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(71) Applicant(s):
SiConnect Limited
(Incorporated in the United Kingdom)
Swindon Innovation Centre,
Marlowe Avenue, SWINDON, Wiltshire,
SN3 3JR, United Kingdom

(72) Inventor(s):
David Wheeler

(74) Agent and/or Address for Service:
Marks & Clerk
90 Long Acre, LONDON, WC2E 9RA,
United Kingdom

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INT CL **H04B, H04L**
Other: **Online: WPI, EPODOC**

(54) Abstract Title: **Optimising data communications in a power line communiation system**

(57) Typically, data communications over a power line use powerful forward error correction coding to compensate for frequency areas of low Signal-to-Noise ratio (SNR). This results in a signalling overhead and hardware complexity. To reduce these problems, data communications are established between a source terminal and a plurality of remote terminals using a spectrum defining a plurality of subcarriers. The said spectrum is characterised by a frequency response, said frequency response of said spectrum is determined, and N channels in said spectrum, each channel comprising the same number of subcarriers, M, are allocated in accordance with said frequency response, and final centre frequencies of said channels are determined through optimisation, such that the available capacity of said spectrum is fully utilised.

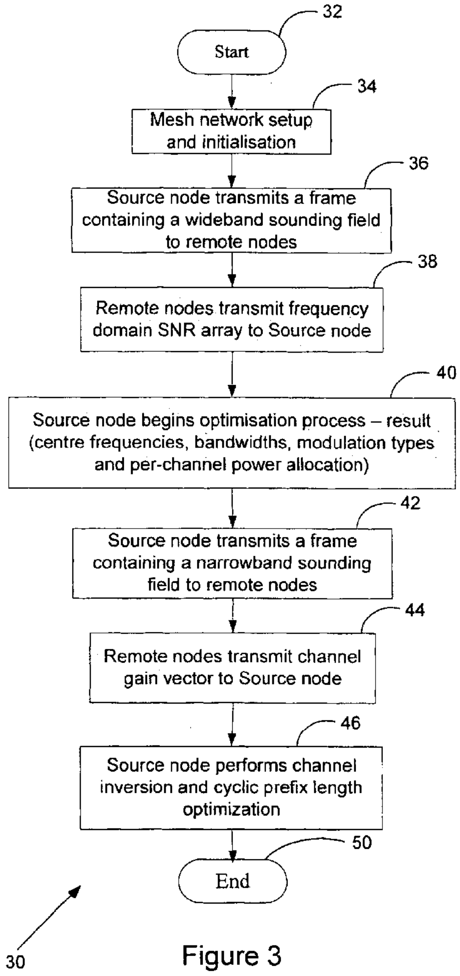

Figure 3

GB 2 443 009 A

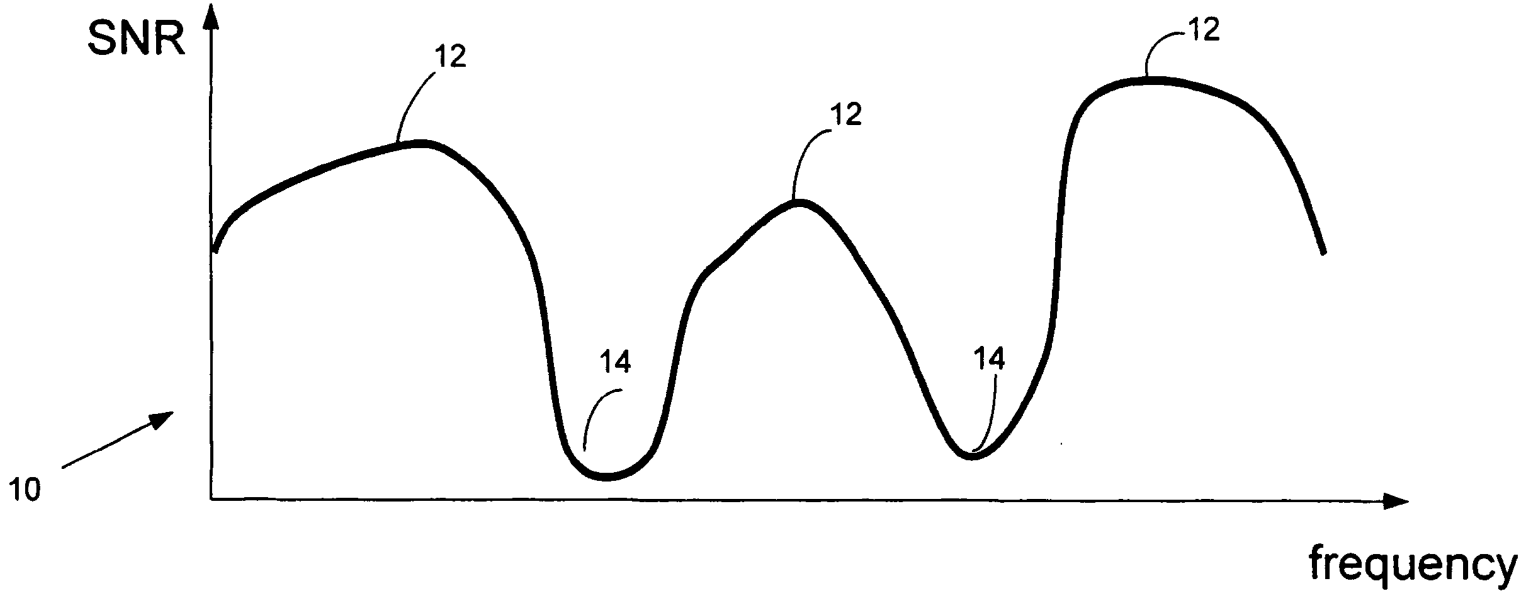

Figure 1

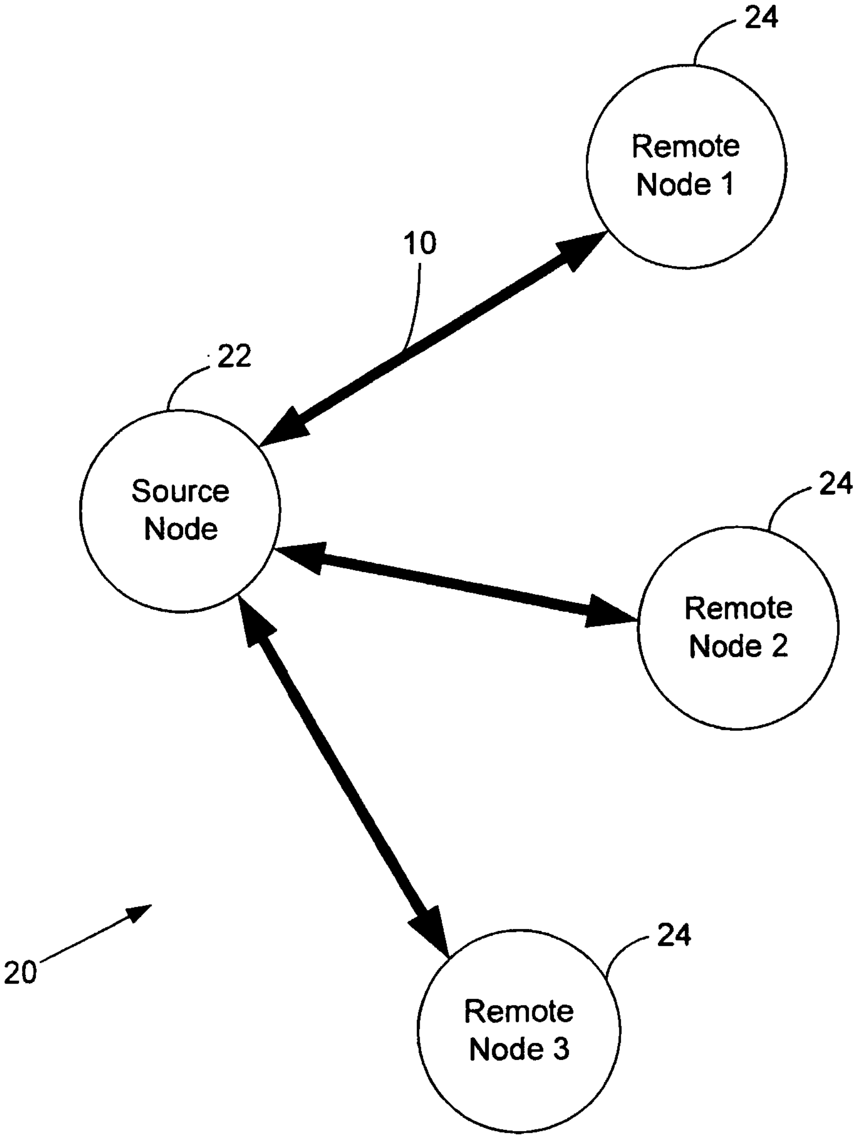
24
Remote Node 1
10
22
Source Node
24
Remote Node 2
24
Remote Node 3
20

Figure 2

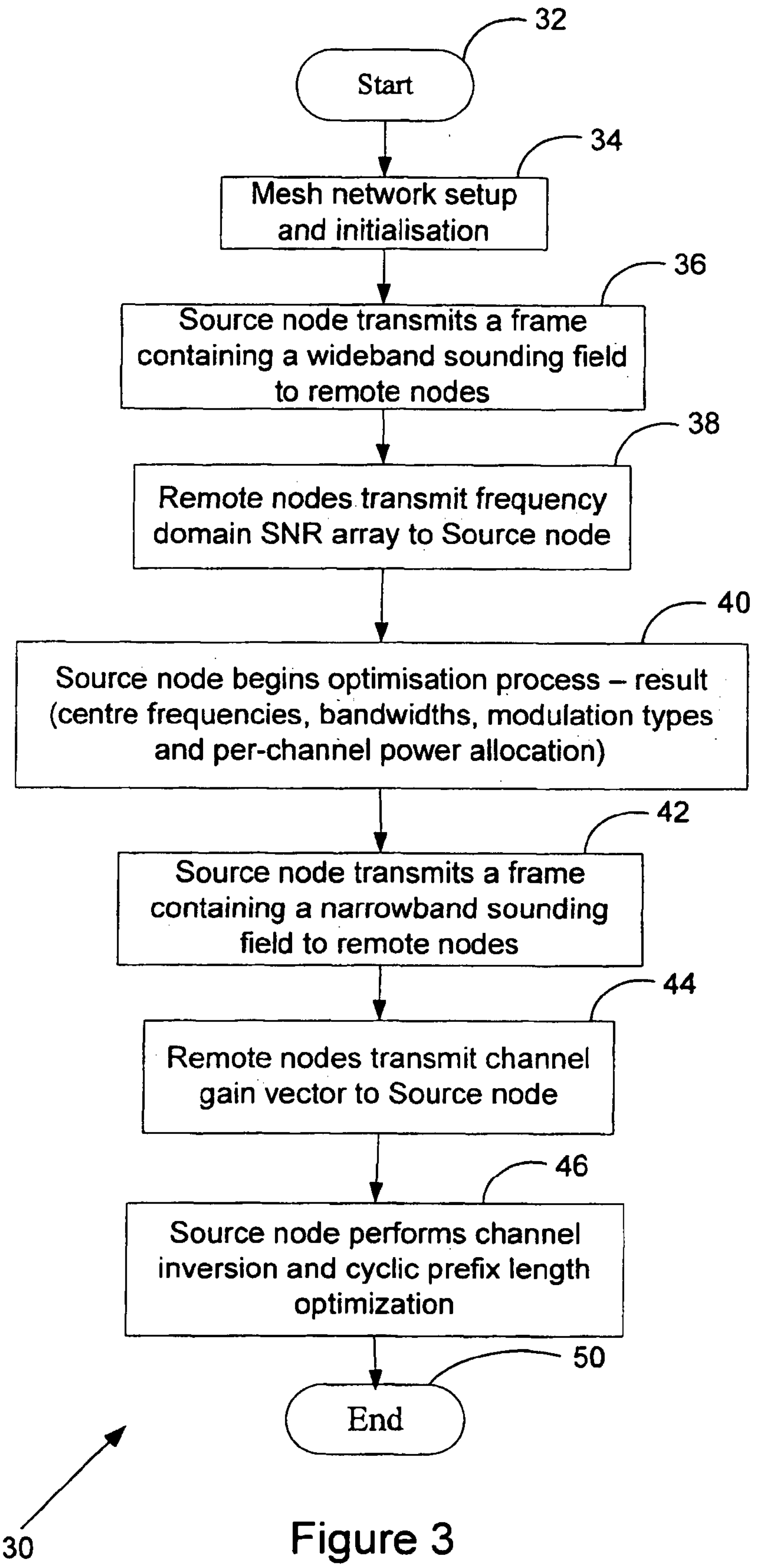
32
Start
34
Mesh network setup and initialisation
36
Source node transmits a frame containing a wideband sounding field to remote nodes
38
Remote nodes transmit frequency domain SNR array to Source node
40
Source node begins optimisation process – result (centre frequencies, bandwidths, modulation types and per-channel power allocation)
42
Source node transmits a frame containing a narrowband sounding field to remote nodes
44
Remote nodes transmit channel gain vector to Source node
46
Source node performs channel inversion and cyclic prefix length optimization
50
End
30

