

Improved continuous phase modulation method and emitter implementing said method

The invention relates to the field of digital communication systems and
5 more particularly to emitters of digital data using, to shape the digital signal to
be transmitted, a continuous phase modulation.

In a digital communication system, it is preferable to use constant
amplitude modulations, for example continuous phase modulations, because
10 the latter allow the range of the transmitted signal to be maximized.
Specifically, constant envelope modulations have the advantage of allowing
the emitted signal to have an almost constant power. The continuity of the
phase allows the signal to occupy a narrower bandwidth, and the constant
envelope of the signal allows nonlinearities in the transmission channel to be
15 better withstood and the amplifiers of the system to function closer to their
saturation point.

Thus, to decrease constraints on the spectral width of the transmitted
signal, notably its occupied frequency bandwidth, and the disruption
potentially caused to adjacent channels, it is known to use continuous phase
20 modulation methods such as Gaussian minimum shift keying (GMSK)
modulation.

Continuous phase modulations, although effective, have the drawback
of introducing substantial interference between symbols in the received
signal. The symbol received at the instant t is distorted at least by its
25 neighbors emitted at the instants $t-1$ and $t+1$, thereby making the decision
that a receiver must make to determine the initial state of said symbol more
difficult. For example, in the case of a binary modulation, a symbol may take
eight different states. The receiver will therefore have to make a decision
among these eight possibilities in order to determine the corresponding bit.
30 Receiver complexity and the disruption caused by interference between
symbols increases as the number of possible symbol states increases. In

addition, prior-art methods for demodulating transmitted continuous phase modulated signals have the drawback of being complex because they often use an equalizer and a maximum likelihood sequence estimator (MLSE) implemented, for example, via a Viterbi algorithm.

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The French patent application of the Applicant, published under the number FR 2 938 988, describes a continuous phase modulation method that allows interference between symbols on reception to be decreased.

The method described in this application is based on implementation
10 on emission of a linear combination of these symbols to be emitted before they are filtered.

Although the aforementioned method improves the level of inter-symbol interference relative to a conventional continuous phase modulation, it does not allow this effect to be completely suppressed.

15 There is therefore a need for an improved continuous phase modulation method that allows inter-symbol interference to be almost completely prevented.

One objective of the present invention is to provide a continuous
20 phase modulation method that allows any interference between symbols on reception of the signal to be almost completely suppressed.

Thus one subject of the invention is a continuous phase modulation method comprising the following steps:

- 25
- receiving a sequence of digital data symbols $a(n)$ to be emitted;
 - transforming the sequence of symbols $a(n)$ to be emitted into a transformed sequence of symbols $b(n)$, each symbol $b(n)$ of which is equal to the sum of a symbol $a(n)$ to be emitted and of a corrective factor equal to a transformation T_f applied to a plurality
30 of differences $(a(n)-a(n-1))$ between two consecutive symbols to be emitted, the transformation T_f applied being a combination c of at

least two differences between two consecutive symbols of the sequence to be emitted, transformed by the application of a non-linear function f ;

- filtering the sequence of transformed symbols $b(n)$ with a shaping filter; and
- modulating the sequence of filtered symbols with a phase modulator in order to obtain a sequence of modulated symbols,
- said transformation T_f being defined so as to minimize interference between modulated symbols filtered by a receiving filter.

10 According to one particular aspect of the invention, said transformation T_f is defined by applying the following iterative steps:

- generating a sequence of digital data symbols $a(n)$, referred to as the test sequence;
- filtering the test sequence with a shaping filter;
- 15 • modulating the sequence of filtered symbols;
- filtering the sequence of modulated symbols with a receiving filter;
- demodulating the sequence of filtered symbols on reception;
- modifying the value of each symbol $a(n)$ of the test sequence by a preset value so as to obtain a transformed test symbol $b(n)$;
- 20 • stopping the iterative process when the error between each demodulated symbol and the corresponding symbol in the test sequence has converged to a minimum value; and
- identifying the combination c and the non-linear function f of the transformation T_f as those that allow the transformed test
- 25 sequence to be substantially identical to the test sequence generated then transformed by applying said transformation T_f .

