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CA 2673760 C 2014/12/09

(11)(21) **2 673 760**

(12) **BREVET CANADIEN
CANADIAN PATENT**

(13) **C**

(86) **Date de dépôt PCT/PCT Filing Date:** 2007/12/21
(87) **Date publication PCT/PCT Publication Date:** 2008/07/03
(45) **Date de délivrance/Issue Date:** 2014/12/09
(85) **Entrée phase nationale/National Entry:** 2009/06/23
(86) **N° demande PCT/PCT Application No.:** EP 2007/064481
(87) **N° publication PCT/PCT Publication No.:** 2008/077950
(30) **Priorité/Priority:** 2006/12/27 (EP06405544.5)

(51) **Cl.Int./Int.Cl.** *H04L 1/00* (2006.01), *H04L 27/26* (2006.01)

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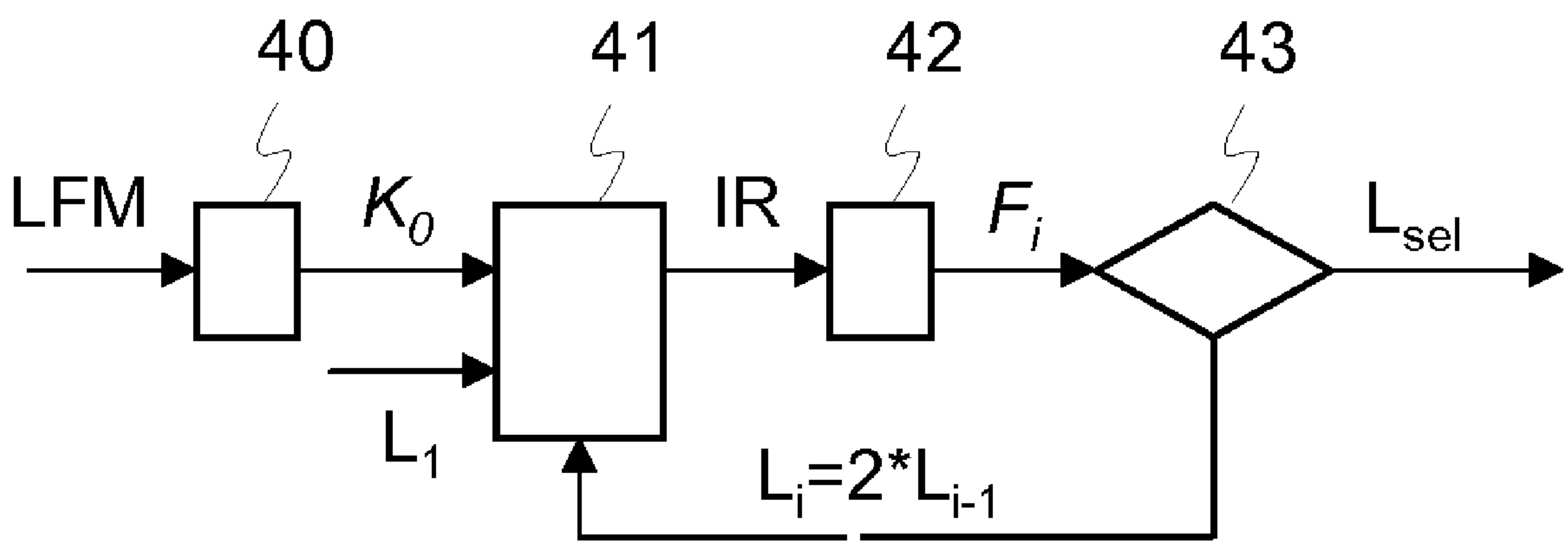
(54) **Titre :** INITIALISATION DE ET MODEM POUR UNE TRANSMISSION DE DONNEES PAR MULTIPLEXAGE PAR REPARTITION ORTHOGONALE DE LA FREQUENCE
(54) **Title:** INITIALIZATION OF AND MODEM FOR AN OFDM DATA TRANSMISSION



(57) **Abrégé/Abstract:**
The present invention is concerned with an optimized efficiency of an Orthogonal Frequency Division Multiplex (OFDM) data transmission, in particular for power line communication. The length or duration of aguard interval or cyclic prefix in an OFDM symbol is selected from scratchat everystart-up of a modem while initializing or preparing the OFDM data transmission. The length of the guard interval is given by the number L of samples in a time-discrete representation, and the value of L that is retained for the subsequent data transmission is selected from a plurality of pre-determined possibilities based on an evaluation of a channel qualityofa communication channel including a physical line to which the modem is connected. Hence, the selected value of L depends on actual transmission conditions, and the optimization potential offered by a more flexible handling of the system parameters L and N is exploited in order to meet changing conditions on the physical line.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
3 July 2008 (03.07.2008)

PCT

(10) International Publication Number
WO 2008/077950 A3

(51) International Patent Classification:
H04L 1/00 (2006.01) *H04L 27/26* (2006.01)

(21) International Application Number:
PCT/EP2007/064481

(22) International Filing Date:
21 December 2007 (21.12.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
06405544.5 27 December 2006 (27.12.2006) EP

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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(54) Title: INITIALIZATION OF AND MODEM FOR AN OFDM DATA TRANSMISSION

