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Tzannes

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(54) **SYSTEM AND METHOD FOR SCRAMBLING THE PHASE OF THE CARRIERS IN A MULTICARRIER COMMUNICATIONS SYSTEM**

(75) Inventor: **Marcos C. Tzannes**, Orinda, CA (US)

(73) Assignee: **Aware, Inc.**, Bedford, MA (US)

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(51) **Int. Cl.**[7] **H04B 17/00**
(52) **U.S. Cl.** **375/220**
(58) **Field of Search** 375/220, 219, 375/226, 327, 362

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,955,141 A *	5/1976	Lyon et al.	325/38 A
4,985,900 A *	1/1991	Rhind et al.	375/10
5,748,677 A *	5/1998	Kumar	375/285
6,507,585 B1 *	1/2003	Dobson	370/420
6,704,317 B1 *	3/2004	Dobson	370/401

FOREIGN PATENT DOCUMENTS

EP	0 584 534 A1	3/1994
EP	0 719 004 A2	6/1996
GB	2 330 491 A	4/1999
WO	WO 98/32065	7/1998
WO	WO 99/22463	5/1999
WO	WO 99/29078	6/1999

OTHER PUBLICATIONS

Provisional U.S. Appl. No. 60/164,134 filed on Nov. 9, 1999.*

Bauml R. W. et al.: "Reducing The Peak-To-Average Power Ratio Of Multicarrier Modulation By Selected Mapping" Electronics Letters, GB, IEE Stevenage, vol. 32, No. 22, Oct. 24, 1996, pp. 2056-2057, XP000643915 ISSN: 0013-5194.

Copy of Annex to Form PCT/ISA/206 for PCT/US00/30958, Mar. 23, 2001.

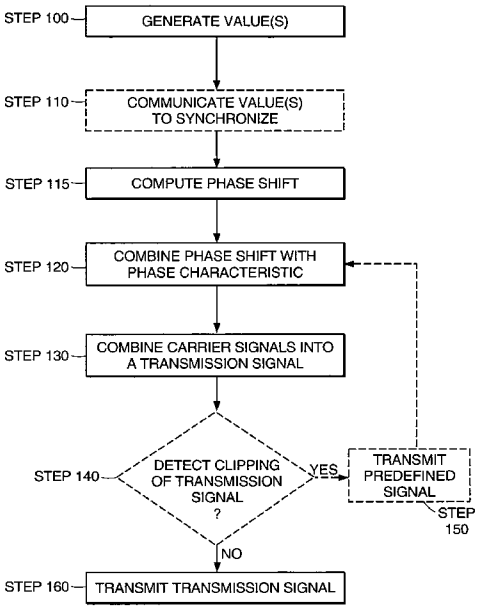
* cited by examiner

Primary Examiner—Kenneth Vanderpuye
Assistant Examiner—Dung X. Nguyen
(74) *Attorney, Agent, or Firm*—Miles & Stockbridge P.C.; Jason H. Vick

(57) **ABSTRACT**

A system and method that scrambles the phase characteristic of a carrier signal are described. The scrambling of the phase characteristic of each carrier signal includes associating a value with each carrier signal and computing a phase shift for each carrier signal based on the value associated with that carrier signal. The value is determined independently of any input bit value carried by that carrier signal. The phase shift computed for each carrier signal is combined with the phase characteristic of that carrier signal so as to substantially scramble the phase characteristic of the carrier signals. Bits of an input signal are modulated onto the carrier signals having the substantially scrambled phase characteristic to produce a transmission signal with a reduced PAR.