According to one particular aspect of the invention, said iterative steps furthermore comprise a step of determining the error between each demodulated symbol and the corresponding symbol in the sequence to be

emitted, the value of each symbol $a(n)$ of the test sequence being corrected by a value dependent on said error.

According to one particular aspect of the invention, said iterative steps are executed for a plurality of different test sequences and the combination c and the non-linear function f are identified using a plurality of test sequence
5 and transformed test sequence pairs.

According to one particular aspect of the invention, the combination c and the non-linear function f of the transformation T_f are identified by applying the following successive steps:

- 10 • limiting the combination c to two coefficients of equal value;
- determining the non-linear function f and the combination c to be applied so that the transformed test sequence is substantially identical to the test sequence generated then transformed by applying said transformation T_f ;
- 15 • setting the non-linear function f and extending the number of coefficients of the combination c ; and
- determining the combination c to be applied so that the transformed test sequence is substantially identical to the test sequence generated then transformed by applying said
20 transformation T_f .

According to one particular aspect of the invention, the combination c and the non-linear function f of the transformation T_f are identified using a numerical solution method of the Monte-Carlo type.

According to one particular aspect of the invention, the non-linear
25 function f is chosen to be an odd function.

According to one particular aspect of the invention, the possible values of the transformed symbols $b(n)$ are calculated beforehand from possible values of the symbols $a(n)$ to be emitted and from the definition of the combination c and of the non-linear function f .

30 According to one particular aspect of the invention, the symbols $a(n)$ to be emitted are taken from a constellation comprising a plurality of states.

Another subject of the invention is a method for generating a mathematical transformation T_f intended to be used in a continuous phase modulation method according to the invention, said method for generating a transformation comprising the following iterative steps:

- generating a sequence of digital data symbols $a(n)$, referred to as the test sequence;
- filtering the test sequence with a shaping filter;
- modulating the sequence of filtered symbols;
- 10 • filtering the sequence of modulated symbols with a receiving filter;
- demodulating the sequence of filtered symbols on reception;
- modifying the value of each symbol $a(n)$ of the test sequence by a preset value so as to obtain a transformed test symbol $b(n)$;
- stopping the iterative process when the error between each
- 15 demodulated symbol and the corresponding symbol in the test sequence has converged to a minimum value; and
- identifying the combination c and the non-linear function f of the transformation T_f as those that allow the transformed test sequence to be substantially identical to the test sequence
- 20 generated then transformed by applying said transformation T_f .

Another subject of the invention is an emitter intended to emit a continuous phase modulated signal, comprising:

- means for receiving a sequence of digital data symbols $a(n)$ to be
- 25 emitted;
- computational means configured to transform the sequence of symbols $a(n)$ to be emitted into a transformed sequence of symbols $b(n)$, each symbol $b(n)$ of which is equal to the sum of a symbol $a(n)$ to be emitted and a corrective factor equal to a
- 30 transformation T_f applied to a plurality of differences $(a(n)-a(n-1))$ between two consecutive symbols to be emitted, the

transformation T_f applied being a combination c of at least two differences between two consecutive symbols of the sequence to be emitted, transformed by applying a non-linear function f ;

- a shaping filter for filtering the sequence of transformed symbols $b(n)$; and
- a phase modulator for modulating the sequence of filtered symbols,
- said transformation T_f being defined so as to minimize interference between the modulated symbols filtered by a receiving filter.

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Other features and advantages of the present invention will become more clearly apparent on reading the following description given with regard to the appended drawings, which show:

- figure 1, a flowchart schematically showing the steps of the continuous phase modulation method according to the invention;
- figure 2, a flowchart schematically showing the steps of the method, according to the invention, allowing the transformation function to be applied to the symbols to be emitted to be defined;
- figure 3, a diagram of an emitter comprising means suitable for implementing the invention;
- figure 4, an illustration of the non-linear function $f()$ obtained for a continuous phase modulation of particular parameters;
- figure 5, an illustration of the linear combination function $c()$ obtained for a modulation of the same parameters as in figure 4; and
- figure 6, an illustration of the variation in the phase of symbols over time, on emission and on reception, with and without application of the invention.