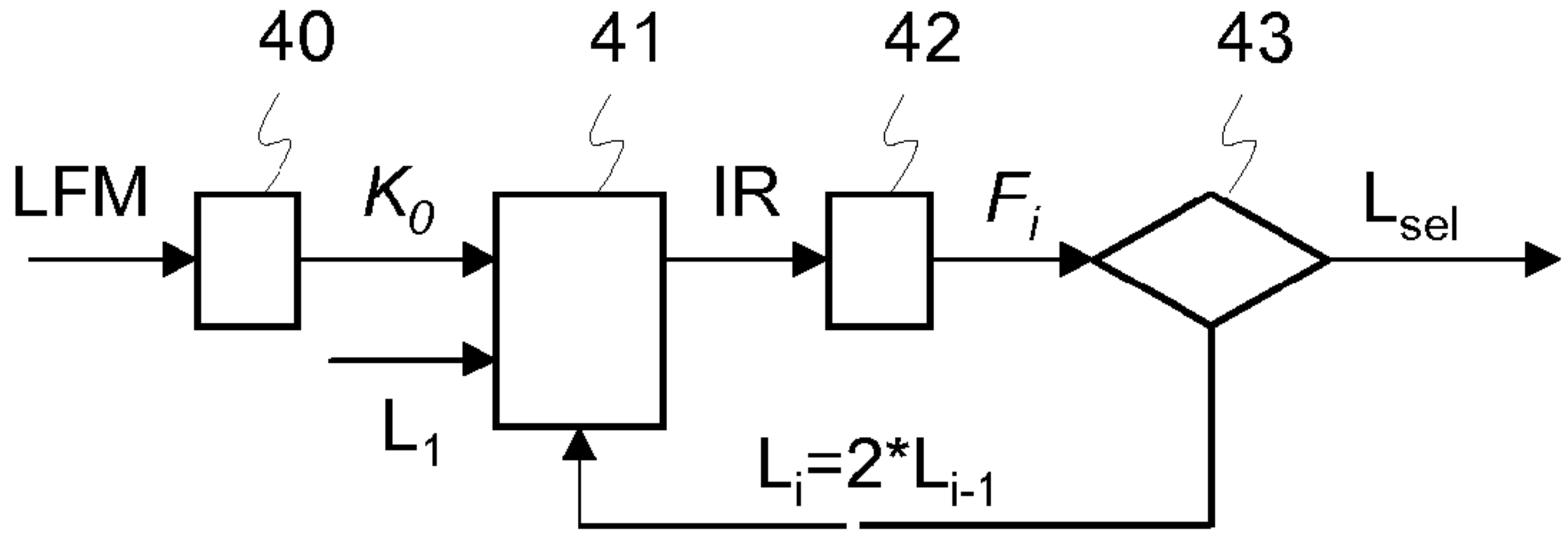


Fig. 3

(57) Abstract: The present invention is concerned with an optimized efficiency of an Orthogonal Frequency Division Multiplex (OFDM) data transmission, in particular for power line communication. The length or duration of aguard interval or cyclic prefix in an OFDM symbol is selected from scratchat everystart-up of a modem while initializing or preparing the OFDM data transmission. The length of the guard interval is given by the number L of samples in a time-discrete representation, and the value of L that is retained for the subsequent data transmission is selected from a plurality of pre-determined possibilities based on an evaluation of a channel qualityofa communication channel including a physical line to which the modem is connected. Hence, the selected value of L depends on actual transmission conditions, and the optimization potential offered by a more flexible handling of the system parameters L and N is exploited in order to meet changing conditions on the physical line.

WO 2008/077950 A3

WO 2008/077950 A3

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(88) Date of publication of the international search report:
16 October 2008

DESCRIPTION

INITIALIZATION OF AND MODEM FOR AN OFDM DATA TRANSMISSION

FIELD OF THE INVENTION

The invention relates to the field of Orthogonal Frequency Division Multiplex (OFDM) data transmission. It is concerned with an initialization of the OFDM data transmission for optimized efficiency, and is particularly suited for Power Line Communication (PLC) over power line communication links at high or medium voltage .

BACKGROUND OF THE INVENTION

For the transmission of digital data, multi-channel data transmission based on Orthogonal Frequency Division Multiplex (OFDM), also known as Discrete Multitone (DMT) modulation, is a well-known flexible modulation scheme. OFDM spreads the data to be transmitted over a large number of sub-carriers or sub-channels comprised in a transmission band and separated from each other by well-defined frequency spacing or carrier separation. The latter ensures *orthogonality* of the sub-carriers and prevents crosstalk or inter-carrier interference between sub-carriers, i.e. the demodulator for one sub-carrier is not affected by the modulation of the other sub-carriers even though there is no explicit filtering and their spectra overlap. The individual OFDM modulation symbols on each of the carriers represent a number of bits that depends on the choice of the QAM alphabet, i.e. the arrangement of data or constellation points in the quadrature amplitude plain. For instance, 2 bit/symbol for Quadrature Phase Shift Keying (QPSK), or 4 bit/symbol for 16-QAM (Quadrature Amplitude Modulation) is commonly used. The complex processes of modulating and demodulating thousands of carriers simultaneously are equivalent to Discrete Fourier Transform operations, for which efficient Fast Fourier Transform (FFT) algorithms exist.

A suitable modem architecture comprises an encoder to multiplex, synchronize and encode the data to be transferred, as well as a modulator to form a discrete multitone signal. The encoder translates incoming bit streams into in-phase and quadrature components for each of a multiplicity of sub-channels, i.e. the encoder outputs a number of sub-symbol sequences that are equal to the number of sub-channels available to the system. A line monitor at a receiver end repeatedly checks the line quality of the sub-channels by determining the noise-level, gain and phase-shift on each of the sub-channels during use. The bit error rate and the signal-to-noise ratio are then used to dynamically determine the bit transmission rate that the sub-channels can support.