12 Claims, 2 Drawing Sheets



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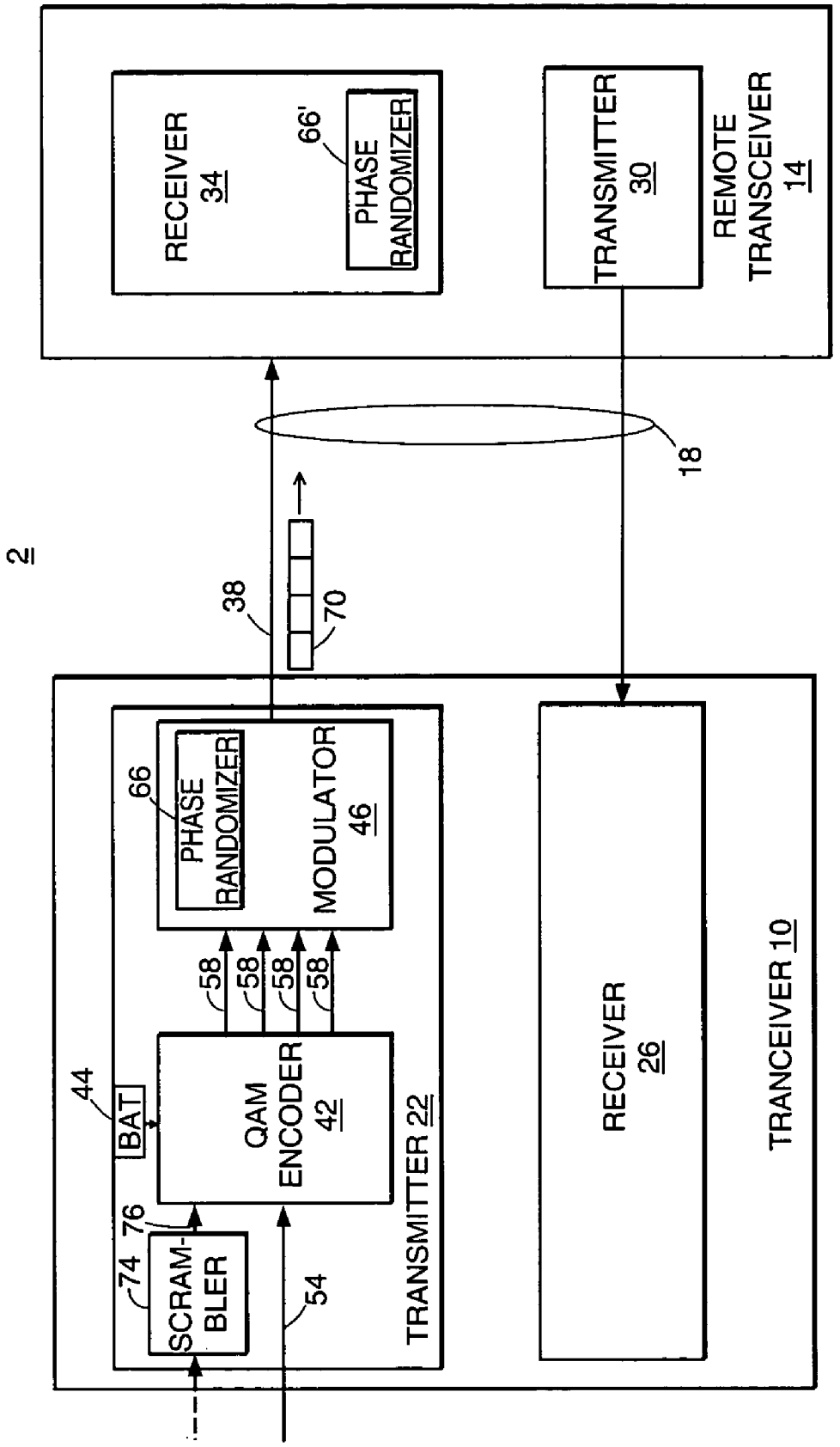
2
RECEIVER
34
66'
PHASE
RANDOMIZER
TRANSMITTER
30
REMOTE
TRANSCEIVER
14
18
38
70
66
PHASE
RANDOMIZER
MODULATOR
46
58
58
58
58
44
BAT
QAM
ENCODER
42
76
74
SCRAM-
BLER
54
TRANSMITTER 22
RECEIVER
26
TRANCEIVER 10

FIG. 1

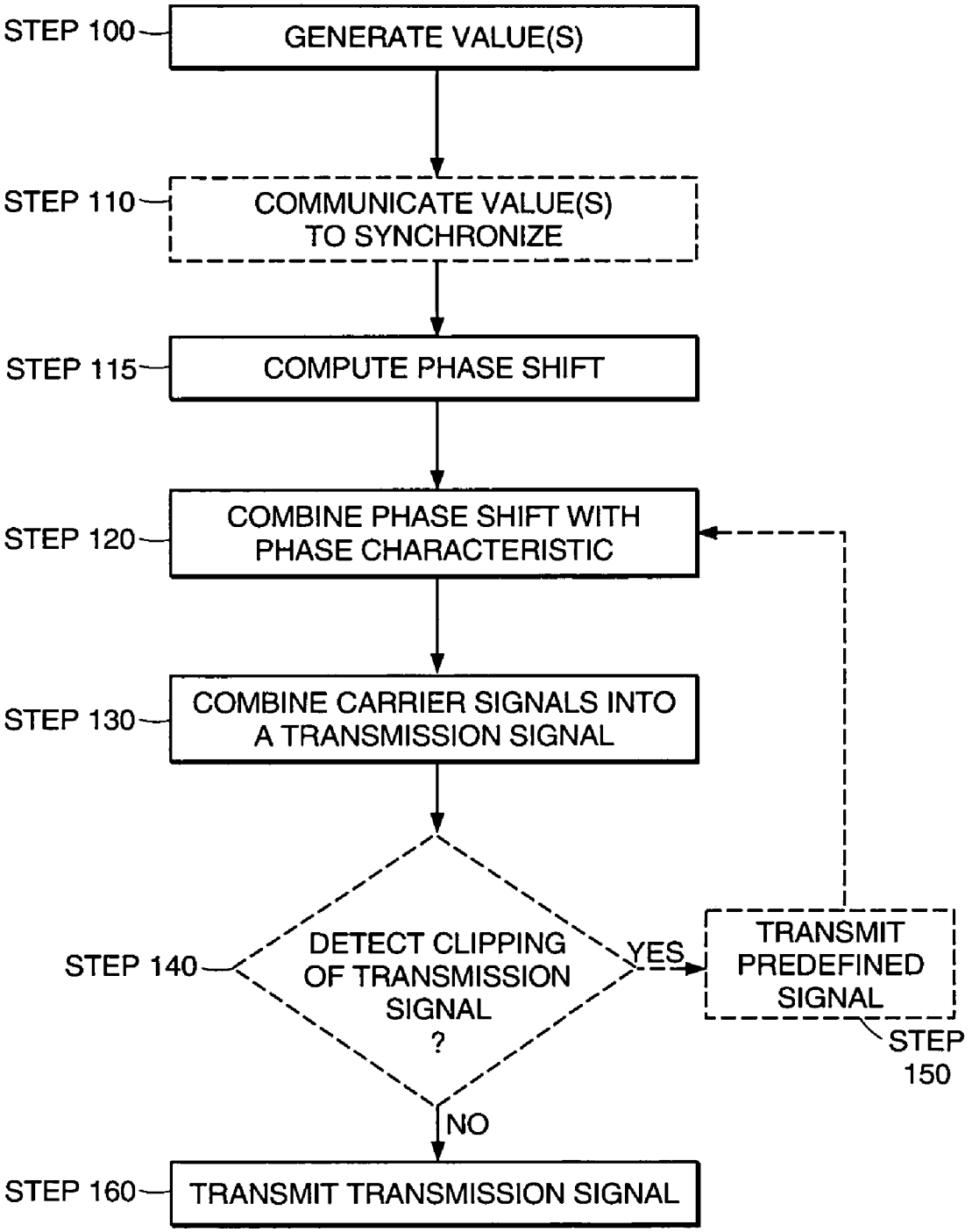
STEP 100
GENERATE VALUE(S)
STEP 110
COMMUNICATE VALUE(S) TO SYNCHRONIZE
STEP 115
COMPUTE PHASE SHIFT
STEP 120
COMBINE PHASE SHIFT WITH PHASE CHARACTERISTIC
STEP 130
COMBINE CARRIER SIGNALS INTO A TRANSMISSION SIGNAL
STEP 140
DETECT CLIPPING OF TRANSMISSION SIGNAL ?
YES
TRANSMIT PREDEFINED SIGNAL
STEP 150
NO
STEP 160
TRANSMIT TRANSMISSION SIGNAL

