatus and a radio link apparatus as the basic components. The optical link apparatus modulates a baseband transmission signal into a radio frequency band signal, converts the radio frequency band signal
30 into an optical signal, and then transmits the optical signal through an optical fiber. This optical signal is then converted back into the electrical domain and the wireless

link apparatus wirelessly carries a signal which has been received through the optical fiber.

In an environment in which various wireless services for voice, broadcasting, data,
5 etc., are provided, it is inefficient to construct a remote antenna link for every type of service. Hence methods for combining multiple signals and transmitting them over a single optical fiber are of significant value and the focus of research.

The distribution of radio signals over optical fibers reduces the complexity of remote
10 antenna units (AUs) and helps centralise communication equipment in the central offices which facilitates routine system maintenance and reduces costs. Compared to the signal distribution using conventional coaxial cables, the low transmission loss characteristic of optical fibers extends the distance the remote antenna units can be located from the central offices. Another advantage of using optical fibers compared
15 to using conventional coaxial cables is the much wider transmission bandwidth which allows a combination of cellular, wireless local area network (WLAN) and other wireless service signals at different frequencies to be distributed together over a single optical fiber. Commercial radio over fiber (ROF) products are already on sale for carrying a multitude of existing wireless services, such as the GSM, UMTS and
20 IEEE 802.11b/g WLAN, using optical fibers.

Considering the wireless network services continued demand for higher data transmission rates without a corresponding increase in the allocated radio channel bandwidth has led to the development of the Multiple Input Multiple Output
25 (MIMO) system. MIMO is a multi-antenna radio transmission technique using multiple antennas for transmitting and multiple antennas for receiving. Compared to the Single Input Single Output (SISO) technique, MIMO has two major performance enhancements.

30 Firstly, the use of multiple antennas in a MIMO system increases the transmission range and/or improves the radio link reliability through the well-known spatial diversity technique.

Secondly, MIMO systems can deliver higher data transmission rates over the airwave than the SISO counterparts for the same channel bandwidth. This transmission rate enhancement is achieved using a technique known as spatial multiplexing. Spatial multiplexing can be compared to solving a set of simultaneous equations where the transmitted radio signals from different transmitting antennas are analogous to the independent variables, and the received radio signals by different receiving antennas are analogous to the dependent variables. Once the different radio transmission path characteristics between each of the transmitting antennas and each of the receiving antennas have been established, the coefficients describing the set of simultaneous equations can be determined. Each of the received radio signals is dependent on all of the different transmitted radio signals. With the received radio signals and the coefficients describing the different radio path characteristics, each of the different transmitted radio signals can then be obtained mathematically, analogous to solving for the independent variables of a set of simultaneous equations. As a result all the different transmitted radio signals, despite having the same frequency occupying the same channel bandwidth, can be radiated to and received by the receiver individually with a higher aggregate transmission rate compared to an SISO system, as if a number of parallel radio channels existed between the transmitter and the receiver.

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New and emerging wireless standards increasingly employ MIMO for greater data throughputs as well as for improving transmission range/reliability. Examples of wireless standards employing MIMO include the IEEE 802.11n WLAN, the IEEE 802.16e WiMAX and all future 4th generation (4G) cellular systems.

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While optical fiber is well suited for carrying radio signals of different frequencies, it is not straightforward to use the same radio over fiber technique for transmitting a group of signals of the same frequency, such as the MIMO signals feeding multiple antennas, over an optical fiber.

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This difficulty arises because to transmit multiple radio signals, they have to be combined first in, for example, a power combiner prior to transmission over an

optical fiber. If the radio signals involved have different frequencies, they can be easily separated and recovered using simple electrical filters after transmission over fiber. If, on the other hand, the radio signals are of the same frequency, it will be impossible to separate and recover the individual radio signals without any form of
5 signal processing or multiplexing/demultiplexing technique before and after transmission over an optical fiber.

A conventional solution for tackling this problem is to employ as many individual optical fibers as there are radio signals. However, it would mean substantially
10 increasing the cost of constructing such MIMO radio over fiber system as each transmitting antenna would need its own optical fiber and associated components.

A number of techniques have been reported by others for transporting radio signals having the same frequency over a single optical fiber.

15 With wavelength division multiplexing (WDM), each of the radio signals to be transmitted is modulated onto and carried by one optical carrier of a different wavelength. Optical wavelength dependent filters are used to multiplex and demultiplex the optical carriers of different wavelengths before and after
20 transmission over the fiber, respectively.

With sub-carrier multiplexing (SCM), also referred to as frequency division multiplexing (FDM), the radio signals are first frequency shifted into different frequency bands using electrical mixers and local oscillator sources so that they can
25 be modulated onto and carried by a single optical carrier for transmission over an optical fiber. After the fiber, the frequency shifted radio signals are separated using electrical filters and then frequency shifted again to their original frequency band.

Allert van Zelst in US Patent Application Publication US 20040017785A1 described,
30 in very broad terms, using the well-known WDM and FDM techniques a method for transporting MIMO radio signals over an optical fiber.

Ichiro Seto et al. in "Optical Subcarrier Multiplexing Transmission for Base Station With Adaptive Array Antenna", IEEE Transactions On Microwave Theory And Techniques, Vol. 49, No. 10, pp. 2036-2041, October 2001, proposed transporting a multitude of radio signals destined for a group of adaptive array antennas over a single optical fiber using SCM. Adaptive array antennas require accurate and stable relative phase relationship between the radio signals radiated by individual antennas. Since all the radio signals are transported over a single optical fiber, any disturbance to the fiber resulting in fluctuating path length will affect all the signals equally but their relative phase relationship remains unaffected. Although such an SCM technique has been proposed for carrying adaptive array antenna signals which are different between them only in the phase and amplitude but not the actual radio content, the same technique can be applied to carry MIMO radio signals.

P. Ritosa et al. in "Optically steerable antenna array for radio over fibre transmission", Electronics Letters, Vol. 41, No. 16, pp. 47-48, 4th August 2005, reported transmitting the received radio signals at 2.1 GHz from the three elements of a smart antenna array over an optical fiber using WDM. The relative signal phase relationship was controlled by the choice of the laser wavelengths since the signal transmission speed over fiber is wavelength dependent. The relative signal amplitude was adjusted using external Mach-Zehnder modulators. Although the system was set up simply to demonstrate its ability to create different radiation patterns by varying the relative signal phase amplitude, it can easily be adapted for carrying MIMO radio signals using the same WDM technique.

There are a number of drawbacks associated with the WDM and SCM techniques for transporting MIMO signals over a single optical fiber.

If WDM is used, then as many optical sources of different wavelengths and the corresponding photodetectors as there are radio signals to be transported will be required since each signal will need its own optoelectronic components for the electrical-to-optical and optical-to-electrical conversion processes. Since many more

components are required, the cost of constructing a WDM based ROF system for MIMO will increase substantially and almost linearly with the number of antennas.

