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(54) **SYSTEM AND METHOD FOR MODULATION OF NON-DATA BEARING CARRIERS IN A MULTI-CARRIER MODULATION SYSTEM**

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(57) **ABSTRACT**

For one aspect of the invention, a method is described for mitigating power spectral density irregularities in a multi-carrier modulation environment. The method involves identifying at least one carrier of a plurality of carriers that is in a non-data bearing state. Thereafter, that carrier is modulated with random data.

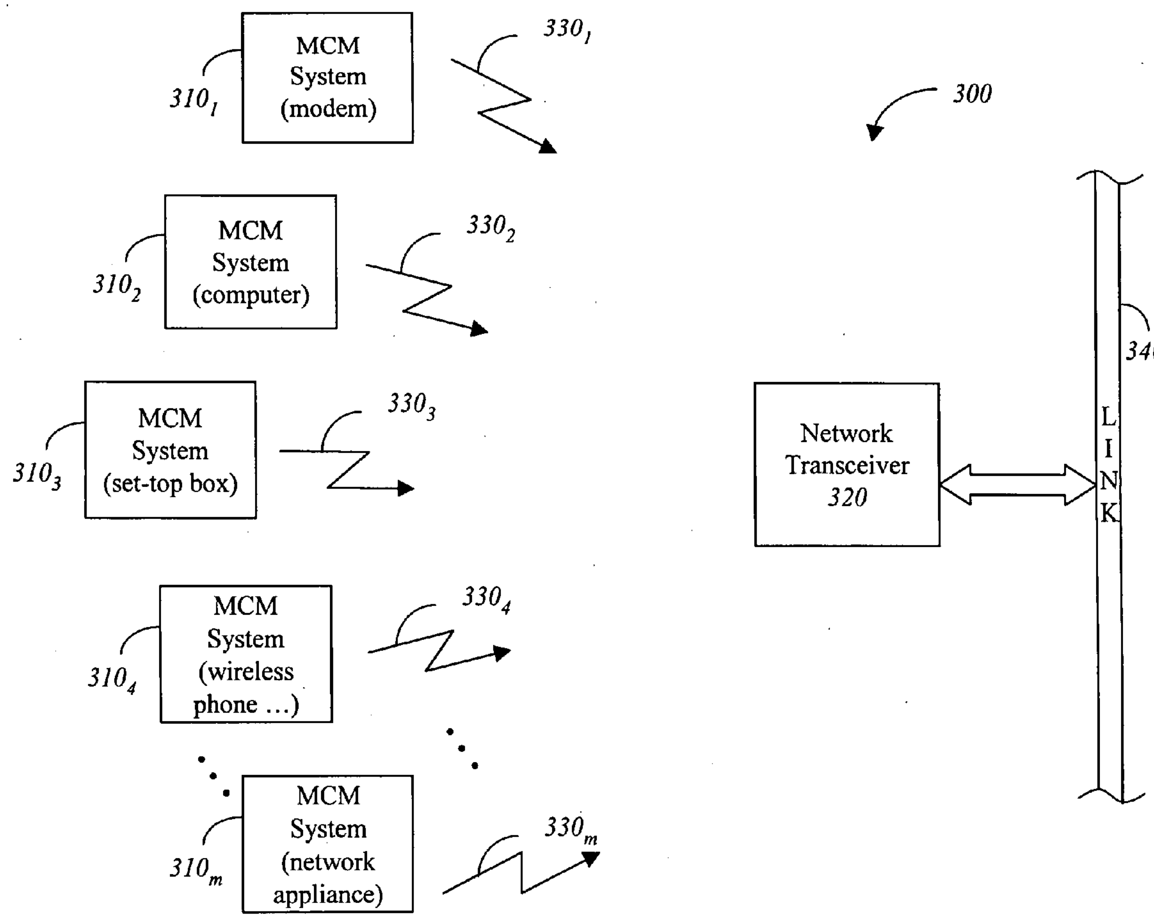


Figure 1

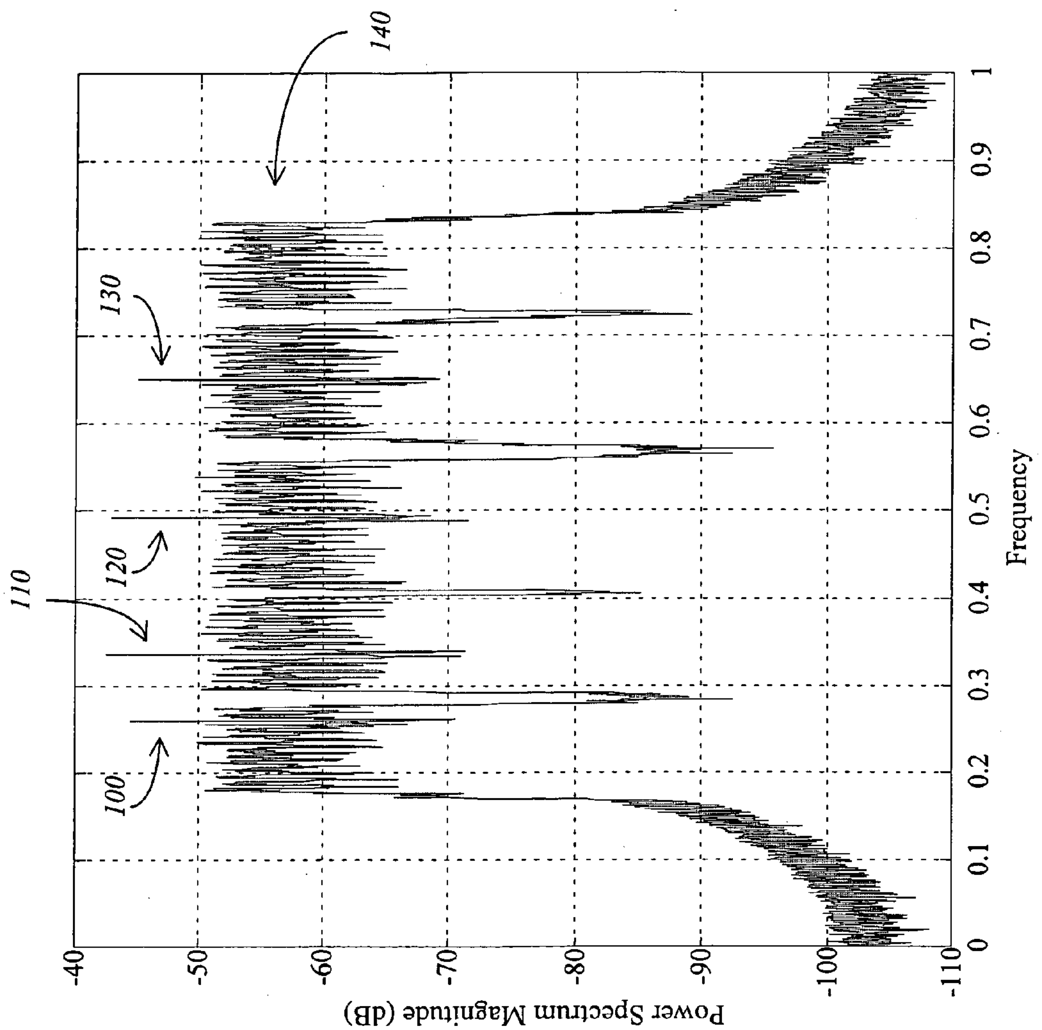
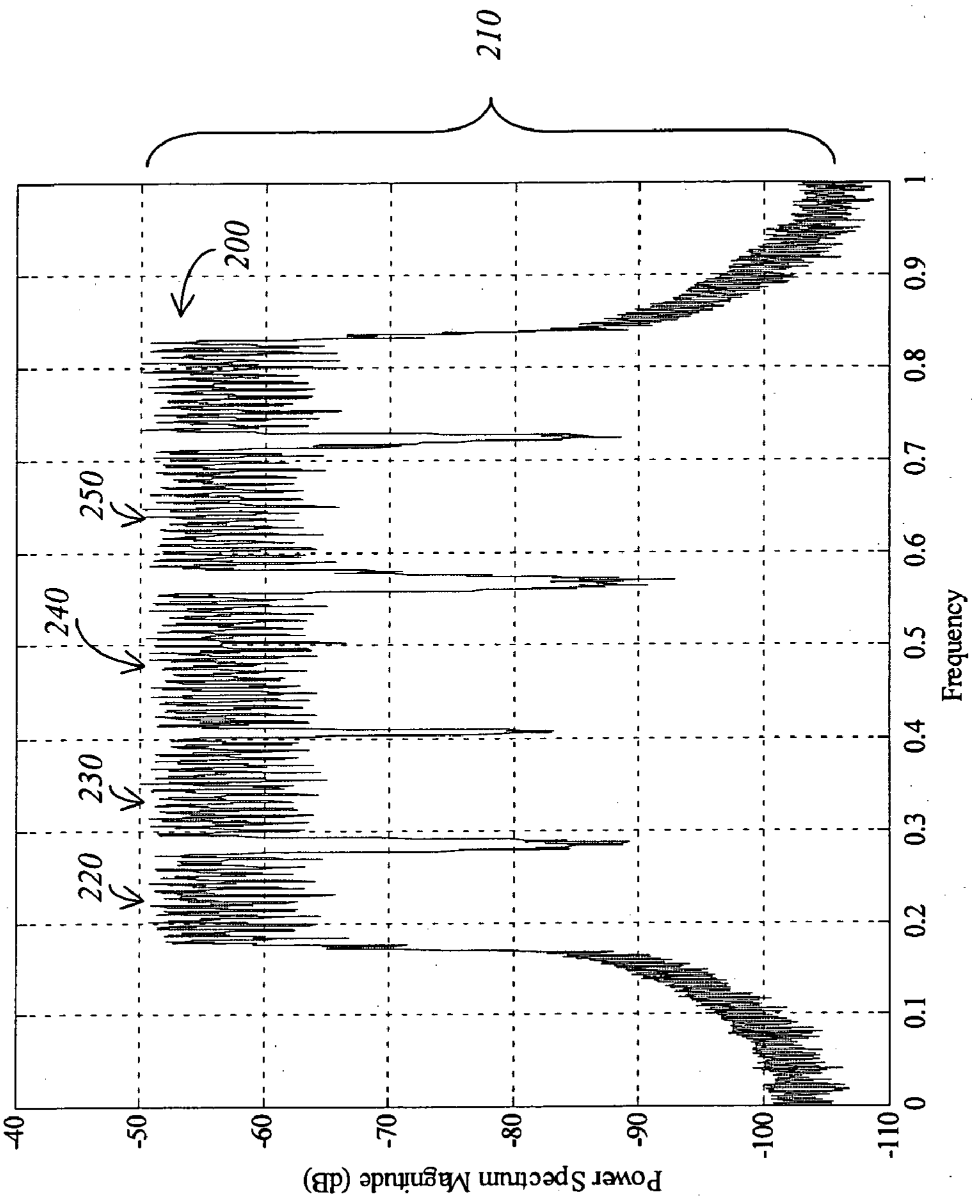