FIG. 2

SYSTEM AND METHOD FOR SCRAMBLING THE PHASE OF THE CARRIERS IN A MULTICARRIER COMMUNICATIONS SYSTEM

RELATED APPLICATION

This application claims the benefit of the filing date of copending U.S. Provisional Application, Ser. No. 60/164,134, filed Nov. 9, 1999, entitled "A Method For Randomizing The Phase Of The Carriers In A Multicarrier Communications System To Reduce The Peak To Average Power Ratio Of The Transmitted Signal," the entirety of which provisional application is incorporated by reference herein.

FIELD OF THE INVENTION

This invention relates to communications systems using multicarrier modulation. More particularly, the invention relates to multicarrier communications systems that lower the peak-to-average power ratio (PAR) of transmitted signals.

BACKGROUND OF THE INVENTION

In a conventional multicarrier communications system, transmitters communicate over a communication channel using multicarrier modulation or Discrete Multitone Modulation (DMT). Carrier signals (carriers) or sub-channels spaced within a usable frequency band of the communication channel are modulated at a symbol (i.e., block) transmission rate of the system. An input signal, which includes input data bits, is sent to a DMT transmitter, such as a DMT modem. The DMT transmitter typically modulates the phase characteristic, or phase, and amplitude of the carrier signals using an Inverse Fast Fourier Transform (IFFT) to generate a time domain signal, or transmission signal, that represents the input signal. The DMT transmitter transmits the transmission signal, which is a linear combination of the multiple carriers, to a DMT receiver over the communication channel.

The phase and amplitude of the carrier signals of DMT transmission signal can be considered random because the phase and amplitude result from the modulation of an arbitrary sequence of input data bits comprising the transmitted information. Therefore, under the condition that the modulated data bit stream is random, the DMT transmission signal can be approximated as having a Gaussian probability distribution. A bit scrambler is often used in the DMT transmitter to scramble the input data bits before the bits are modulated to assure that the transmitted data bits are random and, consequently, that the modulation of those bits produces a DMT transmission signal with a Gaussian probability distribution.

With an appropriate allocation of transmit power levels to the carriers or sub-channels, such a system provides a desirable performance. Further, generating a transmission signal with a Gaussian probability distribution is important in order to transmit a transmission signal with a low peak-to-average ratio (PAR), or peak-to-average power ratio. The PAR of a transmission signal is the ratio of the instantaneous peak value (i.e., maximum magnitude) of a signal parameter (e.g., voltage, current, phase, frequency, power) to the time-averaged value of the signal parameter. In DMT systems, the PAR of the transmitted signal is determined by the probability of the random transmission signal reaching a certain peak voltage during the time interval required for a

certain number of symbols. An example of the PAR of a transmission signal transmitted from a DMT transmitter is 14.5 dB, which is equivalent to having a 1E-7 probability of clipping. The PAR of a transmission signal transmitted and received in a DMT communication system is an important consideration in the design of the DMT communication system because the PAR of a signal affects the communication system's total power consumption and component linearity requirements of the system.

If the phase of the modulated carriers is not random, then the PAR can increase greatly. Examples of cases where the phases of the modulated carrier signals are not random are when bit scramblers are not used, multiple carrier signals are used to modulate the same input data bits, and the constellation maps, which are mappings of input data bits to the phase of a carrier signal, used for modulation are not random enough (i.e., a zero value for a data bit corresponds to a 90 degree phase characteristic of the DMT carrier signal and a one value for a data bit corresponds to a −90 degree phase characteristic of the DMT carrier signal). An increased PAR can result in a system with high power consumption and/or with high probability of clipping the transmission signal. Thus, there remains a need for a system and method that can effectively scramble the phase of the modulated carrier signals in order to provide a low PAR for the transmission signal.