If SCM is used, all but one of the MIMO radio signals need to be initially frequency translated to different frequency bands before fiber transmission, and subsequently frequency translated back to the original frequency band afterwards. Therefore, if there are a total of n MIMO radio signals to be transported, $n-1$ different LO sources are required. Moreover, it is common in SCM to frequency translate those MIMO signals to an intermediate frequency (IF) band which is substantially different from the original radio frequency, e.g. from 2.4 GHz to 100 MHz, therefore separate electrical amplifiers covering different frequency bands are required for the frequency translated and non-translated MIMO signals.

It is an object of the present invention to alleviate, at least partially, any of the above problems.

The present invention provides an apparatus for transporting three or more radio signals of the same frequency over at least one optical fiber, on a single optical carrier, the apparatus comprising:

a first frequency translator arranged to frequency translate a first radio signal to a lower sideband by mixing the first radio signal with a first LO signal, and arranged to frequency translate a second radio signal to an upper sideband by mixing the second radio signal with the same LO signal;

wherein, when the number of radio signals is greater than three, the apparatus comprises a further respective frequency translator for each further pair of signals, arranged to operate in the same way as the first frequency translator to frequency translate each respective pair of radio signals to a different respective lower and upper sideband around the original radio signal frequency, but using a different LO frequency signal for each said further pair of the radio signals;

wherein, when the total number of radio signals is an odd number, the apparatus is arranged such that the last single radio signal that is not part of any of the radio signal pair or pairs is not frequency translated;

one or more combiners arranged to combine together all resulting lower and upper sidebands and said last single radio signal, when present, into a single electrical signal;

an optical source arranged to generate an optical carrier signal modulatable
5 by said single electrical signal;

at least one optical fiber arranged to transport the modulated optical carrier signal generated by the optical source;

a photodetection unit arranged to detect the optical signal after transmission over the at least one optical fiber and produce a corresponding received electrical
10 signal;

wherein, when the total number of radio signals is an odd number, the apparatus comprises at least one filter arranged to separate and recover the last single radio signal from the other lower and upper sidebands in the received electrical signal;

15 at least two filters arranged to separate individually all the lower and upper sidebands, contained in the received electrical signal;

first and second mixers arranged to mix the respective separated lower and upper sidebands, generated by the first frequency translator, with an LO signal having the same LO frequency as used in the first frequency translator to recover the
20 first and second radio signals at their original radio frequency; and

wherein, when the number of radio signals is greater than three, the apparatus comprises further mixers, arranged to operate in the same way as the first and second mixers to recover each other pair of radio signals at the original radio frequency by mixing the respective separated lower and upper sidebands generated from each
25 respective pair of signals, with a respective LO signal having respective LO frequency as used in the respective further frequency translator.

The invention also provides a method for transporting three or more radio signals of the same frequency over at least one optical fiber, on a single optical carrier, the
30 method comprising:



frequency translating a first radio signal to a lower sideband by mixing the first radio signal with an LO signal, and frequency translating a second radio signal to an upper sideband by mixing the second radio signal with the same LO signal;

wherein, when the number of radio signals is greater than three, frequency
5 translating each further pair of radio signals, in the same way as the first and second radio signals, to a different respective lower and upper sideband around the original radio signal frequency, using a different LO frequency signal for each further pair of radio signals;

wherein, when the total number of radio signals is an odd number, the last
10 single radio signal that is not part of any of the radio signal pair or pairs is not frequency translated;

combining together all resulting lower and upper sidebands and said last single radio signal, when present, into a single electrical signal;

modulating an optical carrier signal using said single electrical signal;

15 transporting the modulated optical carrier signal over at least one optical fiber;

detecting the optical signal after transmission over the at least one optical fiber and producing a corresponding received electrical signal;

wherein, when the total number of radio signals is an odd number, separating
20 and recovering the last single radio signal from the lower and upper sidebands in the received electrical signal by filtering;

separating individually all the lower and upper sidebands, contained in the received electrical signal, by filtering;

recovering the first and second radio signals at their original radio frequency
25 by mixing the respective separated lower and upper sidebands, generated by the first frequency translating step, with an LO signal having the same LO frequency as used in the first frequency translating step; and

wherein, when the number of radio signals is greater than three, recovering
each other pair of radio signals at the original radio frequency by mixing the
30 respective separated lower and upper sidebands generated from each respective pair of signals, with a respective LO signal having respective LO frequency as used in the respective frequency translation.

Accordingly the invention enables the transport of three or more radio signals of the same frequency, over an optical fiber or fibers on a single optical carrier. Embodiments of the invention require fewer local oscillator sources or frequencies
5 compared to those employing SCM and fewer optical sources of different wavelengths compared to those employing WDM, and therefore can be substantially cheaper to construct compared to other existing alternatives. Embodiments of the invention also have the advantage that it is not necessary to maintain any phase relationship between the local oscillator (LO) signal at the transmitter and the LO
10 signal at the receiver.

In one embodiment of the invention two MIMO radio signals at a time are processed using one low-frequency local oscillator (LO) source. In the transmitter the first of the two MIMO radio signals is frequency translated to a lower sideband by mixing
15 with the LO source followed by bandpass filtering at the lower sideband frequency while the other MIMO radio signal, being the second of the two, is frequency translated to an upper sideband by mixing with the same LO source followed by bandpass filtering at the upper sideband frequency. As a consequence, the two MIMO radio signals now respectively occupy a lower and an upper sideband which
20 are respectively below and above their original radio frequency in the frequency domain by an offset equal to the LO source frequency. Since the original MIMO radio signal frequency band between the lower sideband and the upper sideband is not used by these two MIMO radio signals at this point after frequency translation, it can be occupied by and used for transmission of a third MIMO radio signal without
25 frequency translation. The lower sideband, the upper sideband and the third MIMO radio signal are then combined using an electrical diplexer/duplexer or power combiner or other components performing similar function before electrical-optical conversion into an optical signal and transmission over an optical fiber.

30 After transmission over fiber and optical-electrical conversion back to the electrical domain in the receiver, the third MIMO radio signal is separated from the lower and upper sidebands using an electrical diplexer or bandpass filter or other components

performing similar function. The lower and upper sidebands are also separated using electrical duplexers or bandpass filters or other components performing similar function. To recover the first MIMO radio signal and return it to the original frequency, the filtered lower sideband is mixed with an LO source whose frequency
5 is the same as the LO source in the transmitter. To recover the second MIMO radio signal and return it to the original frequency, the filtered upper sideband is mixed with the same LO. One advantageous feature of the invention is that it is not necessary to have a separate low-frequency LO in the receiver. The LO signal generated by the LO in the transmitter can be sent over the same fiber to the receiver
10 for the mixing processes. Bandpass filtering will be required to remove unwanted mixed products.

For transporting three MIMO radio signals, the present invention requires only one LO source or frequency. In comparison, a system employing SCM will require at
15 least two LO sources or frequencies in order to frequency translate two of the three MIMO radio signals from their original frequency before transmission over an optical fiber.

The present invention can be adapted for carrying a greater number of MIMO radio
20 signals requiring a smaller number of LO sources or frequencies compared to systems employing SCM performing the same tasks. To transport four or five MIMO radio signals over an optical fiber, the present invention requires only two LO sources or frequencies. An SCM based system will require three and four LO sources or frequencies to transport four and five MIMO radio signals, respectively.
25 Similarly systems employing WDM will require more optical sources of different wavelengths compared to the invention. Systems implemented with the present invention are therefore substantially cheaper to construct compared to other existing alternatives. This reduces the power burden of the system.