100
110
120
130
140
Power Spectrum Magnitude (dB)
Frequency
-40
-50
-60
-70
-80
-90
-100
-110
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 2


210
200
220
230
240
250
Power Spectrum Magnitude (dB)
-40
-50
-60
-70
-80
-90
-100
-110
Frequency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

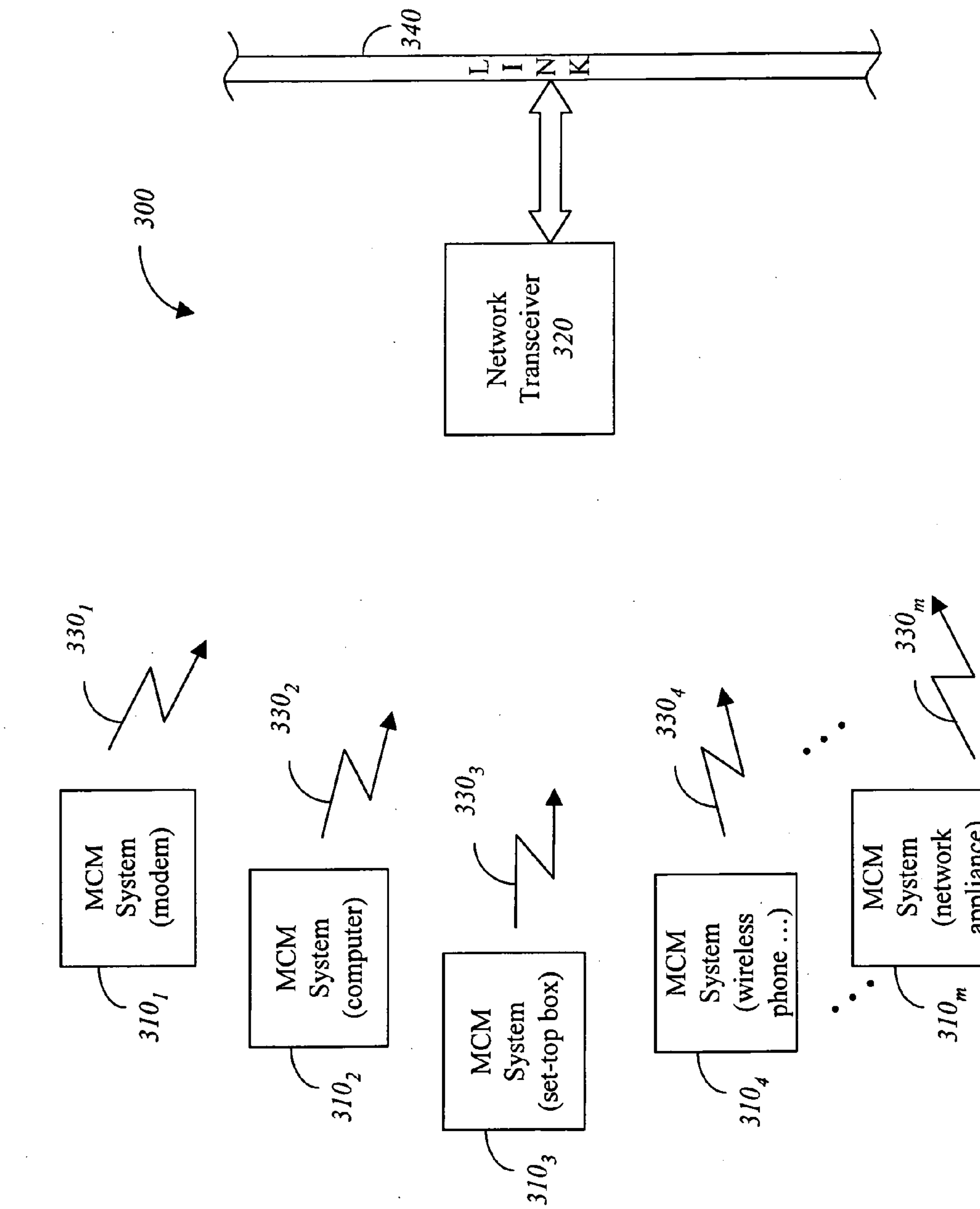

300
340
LINK
Network Transceiver 320
MCM System (modem)
310_1
330_1
MCM System (computer)
310_2
330_2
MCM System (set-top box)
310_3
330_3
MCM System (wireless phone ...)
310_4
330_4
MCM System (network appliance)
310_m
330_m