SUMMARY OF THE INVENTION

The present invention features a system and method that scrambles the phase characteristics of the modulated carrier signals in a transmission signal. In one aspect, a value is associated with each carrier signal. A phase shift is computed for each carrier signal based on the value associated with that carrier signal. The value is determined independently of any input bit value carried by that carrier signal. The phase shift computed for each carrier signal is combined with the phase characteristic of that carrier signal to substantially scramble the phase characteristics of the carrier signals.

In one embodiment, the input bit stream is modulated onto the carrier signals having the substantially scrambled phase characteristic to produce a transmission signal with a reduced peak-to-average power ratio (PAR). The value is derived from a predetermined parameter, such as a random number generator, a carrier number, a DMT symbol count, a superframe count, and a hyperframe count. In another embodiment, a predetermined transmission signal is transmitted when the amplitude of the transmission signal exceeds a certain level.

In another aspect, the invention features a method wherein a value is associated with each carrier signal. The value is determined independently of any input bit value carried by that carrier signal. A phase shift for each carrier signal is computed based on the value associated with that carrier signal. The transmission signal is demodulated using the phase shift computed for each carrier signal.

In another aspect, the invention features a system comprising a phase scrambler that computes a phase shift for each carrier signal based on a value associated with that carrier signal. The phase scrambler also combines the phase shift computed for each carrier signal with the phase characteristic of that carrier signal to substantially scramble the phase characteristic of the carrier signals. In one embodiment, a modulator, in communication with the phase scrambler, modulates bits of an input signal onto the carrier signals

having the substantially scrambled phase characteristics to produce a transmission signal with a reduced PAR.

DESCRIPTION OF THE DRAWINGS

The invention is pointed out with particularity in the appended claims. The advantages of the invention described above, as well as further advantages of the invention, may be better understood by reference to the following description taken in conjunction with the accompanying drawings, in which:

FIG. **1** is a block diagram of an embodiment of a digital subscriber line communications system including a DMT (discrete multitone modulation) transceiver, in communication with a remote transceiver, having a phase scrambler for substantially scrambling the phase characteristics of carrier signals; and

FIG. **2** is a flow diagram of an embodiment of a process for scrambling the phase characteristics of the carrier signals in a transmission signal.

DETAILED DESCRIPTION

FIG. **1** shows a digital subscriber line (DSL) communication system **2** including a discrete multitone (DMT) transceiver **10** in communication with a remote transceiver **14** over a communication channel **18** using a transmission signal **38** having a plurality of carrier signals. The DMT transceiver **10** includes a DMT transmitter **22** and a DMT receiver **26**. The remote transceiver **14** includes a transmitter **30** and a receiver **34**. Although described with respect to discrete multitone modulation, the principles of the invention apply also to other types of multicarrier modulation, such as, but not limited to, orthogonally multiplexed quadrature amplitude modulation (OQAM), discrete wavelet multitone (DWMT) modulation, and orthogonal frequency division multiplexing (OFDM).

The communication channel **18** provides a downstream transmission path from the DMT transmitter **22** to the remote receiver **34**, and an upstream transmission path from the remote transmitter **30** to the DMT receiver **26**. In one embodiment, the communication channel **18** is a pair of twisted wires of a telephone subscriber line. In other embodiments, the communication channel **18** can be a fiber optic wire, a quad cable, consisting of two pairs of twisted wires, or a quad cable that is one of a star quad cable, a Dieselhorst-Martin quad cable, and the like. In a wireless communication system wherein the transceivers **10**, **14** are wireless modems, the communication channel **18** is the air through which the transmission signal **38** travels between the transceivers **10**, **14**.

By way of example, the DMT transmitter **22** shown in FIG. **1** includes a quadrature amplitude modulation (QAM) encoder **42**, a modulator **46**, a bit allocation table (BAT) **44**, and a phase scrambler **66**. The DMT transmitter **22** can also include a bit scrambler **74**, as described further below. The remote transmitter **30** of the remote transceiver **14** comprises equivalent components as the DMT transmitter **22**. Although this embodiment specifies a detailed description of the DMT transmitter **22**, the inventive concepts apply also to the receivers **34**, **36** which have similar components to that of the DMT transmitter **22**, but perform inverse functions in a reverse order.

The QAM encoder **42** has a single input for receiving an input serial data bit stream **54** and multiple parallel outputs to transmit QAM symbols **58** generated by the QAM encoder **42** from the bit stream **54**. In general, the QAM encoder **42** maps the input serial bit-stream **54** in the time domain into parallel QAM symbols **58** in the frequency domain. In particular, the QAM encoder **42** maps the input serial data bit stream **54** into N parallel quadrature amplitude modulation (QAM) constellation points **58**, or QAM symbols **58**, where N represents the number of carrier signals generated by the modulator **46**. The BAT **44** is in communication with the QAM encoder **42** to specify the number of bits carried by each carrier signal. The QAM symbols **58** represent the amplitude and the phase characteristic of each carrier signal.