Figure 3

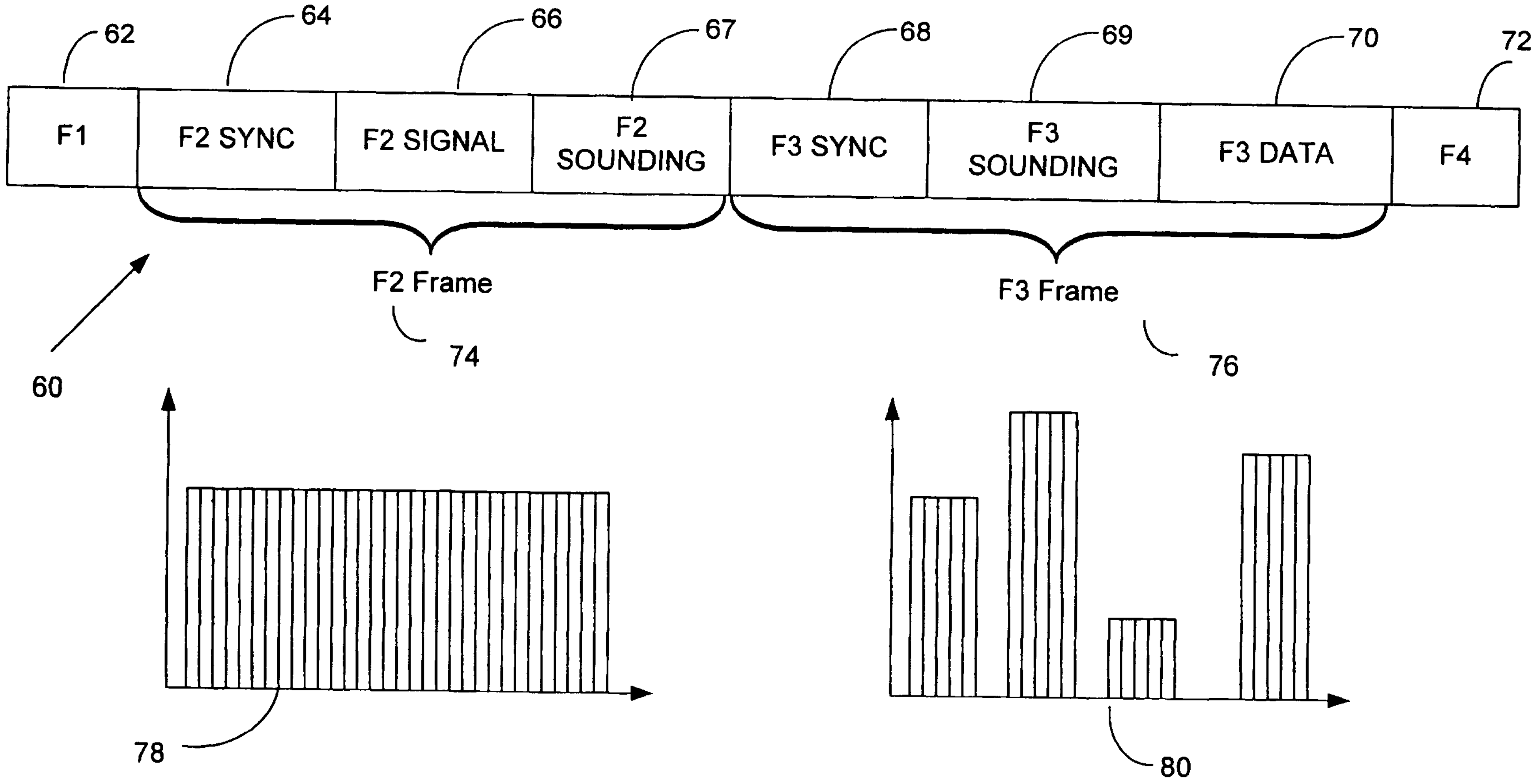
62
64
66
67
68
69
70
72
F1
F2 SYNC
F2 SIGNAL
F2 SOUNDING
F3 SYNC
F3 SOUNDING
F3 DATA
F4
F2 Frame
74
F3 Frame
76
60
78
80