30 Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

- Fig. 1 shows mixing of the first MIMO radio signal with an LO signal followed by bandpass filtering to generate the resultant frequency translated lower sideband;
- Fig. 2 shows mixing of the second MIMO radio signal with the same LO signal followed by bandpass filtering to generate the resultant frequency translated upper sideband;
- 5 Fig. 3 illustrates the process of combining the third MIMO radio signal with the frequency translated lower and upper sidebands from the first and second MIMO radio signals, respectively;
- Fig. 4 illustrates separation of the third MIMO radio signal by bandpass filtering;
- 10 Fig. 5 illustrates separation of the lower sideband due to the first MIMO radio signal by bandpass filtering;
- Fig. 6 illustrates separation of the upper sideband due to the second MIMO radio signal by bandpass filtering;
- Fig. 7 shows recovery of the original first MIMO radio signal by mixing the lower sideband with an LO signal followed by bandpass filtering;
- 15 Fig. 8 shows recovery of the original second MIMO radio signal by mixing the upper sideband with an LO signal followed by bandpass filtering;
- Fig. 9 is a schematic representation of an apparatus embodying the present invention for transporting three MIMO radio signals over optical fiber; and
- 20 Fig. 10 is a schematic representation of an apparatus embodying the present invention for transporting five MIMO radio signals over optical fiber.

The invention can be understood by considering the following schematic descriptions and embodiments of the invention. In a first embodiment the radio signals to be transmitted over optical fiber are MIMO radio signals though it is understood that the invention applies to any radio signals of the same frequency.

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Fig. 1 shows a first MIMO radio signal **101**, with a radio frequency carrier of frequency f_{RF} . Fig. 2 shows a second MIMO radio signal **201**, with a radio frequency carrier of frequency f_{RF} . The two MIMO radio signals **101**, **201** occupy the same frequency band around f_{RF} which has the result that they cannot simply be combined

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together, transported over an optical fiber and separated again afterwards without frequency translation being employed.

The transportation of a multiplicity of MIMO radio signals having the same
 5 frequency over an optical fiber is achieved by means of frequency translation using
 LO sources whose frequencies are substantially lower than those of the MIMO radio
 signals. Such a technique is employed and applied to two MIMO radio signals at a
 time by mixing the two signals with a single low-frequency LO source followed by
 bandpass filtering in order to select for each MIMO signal one of the two sidebands
 10 generated.

Fig. 1 shows a MIMO radio signal **101** of frequency f_{RF} being mixed with a low-
 frequency LO **102** that has a frequency of f_{LO} . This mixing results in a lower
 sideband **103** with frequency $(f_{RF} - f_{LO})$ and an upper sideband **104** with frequency
 15 $(f_{RF} + f_{LO})$.

Similarly Fig. 2 shows another MIMO radio signal **201** of frequency f_{RF} being mixed
 with the same low-frequency LO **102** at frequency f_{LO} . This mixing results in a lower
 sideband **202** with frequency $(f_{RF} - f_{LO})$ and an upper sideband **203** with frequency
 20 $(f_{RF} + f_{LO})$.

Only one of the two sidebands generated from each MIMO radio signal is required
 and needs to be retained. The retained sidebands must be chosen so that they do not
 overlap in the frequency domain. Therefore if the lower sideband **103** from the first
 25 MIMO signal **101** is retained, then the opposite upper sideband **203** from the second
 MIMO signal **201** must be retained. Similarly, if the upper sideband **104** from the
 first MIMO signal **101** is retained, then the opposite lower sideband **202** from the
 second MIMO signal **201** must be retained. In Fig. 1, a bandpass filter **105a** with a
 center frequency of $(f_{RF} - f_{LO})$ is used to select and retain the lower sideband **103**
 30 while rejecting the upper sideband **104** from MIMO signal **101** following the mixing.
 Similarly, in Fig. 2 another bandpass filter **204a** with a center frequency of $(f_{RF} + f_{LO})$

is used to select and retain the upper sideband **203** while rejecting the lower sideband **202** from MIMO signal **201** following the mixing.

Following the mixing processes, the original frequency band at f_{RF} is no longer
 5 occupied by any of the sidebands following the mixing processes with the two
 MIMO signals. The vacant frequency band at f_{RF} can now accommodate a third
 MIMO signal without frequency translation. Fig. 3 shows the combining of a third
 MIMO signal **301** with the lower sideband **103** from the first MIMO signal **101** and
 the upper sideband **203** from the second MIMO signal **201**. The resultant signals are
 10 now suitable for transmission over fiber.

Following transmission over fiber, the original three MIMO signals need to be
 recovered and separated.

15 Firstly, the third MIMO signal **301** can be recovered by simply passing the resultant
 radio signals through a bandpass filter **401a** around f_{RF} as shown in Fig. 4.

To recover the two MIMO radio signals **101** and **201**, the lower sideband **103** and the
 upper sideband **203** first need to be separated. Fig. 5 shows the resultant radio
 20 signals being passed through a bandpass filter **105b** around $(f_{RF} - f_{LO})$ which selects
 the lower sideband **103** generated from MIMO signal **101**. Similarly Fig. 6 shows
 the resultant radio signals being passed through a bandpass filter **204b** around $(f_{RF} + f_{LO})$
 which selects the upper sideband **203** generated from MIMO signal **201**.

25 In Fig. 7 the bandpass filtered lower sideband **103** is then mixed with an LO signal
701 which is of the same frequency as **102**. This mixing process restores the original
 first MIMO signal **101** and in addition produces a new lower sideband **702** at
 frequency $(f_{RF} - 2f_{LO})$. A bandpass filter **401b** around f_{RF} then selects the desired first
 MIMO signal **101** and rejects the unwanted sideband **702**. In Fig. 8 the bandpass
 30 filtered upper sideband **203** is similarly mixed with the same LO signal **701**. The
 mixing process restores the original second MIMO signal **201** and in addition
 produces a new upper sideband **801** at frequency $(f_{RF} + 2f_{LO})$. A bandpass filter **401c**

around f_{RF} selects the desired second MIMO signal **201** and rejects the unwanted sideband **801**.

An embodiment of the present invention for transporting three MIMO radio signals over fiber is shown in Fig. 9. A low-frequency LO signal **904** is first split into two identical signal components in a combiner/splitter **905a** which are then used to drive the two mixers **906a** and **906b**. The first MIMO signal at input **901** is mixed with one of the LO signal components in mixer **906a**. The output from mixer **906a** is then passed through a bandpass filter **907a** around $(f_{RF} - f_{LO})$ in order to select and retain the lower sideband signal at the same frequency while rejecting other mixer output signals at other frequencies. The second MIMO signal at input **902** is mixed with the other component of the LO signal in mixer **906b**. The output from mixer **906b** is then passed through a bandpass filter **908a** around $(f_{RF} + f_{LO})$ in order to select and retain the upper sideband signal at the same frequency while rejecting other mixer output signals at other frequencies.