The modulator **46** provides functionality associated with the DMT modulation and transforms the QAM symbols **58** into DMT symbols **70** each comprised of a plurality of time-domain samples. The modulator **46** modulates each carrier signal with a different QAM symbol **58**. As a result of this modulation, carrier signals have phase and amplitude characteristics based on the QAM symbol **58** and therefore based on the input-bit stream **54**. In particular, the modulator **46** uses an inverse fast Fourier transform (IFFT) to change the QAM symbols **58** into a transmission signal **38** comprised of a sequence of DMT symbols **70**. The modulator **46** changes the QAM symbols **58** into DMT symbols **70** through modulation of the carrier signals. In another embodiment, the modulator **46** uses the inverse discrete Fourier transform (IDFT) to change the QAM symbols **58** into DMT symbols **70**. In one embodiment, a pilot tone is included in the transmission signal **38** to provide a reference signal for coherent demodulation of the carrier signals in the remote receiver **34** during reception of the transmission signal **38**.

The modulator **46** also includes a phase scrambler **66** that combines a phase shift computed for each QAM-modulated carrier signal with the phase characteristic of that carrier signal. Combining phase shifts with phase characteristics, in accordance with the principles of the invention, substantially scrambles the phase characteristics of the carrier signals in the transmission signal **38**. By scrambling the phase characteristics of the carrier signals, the resulting transmission signal **38** has a substantially minimized peak-to-average (PAR) power ratio. The phase scrambler **66** can be part of or external to the modulator **46**. Other embodiments of the phase scrambler **66** include, but are not limited to, a software program that is stored in local memory and is executed on the modulator **46**, a digital signal processor (DSP) capable of performing mathematical functions and algorithms, and the like. The remote receiver **34** similarly includes a phase scrambler **66'** for use when demodulating carrier signals that have had their phase characteristics adjusted by the phase scrambler **66** of the DMT transceiver **10**.

To compute a phase shift for each carrier signal, the phase scrambler **66** associates one or more values with that carrier signal. The phase scrambler **66** determines each value for a carrier signal independently of the QAM symbols **58**, and, therefore, independently of the bit value(s) modulated onto the carrier signal. The actual value(s) that the phase scrambler **66** associates with each carrier signal can be derived from one or more predefined parameters, such as a pseudo-random number generator (pseudo-RNG), a DMT carrier number, a DMT symbol count, a DMT superframe count, a DMT hyperframe count, and the like, as described in more detail below. Irrespective of the technique used to produce each value, the same technique is used by the DMT transmitter **22** and the remote receiver **34** so that the value associated with a given carrier signal is known at both ends of the communication channel **18**.

The phase scrambler **66** then solves a predetermined equation to compute a phase shift for the carrier signal, using the value(s) associated with that carrier signal as input that effects the output of the equation. Any equation suitable for computing phase shifts can be used to compute the phase shifts. When the equation is independent of the bit values of the input serial bit stream **54**, the computed phase shifts are also independent of such bit values.

In one embodiment (shown in phantom), the DMT transmitter **22** includes a bit scrambler **74**, which receives the input serial bit stream **54** and outputs data bits **76** that are substantially scrambled. The substantially scrambled bits **76** are then passed to the QAM encoder **42**. When the bit scrambler **74** is included in the DMT transmitter **22**, the operation of the phase scrambler **66** further assures that the transmission signal **38** has a Gaussian probability distribution and, therefore, a substantially minimized PAR.

FIG. **2** shows embodiments of a process used by the DMT transmitter **22** for adjusting the phase characteristic of each carrier signal and combining these carrier signals to produce the transmission signal **38**. The DMT transmitter **22** generates (step **100**) a value that is associated with a carrier signal. Because the value is being used to alter the phase characteristics of the carrier signal, both the DMT transmitter **22** and the remote receiver **34** must recognize the value as being associated with the carrier signal. Either the DMT transmitter **22** and the remote receiver **34** independently derive the associated value, or one informs the other of the associated value. For example, in one embodiment the DMT transmitter **22** can derive the value from a pseudo-RNG and then transmit the generated value to the remote receiver **34**. In another embodiment, the remote receiver **34** similarly derives the value from the same pseudo-RNG and the same seed as used by the transmitter (i.e., the transmitter pseudo-RNG produces the same series of random numbers as the receiver pseudo-RNG).

As another example, the DMT transmitter **22** and the remote receiver **34** can each maintain a symbol counter for counting DMT symbols. The DMT transmitter **22** increments its symbol counter upon transmitting a DMT symbol; the remote receiver **34** upon receipt. Thus, when the DMT transmitter **22** and the remote receiver **34** both use the symbol count as a value for computing phase shifts, both the DMT transmitter **22** and remote receiver **34** "know" that the value is associated with a particular DMT symbol and with each carrier signal of that DMT symbol.

Values can also be derived from other types of predefined parameters. For example, if the predefined parameter is the DMT carrier number, then the value associated with a particular carrier signal is the carrier number of that signal within the DMT symbol. The number of a carrier signal represents the location of the frequency of the carrier signal relative to the frequency of other carrier signals within a DMT symbol. For example, in one embodiment the DSL communication system **2** provides 256 carrier signals, each separated by a frequency of 4.3125 kHz and spanning the frequency bandwidth from 0 kHz to 1104 kHz. The DMT transmitter **22** numbers the carrier signals from 0 to 255. Therefore, "DMT carrier number **50**" represents the 51st DMT carrier signal which is located at the frequency of 215.625 kHz (i.e., 51×4.3125 kHz).