Continuous phase modulations (CPMs) are a family of modulations widely used to transmit digital data notably in the context of wireless communications. In contrast to other modulation methods in which the phase

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of the modulated signal is subject to abrupt transitions, CPM modulations allow the phase of the transmitted symbols to be continuously modulated.

CPM modulation of a sequence of binary data conventionally comprises the following steps:

- 5 The binary data to be transmitted are first transformed into symbols $a(n)$ via a mapping. This step allows one or more bits to be associated with a symbol to be transmitted. The symbols obtained may be characterized by the representation in the complex plane of their constellation. If the symbol $a(n)$ conveys an information bit, its constellation will comprise two states; if it
- 10 conveys two information bits, its constellation will comprise four states; and, generally, if said symbol conveys n information bits its constellation will comprise 2^n states. The points of the constellation are, for example, evenly distributed on the unity circle. The symbols $a(n)$ are transmitted via a series of Dirac pulses spaced apart from each other by a duration equal to T , where
- 15 T is the duration of a symbol. The Dirac pulse at the instant is represented by the term $a(n)\delta(t-nT)$. The series of Dirac pulses is then filtered by an impulse response filter defined by the function $h(t)$, then transmitted to a phase modulator. The pulse $h(t)$ is defined over a duration LT , where L is generally an integer higher than or equal to 1. The values of this pulse are zero outside
- 20 of the interval $[0, LT]$ and its integral between 0 and LT equals 1. The phase modulator delivers as output a signal $S(t)$ that may be represented by the following formula, where h is the index of the modulation:

$$S(t) = \cos(2\pi F_0 t + 2\pi h \sum_{n=-\infty}^{+\infty} a(n)\delta(t-nT) * h(t)) \quad (1)$$

- 25 In order to combat the interference between symbols inherent to this type of modulation schema, the invention consists in replacing the symbols $a(n)$ with symbols $b(n)$ transformed by a particular mathematical function.

- 30 The method according to the invention is described in figure 1. In a first step 101, a set of symbols $a(n)$ to be emitted is received. As indicated above, the symbols $a(n)$ may convey a plurality of information bits and belong

to a set of symbols from a preset constellation. For example, in the case of an eight-state modulation, the symbols $a(n)$ may take eight separate values. The information symbols $a(n)$ correspond to phase transitions between two modulated symbols.

5 In a second step 102, the symbols $a(n)$ are transformed into symbols $b(n)$ by way of a transformation operation T_f described below. Each symbol $b(n)$ is obtained by applying the transformation T_f to a plurality of consecutive symbols $a(n)$. To carry out step 102, one possible solution consists in memorizing, in a delay line comprising K cells, K consecutive symbols
 10 $a(n), \dots, a(n-K)$ to be emitted. The transformed symbol $b(n)$ is obtained by applying the transformed T_f to the K memorized symbols $a(n), \dots, a(n-K)$. Next, in order to generate the following transformed symbol $b(n+1)$, a new symbol $a(n+1)$ is inserted into the delay line by shifting by one cell the symbols $a(n), \dots, a(n-K+1)$. The delay line is used as a shift register.

15 The transformed symbol $b(n)$ obtained for the instant n (in discrete time) is obtained using the following relationship:

$$b(n) = a(n) + \sum_{j=-p}^p c(j) \cdot f(a(n-j) - a(n-j+1)) \quad (2)$$

$K=2(p+1)$ is the number of buffered symbols $a(n)$;

$c()$ is a linear combination, for example a finite impulse response filter;

20 and

$f()$ is a non-linear function that takes as input the difference between two consecutive symbols $(a(n-j) - a(n-j+1))$ and returns as output a value modified by a non-linear operation.

Without departing from the scope of the invention, the expression
 25 given by the relationship (2) may also be written in the following form, where p and p' are two different positive integers:

$$b(n) = a(n) + \sum_{j=-p}^{p'} c(j) \cdot f(a(n-j) - a(n-j+1))$$

The introduction of a non-linear function associated with the linear combination of a plurality of symbols makes it possible to effectively combat interference between symbols on reception by limiting the spectral width of the modulated signal while nonetheless guaranteeing a good demodulation
 5 performance.