Figure 4

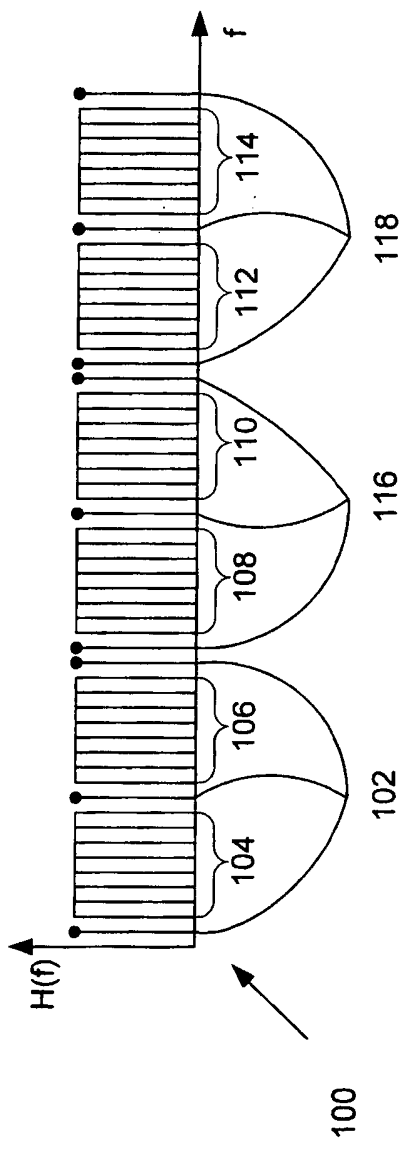

Figure 5

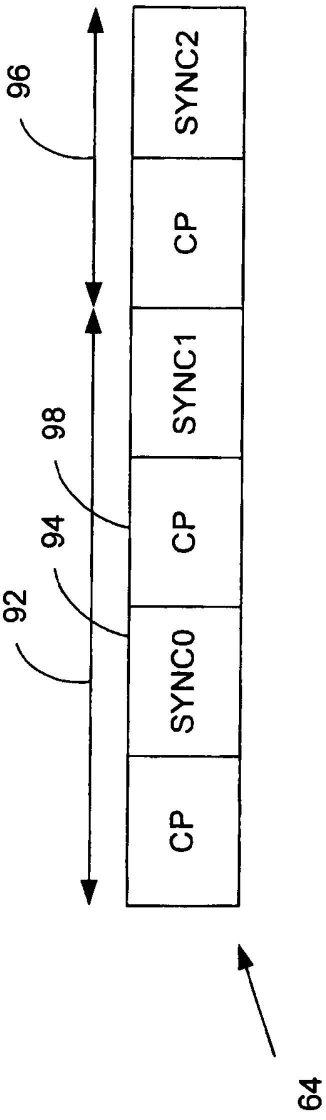

Figure 6

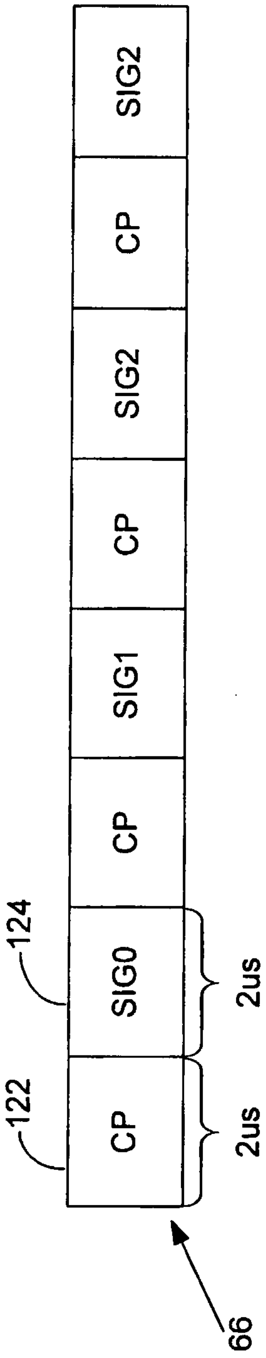

Figure 7

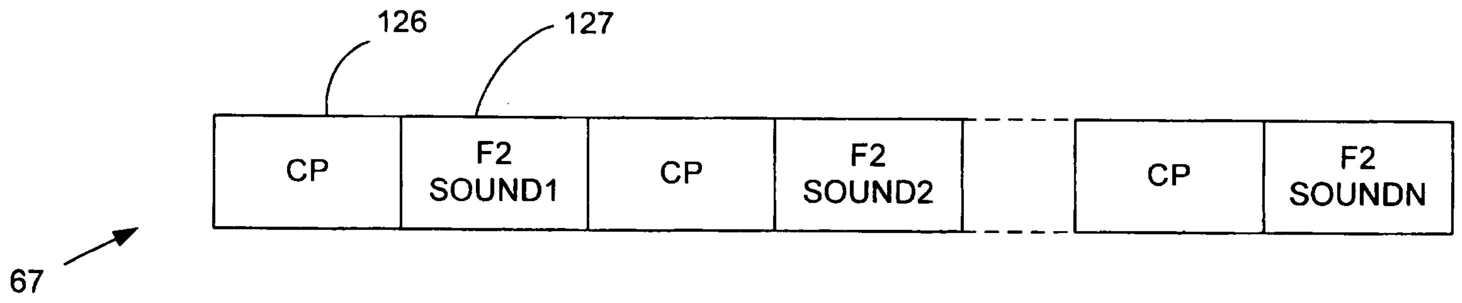

Figure 8

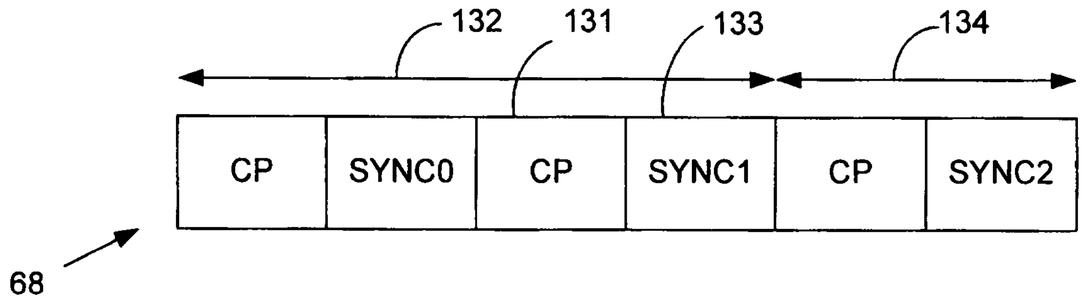

Figure 9

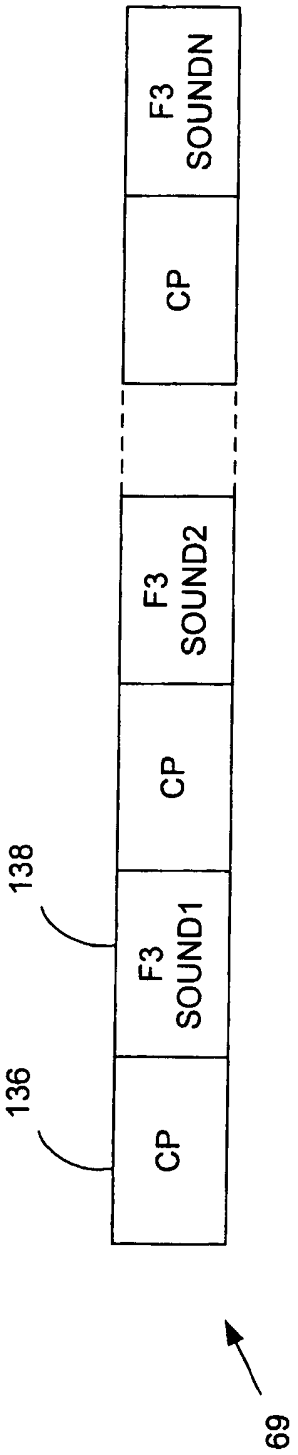

Figure 10

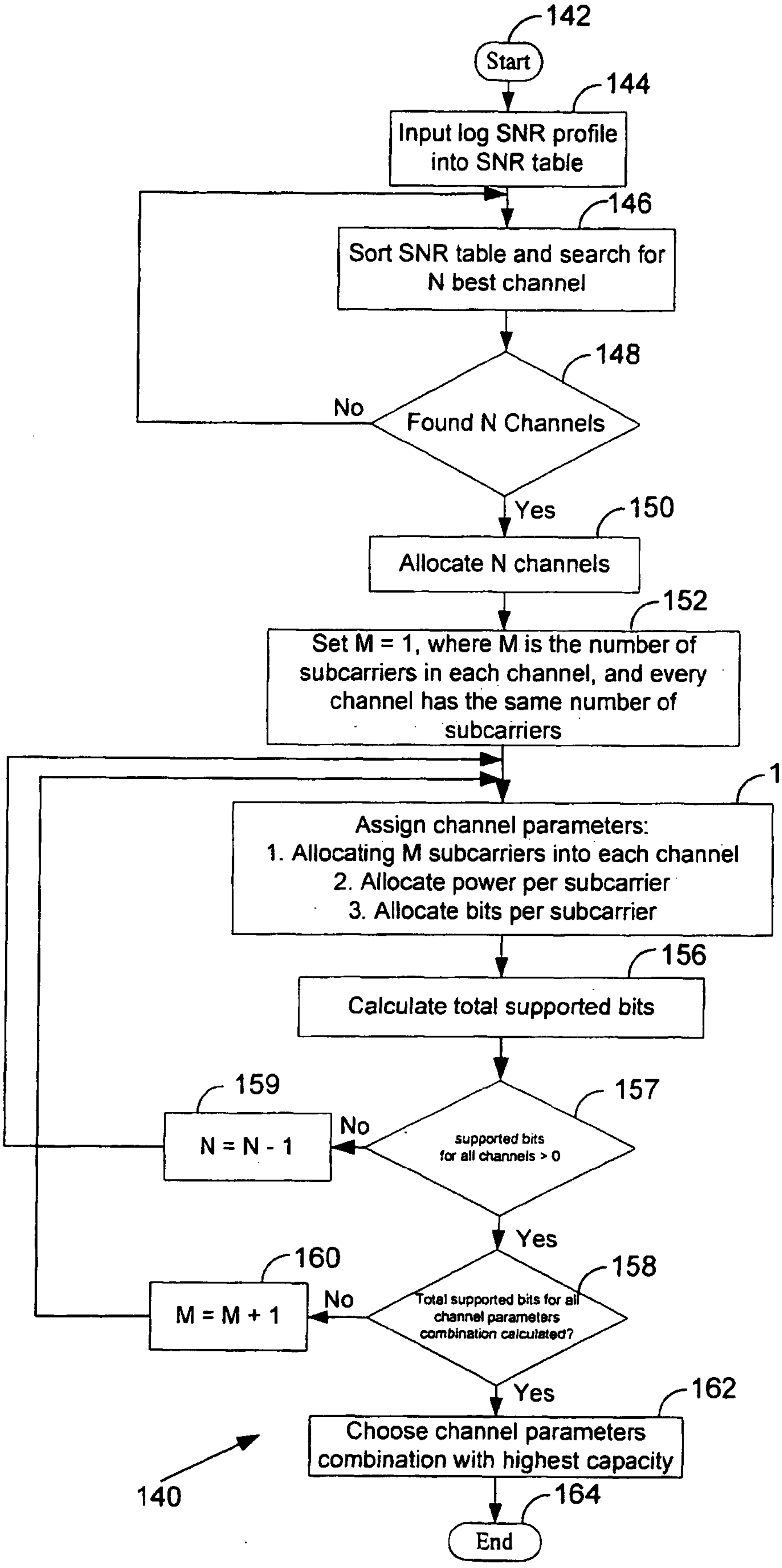
142
Start
144
Input log SNR profile into SNR table
146
Sort SNR table and search for N best channel
148
No
Found N Channels
Yes
150
Allocate N channels
152
Set M = 1, where M is the number of subcarriers in each channel, and every channel has the same number of subcarriers
154
Assign channel parameters:
1. Allocating M subcarriers into each channel
2. Allocate power per subcarrier
3. Allocate bits per subcarrier
156
Calculate total supported bits
159
N = N - 1
No
157
supported bits for all channels > 0
Yes
160
M = M + 1
No
158
Total supported bits for all channel parameters combination calculated?
Yes
162
Choose channel parameters combination with highest capacity
140
164
End