OFDM is suited in particular for Power Line Communication (PLC). Power line channels at high or medium voltage are affected by interferers, because the cable types that are used for the transmission of electric power are unshielded and therefore vulnerable to electromagnetic ingress. The typical noise scenario on power line channels resulting there from comprises so-called narrowband interferers, i.e. signals with a small bandwidth. In addition, the heterogeneous structure of the power line network with numerous branches and impedance mismatching causes numerous reflections (echoes) and multi-path propagation between transmitter and receiver. In the presence of multi-path propagation, the complex transfer function h(i) of a power line link between transmitter and receiver is a sum over a number of paths. In addition, power cables exhibit signal attenuation increasing with length and frequency selective fading.

Intersymbol Interference (ISI) is caused by the interaction of one symbol or waveform with other symbols in time. Multi-path induced ISI can be reduced by the provision of a *guard interval*. Each modulation symbol is transmitted for a total symbol period T_{OFDM} which is longer than an active symbol period T_{ORTH} by a period called the guard interval T_{GUARD}. This implies that the receiver will experience no inter-symbol interference provided that any echoes present in the signal have a delay which does not exceed the guard interval. Naturally, the addition of the guard interval reduces the data capacity by an amount dependent on its length, which prohibits its application to a single-carrier system.

In the Patent DE 44 02 512 C1, a method of shortening a channel Impulse Response IR is disclosed. In order to shorten the overall channel IR of a communication channel comprising a send filter, a physical power line link between transmitter and receiver, and an input or receive filter, a receive filter transfer function is synthesized after channel estimation during a handshaking procedure.

DESCRIPTION OF THE INVENTION

It is therefore an objective of the invention to optimize an efficiency of an Orthogonal Frequency Division Multiplex (OFDM) data transmission, in particular for power line communication. This objective is achieved by a method of initializing an OFDM data transmission and an OFDM modem according to the claims 1 and 9. Preferred embodiments are evident from the dependent patent claims, wherein the claim dependency shall not be construed as excluding further meaningful claim combinations.

According to the invention, the length or duration of a guard interval or cyclic prefix in an OFDM symbol is selected from scratch at every start-up of a modem while initializing or preparing the OFDM data transmission. The length of the guard interval is given by the number L of samples in a time-discrete representation, and the value of L that is retained for the subsequent data transmission is selected from a plurality of pre-determined possibilities. The selection is based on an evaluation of a channel quality of a physical line to which the modem is connected. Hence, the selected value of L depends on actual transmission conditions and is not unnecessarily large as in the case of a modem manufacturer conservatively pre-setting this parameter.

Preferably, a length of an orthogonality interval given by a number N of samples in a time-discrete representation is selected based on the value retained for L and according to further criteria or requirements relating to efficiency and delay. Alternatively, a number N of samples of an orthogonality interval is pre-selected and taken into account during the subsequent selection of the value of L. In any case, the optimization potential offered by a more flexible handling of the system parameters L and N is exploited in order to meet changing conditions on the physical line.

In a preferred variant of the invention, the length of the guard interval is chosen to be as short as possible, but above a suitably defined length of a channel Impulse Response (IR) of a communication channel comprising the physical link. The length of the IR is advantageously minimized by means of a purposely synthesized or prepared input or receive filter at a second modem or receiver, which filter is considered part of said communication channel.

In a refinement of this variant, a first value of L corresponding to a minimum tentative or target guard interval, is chosen, and an input filter is prepared based thereupon. The length of the respective IR of the communication channel including said filter is calculated and compared to the length of the tentative guard interval. If a certain criteria is met, the first value of L is selected as the definite value retained for communication, otherwise the procedure is repeated with an increased tentative or target length of the guard interval until this length conforms with the length of the respective IR.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter of the invention will be explained in more detail in the following text with reference to preferred exemplary embodiments which are illustrated in the attached drawings, in which:

Fig.1 schematically shows the components of an OFDM modem,

Fig.2 shows a transmission channel with transmit filter, physical link and receive filter,

Fig.3 is a flow chart of determining an optimum length of the guard interval, and

Fig.4 depicts a shortened Impulse Response, as well as an estimated and interpolated link transfer function.

The reference symbols used in the drawings, and their meanings, are listed in summary form in the list of reference symbols. In principle, identical parts are provided with the same reference symbols in the figures.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig.1 shows a digital implementation of the orthogonal frequency division multiplexing (OFDM) modulation method. In an OFDM base modulator 10, a QAM-vectoriser 11 generates a vector of frequency coefficients in accordance with parallelised digital input bits from the digital input signal D. According to a mapping scheme such as 2^MQAM (Quadrature Amplitude Modulation) or, as a special case thereof, 2^MDPSK (Differential Phase Shift Keying) modulation, the frequency coefficients are generally complex 2^M-ary symbols D_k. From the vector of frequency coefficients, an Inverse Fast Fourier Transform (IFFT) 12 generates an in-phase component I and an orthogonal quadrature component Q of a discrete multitone signal. In block 13, each of said components is padded with a cyclic prefix or guard interval by copying a part of the discrete multitone signal as detailed below, resulting in two real-valued sequences at sampling rate $1/T_O$, i.e. an in-phase component $o_I(n)$ and a quadrature component $o_Q(n)$ of the modulated digital signal.

In order to prepare the OFDM signal for a frequency shift, the components are upsampled by a factor m_{1O} in upsampler 14, where $m_{1O} > (2f_O + B_O)T_O$, with B_0 being the bandwidth of the OFDM transmission band and f_0 being its center or frequency offset, must be satisfied to fulfil the sampling theorem. In the next modulation step, in OFDM modulator frequency shifter 15, the mid-frequencies of the spectrum of o_I and o_Q are finally moved to $\pm f_O$. The resulting signals are summed up to build a digital signal which is then filtered in send filter 16 and converted, in a D/A converter 17, to an analogue signal Y for amplification and transmission.