Again, the DMT transmitter **22** and the remote receiver **34** can know the value that is associated with the carrier signal because both the DMT transmitter **22** and the remote receiver **34** use the same predefined parameter (here, the DMT carrier number) to make the value-carrier signal association. In other embodiments (as exemplified above with the transmitter pseudo-RNG), the DMT transmitter **22** can transmit the value to the remote receiver **34** (or vice versa) over the communication channel **18**.

In other embodiments, other predefined parameters can be used in conjunction with the symbol count. One example of such a predefined parameter is the superframe count that increments by one every 69 DMT symbols. One exemplary implementation that achieves the superframe counter is to perform a modulo **68** operation on the symbol count. As another example, the DMT transmitter **22** can maintain a hyperframe counter for counting hyperframes. An exemplary implementation of the hyperframe count is to perform a modulo 255 operation on the superframe count. Thus, the hyperframe count increments by one each time the superframe count reaches 255.

Accordingly, it is seen that some predefined parameters produce values that vary from carrier signal to carrier signal. For example, when the predefined parameter is the DMT carrier number, values vary based on the frequency of the carrier signal. As another example, the pseudo-RNG generates a new random value for each carrier signal.

Other predefined parameters produce values that vary from DMT symbol **70** to DMT symbol **70**. For example, when the predefined parameter is the symbol count, the superframe count, or hyperframe count, values vary based on the numerical position of the DMT symbol **70** within a sequence of symbols, superframes, or hyperframes. Predefined parameters such as the pseudo-RNG, symbol count, superframe count, and superframe can also be understood to be parameters that vary values over time. Any one or combination of the predefined parameters can provide values for input to the equation that computes a phase shift for a given carrier signal.

In one embodiment, the phase scrambling is used to avoid clipping of the transmission signal **38** on a DMT symbol **70** by DMT symbol **70** basis. In this embodiment, the DMT transmitter **22** uses a value based on a predefined parameter that varies over time, such as the symbol count, to compute the phase shift. It is to be understood that other types of predefined parameters that vary the values associated with carrier signals can be used to practice the principles of the invention. As described above, the transceivers **10**, **14** may communicate (step **110**) the values to synchronize their use in modulating and demodulating the carrier signals.

The DMT transmitter **22** then computes (step **115**) the phase shift that is used to adjust the phase characteristic of each carrier signal. The amount of the phase shift combined with the phase characteristic of each QAM-modulated carrier signal depends upon the equation used and the one or more values associated with that carrier signal.

The DMT transmitter **22** then combines (step **120**) the phase shift computed for each carrier signal with the phase characteristic of that carrier signal. By scrambling the phase characteristics of the carrier signals, the phase scrambler **66** reduces (with respect to unscrambled phase characteristics) the combined PAR of the plurality of carrier signals and, consequently, the transmission signal **38**. The following three phase shifting examples, PS #1–PS #3, illustrate methods used by the phase scrambler **66** to combine a computed phase shift to the phase characteristic of each carrier signal.

PHASE SHIFTING EXAMPLE #1

Phase shifting example #1 (PS #1) corresponds to adjusting the phase characteristic of the QAM-modulated carrier signal associated with a carrier number N by

$$N \times \frac{\pi}{3},$$

modulo (mod) 2π. In this example, a carrier signal having a carrier number N equal to 50 has a phase shift added to the phase characteristic of that carrier signal equal to

$$50\times\frac{\pi}{3}(\mathrm{mod}2\pi)=\frac{2}{3}\pi.$$

The carrier signal with a carrier number N equal to 51 has a phase shift added to the phase characteristic of that carrier signal equal to

$$51\times\frac{\pi}{3}(\mathrm{mod}2\pi)=\pi.$$

The carrier signal with the carrier number N equal to 0 has no phase shift added to the phase characteristic of that carrier signal.

PHASE SHIFTING EXAMPLE #2

Phase shifting example #2 (PS #2) corresponds to adjusting the phase characteristic of the QAM-modulated carrier signal associated with a carrier number N by

$$(N+M)\times\frac{\pi}{4},$$

mod 2π, where M is the symbol count. In this example, a carrier signal having a carrier number N equal to 50 on DMT symbol count M equal to 8 has a phase shift added to the phase characteristic of that carrier signal equal to

$$(50+8)\times\frac{\pi}{4}(\mathrm{mod}2\pi)=\frac{\pi}{2}.$$

The carrier signal with the same carrier number N equal to 50 on the next DMT symbol count M equal to 9 has a phase shift added to the phase characteristic of that carrier signal equal to

$$(50+9)\times\frac{\pi}{4}(\mathrm{mod}2\pi)=\frac{3\pi}{4}.$$

PHASE SHIFTING EXAMPLE #3

Phase shifting example #3 (PS #3) corresponds to adjusting the phase characteristic of the QAM-modulated carrier signal associated with a carrier number N by

$$(X_N)\times\frac{\pi}{6},$$

mod 2π, where X_N is an array of N pseudo-random numbers. In this example, a carrier signal having a carrier number N equal to 5 and X_N equal to [3, 8, 1, 4, 9, 5, . . .] has a phase shift added to the phase characteristic of the carrier signal that is equal to

$$(9)\times\frac{\pi}{6}(\mathrm{mod}2\pi)=\frac{\pi}{3}.$$

(Note that 9 is the 5th value in X_N.) The carrier signal with a carrier number N equal to 6 has a phase shift added to the phase characteristic of the carrier signal equal to

$$(5)\times\frac{\pi}{6}(\mathrm{mod}2\pi)=\frac{5\pi}{3}.$$

It is to be understood that additional and/or different phase shifting techniques can be used by the phase scrambler **66**, and that PS #1, #2, and #3 are merely illustrative examples of the principles of the invention. The DMT transmitter **22** then combines (step **130**) the carrier signals to form the transmission signal **38**. If the transmission signal is not clipped, as described below, the DMT transmitter **22** consequently transmits (step **160**) the transmission signal **38** to the remote receiver **34**.