Figure 3

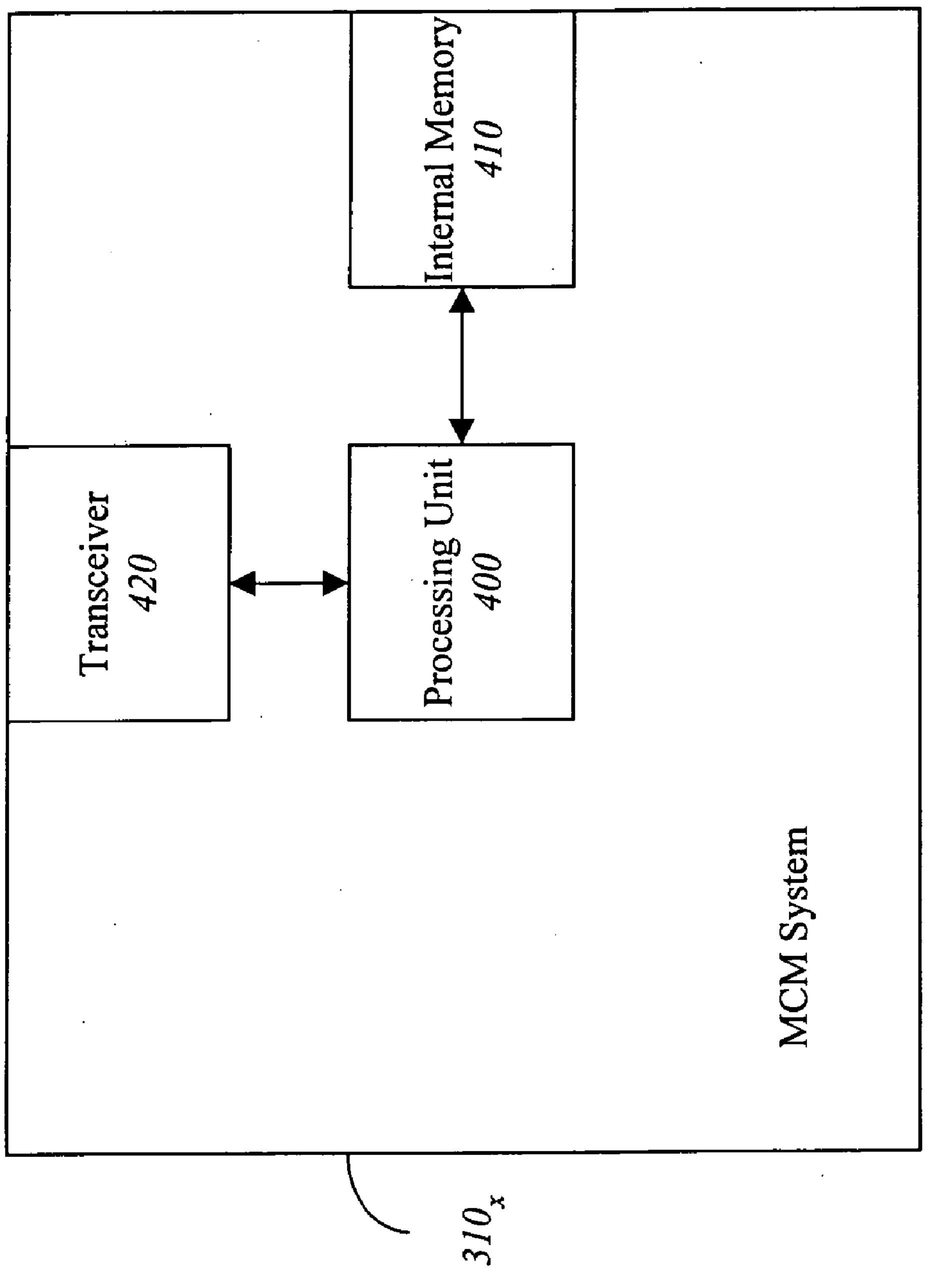

Internal Memory
410
Transceiver
420
Processing Unit
400
MCM System
310_x

Figure 4

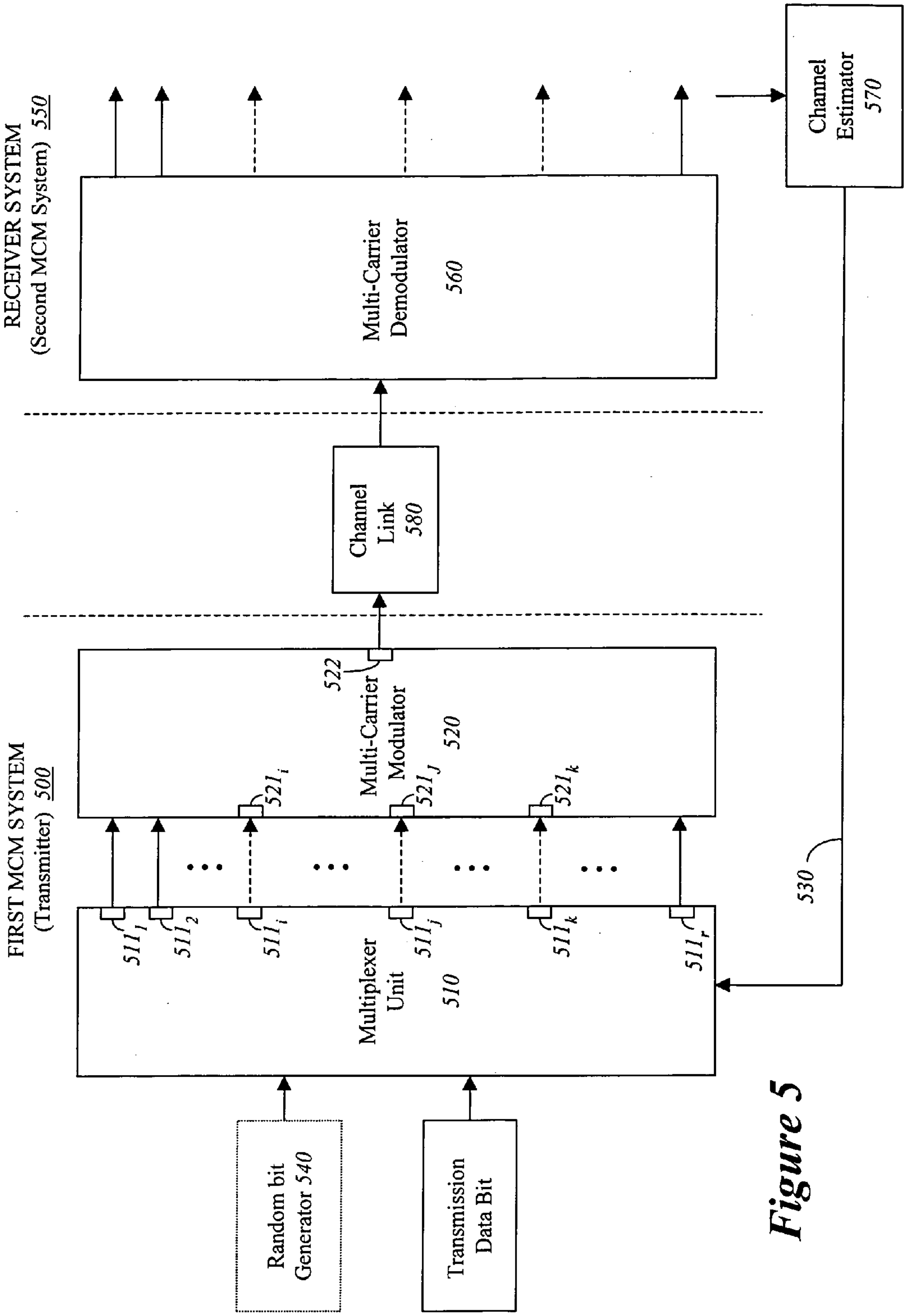

RECEIVER SYSTEM
(Second MCM System) 550
Multi-Carrier
Demodulator
560
Channel
Estimator
570
Channel
Link
580
FIRST MCM SYSTEM
(Transmitter) 500
Multi-Carrier
Modulator
520
522
521_i
521_j
521_k
Multiplexer
Unit
510
511_1
511_2
511_i
511_j
511_k
511_r
530
Random bit
Generator 540
Transmission
Data Bit

Figure 5

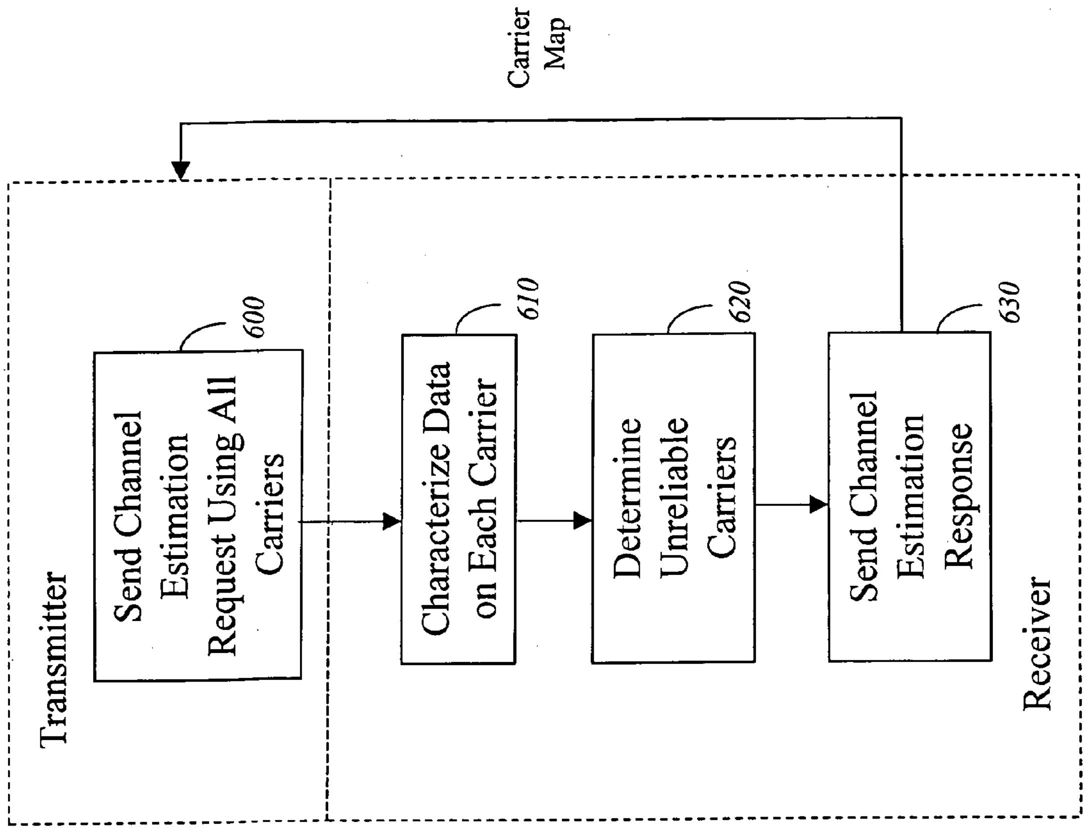

Carrier Map
Transmitter
Send Channel Estimation Request Using All Carriers
600
Characterize Data on Each Carrier
610
Determine Unreliable Carriers
620
Send Channel Estimation Response
630
Receiver

Figure 6

SYSTEM AND METHOD FOR MODULATION OF NON-DATA BEARING CARRIERS IN A MULTI-CARRIER MODULATION SYSTEM

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a continuation of application Ser. No. 09/883,554, filed Jun. 16, 2001.

FIELD

[0002] The invention relates to the field of communications. In particular, one embodiment of the invention relates to a system and method for mitigating power spectral density irregularities through modulation of random data onto non-data bearing carriers.