Specifically, in order to effectively combat the effect of interference between symbols, the compensation to be applied to each symbol to be emitted depends on the actual value of the symbol. Thus, a purely linear transformation does not allow interference between symbols to be integrally
 10 corrected.

Since the digital receiving filter is a low-pass (baseband) filter, it attenuates non-linearly the phase displacements of the symbols depending on their size. This effect causes interference between symbols and therefore requires, on emission, a correction to be applied to the symbols $a(n)$ to be
 15 emitted depending on the difference between the symbols $(a(n-j)-a(n-j+1))$.

In a third step 103, the transformed symbols $b(n)$ are filtered by a shaping filter $h(t)$ then, in a fourth step 104, are modulated by a phase modulator or a frequency modulator in order to generate a continuous phase
 20 modulated signal.

A method for determining numerically the coefficients of the linear combination $c()$ and the values of the non-linear function $f()$ from the values that differences between two consecutive symbols $(a(n)-a(n-1))$ are able to
 25 take, depending on the constellation to which the symbols $a(n)$ belong, will now be described.

The method consists in measuring, using one or more preset sequences of symbols $a(n)$, for example sequences generated randomly, the difference, on reception, between the demodulated symbols and the symbols
 30 emitted and in adjusting, iteratively, the values of the symbols $b(n)$ of the transformed sequence so as to obtain, on reception, demodulated symbols

that display almost zero inter-symbol interference. The emission and reception shaping filters are taken into account when generating the demodulated symbols. Without departing from the scope of the invention, it is possible to take into account the impact of radio filters or amplifiers or any
 5 other element of the transmission chain introducing nonlinearities.

Figure 2 describes steps allowing, for a sequence of given symbols $a(n)$, the optimal sequence of transformed symbols $b(n)$ that allows inter-symbol interference to be suppressed on reception to be generated.

10 In a first step 201, a sequence of digital data symbols $a(n)$ is generated the values of which belong to the set of possible values of the constellation associated with the chosen modulation.

Next, in a second step 202, all of the processing operations of the transmission chain – in other words the filtering with the shaping filter, the
 15 phase modulation then the filtering with the suitable receiving filter and the demodulation of the symbols – are applied to the generated sequence.

Next, in a third step 203, the difference between each demodulated symbol and the corresponding emitted symbol in the sequence is measured.

A step of modifying 205 the values of the symbols $a(n)$ of the initially
 20 generated sequence is then carried out. The correction applied may depend on the measured difference between demodulated and emitted symbols. For example, the correction applied may be equal to this difference. The steps 201, 202, 203, 205 are iterated until the following test 204 is passed. The test 204 consists in verifying whether the difference between demodulated
 25 symbols and emitted symbols is substantially zero or lower than a preset threshold.

When this test 204 is passed, the sequence of modified symbols, which corresponds to the transformed sequence $b(n)$, is retained and it is then sought to numerically identify the transformation function T_f in the form
 30 given in relationship (2).

Of course, the method described in figure 2 is reproduced with a plurality of different generated sequences so as to be able to best approximate numerically the parameters of the transformation T_f .

5 To determine the precise parameters of the transformation T_f , it is possible to use a numerical solution method of the Monte Carlo type.

One possible method consists in initially limiting the combination $c()$ to a symmetric filter having 2 identical coefficients and in determining the values of the non-linear function $f()$ from the values that the inter-symbol differences
10 $a(n)-a(n-1)$ are able to take.

Once the non-linear function $f()$ has been defined, the number of coefficients of the combination $c()$ may be extended and these coefficients determined by identification. Advantageously, the combination $c()$ is a symmetric finite impulse response filter.

15 The precision obtained for the parameters of the transformation T_f notably depends on the number of states of the constellation of the symbols $a(n)$.

According to one particular variant embodiment, the non-linear function $f()$ is chosen to be an odd function. By using an odd function,
20 symbols $a(n)$ of the same absolute value are transformed into symbols $b(n)$ of the same absolute value.

Without departing from the scope of the invention, any numerical identification method allowing the parameters of a transformation model T_f given by the relationship (2) to be identified from a plurality of pairs
25 comprising a sequence of symbols $a(n)$ and a corresponding sequence of symbols $b(n)$ assumed transformed by applying the transformation T_f , is envisionable by a person skilled in the art.