Figure 11

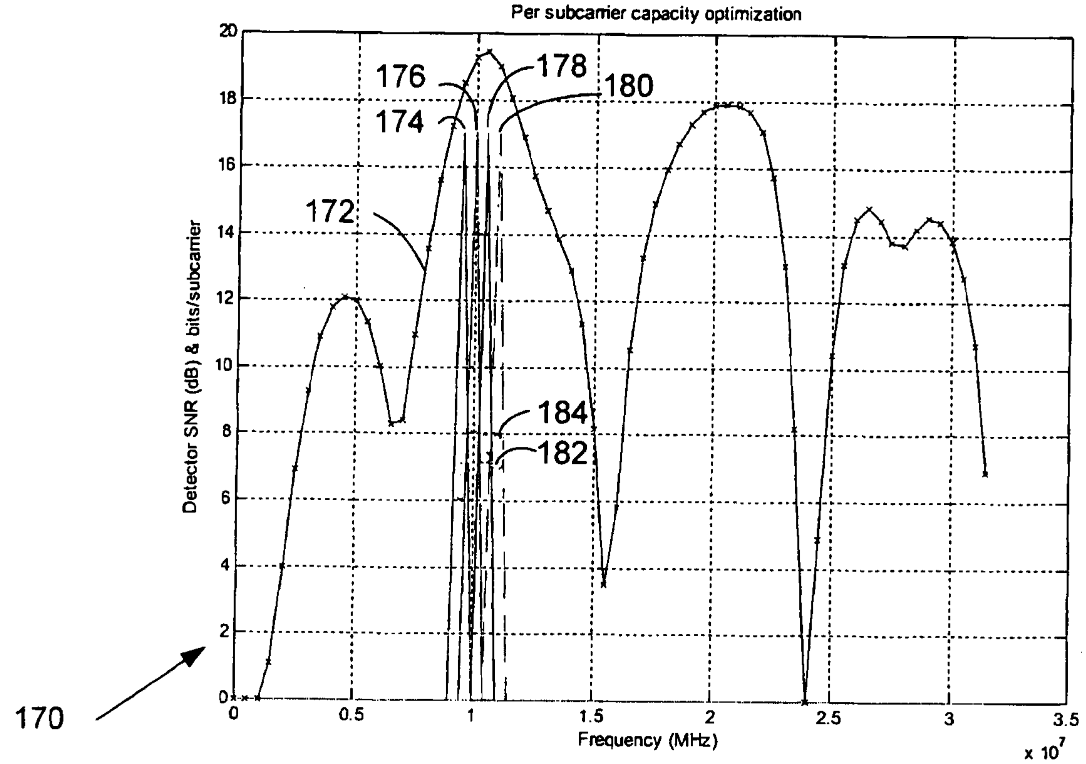

Figure 12

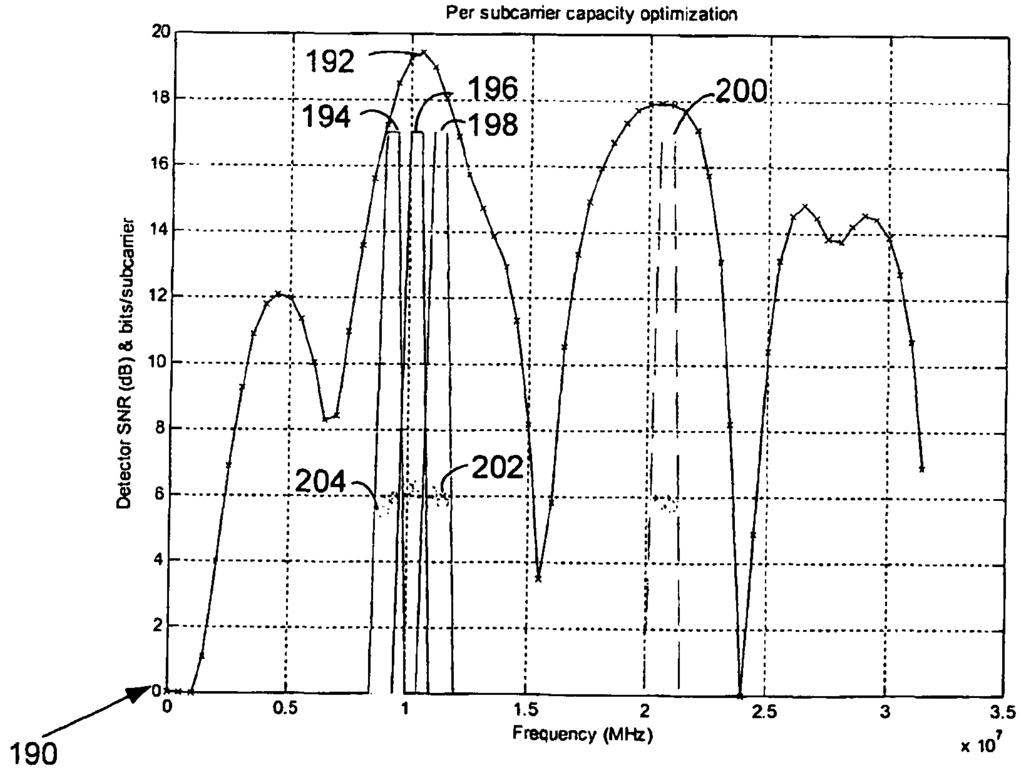

Figure 13

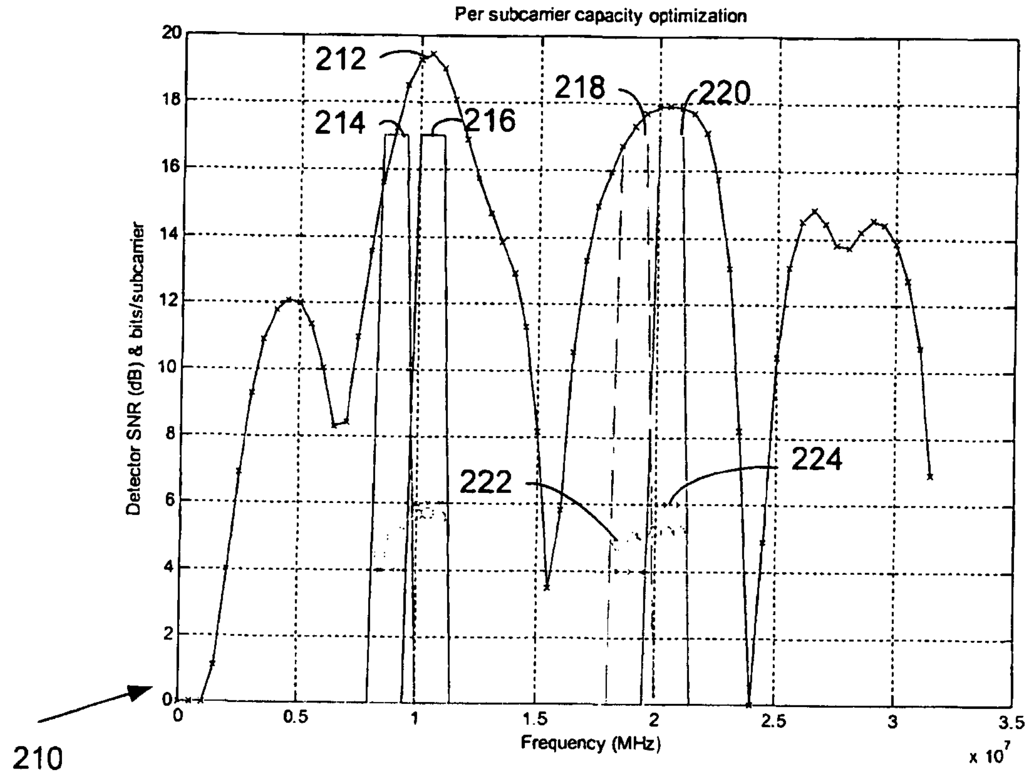

Figure 14

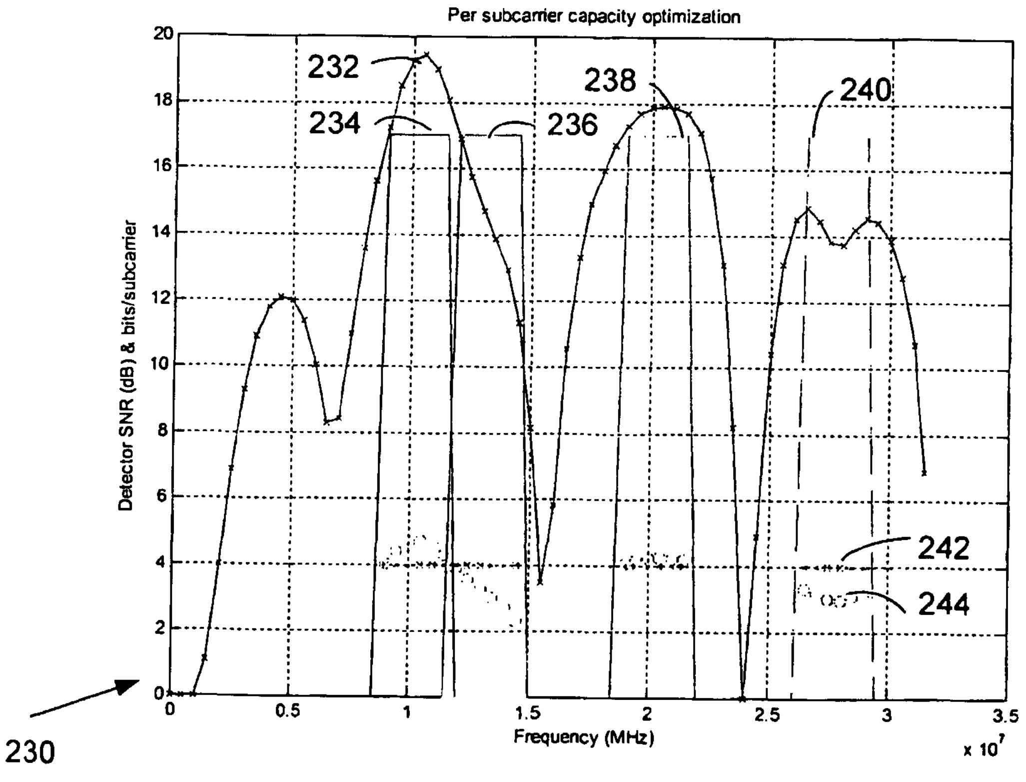

Figure 15

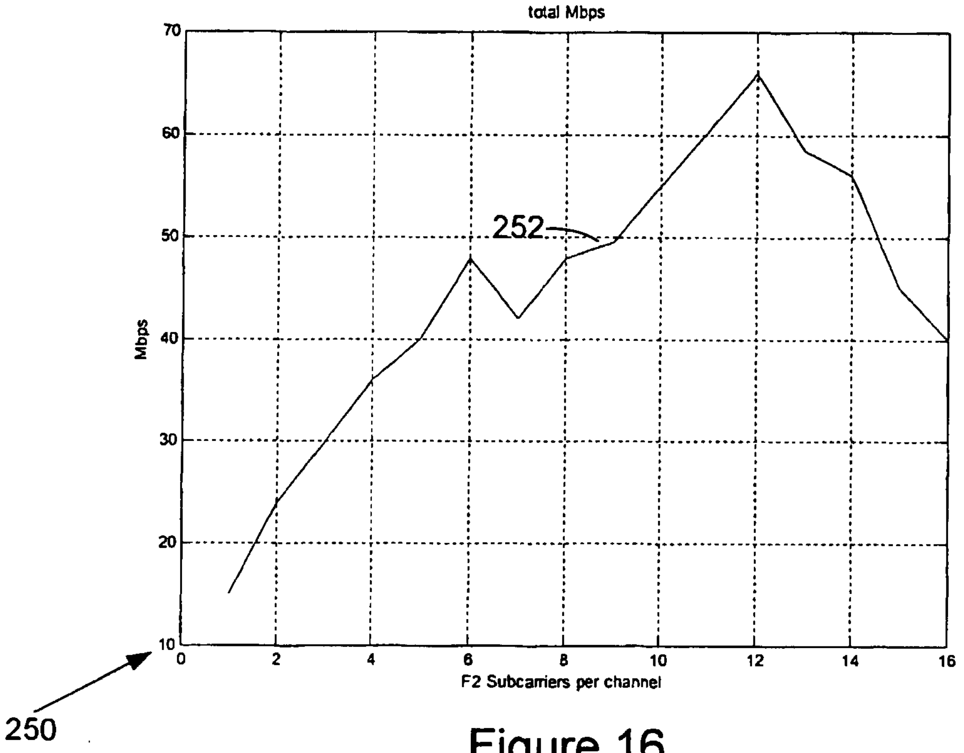

Figure 16

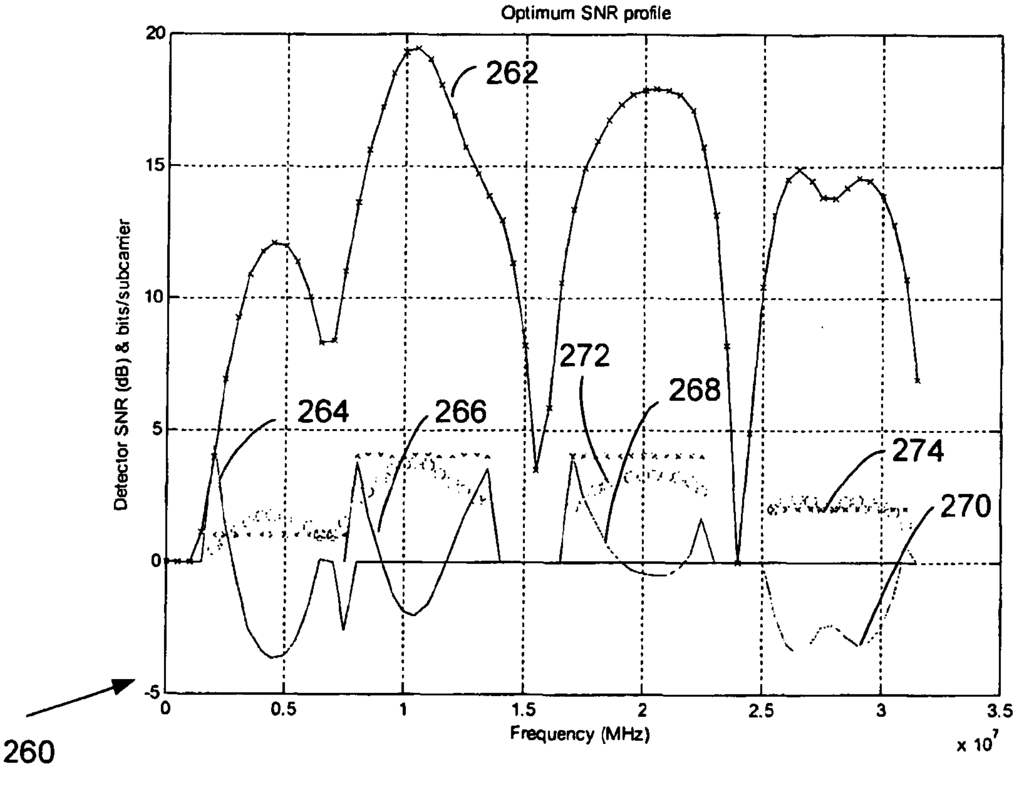

Figure 17

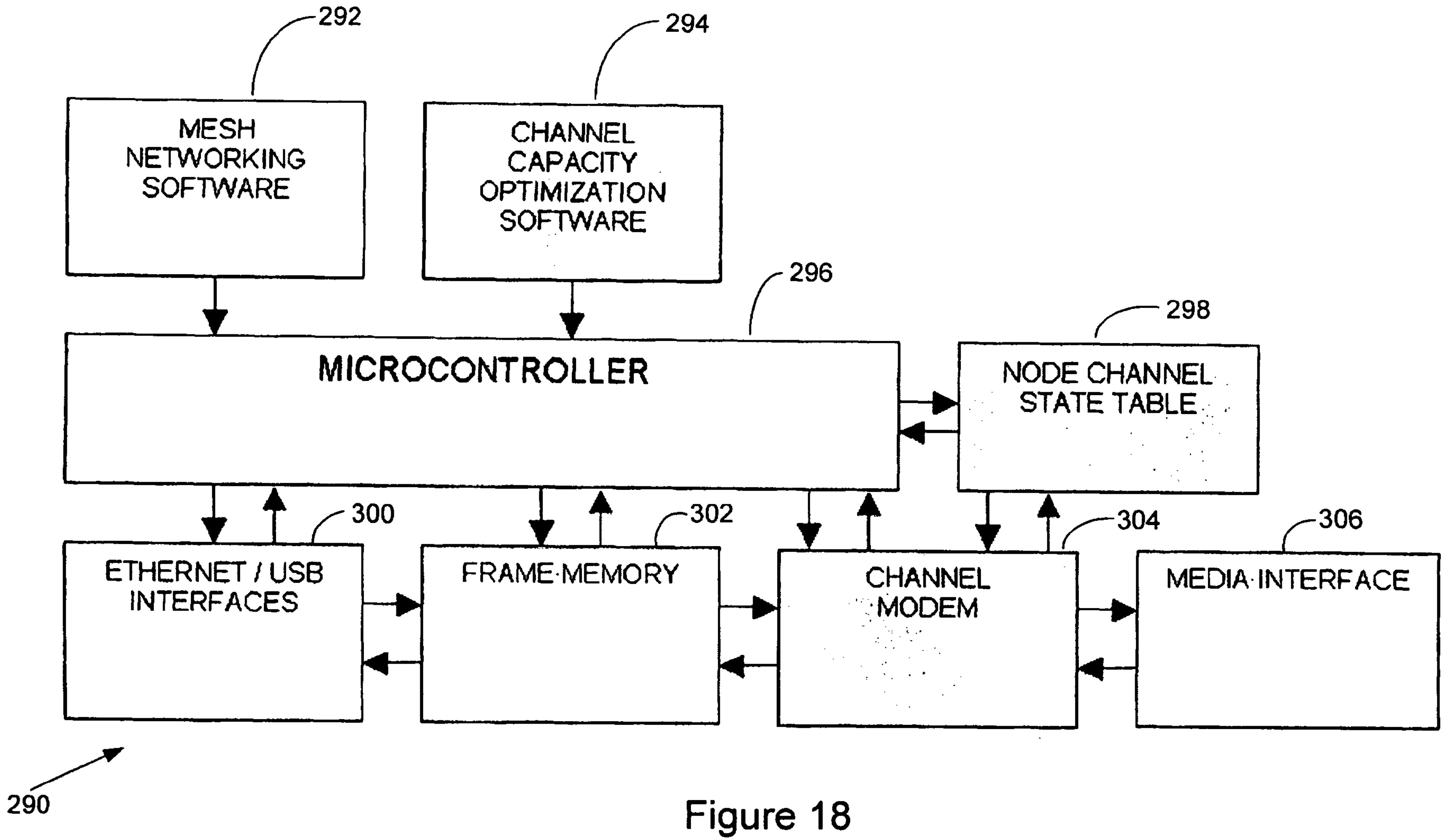
292
294
MESH NETWORKING SOFTWARE
CHANNEL CAPACITY OPTIMIZATION SOFTWARE
296
298
MICROCONTROLLER
NODE CHANNEL STATE TABLE
300
302
304
306
ETHERNET / USB INTERFACES
FRAME·MEMORY
CHANNEL MODEM
MEDIA·INTERFACE
290