The lower sideband signal from bandpass filter **907a** and the upper sideband signal from bandpass filter **908a** are then combined in the power combiner/splitter **909a**.

This mixing and any other signal mixing described herein can be performed using analogue multipliers, variable gain amplifiers and/or electrical mixers examples of which include the following: single diode mixers, double balanced diode mixers, triple balanced diode mixers, active bipolar transistor mixers, active field effect transistor mixers or active transistor mixers configured in a Gilbert cell.

25

The LO source frequency f_{LO} is preferably chosen to be substantially lower than the MIMO radio frequency f_{RF} . For transmission of three MIMO radio signals, there are two criteria for choosing the LO frequency used. Firstly the LO frequency chosen should be high enough so that the lower and upper sidebands generated are sufficiently apart in the frequency domain so that a third non-frequency translated MIMO radio signal can be inserted between them without overlap. Secondly the LO frequency chosen should be low enough so that the lower and upper sidebands

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generated do not interfere or overlap with other co-transported signals in other frequency bands. Using the IEEE 802.11n WLAN standard operating in the 2.4 GHz ISM band (2.4 GHz to 2.483 GHz) as an example, each MIMO signal occupies 40 MHz channel bandwidth. In order for the frequency translated lower and upper sidebands to be sufficiently apart, an LO frequency of at least 40 MHz, preferably even higher, should be used. However the same optical fiber may commonly carry other radio signals for other wireless services such as the UMTS. The UMTS in the frequency division duplex mode has a nearby downlink frequency band allocated between 2.110 GHz and 2.170 GHz. In order for the two sidebands not to interfere with the UMTS system, the LO frequency should be lower than 230 MHz (The difference between 2.4 GHz and 2.170 GHz). Therefore a 100 MHz LO frequency is a suitable choice in this example. Further criteria affecting the choice of the exact LO frequency are the bandwidth and order of the filters employed.

15 A third MIMO radio signal from input **903** is combined with the lower and upper sidebands in power combiner/splitter **910a**. Since this third MIMO radio signal from input **903** is at a different frequency from the lower and upper sidebands, the combiner/splitter **910a** can also be implemented with an electrical diplexer or duplexer or any suitable combination of electrical filters.

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The resultant signals from **910a** are converted to the optical domain in electrical-optical converter **911** (the electrical-optical converter operating using known electrical-optical transmission techniques). Examples of suitable electrical-optical converter **911** include: a directly electrically modulatable laser source; or an external optical intensity modulator in conjunction with a continuous-wave external laser source.

The output of the electrical-optical converter **911** is a modulated optical carrier signal which is launched or coupled into an optical fiber **912**. The optical fiber **912** may be of a singlemode type or of a multimode type. In one optional example, an optical power divider or optical filter is used to split the modulated optical signal between two or more optical fibers in order to feed a number of separate receivers.

Once the optical signal has been transmitted over fiber **912** to a receiver at the required destination, the optical signal can be converted back into the electrical domain using an optical-electrical converter **913** (the optical-electrical converter operating using known electrical-optical transmission techniques). The optical-electrical converter **913** can be a photodetector, such as a PIN photodiode, photoconductive photodetector, avalanche photodiode, metal-semiconductor-metal photodiode, Schottky photodiode, bipolar phototransistor, field effect phototransistor or any such photodetector integrated with or directly connected to an electrical amplifier.

The non-frequency translated third MIMO signal can be recovered from the received resultant signals by simple bandpass filtering. In Fig. 9, the received resultant signals from **913** is first split into two outputs in a combiner/splitter **910b** and one such output is then passed through a bandpass filter **914a** around f_{RF} which selects and retains the third MIMO signal while rejecting all other sidebands at other frequencies. The original third MIMO signal is now available at output **918**.

To recover the first and second MIMO signals, the lower and upper sidebands need to be individually mixed with an LO signal whose frequency is the same as the LO used in the transmitter. The LO signal in the receiver can be generated using an independent signal generator. Alternatively, a fraction of the LO signal power in the transmitter can be sent over the same fiber to the receiver which, after further amplification, is used as the LO signal for recovering the first and second MIMO signals. In Fig. 9, an LO signal **915**, whose frequency is the same as **904**, is split into two identical components which are then used to drive two mixers **906c** and **906d**.

The other output from **910b** containing the resultant signals is further split into two identical output signals in combiner/splitter **909b**. To recover the first MIMO signal, one of the two output signals from **909b** is passed through a bandpass filter **907b** around $(f_{RF} - f_{LO})$ which selects and retains the lower sideband signal while rejecting other signals at other frequencies. The filtered lower sideband is subsequently mixed

with one component of the LO signal **915** in mixer **906c** which restores the original first MIMO signal at f_{RF} but also produces an additional sideband at $(f_{RF} - 2f_{LO})$. Another bandpass filter **914c** around f_{RF} is used to filter and select the original first MIMO signal at f_{RF} . The original first MIMO signal is now available at output **916**.

5

To recover the second MIMO signal, the other output signal from **909b** is passed through a bandpass filter **908b** around $(f_{RF} + f_{LO})$ which selects and retains the upper sideband signal while rejecting other signals at other frequencies. The filtered upper sideband is subsequently mixed with the other component of the LO signal **915** in mixer **906d** which restores the original second MIMO signal at f_{RF} but also produces an additional sideband at $(f_{RF} + 2f_{LO})$. Another bandpass filter **914b** around f_{RF} is used to filter and select the original first MIMO signal at f_{RF} . The original second MIMO signal is now available at output **917**.

15 So far the working principles and the implementation of the present invention have been described for transmission of three MIMO radio signals over optical fiber. However, the present invention can also be adapted for transporting four, five and even a greater number of MIMO radio signals over optical fiber.

20 If five MIMO radio signals are to be transported over optical fiber using the present invention, for example, the embodiment in Fig. 9 can be expanded to that shown in Fig. 10. In Fig. 10, the fourth and the fifth MIMO radio signals present at inputs **1001**, **1002** are mixed with a second LO signal **1003** and the resulting lower and upper sidebands are then filtered and combined in the same manner as for the first and second MIMO radio signals from inputs **901** and **902**. All the lower and upper sidebands from the first, the second, the fourth and the fifth MIMO radio signals are combined with the non-frequency translated third MIMO radio signal from input **903** in a power combiner/splitter **1004** in the transmitter before transmission over fiber.

25

30 In the embodiment in Fig. 10, the second LO frequency used for mixing with the fourth and fifth MIMO signals in the transmitter is chosen so that the generated lower and upper sidebands do not overlap with those generated by the first and

second MIMO signals. Preferably, the second LO frequency used for mixing with the fourth and fifth MIMO signals is twice that for mixing with the first and second MIMO signals.

- 5 Following transmission over optical fiber, the fourth and the fifth MIMO signals can be recovered in the same manner as for the first and the second MIMO signals by first bandpass filtering and then mixing the corresponding lower and upper sidebands with an LO signal **1005** having the same frequency as the second LO **1003** in the transmitter. Following further bandpass filtering, the fourth and the fifth MIMO
10 signals are presented at outputs **1006** and **1007**, respectively.