GENERAL BACKGROUND

[0003] For many years, a number of modulation techniques have been used to transfer data from a source to a destination. One type of modulation technique is referred to as multi-carrier modulation (MCM). In accordance with MCM, data is split into several data components and each of these data components is transmitted over separate carriers so that each individual carrier has a narrower bandwidth than the composite signal. In general, a "carrier" is an electromagnetic pulse or wave transmitted at a steady base frequency of alternation on which information can be imposed. Of course, when used in connection with fiber optic medium, the carrier may be a light beam on which information can be imposed.

[0004] Currently, there exist a number of multi-carrier modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) for example. OFDM subdivides the available spectrum into a number of narrow band channels (e.g., 100 channels or more). The carriers for each channel may be spaced much closer together than Frequency Division Multiplexing (FDM) based systems because each carrier is configured to be orthogonal to its adjacent carriers. This orthogonal relationship may be achieved by setting each carrier to have an integer number of cycles over a symbol period. Thus, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing then to be spaced as close as theoretically possible.

[0005] In many instances, MCM systems are designed to avoid modulating information onto carriers that are unreliable, placing them in a "non-data bearing" state. The carriers are rendered unreliable when they are experiencing unfavorable channel characterizations such as fading, a high degree of interference and the like. Normally, a carrier is determined to be "unreliable" based on channel measurements at the receiver. Since channel characterizations for each unreliable carrier may vary over time, they are periodically monitored through modulation of constant or alternating data (e.g., logic "0"s or "1"s) onto these carriers (i.e., an unreliable carrier is modulated with constant data). Non-data bearing carriers may also be used as pilot tones for channel estimation, timing and carrier recovery.

[0006] When using an Inverse Fast Fourier Transform (IFFT) to produce multiple carriers, constant or alternating data modulated carries result in harmonics with concentrated energy at these non-data bearing carriers, which produce Power Spectral Density (PSD) irregularities or peaks at these carriers.

[0007] For example, as shown in **FIG. 1**, a power spectrum of a transmit signal (e.g., a HOMEPLUG™ packet) using an OFMD modulation technique is illustrated. As shown, four carriers associated with channels **10**, **20**, **40** and **60** are modulated with constant data (e.g., "11" for Differential Quadrature Phase Shift Keying "DQPSK"). This causes PSD peaks **100**, **110**, **120** and **130** at those carriers rising approximately eight decibels (8 dB) above the power spectrum **140**.

[0008] As a result, in order to comply with strict Federal Communication Commission (FCC) power level standards and avoid interference to other users of the band, the total power of the transmit signal must be reduced. This reduces signal quality (e.g., signal-to-noise ratio) detected at the receiver which, in turn, reduces coverage of the receiver, data throughput, and the like.

[0009] Thus, it would be advantageous to develop a modulation technique that mitigates PSD irregularities occurring at non-data bearing carriers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The features and advantages of the present invention will become apparent from the following detailed description of the present invention in which:

[0011] **FIG. 1** is a power spectrum of a transmit signal (e.g., a HOMEPLUG™ packet) using an OFMD modulation technique.

[0012] **FIG. 2** is an exemplary embodiment of a power spectrum of a composite transmit signal of **FIG. 1** produced by a multi-carrier modulation (MCM) system that modulates random data onto non-data bearing carriers.

[0013] **FIG. 3** is an exemplary embodiment of a communication network utilizing the invention.

[0014] **FIG. 4** is an exemplary embodiment of internal logic of a MCM system.

[0015] **FIG. 5** is an exemplary embodiment of a general block diagram illustrative of logic within a first MCM system (transmitter) that modulates non-data bearing carriers with random data for transmission to a second MCM system (receiver)

[0016] **FIG. 6** is an exemplary embodiment of operations between a transmitter and a receiver in accordance with non-data bearing carrier random modulation.

DETAILED DESCRIPTION

[0017] Herein, various embodiments of the invention relate to a system and method for mitigating power spectral density irregularities through modulation of random data onto non-data bearing carriers, namely modulating each carrier currently in a non-data bearing state with random data. Herein, this "non-data bearing" state compromises a level of operation where a carrier is used for other purposes besides data transmission such as synchronization, carrier recovery, timing recovery, channel characterization, and may be also in an "unreliable" state when that carrier is experiencing unfavorable channel characterizations. Of course, non-data bearing carriers may also be used as pilot tones for channel estimation, timing and carrier recovery.

[0018] The embodiments described herein are not exclusive; rather, they merely provide a thorough understanding of the invention. Also, well-known circuits are not set forth in detail in order to avoid unnecessarily obscuring the invention.

[0019] In the following description, certain terminology is used to describe certain features of the invention. For example, "logic" includes hardware, firmware, software or any combination thereof that performs a desired function on input data. For example, in one embodiment, logic comprises a processing unit accessing software contained in memory to perform a non-data bearing carrier random data modulation scheme as described in greater detail in **FIGS. 5-6**. Examples of a "processing unit" include as a digital signal processor, a microprocessor, a micro-controller, an application specific integrated circuit (ASIC), a field programmable gate array, a state machine, combinatorial logic and the like.

[0020] In addition, a "link" is generally defined as one or more physical or virtual information-carrying mediums to establish a communication pathway. Examples of the medium include a physical medium (e.g., electrical wire, optical fiber, cable, bus traces, etc.) or a wireless medium (e.g., air in combination with wireless signaling technology). In one embodiment, the link may be an Alternating Current (AC) power line, perhaps routing information in accordance with a HOMEPLUG™ standard. One version of the HOMEPLUG™ standard is entitled "Release V0.8 Medium Interface Specification" published on or around May 25, 2001.