Clipping of Transmission Signals

A transmission signal **38** that has high peak values of voltage (i.e., a high PAR) can induce non-linear distortion in the DMT transmitter **22** and the communication channel **18**. One form of this non-linear distortion of the transmission signal **38** that may occur is the limitation of the amplitude of the transmission signal **38** (i.e., clipping). For example, a particular DMT symbol **70** clips in the time domain when one or more time domain samples in that DMT symbol **70** are larger than the maximum allowed digital value for the DMT symbols **70**. In multicarrier communication systems when clipping occurs, the transmission signal **38** does not accurately represent the input serial data bit signal **54**.

In one embodiment, the DSL communication system **2** avoids the clipping of the transmission signal **38** on a DMT symbol **70** by DMT symbol **70** basis. The DMT transmitter **22** detects (step **140**) the clipping of the transmission signal **38**. If a particular DMT symbol **70** clips in the time domain to produce a clipped transmission signal **38**, the DMT transmitter **22** substitutes (step **150**) a predefined transmission signal **78** for the clipped transmission signal **38**.

The predefined transmission signal **78** has the same duration as a DMT symbol **70** (e.g., 250 ms) in order to maintain symbol timing between the DMT transmitter **22** and the remote receiver **34**. The predefined transmission signal **78** is not based on (i.e., independent of) the modulated input data bit stream **54**; it is a bit value pattern that is recognized by the remote receiver **34** as a substituted signal. In one embodiment, the predefined transmission signal **78** is a known pseudo-random sequence pattern that is easily detected by the remote receiver **34**. In another embodiment, the predefined transmission signal **78** is an "all zeros" signal, which is a zero voltage signal produced at the DMT transmitter **22** output (i.e., zero volts modulated on all the carrier signals). In addition to easy detection by the remote receiver **34**, the zero voltage signal reduces the power consumption of the DMT transmitter **22** when delivered by the DMT transmitter **22**. Further, a pilot tone is included in the predefined transmission signal **78** to provide a reference signal for coherent demodulation of the carrier signals in the remote receiver **34** during reception of the predefined transmission signal **78**.

After the remote receiver **34** receives the transmission signal **38**, the remote receiver **34** determines if the transmission signal **38** is equivalent to the predefined transmission signal **78**. In one embodiment, when the remote receiver **34** identifies the predefined transmission signal **78**, the remote receiver **34** ignores (i.e., discards) the predefined transmission signal **78**.

Following the transmission of the predefined transmission signal **78**, the phase scrambler **66** shifts (step **120**) the phase characteristic of the QAM-modulated carrier signals (based on one of the predefined parameters that varies over time). For example, consider that a set of QAM symbols **58** produces a DMT symbol **70** comprising a plurality of time domain samples, and that one of the time domain samples is larger than the maximum allowed digital value for the DMT symbol **70**. Therefore, because the transmission signal **38** would be clipped when sent to the remote receiver **34**, the DMT transmitter **22** sends the predefined transmission signal **78** instead.

=After transmission of the predefined transmission signal **78**, the DMT transmitter **22** again attempts to send the same bit values that produced the clipped transmission signal **38** in a subsequent DMT symbol **70'**. Because the generation of phase shifts in this embodiment is based on values that vary over time, the phase shifts computed for the subsequent DMT symbol **70'** are different than those that were previously computed for the DMT symbol **70** with the clipped time domain sample. These different phase shifts are combined to the phase characteristics of the modulated carrier signals to produce carrier signals of the subsequent DMT symbol **70'** with different phase characteristics than the carrier signals of the DMT symbol **70** with the clipped time domain sample.

DMT communication systems **2** infrequently produce transmission signals **38** that clip (e.g., approximately one clip every 10^7 time domain samples **70**). However, if the subsequent DMT symbol **70'** includes a time domain sample that clips, then the predefined transmission signal **78** is again transmitted (step **150**) to the remote receiver **34** instead of the clipped transmission signal **38**. The clipping time domain sample may be on the same or on a different carrier signal than the previously clipped DMT symbol **70**. The DMT transmitter **22** repeats the transmission of the predefined transmission signal **78** until the DMT transmitter **22** produces a subsequent DMT symbol **70'** that is not clipped. When the DMT transmitter **22** produces a DMT symbol **70'** that is not clipped, the DTM transmitter **22** transmits (step **160**) the transmission signal **38** to the remote receiver **34**. The probability of a DMT symbol **70** producing a transmission signal **38** that clips in the time domain depends on the PAR of the transmission signal **38**.

For example, the following phase shifting example, PST #4, illustrates the method used by the phase scrambler **66** to combine a different phase shift to the phase characteristic of each carrier signal to avoid the clipping of the transmission signal **38**.