Figure 3 is a diagram of an emitter comprising means suitable for
30 implementing the invention.

The emitter 300 is a wireless emitter that may be employed in a wireless communication system, for example a radio-frequency or cellular system.

The emitter 300 comprises means 301 for receiving a sequence of
 5 symbols $a(n)$ to be emitted. These symbols are issued from information bits that have been converted into symbols according to the constellation of the modulation chosen. The means 301 may, for example, take the form of a piece of application software and/or a specific or generic processor.

Computational means 302 are configured to transform the sequence
 10 of symbols $a(n)$ to be emitted into a transformed sequence $b(n)$ by applying the transformation function T_f , which is calculated beforehand. The computational means 302 may for example implement a processor and a memory in which the values of the transformation T_f are tabulated. The processor may be a generic processor, a specific processor, an application-specific integrated circuit (ASIC) or a field-programmable gate array (FPGA).
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The emitter 300 also comprises a shaping filter 303 and a phase modulator 304 that produces as output modulated symbols that are then converted analogously and shaped by filtering and amplification with a view to the transmission of the signal over a radio channel.

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Figures 4, 5 and 6 illustrate the results obtained by applying the invention for a particular nonlimiting example of a continuous phase modulation using symbols conveying 4 bits per symbol, or in other words belonging to a 16-state constellation. The shaping pulse $h(t)$ employed is a
 25 Gaussian pulse of standard deviation equal to 0.45 times the duration of a symbol. The storage of the modulation is of length L equal to 8 times the duration of a symbol.

Figure 4 illustrates the non-linear function $f()$ obtained on a graph the x-axis of which corresponds to the values of the differences between symbols
 30 of the 16-state constellation, the measured differences being limited to equivalent phase differences of between $-\pi$ and π .

Figure 5 illustrates the linear combination $c()$ obtained, which comprises 10 coefficients.

Figure 6 shows the variation in phase over time for an emitted sequence of symbols represented by circles in figure 6. The curves 601 and 602 respectively show the phase of the modulated signal on emission and on reception (i.e. after suitable filtering on reception) in the case where the invention is not implemented, or in other words when a conventional continuous phase modulator is applied without transformation of the symbols to be emitted.

The curves 603 and 604 respectively show the phase of the modulated signal on emission and on reception in the case where the invention is implemented. As may be seen, the phase of the signal on reception 604 is identical or similar to that of the emitted symbols when the invention is used. When the invention is not used, the interference between symbols is substantial, this causing the phase of the received symbols and that of the emitted symbols to differ.

CLAIMS

1. A continuous phase modulation method comprising the following steps:
 - 5 • receiving (101) a sequence of digital data symbols $a(n)$ to be emitted;
 - transforming (102) the sequence of symbols $a(n)$ to be emitted into a transformed sequence of symbols $b(n)$, each symbol $b(n)$ of which is equal to the sum of a symbol $a(n)$ to be emitted and of a
10 corrective factor equal to a transformation T_f applied to a plurality of differences $(a(n)-a(n-1))$ between two consecutive symbols to be emitted, the transformation T_f applied being a combination c of at least two differences between two consecutive symbols of the sequence to be emitted, transformed by the application of a non-
15 linear function f ;
 - filtering (103) the sequence of transformed symbols $b(n)$ with a shaping filter; and
 - modulating (104) the sequence of filtered symbols with a phase modulator in order to obtain a sequence of modulated symbols,
 - 20 • said transformation T_f being defined so as to minimize interference between modulated symbols filtered by a receiving filter.