In an OFDM transmission system, modulation is performed on a block of M bits of data at a time, yielding, according to a coding scheme as detailed above, N complex numbers C_k that are assigned to the N orthogonal frequencies. An Inverse fast or discrete Fourier Transform (IFT) converts the N complex numbers C_k into a time-discrete orthogonality symbol or interval of length $T_{ORTH} = t_s$ and comprising N complex sampling values such that $T_{ORTH} = t_s = NT$ with T being a transmitter timing or sampling period. The signal for the guard interval of length $T_{GUARD} = t_g = LT$, i.e. comprising L complex sampling values, is prefixed to, as an extension of, each of the orthogonality symbols to form an OFDM or transmission symbol of length T_{OFDM}. In short, each OFDM symbol consists of an orthogonality interval of length T_{ORTH} and a guard interval of length T_{GUARD}, and has a length $T_{OFDM} = T_{ORTH}+T_{GUARD} = (N+L)/f_s$, where the sampling frequency $f_s = 1/T$ equals the Nyquist frequency of the transmission band of the channel.

For optimal use of the available frequency band of the communication channel, the sampling rate or frequency $f_s = 1/T$ at which samples of the transmit signal are generated should be chosen close to the channel bandwidth (e.g. 4 kHz or 32 kHz), which usually is not a design parameter but given by the application. The interval or separation between adjacent carrier or transmission frequencies is denoted Δf, and in the following, is assumed equal to the symbol rate, i.e. $\Delta f = 1/NT$. Therefore, in practice, the selection of N as detailed below also determines Δf.

Fig.2 depicts a communication channel 2 as defined in the context of the present invention. The channel 2 is understood to comprise all the elements between the modulation and cyclic prefix in a sender/transmitter modem 1 and extraction of the orthogonality interval and demodulation in a receiver modem 3. In particular, besides the physical power line link 21 between transmitter and receiver, send filter 16 and input filter 32, also known as receive filter, are part of the communication channel 2 per definition.

In accordance with the invention, a manual or automated selection of a guard interval, i.e. the specification of the number L of samples comprised or the corresponding length $T_{GUARD}=t_g=LT$, the following requirements have to be observed:

A) In order to avoid Intersymbol-Interference (ISI) between successive OFDM symbols, the length T_{GUARD} of the guard interval must be chosen to be at least equal to a suitably defined length $T_{CHANNEL}$ of the channel Impulse Response (IR) function of the above-defined communication channel 2, wherein per said definition a major share of the energy of the channel IR function is comprised within an interval of length $T_{CHANNEL}$.

B) The efficiency of the transmission represents a further requirement related to the choice of the integers N and L. As the receiver discards the guard interval and extracts the orthogonality interval for demodulation, the efficiency increases with the decrease of the length of the guard interval and can conveniently be defined by the ratio L/N.

C) The delay of the transmission represents a third requirement influencing the choice of the numbers N and L. The delay is due to the block-wise transmission and processing of the signals and data, and is proportional to the OFDM symbol length, and empirically $T_{DELAY} \approx 5\ T_{OFDM}$. For instance, for a channel bandwidth of 4 kHz and N=64, the delay is close to 100 ms. In general, this delay may not exceed certain upper limits due to constraints of the underlying real time application. Hence, if e.g. the length of the guard interval is given, the maximum allowed delay imposes an upper limit to T_{ORTH}.

So far, OFDM modems have been known with a fixed, predetermined, or at best manually selectable length of the orthogonality and guard interval, with exemplary factory settings of N=128 or 64 and L=8. In an advantageous embodiment of the present invention, and respecting $L/N \leq 1/8$ for reasons of efficiency as the only constraint, the following combinations of L and N may be selected:

N	L			
64	8			
128	8	16		
256	8	16	32	
512	8	16	32	64

As a consequence of requirement A) above, the derivation of a minimal length of the guard interval is closely linked to the length $T_{CHANNEL}$ of the channel Impulse Response

(IR). By virtue of the above definition of the channel 2, the latter comprises a convolution of the impulse response of the filters 16, 32 and the complex link transfer function K of the physical power line link 21. The Patent DE 44 02 512 mentioned above discloses an advantageous procedure to shorten the channel IR. According to this procedure, the input or receive filter 32 of the receiver is synthesized such that the transmission channel has an IR that concentrates a major share of its energy in a small temporal range that is, for the purpose of this invention, designated the length $T_{CHANNEL}$ of the shortened IR. A successful shortening of the channel IR allows reducing subsequently the length of the guard interval without violating requirement A) above, i.e. $T_{GUARD} \geq T_{CHANNEL}$. Finally, the length N of the orthogonality symbol can be chosen in accordance with the above table and requirements B) and C).

Fig.3 depicts a flowchart of the procedure of adapting the length of the guard interval. The outcome of the procedure depends on the properties of the physical link 21 of the communication channel 2, and in particular on a channel quality such as the link transfer function K of the physical link 21. Accordingly, in preparatory step 40, the receiver 3 receives a signal that has been emitted by the sender 1 as a pre-defined Linear Frequency Modulated (LFM) sweep-signal or sequence, or alternatively, as a pseudo noise signal covering all the frequencies of the channel, and from which the transfer function K can be estimated accurately. As the transfer function K can be quite long, an initial estimate of the sweep-signal is obtained with a large number of samples $K_0(k)$, wherein this number is related to the maximum symbol length of N_{MAX}=512 and L_{MAX}=64 of the modem 3, and in the following assumed to be equal to $2*N_{MAX}$. Next, a starting value L_1 corresponding to a first target length of a tentative guard interval is defined. This first target length may either be the smallest value of L provided by the modem, e.g. $L_1 = 8$ or even $L_1 = 7$, or the smallest value in accordance with a pre-selected length of the orthogonality interval.