[0021] In general, a "non-data bearing" carrier may occur in any modulation scheme that produces a carrier or pilot tone that is used for other purposes besides data transmission, such as synchronization, carrier recovery, timing recovery or channel characterization for example. Various applications may include, but are not limited or restricted to Orthogonal Frequency Division Multiplexing (OFDM), Frequency Division Multiple Access (FDMA), Spread Spectrum, Frequency Division Multiplexing (FDM) or even wavelet based modulation.

[0022] Referring to **FIG. 2**, an exemplary embodiment of a power spectrum of a composite transmit signal produced by a multi-carrier modulation (MCM) system that modulates random data onto non-data bearing carriers is shown. The power spectrum **200** is produced for a composite transmit signal **210** having N carriers, where "N" is a positive integer ($N \geqq 1$). As shown previously in **FIG. 1**, the transmit signal **210** features non-data bearing carrier numbers **10**, **20**, **40** and **60**, which are represented by labels **220**, **230**, **240** and **250**, that are now modulated with random data. This method is referred to herein as "non-data bearing carrier random modulation." The "random data" may be either (1) truly random in nature and produced by a random bit generator or (2) pseudo-random in nature and produced by a pseudo-random bit generator.

[0023] As shown in **FIG. 2**, the modulation of non-data bearing carriers with random data greatly mitigates the presence of power spectral density (PSD) irregularities at frequencies associated with non-data bearing carriers **220**, **230**) and **240** and **250**. The reduction of PSD irregularities is due to the non-periodic nature of the modulated carrier. Thus, power is not concentrated at these portions of the power spectrum **200**, but rather is continuously distributed.

[0024] Referring to **FIG. 3**, an exemplary embodiment of a communication network utilizing the invention is shown. The communication network **300** comprises a plurality of MCM systems $\mathbf{310}_1$-$\mathbf{310}_M$ ($M \geqq 1$) in communication with a network transceiver **320** via links $\mathbf{330}_i$-$\mathbf{330}_M$. These links $\mathbf{330}_1$-$\mathbf{330}_M$ may be wired or wireless links. In addition, the network transceiver **320** may be further coupled to a link **340** operating as networking lines for an establishment (e.g., residence, apartment building, place of business, etc.) as shown. For instance, the link **340** may be electrical wiring (e.g., AC power line) which data is transmitted over such wiring in accordance with current or future HOMEPLUG™ standards. Examples of the "network transceiver" include a computer (e.g., gateway, server, etc.), a router, a switching device, a wireless networking access point (e.g., WLAN access point). Of course, although not shown, one or more of the MCM systems $\mathbf{310}_1$-$\mathbf{310}_M$ may be configured to communicate with other MCM system(s) acting as transceiver(s).

[0025] Each MCM system $\mathbf{310}_1$, . . . , or $\mathbf{310}_M$ is a product that supports the non-data bearing carrier random modulation scheme, namely the modulation of reliable carriers with the data to be transmitted and the modulation of the non-data bearing carriers with random data. The modulated carriers are transmitted over a composite channel to the network transceiver **320** (or another MCM system) acting as a receiver. Examples of certain types of MCM systems include various types of MCM modems (wired or wireless), a computer with wireless connectivity (e.g., a gateway or server, hand-held "PDA", a data terminal, laptop, desktop, etc.), a set-top box, a network appliance, a wireless communication device (e.g., phones, pager, etc.) and the like.

[0026] Referring now to **FIG. 4**, an exemplary embodiment of internal logic of a MCM system is shown. The MCM system $\mathbf{310}_x$ includes a processing unit **400**, an internal memory **410** and a transceiver **420**. Configured as any readable storage device such as a magnetic, optical, or semiconductor storage medium, the internal memory **410** may be either physically independent from the processing unit **400** or integrated within the processing unit **400**. In one embodiment, the internal memory **410** may be implemented as any type of non-volatile memory such as flash memory, hard disk, on-chip ROM and the like. Of course, it is contemplated that the internal memory **410** may include volatile memory or a combination of volatile and non-volatile memory. The internal memory **410** stores multi-carrier modulation software, which enables the processing unit **400** to perform non-data bearing carrier random modulation. Of course, it is contemplated that the MOM system $\mathbf{310}_x$ does not require memory if its non-data bearing carrier random modulation functionality is hard-wired.

[0027] The transceiver **420** enables modulated carrier signals to be output over a link and destined for receipt by the network transceiver **320** of **FIG. 3** or perhaps another MCM system (not shown). The transceiver **420** further enables channel characterization data to be received from the network transceiver **320** (or another MCM system) as well.

[0028] Referring to **FIG. 5**, an exemplary embodiment of a general block diagram illustrative of logic within a first

MCM system (transmitter) **500** (e.g., MCM system **310**$_x$) that modulates non-data bearing carriers with random data for transmission to a receiver system **550** (e.g., a second MCM system, network transceiver **320** of **FIG. 3**, etc.) is shown. For this embodiment, the first MCM system **500** comprises a multiplexer unit **510**, a multi-carrier modulator **520** and a feedback link **530**. A (pseudo) random bit generator **540** may be implemented within the first MCM system **500** as represented by dashed lines. The receiver system **550** includes a multi-carrier demodulator **560** and a channel estimator **570**. These systems **500** and **550** communicate over a channel link **580**.