Figure 18

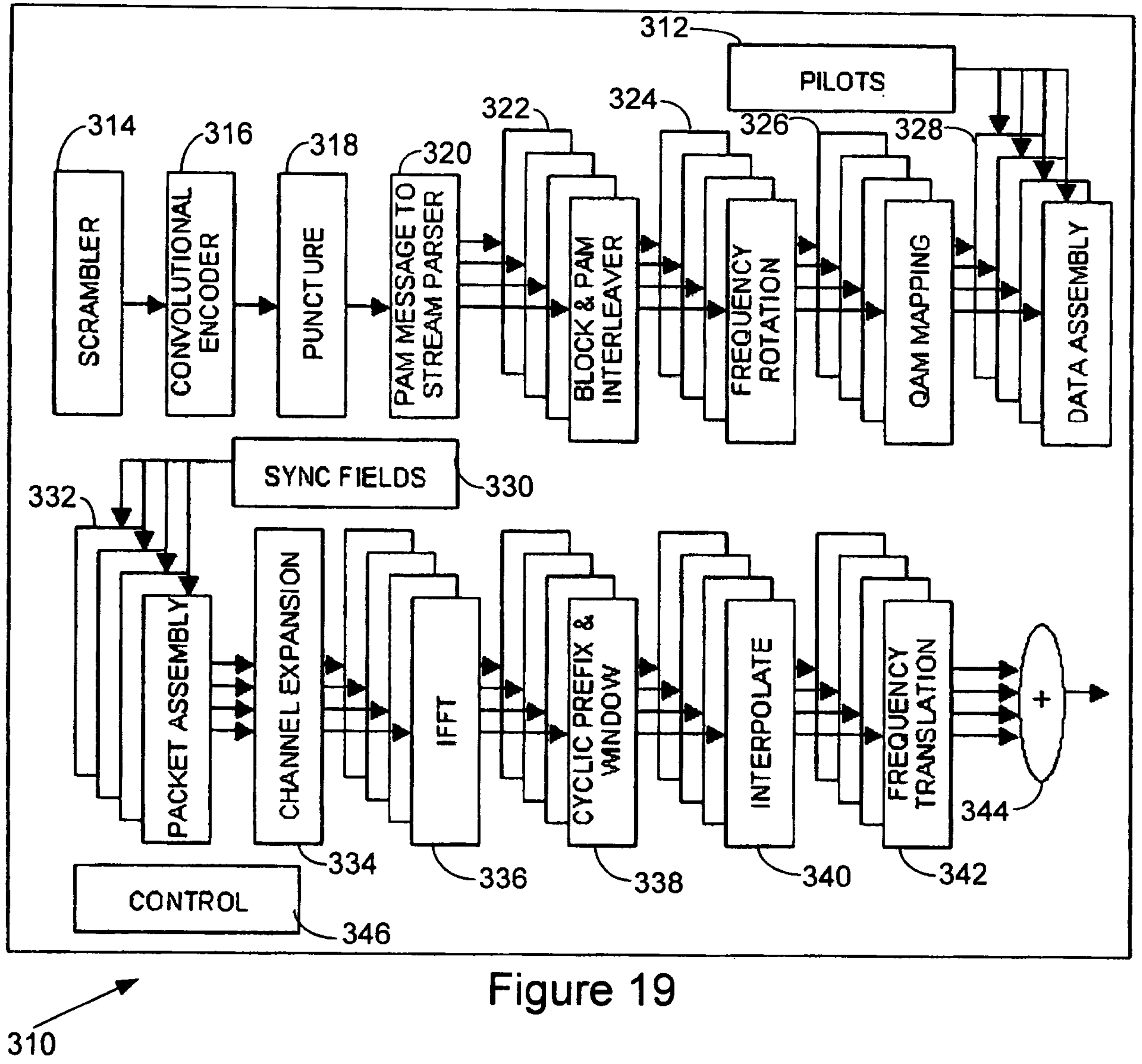
312
PILOTS
314
SCRAMBLER
316
CONVOLUTIONAL ENCODER
318
PUNCTURE
320
PAM MESSAGE TO STREAM PARSER
322
BLOCK & PAM INTERLEAVER
324
FREQUENCY ROTATION
326
QAM MAPPING
328
DATA ASSEMBLY
SYNC FIELDS
330
332
PACKET ASSEMBLY
CHANNEL EXPANSION
334
IFFT
336
CYCLIC PREFIX & WINDOW
338
INTERPOLATE
340
FREQUENCY TRANSLATION
342
+
344
CONTROL
346
310

Figure 19

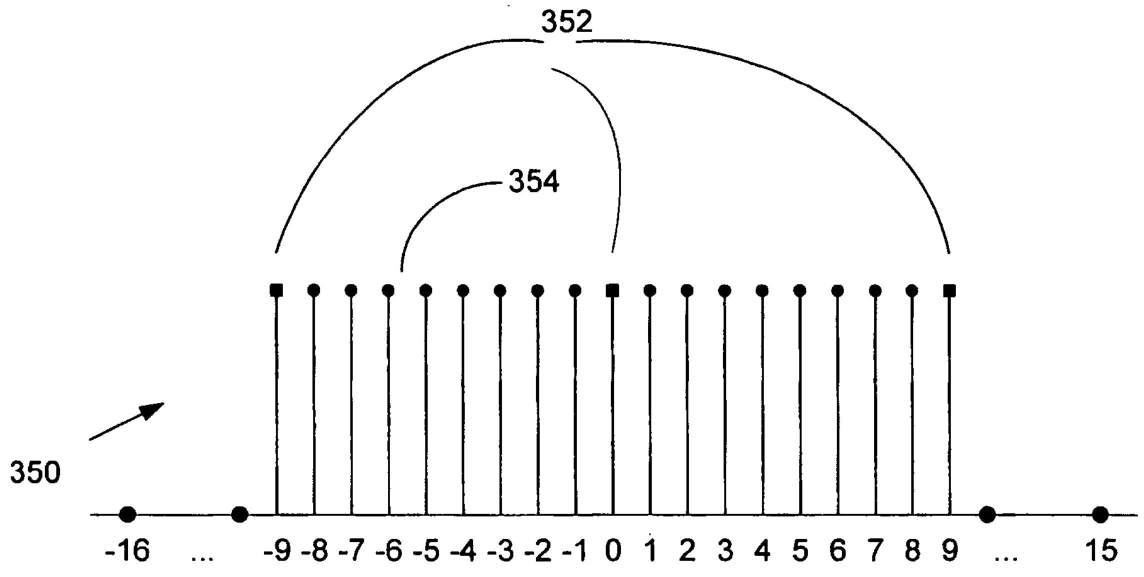

Figure 20

Data Communications

Field of the Invention

The present invention relates to data communications. In particular, it relates to data communications over a power line network.

Background of the Invention

Power line communications uses power distribution wires for simultaneous distribution of data such as audio, video and voice. Power line communications takes advantage of the fact that the power distribution wires in or to an average home or office can support a variety of frequencies. As electricity uses 50 or 60 Hz signals, data can also be transported along the same wiring at a higher frequency without causing any interference.

A power line channel 10 as shown in Figure 1 is characterised by having a frequency response between two nodes having areas of high signal to noise ratio (SNR) 12 and areas of low SNR 14. The areas of low SNR 14 may be wideband and within these areas communications are limited or sometimes even impossible. The available spectrum of a power line channel covers from 0.5MHz to 32MHz, and within this spectrum it is unusual to find more than 15MHz of useable spectrum.

Current power line communications technologies, for example HomePlug AV, use wideband Orthogonal Frequency Division Multiplexing (OFDM) to cover the available 1MHz to 28MHz power line spectrum, and associated powerful forward error correction (FEC) coding to circumvent areas of low SNR. Furthermore, HomePlug AV also provides means of avoiding areas of low SNR by not populating OFDM subcarriers. However, this carries a signalling overhead to inform the receiver of the used subcarriers per frame, and excluding subcarriers results in the available hardware being used inefficiently. Another disadvantage of the HomePlug AV system is its hardware complexity as it uses 3070 very closely spaced subcarriers, deep interleaving and turbo coding which together take up considerable die area. This level of complexity is not required for all applications.

A loading algorithm for discrete multitone transmission is proposed in *Fisher, R.F.H. and Huber, J.B., "A new loading algorithm for discrete multitone transmission", IEEE Proceedings Globecomm, pp. 724 – 728, 1996.* In this document, high data rates are assigned to carriers with high SNR and low data rate are assigned to carriers with low SNR. Subcarriers with very low SNR are not used. The adaptation of data rate is carried out by varying the size of the signal constellation, e.g. from 2 Amplitude Shift Keying (ASK) up to 1024 Quadrature Amplitude Modulation (QAM) or even larger sets. Furthermore, transmit power are also assigned so as to maximise the SNR of each subcarrier.

However, that example does not provide flexibility for a protocol that enables optimisation of point-to-multipoint and point-to-point communication through wide and narrowband channel sounding, and the allocation of a plurality of channels whose bandwidth and centre frequencies are also optimised to avoid areas of low SNR. The channel capacity is further enhanced through channel inversion at the transmitter, enabled from narrowband sounding measurements, and optimisation of the symbol cyclic prefix to match the resultant channel response.

Summary of the Invention

A first aspect of the present invention provides a protocol to enable a source terminal to communicate with a plurality of remote terminals where the protocol enables the source terminal to send fields of wide and narrow bandwidth that sound the channel (sounding fields), and to request channel measurements of one or more remote terminals on the sounding field, and to request the return of those measurements to the source terminal, and to provide all the necessary signalling information in a field to enable a remote terminal to decode narrowband channels that contain data fields within the same protocol.