In step 41, the abovementioned channel Impulse Response (IR) shortening procedure is carried out. When the input or receive filter 32 is implemented with the well-known "overlap-save" method for block oriented processing, the length of the input filter 32 will be limited to N-L+1 for minimum processing time. Accordingly, the input filter 32, i.e. the input or receive filter transfer function, cannot be calculated with an unchanged number ($2*N_{MAX}$) of samples directly from the link transfer function K. Hence, synthesizing or preparing the input filter 32 starts with the selection of L_1 samples by decimating, and optionally weighting, the samples $K_0(k)$ of the link transfer function in frequency domain. Inverse Fourier Transformation, zero filling, and Forward Fourier Transformation yields again $2*N_{MAX}$ samples $K_1(k)$ of an interpolated link transfer function. From the latter, $2*N_{MAX}$ samples of the synthesized input filter transfer function are obtained. Convolution with the link transfer function K and Inverse Fourier Transformation finally yield $2*N_{MAX}$ samples $R_1(n)$ of the shortened channel IR.

In step 42, and as further detailed below, a quantitative measure F_1 is determined, indicating quantitatively to which extent the energy of the shortened impulse response is contained within the range of the target length L_1 of the guard interval. In step 43, a decision is taken whether the measure F_1 is acceptable or not. In other words, the fraction of energy of the channel impulse response contained in a section of length T_{GUARD} is used as a measure of acceptance. If the latter is considered sufficient, the starting value L_1 is retained as the optimum value L_{sel} for the length L of the guard interval. Otherwise, the target length is increased to the next higher value L_2, e.g. as $L_2=2*L_1$. Steps 41 to 43 are then repeated. If the measure F_2 is still not acceptable, the procedure is repeated with a further increased value L_i of the target length, i.e. $L_3=32$, $L_4=64$.

Fig.4 illustrates an exemplary outcome of the IR shortening in step 41, based on which the measure F_i is determined in step 42. On the left hand side of Fig.4 are depicted 2N samples $R_i(n)$ of a time-domain representation of the i^{th} shortened IR of the communication channel. The interval of width L_i represents the target length. By means of Fisher Statistics, the energy of the samples inside a moving window of width W equal to L_i is calculated and compared to the total energy of the 2N samples as

$$F_i(W) = \frac{\frac{1}{W}\sum_{n \in W} R_i^2(n)}{\sum_{n=1}^{2N} R_i^2(n)}$$

The maximum value for the measure $F_i(W)$ obtained for all windows of width W is then compared to a threshold in step 43.

Alternatively, on the right hand side of Fig.4, a representation in frequency domain is depicted of the link transfer function $K_0(k)$ and the i^{th} interpolated link transfer function $K_i(k)$ as an approximation of the former. The normalized difference between the two, calculated as

$$F_i = \frac{\sum_k |K_0 - K_i|^2}{\sum_k |K_0|^2}$$

defines another measure of the accuracy of the subsequently synthesized filter transfer function and shortened channel IR. In fact, the smaller the above difference, the better the approximation of the estimated “true” link transfer function K_0 by the interpolated transfer function K_i, and the shorter the IR of the communication channel comprising the input filter synthesized on the basis of the interpolated transfer function K_i. Again, the measure F_i obtained is compared to a threshold in step 43, wherein the latter actually can be determined in a semi-heuristic way, but with less ambiguity than the threshold provided above.

As a result of the above procedure, the length of the guard interval is assured to exceed the suitably defined length of the shortened impulse response, i.e. $T_{GUARD} = L_{sel}/f_s \geq T_{CHANNEL}$. The length N of the orthogonality interval finally is determined by considering the remaining requirements B) and C). Maximized efficiency is reached for $N = N_{MAX} = 512$. However, if the maximum delay is not respected for this combination ($N_{MAX}+L_{sel}$), the next smaller values of N are successively selected, i.e. $N_i = N_{i-1}/2$ with $N_1 = N_{MAX}$ as long as the efficiency requirement is still respected, i.e. as long as the combination N_i, L_{sel} is represented in the table above.

Alternatively, the above procedure assuring the length of the guard interval to exceed the length of the shortened impulse response can be executed after a pre-selection of N by an operator based on overall delay and/or efficiency criteria. Considering the remaining requirements B) and C), the lowest value of L is chosen from the table above, and input as L_1 in the IR shortening procedure. If the IR shortening procedure is successful for this value of L, the procedure stops, otherwise another, larger L is tested.

The automatic selection of the guard interval as detailed above is typically executed as part of an initialisation procedure carried out at a start-up of the modems connected to the power line, initiated e.g. after a switch in the primary network has been operated. The beginning of this procedure is signalled by means of purportedly coding pilot signals broadcasted by a first modem 1, 3 connected to a first end of a power line link 21. A second modem 3, 1 connected to a second end of the link 21 acknowledges reception and emits a LFM signal. At the first modem 1, 3, after an estimation of the channel transfer function, the IR shortening is performed repeatedly, and first optimized values of N and L are provisionally determined. This result is then transmitted to the second modem 3, 1 via a robust and redundant QAM4 modulation. By comparison with second provisional optimized values of N and L determined at the second modem, the final combination N_{sel}, L_{sel} is determined. If the first and second provisional values for N and L diverge, the higher value for L is selected, and N is chosen as proposed by the modem proposing the higher value for L.