- If an even greater number of MIMO radio signals are to be transported over optical fiber using the present invention, each additional pair of MIMO radio signals can be mixed with another LO signal having a higher frequency than the previous LO
15 frequencies, for example at successive harmonics of the original LO frequency. If an even number of signals is to be used, then one option is simply to omit the central un-shifted signal at frequency f_{RF} and input **903**; the even number of signals are transmitted as pairs of upper and lower sidebands.

CLAIMS

1. An apparatus for transporting three or more radio signals of the same frequency over at least one optical fiber, on a single optical carrier, the apparatus comprising:
- 5 a first frequency translator arranged to frequency translate a first radio signal to a lower sideband by mixing the first radio signal with a first LO signal, and arranged to frequency translate a second radio signal to an upper sideband by mixing the second radio signal with the same LO signal;
- 10 wherein, when the number of radio signals is greater than three, the apparatus comprises a further respective frequency translator for each further pair of signals, arranged to operate in the same way as the first frequency translator to frequency translate each respective pair of radio signals to a different respective lower and upper sideband around the original radio signal frequency, but using a different LO
- 15 frequency signal for each said further pair of the radio signals;
- wherein, when the total number of radio signals is an odd number, the apparatus is arranged such that the last single radio signal that is not part of any of the radio signal pair or pairs is not frequency translated;
- one or more combiners arranged to combine together all resulting lower and upper sidebands and said last single radio signal, when present, into a single
- 20 electrical signal;
- an optical source arranged to generate an optical carrier signal modulatable by said single electrical signal;
- at least one optical fiber arranged to transport the modulated optical carrier
- 25 signal generated by the optical source;
- a photodetection unit arranged to detect the optical signal after transmission over the at least one optical fiber and produce a corresponding received electrical signal;
- wherein, when the total number of radio signals is an odd number, the
- 30 apparatus comprises at least one filter arranged to separate and recover the last single radio signal from the other lower and upper sidebands in the received electrical signal;

at least two filters arranged to separate individually all the lower and upper sidebands, contained in the received electrical signal;

first and second mixers arranged to mix the respective separated lower and upper sidebands, generated by the first frequency translator, with an LO signal
5 having the same LO frequency as used in the first frequency translator to recover the first and second radio signals at their original radio frequency; and

wherein, when the number of radio signals is greater than three, the apparatus comprises further mixers, arranged to operate in the same way as the first and second mixers to recover each other pair of radio signals at the original radio frequency by
10 mixing the respective separated lower and upper sidebands generated from each respective pair of signals, with a respective LO signal having respective LO frequency as used in the respective further frequency translator.

2. An apparatus according to claim 1, wherein the frequency for the first LO
15 signal for frequency translating the first pair of radio signals is such that the lower and upper sidebands generated are sufficiently apart in the frequency domain so that a non-frequency translated radio signal can be placed between the said lower and upper sidebands in the frequency domain without overlap.

20 3. An apparatus according to claim 1 or 2, wherein the frequency for any subsequent LO signal is selected so as to produce lower and upper sidebands sufficiently far apart that they can accommodate, between them in the frequency domain, any lower and upper sidebands generated earlier and any non-frequency translated radio signal, without overlap.

25 4. An apparatus according to claim 1, 2 or 3, wherein the frequency for any LO signal is selected so as to produce such lower and upper sidebands that in the frequency domain will not interfere or overlap with other lower and upper sidebands generated using other respective LO frequencies, and will not interfere or overlap
30 with other co-transported signals in other frequency bands.

5. An apparatus according to any one of the preceding claims, wherein the mixers for recovering the radio signals are arranged to receive LO signals generated by one or more independent phase-locked LOs or derived and sent over the optical fiber or fibers from one or each original LO signal used by the frequency translators.

5

6. An apparatus according to any one of the preceding claims, wherein the radio signals of the same frequency are MIMO radio signals.

7. An apparatus according to any one of the preceding claims, wherein the first frequency translator further comprises: a first filter for selecting only the lower sideband resulting from the mixing of the first radio signal with the first LO signal; and a second filter for selecting only the upper sideband resulting from the mixing of the second radio signal with the first LO signal, and

15 wherein any further frequency translator further comprises: a lower sideband filter for selecting only the lower sideband resulting from the mixing of the first of a pair of radio signals with an LO signal; and an upper sideband filter for selecting only the upper sideband resulting from the mixing of the second of a pair of radio signals with the LO signal.

20 8. A method for transporting three or more radio signals of the same frequency over at least one optical fiber, on a single optical carrier, the method comprising:

frequency translating a first radio signal to a lower sideband by mixing the first radio signal with an LO signal, and frequency translating a second radio signal to an upper sideband by mixing the second radio signal with the same LO signal;

25 wherein, when the number of radio signals is greater than three, frequency translating each further pair of radio signals, in the same way as the first and second radio signals, to a different respective lower and upper sideband around the original radio signal frequency, using a different LO frequency signal for each further pair of radio signals;

30 wherein, when the total number of radio signals is an odd number, the last single radio signal that is not part of any of the radio signal pair or pairs is not frequency translated;

combining together all resulting lower and upper sidebands and said last single radio signal, when present, into a single electrical signal;

modulating an optical carrier signal using said single electrical signal;

transporting the modulated optical carrier signal over at least one optical
5 fiber;

detecting the optical signal after transmission over the at least one optical fiber and producing a corresponding received electrical signal;

wherein, when the total number of radio signals is an odd number, separating and recovering the last single radio signal from the lower and upper sidebands in the
10 received electrical signal by filtering;

separating individually all the lower and upper sidebands, contained in the received electrical signal, by filtering;

recovering the first and second radio signals at their original radio frequency by mixing the respective separated lower and upper sidebands, generated by the first
15 frequency translating step, with an LO signal having the same LO frequency as used in the first frequency translating step; and

wherein, when the number of radio signals is greater than three, recovering each other pair of radio signals at the original radio frequency by mixing the respective separated lower and upper sidebands generated from each respective pair
20 of signals, with a respective LO signal having respective LO frequency as used in the respective frequency translation.

9. A method according to claim 8, wherein the frequency for the first LO signal for frequency translating the first pair of radio signals is selected such that the lower
25 and upper sidebands generated are sufficiently apart in the frequency domain so that a non-frequency translated radio signal can be placed between the said lower and upper sidebands in the frequency domain without overlap.

10. A method according to claim 8 or 9, wherein the frequency for any
30 subsequent LO signal is selected so as to produce lower and upper sidebands sufficiently far apart that they can accommodate, between them in the frequency

domain, any lower and upper sidebands generated earlier and any non-frequency translated radio signal, without overlap.

11. A method according to claim 8, 9 or 10, comprising selecting the frequency
5 for any LO signal so that it is below an upper limit so as to produce such lower and upper sidebands that in the frequency domain will not interfere or overlap with other lower and upper sidebands generated using other respective LO frequencies, and will not interfere or overlap with other co-transported signals in other frequency bands.

10 12. A method according to any one of claims 8 to 11, wherein the LO signals for recovering the radio signals are generated by one or more independent phase-locked LOs or are derived and sent over the optical fiber or fibers from one or each original LO signal used for the frequency translating.