A second aspect of the present invention provides a method of managing data communication between a source terminal and a plurality of remote terminals over a wideband spectrum, wherein said spectrum between said source terminal and each remote terminal is characterised by a different frequency response, said method comprising determining, for each remote terminal, said frequency response of said spectrum, allocating N channels in said spectrum, each channel having substantially equal bandwidth, in accordance with said frequency response, and determining final centre frequencies of said channels through optimisation, such that the available capacity of said spectrum is fully utilised.

Preferably, said step of determining said frequency response includes transmitting a wideband channel sounding frame consisting of K equally spaced subcarriers covering the frequency band to be optimised from said source terminal to said plurality of remote terminals, and receiving signal-to-noise ratio (SNR) information from said remote terminals to said source terminal in response to said wideband channel sounding.

In an embodiment of the invention, said step of allocating N channels includes determining initial centre frequencies of said channels by selecting N subcarriers with N highest SNR.

Preferably, said optimisation includes assigning channel parameters to said channels and determining the capacity of said channel based on said assigned channel parameters.

Preferably, said step of assigning channel parameters includes allocating, for each said channel, the same number of adjacent subcarriers, M, symmetrically around said initial centre frequencies, so that each channel occupies a particular bandwidth, and allocating suitable transmission bits to each channel and transmission power to each subcarrier based on said SNR for the purpose of finding channel capacity.

Preferably, said step of assigning channel parameters is performed for different values of M, which results in different channel bandwidths for the channels, and selecting the channel parameters giving the best capacity for subsequent communication between said source terminal and remote terminal.

In another embodiment of the above aspect, there is provided the steps of transmitting a narrowband sounding frame from said source terminal to said plurality of remote terminals, and receiving channel gain vectors from said plurality of remote terminals to said source terminal in response to said narrowband sounding.

In yet another embodiment of the above aspect, there is provided the step of performing channel inversion at the source terminal based on said channel inversion gain vectors.

In yet another embodiment of the above aspect, there is provided the step of using the channel gain vectors to determine the channel delay spread and using said delay spread to determine the optimum spacing between symbols to minimise inter-symbol interference.

Preferably, said step of performing wideband sounding and narrowband sounding is performed periodically so as to monitor said frequency response during data communication.

In another aspect of the present invention, there is provided an apparatus for use in a data communications system having a wideband spectrum, wherein said spectrum between any two communicating terminals is characterised by a frequency response, said apparatus comprising means for obtaining said frequency response of said spectrum, channel allocation means for allocating N channels in said spectrum, each channel comprising a fixed number of subcarriers covering a particular bandwidth in accordance with said frequency response; and signal processing means for determining final centre frequencies of said channels through optimisation, such that the available capacity of said spectrum is fully utilised.

Brief description of the drawings

Embodiments of the present invention will now be described with reference to the accompanying drawings, wherein:

Figure 1 illustrates an example of a power line channel having areas of good SNR and areas of low SNR;

Figure 2 illustrates a power line communication network including a source node and a plurality of remote nodes in accordance with an embodiment of the present invention;

Figure 3 illustrates an overall operation of the channel optimisation in accordance with an embodiment of the present invention;

Figure 4 illustrates the protocol comprising packet transmission fields and the respective frequency coverage in accordance with an embodiment of the present invention;

Figure 5 illustrates the Frequency domain representation of the data and pilot subcarriers in the F2 fields;

Figure 6 illustrates the F2 SYNC field in accordance with an embodiment of the present invention;

Figure 7 illustrates the F2 SIGNAL field in accordance with an embodiment of the present invention;

Figure 8 illustrates the F2 SOUNDING field in accordance with an embodiment of the present invention;

Figure 9 illustrates the F3 SYNC field in accordance with an embodiment of the present invention;

Figure 10 illustrates the F3 SOUNDING field in accordance with an embodiment of the present invention;

Figure 11 illustrates the method of optimising the channel parameters in accordance with an embodiment of the present invention;

Figure 12 illustrates an example of four optimum channels including one F2 sounding subcarrier in each channel in accordance with an embodiment of the present invention;

Figure 13 illustrates an example of four optimum channels including two F2 sounding subcarriers in each channel in accordance with an embodiment of the present invention;

Figure 14 illustrates an example of four optimum channels including three F2 sounding subcarriers in each channel in accordance with an embodiment of the present invention;

Figure 15 illustrates an example of four optimum channels including six F2 sounding subcarriers in each channel in accordance with an embodiment of the present invention;

Figure 16 illustrates a graph of performance of the channel capacity obtained from channel optimisation having a common modulation per subcarrier, but possibly different per channel;

Figure 17 illustrates an example of four optimum channels having an optimum channel bandwidth in accordance with an embodiment of the present invention;

Figure 18 illustrates a system architecture in accordance with an embodiment of the present invention;

Figure 19 illustrates a four-channel transmitter architecture in accordance with an embodiment of the present invention;

Figure 20 illustrates a frequency domain representation of the data and pilot tones for one channel, modulated by an OFDM subsystem in accordance with an embodiment of the present invention.

Detailed description

Specific embodiments of the present invention will be described in further detail on the basis of the attached diagrams. It will be appreciated that this is by way of example only, and should not be viewed as presenting any limitation on the scope of protection sought.

Referring now to Figure 2, an example power line communication environment is presented, in which the teaching of the present invention may be practiced is presented, according to one embodiment of the invention. The power line mesh network 20 comprises a plurality of remote nodes 24 coupled in power line communication through the power line channel 10 established between a source node 22 and the remote nodes 24.

Figure 3 shows an overall operation of the channel management 30 of one embodiment of the present invention. Channel management begins after connections within the mesh are established and a steady state is achieved, in step 34, between the source node and the remote nodes. The source node also initiates and maintains a list of point-to-point connections for optimisation. In step 36, a source node may send either a multicast or unicast management frame containing a F2 SOUNDING field to each remote node. Bits within the F2 SIGNAL field inform the receiving nodes to perform measurements on the F2 SOUNDING field. These remote nodes then reply with their frequency domain SNR array, in step 38. In step 40, the source node collects the SNR array and processes it (herein referred to as the optimisation process). The result of the processing is a set of channel centre frequencies, bandwidths, modulation types and per-channel power allocation. The source node then sends a unicast management frame containing a F3 SOUNDING field, in step 42. Bits within the F2 SIGNAL field inform the receiving node to perform measurements on the F3 SOUNDING field. The F3 fields are always sent in the correct format (that is in the optimised centre frequencies, bandwidths, modulation types and per-channel power allocation) to the remote node which replies with a channel gain vector in step 44. The channel gain vector is used to modify the power allocation gain and phase information in order to allow the source node to perform channel inversion in step 46, and optimise a cyclic prefix length knowing the end-to-end channel impulse response. Subsequent communication uses the channel inversion and optimised cyclic prefix for transmission.

The channel management process performs regular sounding to get SNR and channel gain and phase information from measurements on the F3 SOUNDING field. These are used to update the stored information and track slow changes in the channel profile. The channel management process further performs regular sounding to get wideband SNR measurements on the F2 SOUNDING field. These are used to update the channel parameters.

Packet transmission format

Packet 60 comprises 4 distinct frames namely: F1 frame 62, F2 frame 74, F3 frame 76 and F4 frame 72 as shown in Figure 4. The F1 frame 62 is used for arbitration to allow one node to take control of the medium. At the end of a F1 frame 62 each remote node would have the knowledge of whether it has lost the arbitration. By elimination, a node which has not lost arbitration has gained control of the medium. This node will then have an ability to transmit the F2 frame 74 and the F3 frame 76. Nodes will then participate in the F4 frame 72 that encompasses an acknowledgement protocol.

The F2 Frame format

In this embodiment, all the remote nodes are configured to decode the F2 SIGNAL field 66 of a packet transmission 60. This field contains information about the F2 SOUNDING field 67, F3 SOUNDING field 69, F3 DATA field 70, modulation and coding in the F3 frame 76. It therefore conveys the length of F2 and F3 SOUNDING fields, which may be zero in which case they are not present, the number of channels, centre frequencies, bandwidth, modulation and cyclic prefix length, as determined by the optimisation above, together with other necessary data such as the length, in bytes, of the F3 DATA field payload. Therefore the F2 frame is sent in a wideband (multicast) channel 78, whereas the F3 frame is sent using the optimised channel configuration 80 (point-to-point) determined according to the method described in the above paragraphs.

Figure 5 illustrates the frequency domain subcarriers 100 comprising an F2 frame. There are 57 subcarriers in total comprising groups of 8 data subcarriers 104, 106, 108, 110, 112 and 114, and groups of 3 pilot subcarriers 102, 116, 118. The data subcarriers 104, 106 and pilots 102 are formed by OFDM channel modulator 0. Data subcarriers 108, 110 and pilots 116 are formed by OFDM channel modulator 1. Data subcarriers 112, 114 and pilots 118 are formed by OFDM channel modulator 2.

The F2 SYNC field format

As shown in Figure 4, the F2 frame 74 consists of a synchronisation preamble, F2 SYNC field 64, the SIGNAL field 66, which conveys the signalling information, and a F2 SOUNDING field 67. The F2 SYNC field 64 consists of N repetitions of a training field 94 as illustrated in Figure 6. The training field is defined in the frequency domain as having 57 subcarriers. The field carries a 57-bit BPSK modulated pattern known to both the receiver and transmitter. The data and pilot subcarriers are considered as one continuous set of pattern carrying subcarriers. Consequently, after the conversion to the time domain, N repetitions are formed. In the example illustrated in Figure 6, N=3 sync symbols are formed each with a cyclic prefix 98.

Typically a receiver performs operations on the F2 SYNC field as embodied in Figure 6. This allows the receiver to optimise its automatic gain control (AGC) 92, estimate and cancel frequency offset, and estimate the channel gains and noise power 96. Each of the SYNC field lasts for 2μs and has a 2μs cyclic prefix. Thus the F2 SYNC 64 lasts N*4μs.

F2 SIGNAL field format

An example embodiment of the F2 SIGNAL field 66 contains the modulated data fields as illustrated in Table 1.

Bits	Name	Description	Detail
7	F0	Channel 0 centre	Fc = F0*0.25MHz, 0<=F0<128
7	F1	Channel 1 centre	As F0
7	F2	Channel 2 centre	As F0
7	F3	Channel 3 centre	As F0
3	BW	Bandwidth	0 = 9MHz 1 = 6MHz 2 = 4.5MHz 3 = 3MHz 4 = 2MHz 5 = 1.5MHz 6 = 1.0MHz 7 = 0.5MHz
3	M0	Channel 0 modulation	0 = BPSK 1 = QPSK 2 = 16-QAM 3 = 64-QAM 4 = 256-QAM 5 = 1024-QAM >5 reserved
3	M1	Channel 1 modulation	As M0
3	M2	Channel 2 modulation	As M0
3	M3	Channel 3 modulation	As M0
3	CP	Cyclic Prefix as fraction of FFT length	0 = 1 1 = 1/2 2 = 1/4 3 = 1/8 4 = 1/16 >4 reserved
2	FEC1	Convolutional coding puncture rate	0 = ½ 1 = 2/3 2 = 3/4 3 = 5/6
2	WS	Number of symbols in F2 SOUNDING field	0 = 0 symbols1= 16 symbols 2 = 32 symbols 3 = 64 symbols
2	NS	Number of symbols in F3 SOUNDING field	As WS
2	ST	Data streams	0 = 1 data stream 1 = 2 data streams 2 = 3 data streams 3 = 4 data streams
2	CH	Transmit channels	0 = 1 channel 1 = 2 channels 2 = 3 channels 3 = 4 channels
16	LT	Length	Number of bytes in the data payload of field F3 DATA
	-	Reserved bits to pad to 96	Written as zero
8	CRC	8 bit CRC	
6	TAIL	Convolutional encoder tail bits	Written as zero

Table 1. F2 SIGNAL field format

The 96 bit SIGNAL field is convolutionally encoded with rate ½ to produce 192 coded bits. These coded bits are block interleaved, modulated by BPSK. This is sent over 48 subcarriers with 9 pilot carriers, totalling 57 carriers with bandwidth 500kHz, evenly spread from 0.5MHz to 28.5 MHz inclusive. Therefore 4 symbols (192/48) are needed to convey the coded information. The frequency domain representation of the subcarriers in a SIGNAL field symbol is illustrated in Figure 5.