In addition, in a second phase following start-up of the modem, and generally following any automatic selection of the guard interval, the value of L retained is verified. To this end, the channel transfer function is repeatedly estimated during data transmission. If the presently selected value L_{sel} is found to be insufficient or sub-optimal, a procedure according to the preceding paragraph is initiated. In power line communication, as long as there are no switching actions or faults in the primary network, the channel qualities are expected to vary slowly, i.e. on a time scale of hours, due mainly to weather conditions (humidity, temperature). Accordingly, such variations can be readily accounted for by a continual adaptation of the input filter.

LIST OF DESIGNATIONS

1	OFDM modem
10	OFDM modulator
11	QAM vectoriser
12	Inverse Fast Fourier Transform
13	Cyclic Prefix
14	Upsampler
15	Frequency shifter
16	Send filter
17	D/A converter
2	communication channel
21	Physical link/line
3	OFDM modem
31	A/D converter
32	Input/Receive filter

PATENT CLAIMS

1. A method of initializing an Orthogonal Frequency Division Multiplex OFDM data transmission, wherein OFDM symbols consisting of an orthogonality interval of length N and a guard interval of length L are to be transmitted over a physical link (21), characterized in that the method comprises
   a) choosing a target length L_1 of a guard interval,
   b) synthesizing, based on L_1 and based on an estimated link transfer function K_0 of the physical link (21), an input filter (32) at a modem (3) connected to the physical link (21),
   c) calculating a shortened Impulse Response IR of a communication channel (2) comprising the physical link (21) and the synthesized input filter (32),
   d) calculating a measure F_1 indicative of an extent to which an energy of the shortened IR is contained within the target length L_1 of the guard interval,
   e) if the measure F_1 is above a threshold, selecting the target length L_1 as the optimum length L_{sel} for the guard interval,
   f) otherwise, choosing a further target length $L_2 > L_1$ of the guard interval and returning to step b).

2. The method according to claim 1, characterized in that it comprises
   - selecting, following the selection of the length L_{sel} of the guard interval, an orthogonality interval of length N_{sel} based on the length L_{sel}.

3. The method according to claim 1, characterized in that step d) comprises
   - calculating the measure F_1 as a Fisher statistics relating an energy of the shortened IR comprised in a moving window of width W equal to L_1 to the total energy of the shortened IR.

4. The method according to any one of claims 1 to 3, characterized in that it comprises - selecting N_{sel}, L_{sel} by comparing provisional values of N and L obtained by two modems (1, 3) connected to two ends of the physical link (21).

5. The method according to any one of claims 1 to 4, characterized in that it comprises - transmitting OFDM data over a high or medium voltage power line as the physical link (21).

6. An OFDM modem for Orthogonal Frequency Division Multiplex OFDM data transmission, wherein OFDM symbols consisting of an orthogonality interval of length N and a guard interval of length L are transmitted over a physical link (21) to which the OFDM modem is connected, characterized in that the modem comprises
- means for choosing a target length L1 of a guard interval,
- means for synthesizing, based on L1 and based on an estimated link transfer function K0 of the physical link (21), an input filter (32) of the modem,
- means for calculating a shortened Impulse Response IR of a communication channel (2) comprising the physical link (21) and the synthesized input filter (32),
- means for calculating a measure F1 indicative of an extent to which an energy of the shortened IR is contained within the target length L1 of the guard interval, and
- means for selecting, if the measure F1 is above a threshold, the target length L1 as the optimum length Lsel for the guard interval, and
- means for choosing, if the measure F1 is below the threshold, a further target length L2 > L1 of the guard interval and for returning the further target length L2 to the means for synthesizing.