15 13. A method according to any of claims 8 to 12, wherein the radio signals of the same frequency are MIMO radio signals.

14. A method according to any one of the claims 8 to 13, wherein the frequency translating operations further comprise: filtering to select only the lower sideband
20 resulting from the mixing of the first radio signal with the LO signal; and filtering to select only the upper sideband resulting from the mixing of the second radio signal with the same LO signal, and

wherein any further frequency translating further comprises: filtering to select only the lower sideband resulting from the mixing of the first of a pair of radio
25 signals with an LO signal; and filtering to select only the upper sideband resulting from the mixing of the second of a pair of radio signals with the LO signal.

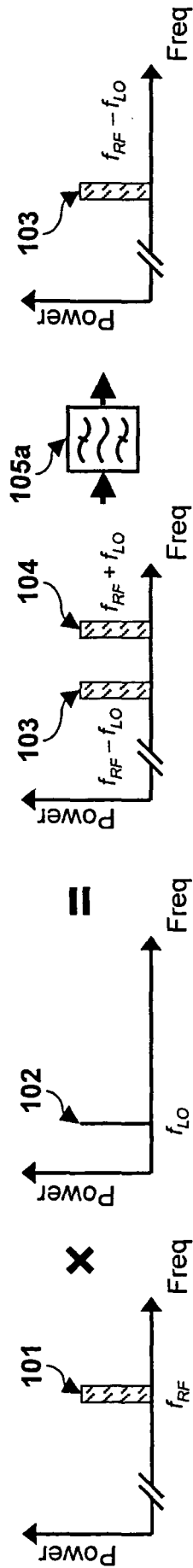


Fig. 1

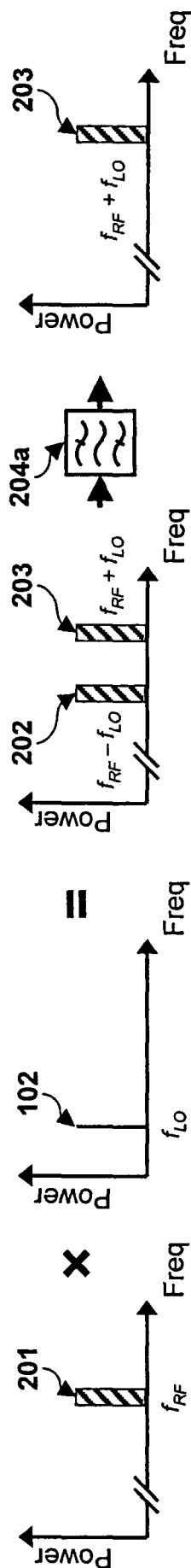


Fig. 2

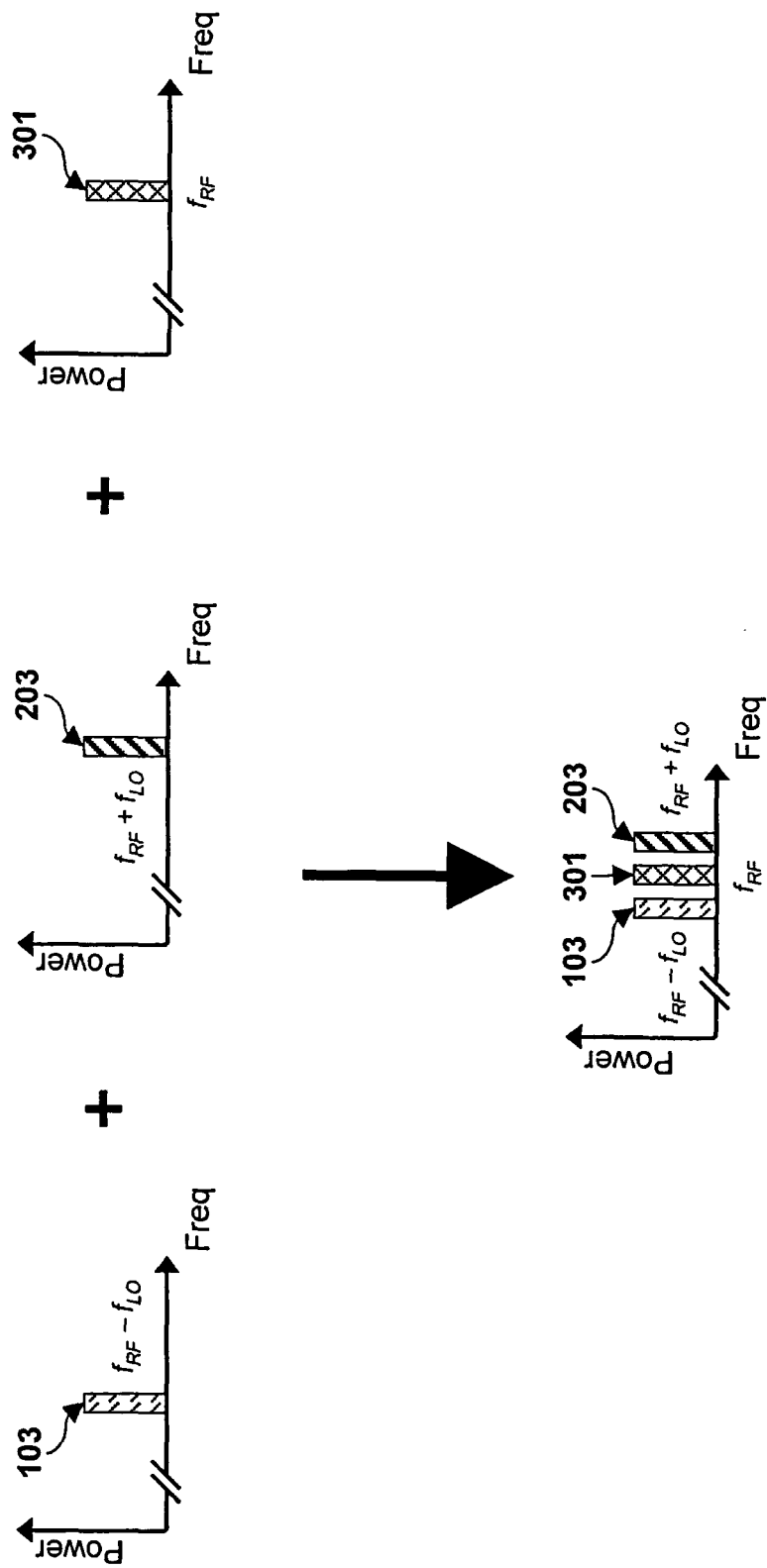


Fig. 3

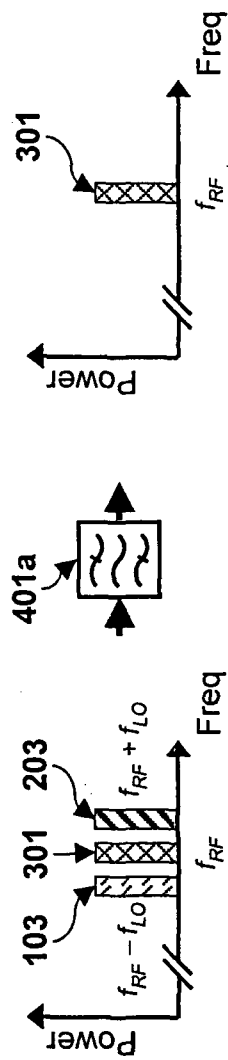


Fig. 4

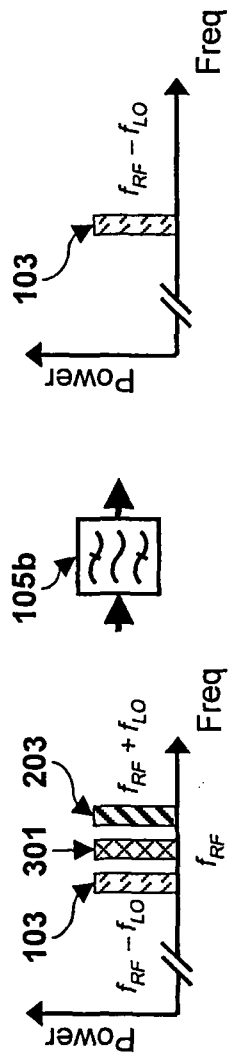


Fig. 5

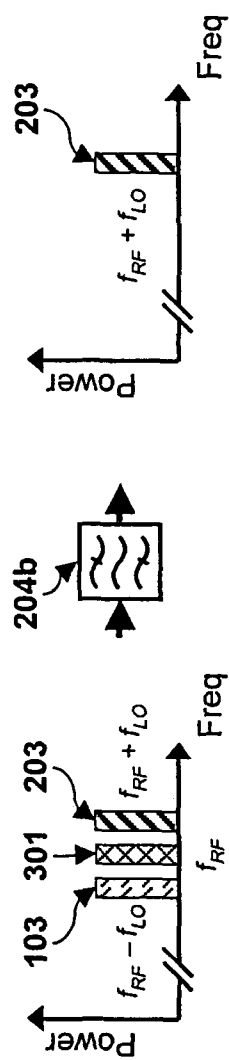


Fig. 6