The SIGNAL field symbols need a long cyclic prefix because they are transmitted wideband. The cyclic prefix 122 for these 2μs symbols 124 will be 2μs, resulting in 4μs symbols. The 4 symbols shown in Figure 7 constituting a SIGNAL field 66 transmission therefore last for 16μs.

F2 SOUNDING field format

As shown in Figure 8 the F2 SOUNDING field 67 consists of 0 or more F2 SOUNDING symbols 127, each preceded by a cyclic prefix 126. The F2 SOUNDING symbols are formed from BPSK modulating a pseudo random bit stream onto the data and pilot subcarriers in the frequency domain. Both the transmitter and receiver know the pseudo random bit stream. The SIGNAL field includes data field WS (wideband sounding) that informs the transmitter and receiver how many F2 SOUNDING symbols will be present. This can be used to ask the remote nodes to return SNR measurements made on the F2 SOUNDING field of the current frame in a dedicated channel measurement frame.

F3 frame format

The F3 frame consists of a synchronisation preamble, F3 SYNC 68, the sounding field F3 SOUNDING 69 and the F3 DATA field 70, which conveys the payload data. The F3 frame is formed from 1 to 4 channels of OFDM modulated data. Each OFDM channel modulator uses the same data and pilot subcarrier placement as was used for the F2 SIGNAL field. Shown in Figure 20 are the 16 data subcarriers 354 and 3 pilot subcarriers 352 placed in the frequency domain 350 relative to the channel centre frequency. The frequency in this figure is normalised to the subcarrier bandwidth.

F3 SYNC field format

The F3 SYNC 68 consists of N training fields as shown in Figure 9. Each channel modulates a training field defined in the frequency domain as having a 19-subcarrier sequence which is known to both the transmitter and receiver. After conversion to the time domain N repetitions are formed, and each symbol 133 is preceded by a cyclic prefix 131. In the example shown in Figure 8, N=3 sync symbols are formed.

Typically a receiver performs operations on the SYNC fields as embodied in Figure 8. This allows a receiver to optimise its AGC 132, estimate and cancel frequency offset, and estimate the channel gains and noise power 134. The time duration of the F3 SYNC is variable since it depends on the channel bandwidth that resulted from the optimisation process.

F3 SOUNDING field format

In Figure 10 the F3 SOUNDING field 69 consists of a variable number of F3 SOUNDING symbols 138 each preceded by a cyclic prefix 136. The F3 SOUNDING symbols are formed from BPSK modulating a pseudo random bit stream onto the data and pilot subcarriers in the frequency domain. Both the transmitter and receiver know the pseudo random bit stream. The SIGNAL field 66 includes data field NS (narrowband sounding) that informs the transmitter and receiver how many F3 SOUNDING symbols will be present. This can be zero or more. When zero the F3 SOUNDING field is absent. The SNR and channel gains can be calculated for each subcarrier (including the pilot positions) and this is returned to the transmit node in a normal layer 2 management frame.

F3 DATA field format

The F3 DATA field carries payload data that can be any type of upper layer frame. These frames will typically contain a source and destination terminal address followed by a management, control or data frame. At least one management frame will be defined to carry F2 or F3 SOUNDING field measurements from the remote terminal back to the source terminal. Other management frames will be of interest only to controlling features that are not covered in the present invention.

The F3 DATA field is physically formed from OFDM symbols modulated according to the information transferred in the SIGNAL field. The design of this follows well-known OFDM modulation principles extended to allow for multi-channel, adaptive bit rate, adaptive cyclic prefix, and adaptive bandwidth, technology as required by the present invention.

Optimisation of channel parameters from sounding frames

The method of choosing the best channel usage once the log SNR profile is returned from a F2 or F3 SOUNDING field will be now be described in further detail in accordance with Figure 11 to Figure 17.

The capacity of a channel, for a given "capacity gap" is given by

$$C = \int \log_2 \left[1 + \frac{\gamma(f)}{\gamma_{GAP}} \right] df \qquad (1)$$

in bits per second. For a multi-carrier system, where the sub-carriers have bandwidth W Hz, the integral can be replaced with a sum over all K active sub-carriers.

$$C = W \sum_{k=0}^{K-1} \log_2 \left[1 + \frac{\gamma(k)}{\gamma_{GAP}} \right] = W \sum_{k=0}^{K-1} B_k = W B_{tot} \qquad (2)$$

The number of bits sub-carrier k supports is given by B_k. Defining the *average* SNR as $\bar{\gamma}$, and the average number of bits per sub-carrier as B_{av}, this can be re-written as

$$C = WK \log_2 \left[1 + \frac{\bar{\gamma}}{\gamma_{GAP}} \right] = WKB_{av} \qquad (3)$$

For high SNR, the average SNR can be approximated by

$$\bar{\gamma} = \left(\prod_{k=0}^{K-1} \gamma(k) \right)^{\frac{1}{K}} \qquad (4)$$

This is calculated in the log domain as

$$\log_2 \bar{\gamma} = \frac{1}{K} \sum_{k=0}^{K-1} \log_2 \left(\gamma(k) \right) \qquad (5)$$

So, to a first approximation, the capacity, of the channel (in bps) depends on the geometric mean of the SNR, or equivalently the mean log SNR.

The step of finding equal bandwidth channels containing M sub-carriers each (where the sub-carriers in a channel must be adjacent and the channels cannot overlap) will now be described.

In this example, the used channels are indexed as $i = 0 \ldots i_{\max} - 1$, where $i_{\max}$ is between 2 and 4. The total number of sub-carriers M_{tot} is now taken over the used channels. A sub-carrier set is defined as the set I_i listing the sub-carrier indices k belonging to that channel. The set $I = I_0 \cup I_1 \ldots I_{i_{\max}-1}$ denotes all used sub-carriers.

The optimisation of bits to sub-carriers follows the equivalent methods in *Fischer, R.F.H., Huber, J.B., "A new loading algorithm for discrete multitone transmission". IEEE Proceedings Globecom, pp724-728, 1996, and Bingham, J.A.C., "The theory and practice of Modem Design". Wiley publishers 1988,* but modified for 2 to 4 channels where the SNR of subcarriers within the channel is known.

Referring to Figure 9, the optimisation of the channel parameters begins, in step 144, by reading the SNR profile into an SNR table. In step 146, the SNR table is then sorted to search for the best channels. In this example the number of best channels is 4. However, the person skilled in the art will appreciate that the number of best channels can be any number which is greater than 1. Evidently the "best" 4 channels to use are the sub-carriers with the highest SNR.

The optimisation begins with four channels of 1 carrier each in step 152. Since the modulation is only required to support 4 carriers instead of 57 carriers, these 4 carriers could be sent with their transmit power increased by a factor 57/4. So each of the 3 channels would appear at the receiver with SNR increased by 57/4 compared to the wideband sounding frame.

Power and bits are allocated per channel, in step 154, and the total supported bits are calculated in step 156. In step 157, if the total supported bits for any channel is < 1 then BPSK modulation is not possible on that channel. The number of channels is reduced by one in step 159 and bits are reallocated. The process repeats with the best four channels of 2 sub-carriers, and so on until the total supported bits for all channel combinations are achieved. The combination with the highest capacity is chosen in step 162.

This operation is further illustrated Figures 12 to 17. In Figure 12, the SNR profile 172 is sampled every 500kHz. The profile 172 has been sorted and the 4 channels 174, 176, 178 and 180 with highest SNR are shown. The circles 182 represent the number of bits (unquantised) with which these subcarriers can be loaded and, in this case, between 7 to 8. The crosses 184 are the actual number of quantised bits to produce square QAM constellation between BPSK and 1024-QAM. In this case, 256-QAM loads 8 bits per subcarrier. The capacity is 8 bits times 4 subcarriers times 500kHz = 16Mbps.

Figure 13 shows an example of the 4 best channels 194, 196, 198, and 200 containing two subcarriers each 190. The 4th channel occupies the SNR band where the next highest SNR peak is located. This time each subcarrier can take 6 bits, so the capacity is now 24Mbps.

Figure 14 shows an example for 3 subcarriers per channel 210. It shows that some subcarriers can no longer support 64-QAM, and must back off to 16-QAM using only 4 bits per subcarrier. The capacity is now (6*6+6*4)*500kHz = 30Mbps. The capacity is still improving but the increase is no longer linear.

Figure 16 illustrates the channel capacity for each step as the optimisation proceeded with channels of increasing bandwidth. The optimum capacity is for channels containing 12 F2 SOUNDING subcarriers. This is used to set the common channel bandwidth for F3 field transmission to be 12*500kHz = 6MHz.

In Figure 17, the optimum channel selection is shown 260, together with a power profile per subcarrier within each channel, 264, 266, 268, 270 that equalises the symbol error probability on each subcarrier.

The following describes the method of sorting and finding the best channels. Averaging over the log SNR for L adjacent subcarriers, k to $k+L-1$, provides the average SNR profile for channels containing L subcarriers, herein referred to as the *L-average array*. The maximum in this array, k_0 is the best channel covering subcarriers k_0 to $k_0 + L$-1. To find the next best channel, zeros are inserted into the *L-average array* from k_0-L+1 to k_0+L-1, ensuring the beginning or end of the array is not read past to form the *modified L-average array*. The next highest index k_1 in the *modified L-average array* is the next best non-overlapping channel. This process is repeated until 4 channels have been selected. If the whole *modified L-average* array is zero at any stage, this indicates fewer than 4 channels can be fitted in the available bandwidth, and the channel allocation terminates early.

Figures 12 to 15 and Figure 17 are illustrative of what bit loading could be achieved with independent subcarrier optimisation 272. In a preferred embodiment, a common modulation format per channel 274 is applied rather than per subcarrier.

The steps to produce this are shown below. This is achieved by having an optimisation that finds the rate and power distribution to achieve the highest capacity with a known error probability.

Step 1. Define the wanted error rate, which is equivalent to defining a capacity gap. The capacity gap is derived from the coding gain of the error correction and the free distance of the multilevel modulation, and its determination is outside of the scope of this note, however, in practice we choose $5 \le \gamma_{GAP} \le 10$.

Step 2. Assume transmit power is allocated equally over the used sub-carriers. This means the SNR is increased from the sounding frame by the following factor

$$\gamma_M(k) = \gamma(k)\frac{K}{M_{tot}}$$

Step 3. Calculate the average SNR $\bar{\gamma}_I$ using Equation (5) over sub-carriers in the set $k \in I$.

Step 4. Calculate the average SNR $\bar{\gamma}_{I_i}$ over each channel using Equation (5) over sub-carriers in the sets $k \in I_i$.

Step 5. Find the *average* number of bits that the sub-carrier SNR profile within a channel can support. This is approximately the same as the considering the average number of bits that the channel SNR can sustain.

$$B_{av} = \frac{1}{K}\log_2\left(1 + \frac{\bar{\gamma}_I}{\gamma_{GAP}}\right)$$

Step 6. Allocate bits to channels

$$B_i = B_{av} + \log_2 \bar{\gamma}_{I_i} - \log_2 \bar{\gamma}_I, \quad i = 0, \ldots, i_{\max} - 1$$

Step 7. If all $B_i \le 0$ then the channel does not support communication. If any $B_i \le 0$ then channel i is excluded, $i_{\max}$ is decremented, I and M_{tot} are modified to reflect one less channel, and process then returns to step 2.

Step 8. B_i is quantised into allowable numbers of bits given square QAM constellations BPSK to 64-QAM, $B_{Qi} \in \{1,2,4,6\}$.