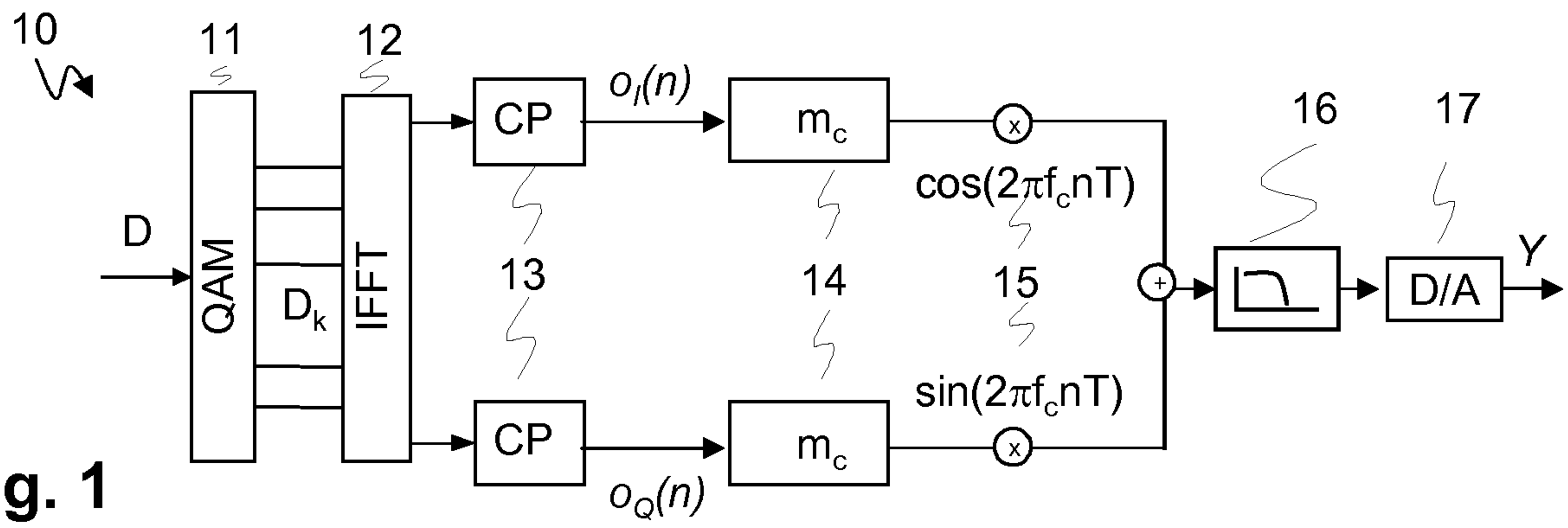


Fig. 1

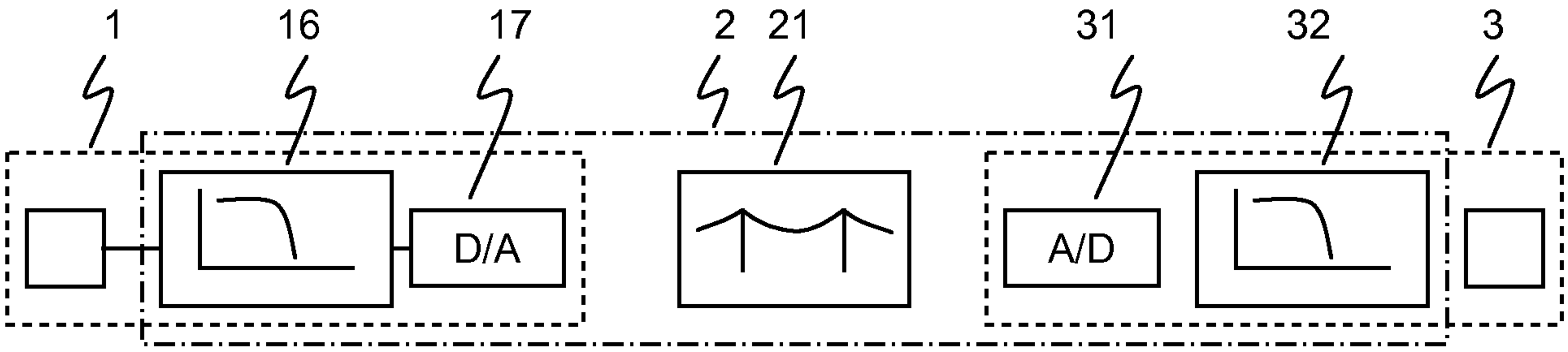


Fig. 2

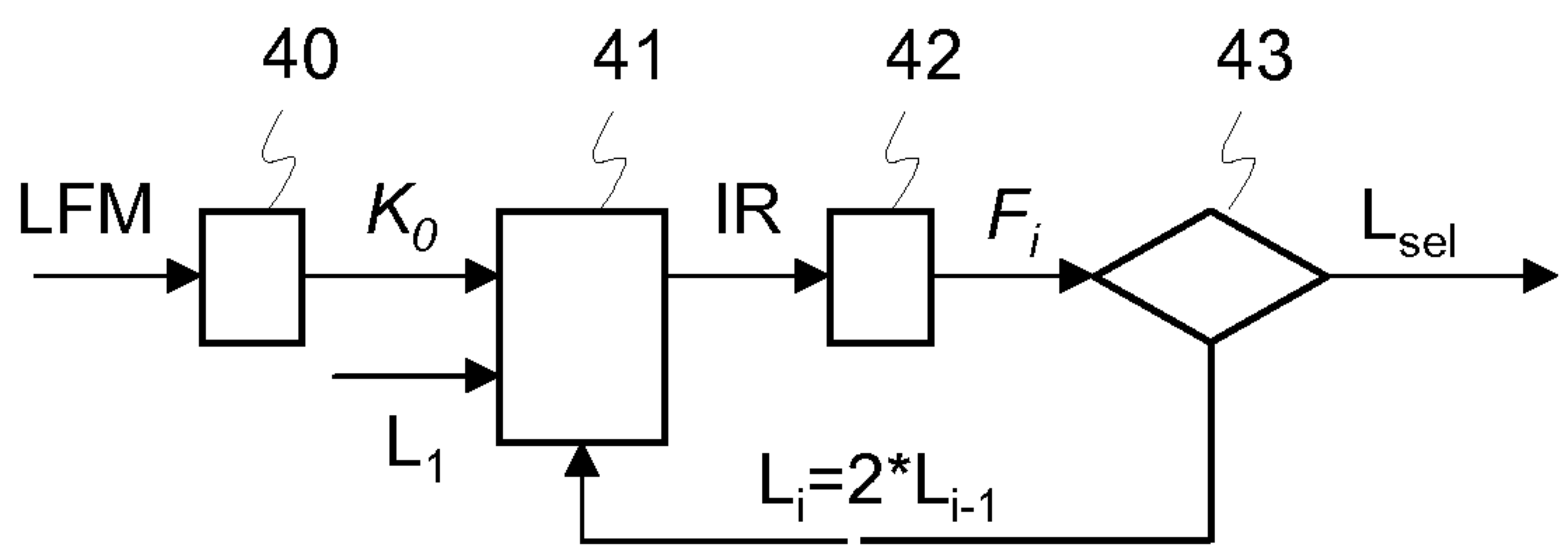


Fig. 3