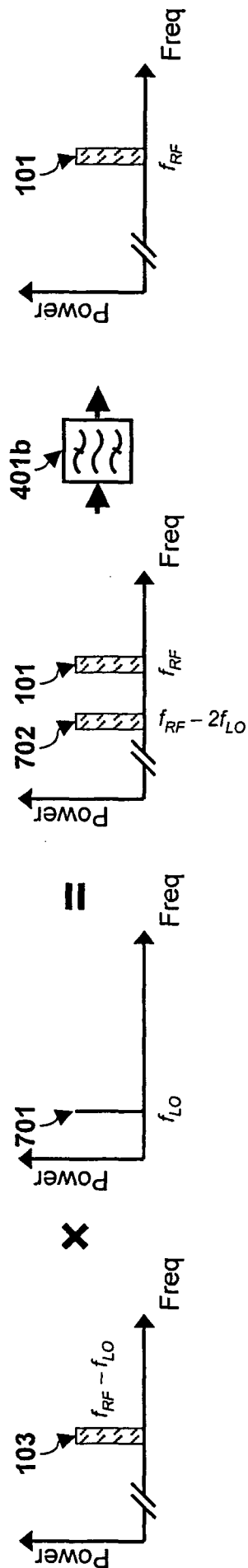


Fig. 7

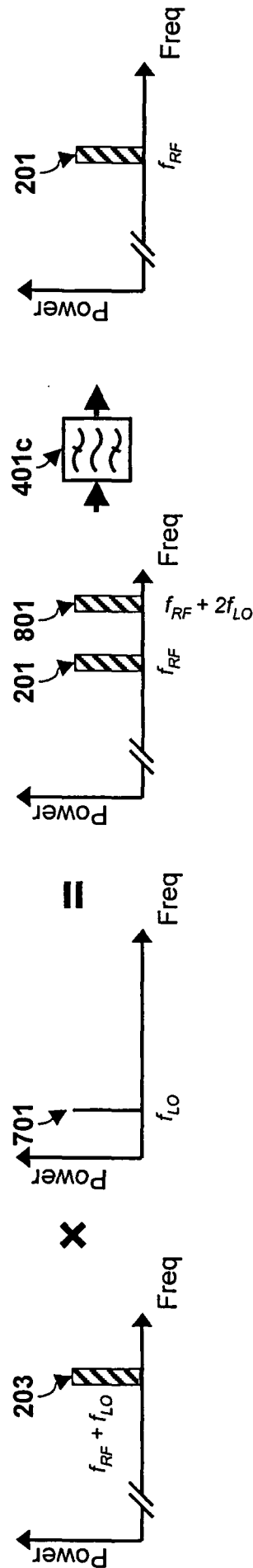


Fig. 8

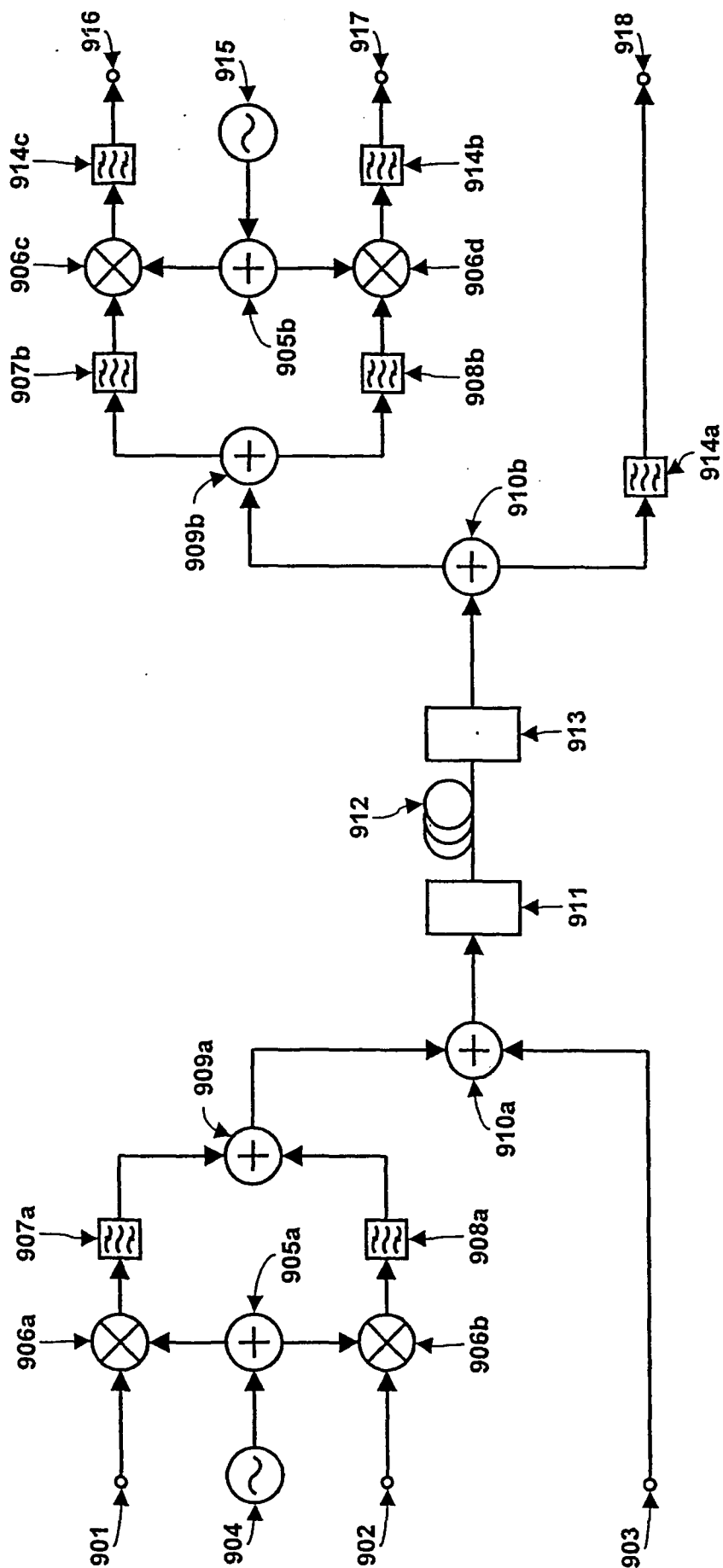


Fig. 9

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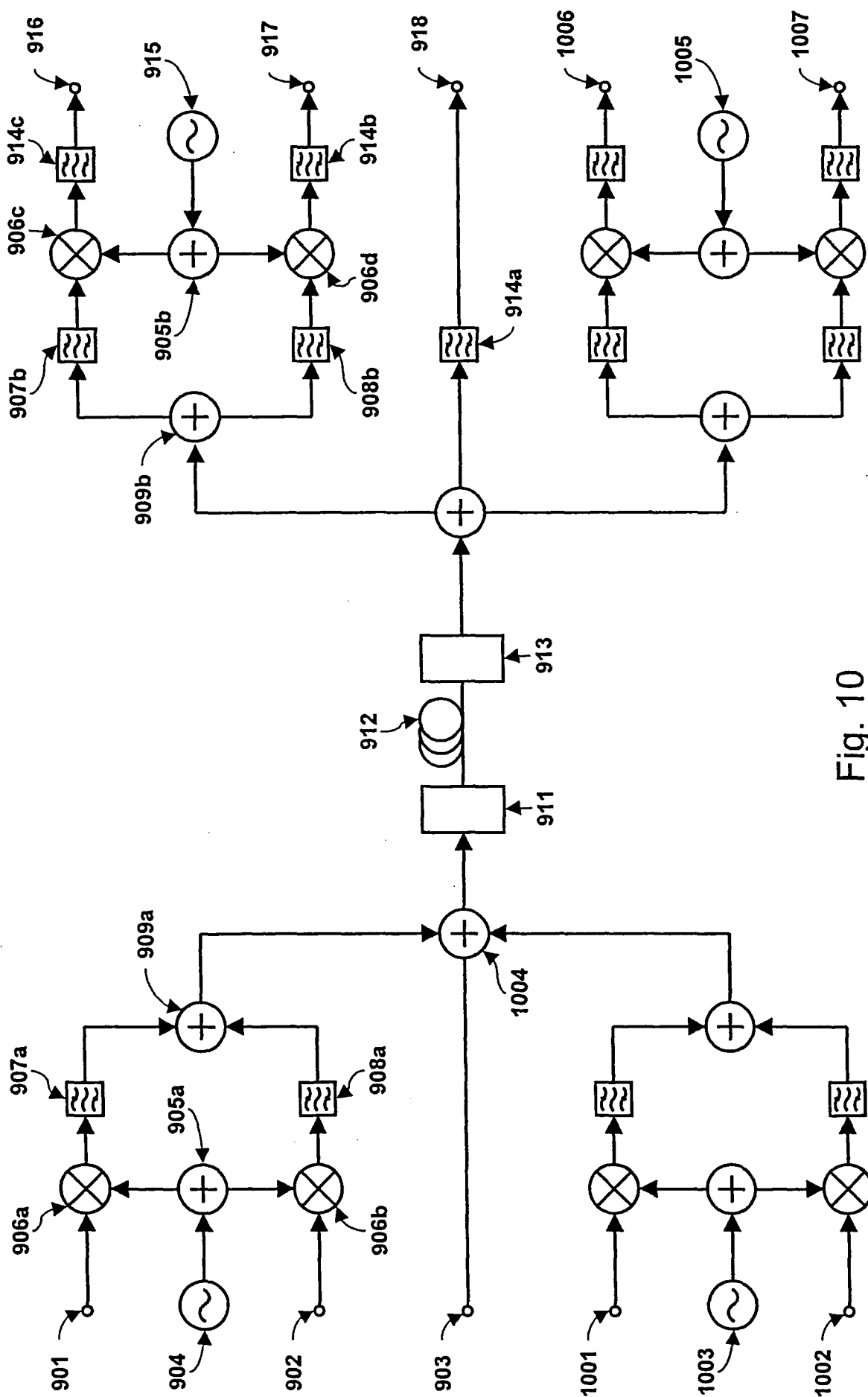


Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/002306

A. CLASSIFICATION OF SUBJECT MATTER

INV. H04B10/12 H04J14/02 H04B7/04 H04W88/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04B H04J H04Q H04W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EP0-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CHIN-PANG LIU ET AL: "Transmission of MIMO radio signals over fibre using a novel phase quadrature double sideband frequency translation technique" MICROWAVE PHOTONICS, 2008. JOINTLY HELD WITH THE 2008 ASIA-PACIFIC MICROWAVE PHOTONICS CONFERENCE. MWP/APMP 2008. INTERNATIONAL TOPICSL MEETING ON, IEEE, PISCATAWAY, NJ, USA, 9 September 2008 (2008-09-09), pages 23-26, XP031358026 ISBN: 978-1-4244-2168-8 the whole document ----- -/-	1-14

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

14 December 2009

Date of mailing of the international search report

28/12/2009

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/002306

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ICHIRO SETO ET AL: "Optical Subcarrier Multiplexing Transmission for Base Station With Adaptive Array Antenna" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 49, no. 10, 1 October 2001 (2001-10-01), XP011038458 ISSN: 0018-9480 abstract; figure 5	1-14
A	US 2004/017785 A1 (ZELST ALLERT VAN [NL]) 29 January 2004 (2004-01-29) abstract; figure 4	1-14
A	HSU R C J ET AL: "Coherent Optical MIMO (COMIMO)" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 23, no. 8, 1 August 2005 (2005-08-01), pages 2410-2419, XP011138114 ISSN: 0733-8724 abstract; figure 2	1-14
A	MA ET AL: "Generation and transmission of the double-sideband optical millimeter-wave with signal carried only by optical carrier" OPTICS COMMUNICATIONS, NORTH-HOLLAND PUBLISHING CO. AMSTERDAM, NL, vol. 281, no. 10, 5 February 2008 (2008-02-05), pages 2799-2805, XP022561872 ISSN: 0030-4018 abstract; figure 1	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2009/002306

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004017785 A1	29-01-2004	JP 2004056821 A	19-02-2004