2. The continuous phase modulation method as claimed in claim 1, in which said transformation T_f is defined by applying the following iterative steps:
 - 25 • generating (201) a sequence of digital data symbols $a(n)$, referred to as the test sequence;
 - filtering (202) the test sequence with a shaping filter;
 - modulating (202) the sequence of filtered symbols;
 - filtering (202) the sequence of modulated symbols with a receiving
30 filter;
 - demodulating (202) the sequence of filtered symbols on reception;

- modifying (203) the value of each symbol $a(n)$ of the test sequence by a preset value so as to obtain a transformed test symbol $b(n)$;
 - stopping (204) the iterative process when the error between each demodulated symbol and the corresponding symbol in the test sequence has converged to a minimum value; and
 - identifying (205) the combination c and the non-linear function f of the transformation T_f as those that allow the transformed test sequence to be substantially identical to the test sequence generated then transformed by applying said transformation T_f .
3. The continuous phase modulation method as claimed in claim 2, in which said iterative steps furthermore comprise a step of determining the error between each demodulated symbol and the corresponding symbol in the sequence to be emitted, the value of each symbol $a(n)$ of the test sequence being corrected by a value dependent on said error.
4. The continuous phase modulation method as claimed in either one of claims 2 and 3, in which said iterative steps are executed for a plurality of different test sequences and the combination c and the non-linear function f are identified using a plurality of test sequence and transformed test sequence pairs.
5. The continuous phase modulation method as claimed in one of claims 2 to 4, in which the combination c and the non-linear function f of the transformation T_f are identified by applying the following successive steps:
- limiting the combination c to two coefficients of equal value;
 - determining the non-linear function f and the combination c to be applied so that the transformed test sequence is substantially identical to the test sequence generated then transformed by applying said transformation T_f ;

- setting the non-linear function f and extending the number of coefficients of the combination c ; and
 - determining the combination c to be applied so that the transformed test sequence is substantially identical to the test sequence generated then transformed by applying said transformation T_f .
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6. The continuous phase modulation method as claimed in one of claims 2 to 5, in which the combination c and the non-linear function f of the transformation T_f are identified using a numerical solution method of the Monte-Carlo type.
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7. The continuous phase modulation method as claimed in one of the preceding claims, in which the non-linear function f is chosen to be an odd function.
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8. The continuous phase modulation method as claimed in one of the preceding claims, in which the possible values of the transformed symbols $b(n)$ are calculated beforehand from possible values of the symbols $a(n)$ to be emitted and from the definition of the combination c and of the non-linear function f .
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9. The continuous phase modulation method as claimed in one of the preceding claims, in which the symbols $a(n)$ to be emitted are taken from a constellation comprising a plurality of states.
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10. A method for generating a mathematical transformation T_f intended to be used in a continuous phase modulation method as claimed in claim 1, said method for generating a transformation comprising the following iterative steps:
- 30
- generating (201) a sequence of digital data symbols $a(n)$, referred to as the test sequence;

- filtering (202) the test sequence with a shaping filter;
 - modulating (202) the sequence of filtered symbols;
 - filtering (202) the sequence of modulated symbols with a receiving filter;
 - 5 • demodulating (202) the sequence of filtered symbols on reception;
 - modifying (203) the value of each symbol $a(n)$ of the test sequence by a preset value so as to obtain a transformed test symbol $b(n)$;
 - stopping (204) the iterative process when the error between each demodulated symbol and the corresponding symbol in the test
 - 10 sequence has converged to a minimum value; and
 - identifying (205) the combination c and the non-linear function f of the transformation T_f as those that allow the transformed test sequence to be substantially identical to the test sequence generated then transformed by applying said transformation T_f .
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11. An emitter (300) intended to emit a continuous phase modulated signal, comprising:
- means (301) for receiving a sequence of digital data symbols $a(n)$ to be emitted;
 - 20 • computational means (302) configured to transform the sequence of symbols $a(n)$ to be emitted into a transformed sequence of symbols $b(n)$, each symbol $b(n)$ of which is equal to the sum of a symbol $a(n)$ to be emitted and a corrective factor equal to a transformation T_f applied to a plurality of differences $(a(n)-a(n-1))$
 - 25 between two consecutive symbols to be emitted, the transformation T_f applied being a combination c of at least two differences between two consecutive symbols of the sequence to be emitted, transformed by applying a non-linear function f ;
 - a shaping filter (303) for filtering the sequence of transformed
 - 30 symbols $b(n)$; and

- a phase modulator (304) for modulating the sequence of filtered symbols,
- said transformation T_f being defined so as to minimize interference between the modulated symbols filtered by a receiving filter.

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12. The emitter as claimed in claim 11 in which said transformation T_f is defined by executing the method as claimed in claim 10.