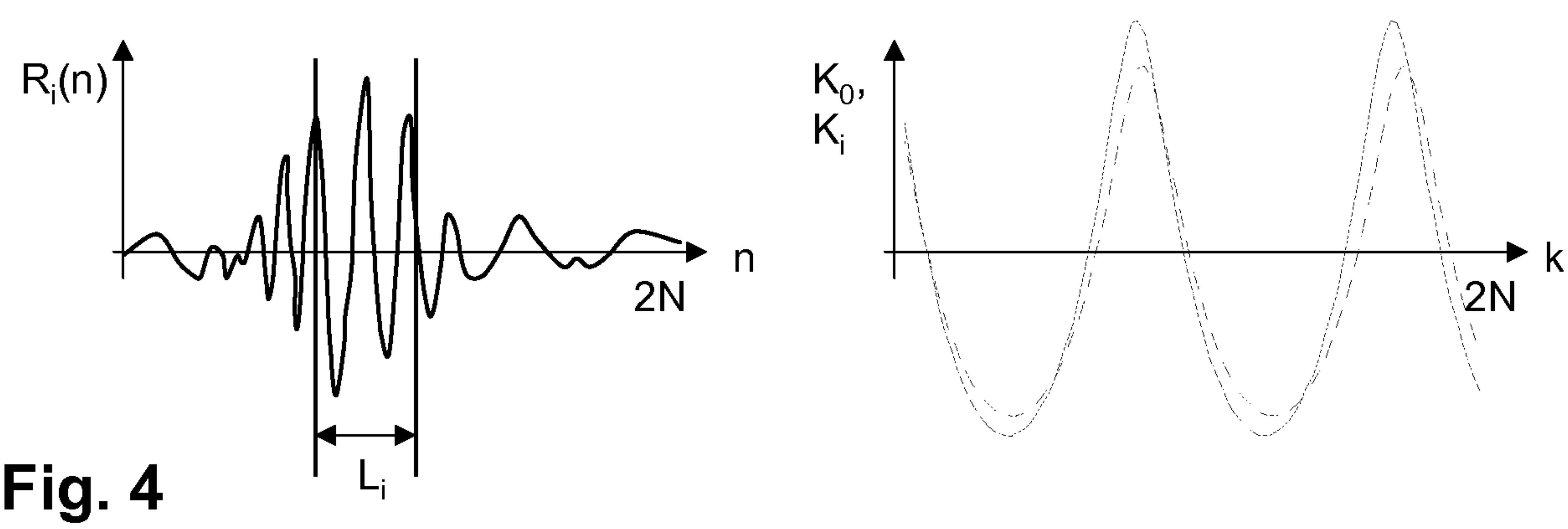
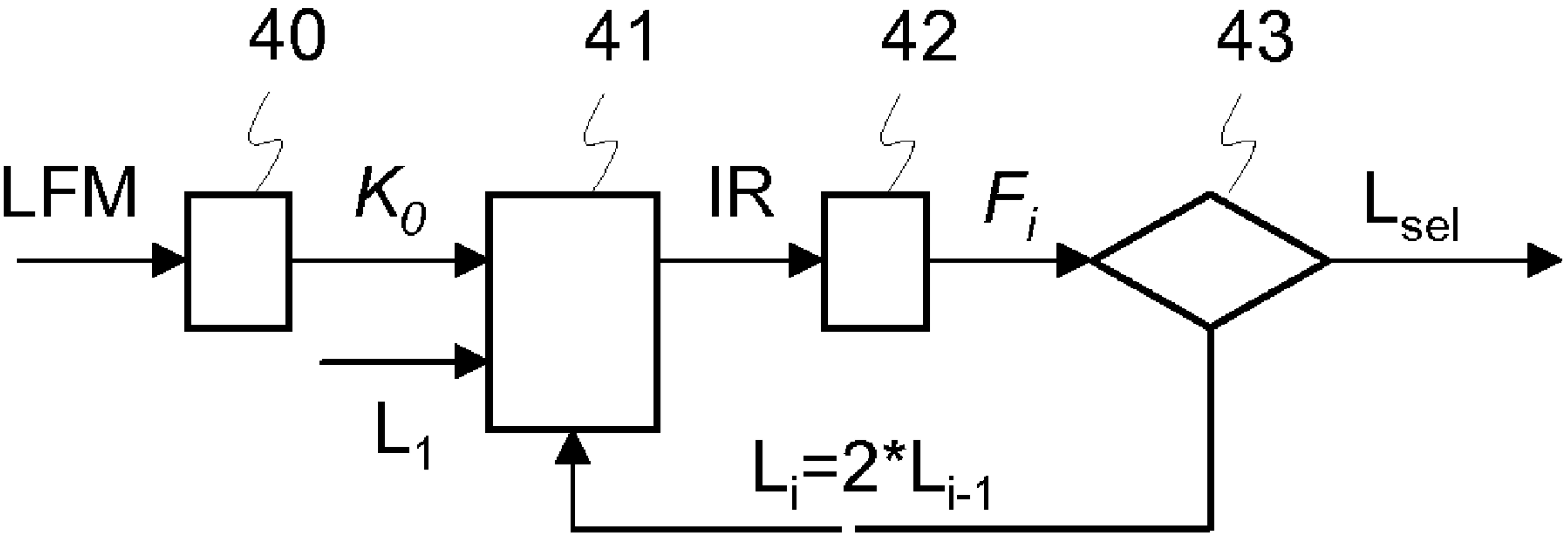


Fig. 4


40
41
42
43
LFM
K_0
IR
F_i
L_{sel}
L_1
$L_i=2*L_{i-1}$