Step 9. The supported channel bit rate is calculated by

$$C = W\frac{M_{tot}}{i_{\max}}\sum_{i=0}^{i_{\max}-1} B_{Qi}$$

Step 10. The total transmitted power P_T is redistributed so the probability of error per channel is made equal again.

$$P_i = \frac{P_T 2^{B_{Qi}} / \bar{\gamma}_{I_i}}{\sum_j 2^{B_{Qj}} / \bar{\gamma}_{I_j}}, \quad i = 0,\ldots,i_{\max}-1$$

This means the power per channel can vary by +/- 6dB from the average, given the 2-bit difference between the quantized bit resolutions.

Narrowband sounding channel inversion from F3 SOUNDING field measurements

The SIGNAL field 66 includes data field NS (narrowband sounding). This field is used to ask the receiving node to return F3 SOUNDING 69 channel gain measurements to the transmitting node in a dedicated channel measurement frame. The channel gain measurements allow the transmitter to invert the channel before transmission (equalise the gain and phase, whereas the last section only equalised the gain). After going through the channel the receiving node will then see a flat pre-equalised channel. The advantage of this is that the OFDM symbols can be sent with a shorter cyclic prefix, thereby allowing a higher net data throughput.

The SNR profile from the wideband sounding frame is designed to aid in choosing the channel parameters as discussed above. The second part of the embodiment is to ensure that the chosen channels appear equalised at the receiving node. This is advantageous because it means the cyclic prefix, required by OFDM symbols to combat ISI, can be made very short.

The F3 SOUNDING field contains reference symbols known to both the transmitting node and the receiving node, prior to the data symbols. The OFDM receiver calculates for each reference tone m a channel gain $H(m,n)$. The channel gain is found by dividing the received tone amplitude by the transmitted tone amplitude.

$$H(m,n) = \frac{r(m,n)}{s(m,n)}$$

The channel gain may be averaged over several reference symbols, n, to get a stable estimate $\hat{H}(m)$. A maximum likelihood estimate of the noise on each sub-carrier can be determined by the following formula, which operates over the remaining F3 SOUNDING symbols once a stable channel gain has been obtained.

$$\hat{\sigma}_m^2 = \frac{1}{N}\sum_n \left|\hat{H}(m)s(m,n) - r(m,n)\right|^2$$

where $s(m,n)$ is the transmitted symbol.

The receiving node shall be responsible for calculating the channel gain and noise variance for every F3 SOUNDING frame it receives. These are combined and returned in a dedicated channel measurement frame.

$$g(m)=\frac{H(m)}{\sigma_m}$$

The transmitting node will use the returned channel gain $g(m)$, so it can invert the channel at the transmitting node. So for optimised frames the power allocation per subcarrier becomes a channel gain per subcarrier in amplitude and phase, distributed as follows

$$G(m)=\frac{\sqrt{P_T}\,2^{B_{Qm}/2}g(m)^*/|g(m)|^2}{\sum_j 2^{B_{Qj}/2}g(j)^*/|g(j)|^2},\quad m=0,\ldots,M_{tot}-1$$

The transmitting node will be responsible for keeping a rolling estimate of the channel gain. The channel gains are applied in the *channel expansion* block in the modem architecture described later. Note that the returned channel gain is normalised by the noise standard deviation. This means that for a non-flat noise power spectrum, which is common in powerline communications, the channel seen by the receiver will not be perfectly equalised in gain.

System Architecture

An example of the system architecture is illustrated in Figure 18. The system architecture shown in Figure 18 includes a controller 296 to manage the mesh and to perform channel optimisation as well as handling the host interface and Media Access Control (MAC) layer protocol.

The controller 296 runs software 292 that handles the node management within the mesh. The software extension to schedule channel sounding and collation of channel information for each node is specific to the present invention. The software maintains a table 298 for each node that is used by the transmit modem 304 in a point-to-point communication. The F2 and F3 framing protocol and the way by which the modem communicates over the channel using multiple frequency agile adaptive OFDM channels, the optimisation routines and the final modem architecture to take advantage of the optimisation result is in accordance with a specific embodiment of the invention.

Transmit modem

A simplified illustration of the system transmitter 310 is shown in Figure 19.

The architecture consists of:

1. A channel coding stage through the scrambler 314, convolutional encoder 316 and puncture blocks 318. It is well known to the skilled person in the industries of transmitter that any standard channel coding technology could be used, for example Reed Solomon, concatenated Reed Solomon and Viterbi, turbo product or convolutional code, or low-density parity check (LDPC) codes.
2. Distribution of bits to channels by the stream parser 320.
3. Four 16-data subcarrier OFDM engines, supporting adaptive bit loading.
4. Interpolation 340, frequency translation 342 and combining 344.

The architecture is specified in such a way that it can be implemented in hardware with low cost. The following design details ensure this:

- The shortest symbol has a minimum 50% guard interval – this simplifies the interleaver and FFT implementation, in particular the need for buffer memory is avoided.
- The FFT is 32 point with 16 active data subcarriers and 3 pilots.
- The sparse FFT allows low complexity interpolation filtering.
- A maximum 64 MHz system clock for both the modem and analog subsystem.

As shown in Figure 20, the subsystem modulates 16 data 354 and 3 pilots 352 in the available 32 subcarrier frequency bins.

The interpolation block 340, can be designed by anyone skilled in the art to provide the variable symbol duration, and hence channel bandwidth as required by the optimisation process. In a preferred embodiment the interpolation is performed in three stages. The first stage is a fixed interpolation by 2 using a halfband filter. The second stage is an interpolation by 2 or 3 using a half or thirdband filter, and the third stage is interpolation by 1, 2, 4, 8 or 16 using cascaded integrator comb filters.

The invention has been described by way of a software implementation. This software implementation can be introduced as a stand alone software product, such as borne on a storage medium, e.g. an optical disk, or by means of a signal. Further, the implementation could be by means of an upgrade or plug-in to existing software.

Whereas the invention can be so provided, it could also be by way exclusively by hardware, such as on an ASIC.

The reader will appreciate that the foregoing is but one example of implementation of the present invention, and that further aspects, features, variations and advantages may arise from using the invention in different embodiments. The scope of protection is intended to be provided by the claims appended hereto, which are to be interpreted in the light of the description with reference to the drawings and not to be limited thereby.

CLAIMS:

1. A method of managing data communication between a source terminal and a plurality of remote terminals over a wideband spectrum, wherein said spectrum between said source terminal and each remote terminal is characterised by a different frequency response, said method comprising

   determining, for each remote terminal, said frequency response of said spectrum;

   allocating N channels in said spectrum, each channel having substantially equal bandwidth, in accordance with said frequency response; and

   determining final centre frequencies of said channels through optimisation, such that the available capacity of said spectrum is fully utilised.

2. A method in accordance with claim 1 wherein said step of determining said frequency response includes transmitting a wideband channel sounding frame from said source terminal to said plurality of remote terminals, and receiving signal-to-noise ratio (SNR) information from said remote terminals to said source terminal in response to said wideband channel sounding.

3. A method in accordance with claim 2 wherein said wideband channel sounding frame consist of K equally spaced subcarriers covering said channel to be optimised.

4. A method in accordance with any preceding claim wherein the step of allocating N channels includes determining initial centre frequencies of said channels by selecting N subcarriers with N highest SNR.

5. A method in accordance with any preceding claim wherein said optimisation includes assigning channel parameters to said channels and determining the capacity of said channel based on said assigned channel parameters.

6. A method in accordance with claim 5 wherein said step of assigning channel parameters includes allocating, for each said channel, the same number of adjacent subcarriers, M, symmetrically around said initial centre frequencies, so that each channel occupies a particular bandwidth, and allocating suitable transmission bits to each channel and transmission power to each subcarrier based on said SNR for the purpose of finding channel capacity.

7. A method in accordance with claim 5 and claim 6 wherein said step of assigning channel parameters is performed for different values of M, which results in different channel bandwidth for the channels, and selecting the channel parameters giving the best capacity for subsequent communication between said source terminal and remote terminal.

8. A method in accordance with any preceding claims and including the steps of: transmitting a narrowband sounding frame from said source terminal to said plurality of remote terminals; and receiving channel gain vectors from said plurality of remote terminals to said source terminal in response to said narrowband sounding.

9. A method in accordance with claim 8 and including performing channel inversion at the source terminal based on said channel inversion gain vectors.

10. A method in accordance with any preceding claims and including the step of performing wideband sounding and narrowband sounding periodically thereby monitoring frequency response during data communication.

11. A method of establishing data communications between a source terminal and a plurality of remote terminals over a spectrum, wherein said spectrum between said source terminal and each remote terminal is characterised by a different frequency response, said method comprising:

transmitting a sounding field from said source terminal to said plurality of remote terminal;

requesting channel measurements on said sounding field from at least one remote terminal;

requesting said at least one remote terminal to transmit said channel measurements to said source terminal; and

transmitting signalling information in response to said channel measurements in a signal field from said source terminal so as to enable said remote terminals to decode a narrowband channel in subsequent data communications.

12. A method in accordance with claim 11 wherein said sounding field includes any one of the following: a wideband sounding field and a narrowband sounding field.

13. An apparatus for use in a data communications system having a wideband spectrum, wherein said spectrum between any two communicating terminals is characterised by a frequency response, said apparatus comprising:

means for obtaining said frequency response of said spectrum;

channel allocation means for allocating N channels in said spectrum, each channel comprising a fixed number of subcarriers covering a particular bandwidth in accordance with said frequency response; and

signal processing means for determining final centre frequencies of said channels through optimisation, such that the available capacity of said spectrum is fully utilised.

14. An apparatus in accordance with claim 13, wherein said means for obtaining said frequency response is configured to perform wideband sounding through a

wideband sounding frame to a plurality of remote terminals so as to obtain SNR information from said remote terminals.

15. An apparatus in accordance with claim 14 wherein said wideband channel sounding frame consist of K equally spaced subcarriers covering said channel to be optimised.

16. An apparatus in accordance with any one of claims 13 to 15, wherein said channel allocation means is configured to allocate initial centre frequencies of said channels by selecting N subcarriers with N highest SNR.

17. An apparatus in accordance with any one of claims 13 to 16, wherein said signal processing means is operable to assign channel parameters to said channels, determine the capacity of said channel based on said assigned channel parameters and to select said channel parameters giving the best capacity for subsequent communication between said source terminal and remote terminal.

18. An apparatus in accordance with any one of claims 13 to 17, wherein said means for obtaining frequency response is further configured to perform narrowband sounding through a narrowband sounding frame to a plurality of remote terminals to as to obtain channel gain vectors from said remote terminals.

19. An apparatus in accordance with any one of claims 13 to 18, wherein said signal processing means is further configured to perform channel inversion based on said channel inversion gain vectors.

20. An apparatus in accordance with any one of claims 13 to 19, wherein said means for obtaining said frequency response is further configured to perform wideband sounding and narrowband sounding periodically so as to monitor said frequency response during data communication.

21. A computer program product comprising computer executable instructions operable to configure general purpose computer controlled communications apparatus to perform a method in accordance with any one of claims 1 to 12.

22. A storage medium storing computer executable instructions which, when executed on general purpose computer controlled communications apparatus, cause the apparatus to become configured to perform the method of any of claims 1 to 12.

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Application No: GB0620600.7 **Examiner:** Steve Evans
Claims searched: All **Date of search:** 18 January 2007

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	CN 1708927 A (QUALCOMM) - WPI Abstract Accession No.: 2004-400444
A	-	EP 1496658 A1 (SAMSUNG) - Whole document
A	-	GB 2050124 A (CODATA) - Whole document

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

H4P; H4R

Worldwide search of patent documents classified in the following areas of the IPC

H04B; H04L

The following online and other databases have been used in the preparation of this search report

Online: WPI, EPODOC