

Method for detecting the presence of an interference signal and associated devices

The present invention relates to a method for detecting the presence of an interference signal. The present invention also relates to an associated computer, receiving device, platform, computer program product and readable information medium.

In the field of telecommunications, a transmitter seeks to transmit a signal to a recipient, called the receiver. Ideally, the receiver would receive an incident signal exactly equal to the transmitted signal.

However, this is not the case; the incident signal is deformed for several reasons: the incident signal interacts with the environment such that the incident signal propagates according to multiple propagation paths, the incident signal is mixed with the thermal noise produced by the receiver and the incident signal may be jammed (the term "interference" is often used to refer to this last phenomenon). There may be multiple sources of interference, one of the most frequent sources being the transmission of another signal on another channel.

It is therefore beneficial to be able to determine the different components of the signal, which are the wanted signal, the thermal noise and any interference, so as to be able to extract the wanted signal.

One example of such extraction consists in developing a dedicated filter making it possible, for the considered receiver, to filter the unwanted components of the signal, namely the thermal noise and any interference.

However, such a technique assumes precise knowledge of the receiver and its operation.

There is therefore a need for a method for detecting interference in an incident signal which can be implemented on any type of receiver.

To this end, proposed is a method for detecting any presence of an interference signal in a signal received by a receiving device, the received signal comprising a wanted component and an unwanted component, the receiving device comprising N receiving channels and a computer, N being an integer greater than or equal to 2, the method being implemented by the computer, the method comprising a step for obtaining at least one matrix among an autocorrelation matrix of the signal received by each receiving channel, and an autocorrelation matrix of the unwanted component so as to obtain at least one determined matrix, a step for calculating eigenvalues of the at least one determined matrix, a step for estimating the signal to interference plus noise ratio of the recombined signal, the recombined signal being obtained by recombination of the signals of each of the N receiving

channels, and a step for detecting any presence of an interference signal as a function of at least one of the calculated eigenvalues and of the estimated signal to interference plus noise ratio.

According to specific embodiments, the detection method includes one or more of the following features, considered alone or according to any technically possible combinations:

- the detection step comprises applying a function to at least one eigenvalue, the comparison to a threshold depending on the estimated signal to interference plus noise ratio, and detecting any presence of interference as a function of the result of the comparison.
- the function is an identity function, a linear function, a trace function, a division function or a multiplication function.
- during the detection step, each eigenvalue is chosen from the list made up of the largest eigenvalue of the autocorrelation matrix of the received signal, the largest eigenvalue of the autocorrelation matrix of the unwanted component, the smallest eigenvalue of the autocorrelation matrix of the received signal, the smallest eigenvalue of the autocorrelation matrix of the unwanted component.
- the method further includes a step for an estimator of the power ratio between the power of the interference signal and the power of the thermal noise of the receiving device, the estimator depending on the calculated eigenvalues

The present disclosure also relates to a computer suitable for detecting any presence of an interference signal in a signal received by a receiving device, the received signal comprising a wanted component and an unwanted component, the receiving component comprising N receiving channels, N being an integer greater than or equal to 2, the computer being able to obtain at least one matrix among an autocorrelation matrix of the signal received by each receiving channel, and an autocorrelation matrix of the unwanted component so as to obtain at least one determined matrix, calculating eigenvalues of the at least one determined matrix, estimating the signal to interference plus noise ratio of the recombined signal, the recombined signal being obtained by recombination of the signals of each of the N receiving channels, and detecting any presence of an interference signal as a function of at least one of the calculated eigenvalues and of the estimated signal to interference plus noise ratio.

The present disclosure also relates to a receiving device comprising a computer as previously described.

The present disclosure also relates to a platform comprising a receiving device as previously described or a computer as previously described.

The present disclosure also relates to a computer program product including a readable information medium, on which a computer program is stored comprising program instructions, the computer program being able to be loaded on a data processing unit and suitable for driving the implementation of at least one step of a method as previously described when the computer program is implemented on the data processing unit.

The present disclosure also relates to a readable information medium including program instructions forming a computer program, the computer program being able to be loaded on a data processing unit and being suitable for driving the implementation of at least one step of a method as previously disclosed when the computer program is implemented on the data processing unit.