[**0029**] Herein, the feedback link **530** provides data from the channel estimator **570** of the receiver system **550** as to which carriers of a transmit signal, if any, possess channel characterization that would cause them to be deemed to exist in an unreliable state. For example, the channel estimator **570** may operate in accordance with blind channel estimation (no knowledge of the transmitted data is required) or data based channel estimation (knowledge of the transmitted data is required so pseudo-RNG used). Both types of channel estimation may analyze signal-to-noise ratio (SNR), bit error rate (BER) and/or other signal characteristics of each carrier. The channel characterization of each carrier may be carried out by observing the general characteristics of the signal such as SNR (blind) or by observing the quality of the values transferred to the receiver system (data based) **550** and/or comparing them to values previously stored therein. For example, the transmit signal may be transferred in an encoded format, decoded at the receiver system **550** and re-encoded for comparison with the original received signal.

[**0030**] The multiplexer unit **510** uses the data provided from the channel estimator **570**, which is referred to as "carrier map," to select which output ports **511**$_1$, . . . , **511**$_R$ provide desired transmission data or random data. Perhaps, as an option, the number of output ports corresponding to the number of carriers forming the transmit signal as shown (e.g., R=N). For clarity, as represented by dashed lines, outputs from ports **511**$_i$, **511**$_j$ and **511**$_k$ (where $i \neq j \neq k$) are random data because these carriers are non-data bearing and even deemed to be unreliable. Thus, the input ports **521**$_i$, **521**$_j$ and **521**$_k$ of the multi-carrier modulator **520** receive random data in lieu of transmission data. This causes the ith, jth and kth carriers to be modulated with the random data and transmitted from output port **522** over channel link **580** as part of the transmit signal to the receiver system **550**. The ith, jth and kth carriers are modulated in accordance with OFDM, FDMA, Spread Spectrum, FDM, wavelet based or other types of modulation techniques.

[**0031**] Referring now **FIG. 6**, an exemplary embodiment of the operations between a transmitter and a receiver in accordance with non-data bearing carrier random modulation is shown. Initially, the transmitter (e.g., first MCM system) sends a channel information request to the receiver (e.g., second MCM system, network transceiver, etc.) to characterize all carriers associated with the channel link (block **600**). In response to receiving the channel information request, the receiver analyzes the received signal and characterizes the data placed on each carrier (block **610**). Such characterization may be through analysis of the SNR, BER, and the like. Thereafter, the receiver determines which carriers are in an unreliable state and outputs a carrier map over the feedback link to the transmitter (blocks **620** and **630**). The carrier map indicates to the transmitter which carriers are deemed to be unreliable so that no data is placed on to such carriers. In addition, the carrier map is used by the transmitter to control placement of random data on to those non-data bearing carriers.

[**0032**] While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and not restrictive on the broad invention, and that this invention not be limited to the specific constructions and arrangements shown and described, since various other modifications may occur to those ordinarily skilled in the art. For example, it may be possible to implement the invention or some of its features in hardware, firmware, software or a combination thereof.

1-27. (canceled)

28. A method comprising:

identifying a carrier of a plurality of carriers that is in a non-data bearing state, including (i) receiving information as to which carriers of the plurality of carriers are to be in a non-data bearing state, and (ii) selecting the non-data bearing carrier based on the information; and

modulating the non-data bearing carrier with random data.

29. The method of claim 28, wherein the non-data bearing carrier is a pilot tone.

30. The method of claim 28, wherein the non-data bearing carrier is used for a function besides data transmission including channel characterization.

31. The method of claim 31, wherein the non-data bearing carrier is used for synchronization.

32. The method of claim 31, wherein the non-data bearing carrier is used for carrier recovery.

33. The method of claim 31, wherein the non-data bearing carrier is used for timing recovery.

34. The method of claim 28, wherein prior to modulating the non-data bearing carrier, the method further comprises producing the random data as a pseudo-random bit stream.

35. The method of claim 34, wherein the modulating of the non-data bearing carrier is performed in accordance with Orthogonal Frequency Division Multiplexing (OFDM).

36. A method comprising:

identifying carriers of a plurality of carriers that are in a non-data bearing state;

selecting a first non-data bearing carrier of the identified carriers in the non-data bearing state;

modulating the first non-data bearing carrier with random data in order to reduce power spectral density irregularities at a frequency associated with the first non-data bearing carrier.

37. The method of claim 36, wherein the first non-data bearing carrier is a pilot tone.

38. The method of claim 36, wherein the first non-data bearing carrier is used for a function besides data transmission including channel characterization.

39. The method of claim 36, wherein the first non-data bearing carrier is modulated with the random data being date produced by a random bit generator.

40. The method of claim 36, wherein the first non-data bearing carrier is modulated with the random data being data produced by a pseudo-random bit generator.

41. The method of claim 36 further comprising:

selecting a second non-data bearing carrier of the identified carriers in the non-data bearing state;

modulating the second non-data bearing carrier with random data in order to reduce power spectral density irregularities at a frequency associated with the second non-data bearing carrier.

42. The method of claim 41, wherein at least one of the first and second non-data bearing carriers is used for carrier recovery.

43. The method of claim 36, wherein prior to modulating the first non-data bearing carrier, the method further comprises producing the random data as a pseudo-random bit stream.

44. The method of claim 43, wherein the modulating of the first non-data bearing carrier is performed in accordance with Orthogonal Frequency Division Multiplexing (OFDM).

45. A method comprising:

identifying a non-data bearing carrier from a plurality of carriers that are in a non-data bearing state, the non-date bearing carrier being used for channel characterization; and

modulating the non-data bearing carrier with random data.

46. The method of claim 45, wherein the non-data being carrier being used for channel characterization in determining a level of interference experienced by the plurality of carriers.

* * * * *