PHASE SHIFTING EXAMPLE #4

Phase shifting example #4 (PS #4) corresponds to adjusting the phase characteristic of the carrier signal associated with a carrier number N by

$$\frac{\pi}{3}\times(M+N),$$

mod 2π, where M is the DMT symbol count. In this example, if the DMT symbol **70** clips when the DMT symbol count M equals 5, the predefined transmission signal **78** is transmitted instead of the current clipped transmission signal **38**. On the following DMT symbol period, the DMT count M equals 6, thereby causing a different set of time domain samples to be generated for the subsequent DMT symbol **70'**, although the QAM symbols **58** used to produce both DMT symbols **70**, **70'** are the same.

If this different set of time domain samples (and consequently the transmission signal **38**) is not clipped, the DMT transmitter **22** sends the transmission signal **38**. If one of the time domain samples in the different set of time domain samples **70** (and consequently the transmission signal **38**) is clipped, then the DMT transmitter **22** sends the predefined transmission signal **78** again. The process continues until a DMT symbol **70** is produced without a time domain sample **70** that is clipped. In one embodiment, the transmitter **22** stops attempting to produce a non-clipped DMT symbol **70'** for the particular set of QAM symbols **58** after generating a predetermined number of clipped DMT symbols **70'**. At that moment, the transmitter **22** can transmit the most recently produced clipped DMT symbol **70'** or the predetermined transmission signal **78**.

The PAR of the DSL communication system **2** is reduced because the predefined transmission signal **78** is sent instead of the transmission signal **38** when the DMT symbol **70** clips. For example, a DMT communication system **2** that normally has a clipping probability of 10^{-7} for the time domain transmission signal **38** can therefore operate with a 10^{-5} probability of clipping and a lower PAR equal to 12.8 dB (as compared to 14.5 dB). When operating at a 10^{-5} probability of clipping, assuming a DMT symbol **70** has 512 time-domain samples **70**, the DMT transmitter **22** experiences one clipped DMT symbol **70** out of every

$$\frac{10^5}{512},$$

or 195 DMT symbols **70**. This results in the predefined (non-data carrying) transmission signal **78** being transmitted, on average, once every 195 DMT symbols. Although increasing the probability of clipping to 10^{-5} results in approximately a 0.5% (1/195) decrease in throughput, the PAR of the transmission signal **38** is reduced by 1.7 dB, which reduces transmitter complexity in the form of power consumption and component linearity.

While the invention has been shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the following claims. For example, although the specification uses DSL to describe the invention, it is to be understood that various form of DSL can be used, e.g., ADSL, VDSL, SDSL, HDSL, HDSL2, or SHDSL. It is also to be understood that the principles of the invention apply to various types of applications transported over DSL systems (e.g., telecommuting, video conferencing, high speed Internet access, video-on demand).

What is claimed is:

1. In multicarrier modulation communications utilizing a plurality of QAM-modulated carrier signals, each carrier signal having a phase characteristic based on a QAM modulation, a method of randomizing the phase characteristics of the carriers comprising:

generating an array of pseudo-random numbers;

determining a phase shift for each carrier signal by multiplying a value from the array of pseudo-random numbers times (π/m) mod 2π, where m is an integer; and

adding the determined phase shift for each carrier signal to the phase characteristic of each carrier signal.

2. The method of claim **1**, wherein the method is performed in a multicarrier transmitter.

3. The method of claim **1**, wherein the method is performed in a multicarrier receiver.

4. In multicarrier modulation communications utilizing a plurality of QAM-modulated carrier signals, each carrier signal having a phase characteristic based on a QAM modulation, a system for randomizing the phase characteristics of the carriers comprising:

means for generating an array of pseudo-random numbers;

means for determining a phase shift for each carrier signal by multiplying a value from the array of pseudo-random numbers times $(\pi/m) \bmod 2\pi$, where m is an integer; and

means for adding the determined phase shift for each carrier signal to the phase characteristic of each carrier signal.

5. The system of claim **4**, wherein the system is associated with a multicarrier transmitter.

6. The method of claim **4**, wherein the system is associated with a multicarrier receiver.

7. In multicarrier modulation device utilizing a plurality of QAM-modulated carrier signals, each carrier signal having a phase characteristic based on a QAM modulation, the device configured to randomize the phase characteristics of the carriers comprising:

A generator generates an array of pseudo-random numbers;

a modulator adapted to determine a phase shift for each carrier signal by multiplying a value from the array of pseudo-random numbers times $(\pi/m) \bmod 2\pi$, where m is an integer and to add the determined phase shift for each carrier signal to the phase characteristic of each carrier signal.

8. The device of claim **7**, wherein the device is a transmitter.

9. The device of claim **7**, wherein the device is a receiver.

10. In multicarrier modulation communications utilizing a plurality of QAM-modulated carrier signals, each carrier signal having a phase characteristic based on a QAM modulation, an information storage media having information stored thereon that randomizes the phase characteristics of the carriers comprising:

information that generates an array of pseudo-random numbers;

information that determines a phase shift for each carrier signal by multiplying a value from the array of pseudo-random numbers times $(\pi/m) \bmod 2\pi$, where m is an integer; and

information that adds the determined phase shift for each carrier signal to the phase characteristic of each carrier signal.

11. The media of claim **10**, wherein the information operates in a multicarrier transmitter.

12. The media of claim **10**, wherein the information operates in a multicarrier receiver.

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