Other features and advantages of the invention will appear upon reading the following description of embodiments of the invention, provided as an example only and in reference to the drawings, which are:

- figure 1, a schematic view of a platform, and
- figure 2, a flowchart of an example embodiment of a method for detecting an interference signal.

A platform 10 is schematically illustrated in figure 1.

For example, the platform 10 is an aircraft such as an airplane, a helicopter, a drone.

In a variant, the platform 10 is a non-flying vehicle.

The platform 10 comprises a set of elements including a receiving device 12.

The receiving device 12 comprises N receiving channels 14 and a computer 16.

N is an integer greater than or equal to 2.

Each receiving channel is identified by a respective index i ; the index i is an integer between 1 and N.

According to the example of figure 1, only three receiving channels 14 are shown for clarity reasons.

Each receiving channel 14 comprises an antenna 18 and a processing chain 20.

The antenna 18 is capable of converting an incident signal, called received signal, into an analog signal.

The signal received by the antenna 18 is a radiofrequency signal.

The signal received in the i -th receiving channel 14 is denoted $x_i(t)$.

In the present example, the signal received on a receiving channel 14 corresponds to the sum of three signal components, namely a wanted signal component denoted $s_i(t)$, a thermal noise component denoted $b_i(t)$ and an interference signal component denoted $j_i(t)$.

The interference signal component $j_i(t)$ is an interference signal whose potential presence is sought.

The set of the thermal noise components denoted $b_i(t)$ and the interference signal components denoted $j_i(t)$ forms an unwanted signal component.

This is written mathematically as:

$$\mathbf{X}(t) = \mathbf{S}(t) + \mathbf{J}(t) + \mathbf{B}(t) = \begin{pmatrix} s_1(t) \\ \vdots \\ s_i(t) \\ \vdots \\ s_N(t) \end{pmatrix} + \begin{pmatrix} j_1(t) \\ \vdots \\ j_i(t) \\ \vdots \\ j_N(t) \end{pmatrix} + \begin{pmatrix} b_1(t) \\ \vdots \\ b_i(t) \\ \vdots \\ b_N(t) \end{pmatrix}$$

5 The wanted signal component $s_i(t)$ is generally a sum of signals.

More specifically, the wanted signal component $s_i(t)$ the sum of the different paths of the wanted signal. In general, the expression of $s_i(t)$ is thus:

$$s_i(t) = \sum_{p=1}^P h_{i,p} * s(t - \tau_p)$$

10 Where τ_p is the delay of the path p and $h_{i,p}$ is the channel coefficient of the path p of the antenna i .

A maximum delay duration of a multipath is then considered as a function of the propagation channel. This maximum value depends on the usage context (land, air), the environment (relief, presence of reflectors) and the frequency band used.

15 Considering a digital signal, such a maximum duration translates to a symbol number. In this case, the preceding relationship can be written in matrix form:

$$s_i(t) = \mathbf{h}_i * \mathbf{s}(t) = (h_{i,1} \quad \dots \quad h_{i,p} \quad \dots \quad h_{i,P}) \begin{pmatrix} s(t) \\ \vdots \\ s(t - p) \\ \vdots \\ s(t - p + 1) \end{pmatrix}$$

Taking account of all of the N receiving channels 14, the following equation is obtained:

$$\mathbf{S}(t) = \mathbf{H} * \mathbf{s}(t)$$

20 Where $\mathbf{H} = \begin{pmatrix} \mathbf{h}_1 \\ \vdots \\ \mathbf{h}_i \\ \vdots \\ \mathbf{h}_N \end{pmatrix}$ is a matrix with size $N \times P$ (N antennas and P paths).

Similarly, the interference signal component denoted $j_i(t)$ usually comprises several independent interference signals. In general, one therefore has:

$$j_i(t) = \sum_{k=1}^K j_{i,k}(t)$$

In the same manner as for the wanted signal component, each interference signal component is the multipath sum. It is also possible to implement a digitalization of the signals to lead to an expression similar to the preceding formula.

The computer 16 is able to collect the measurements on each receiving channel 14 in order to perform the processing making it possible to extract the wanted signal.

In particular, according to the described example, the computer 16 is able to form vectors from the collected measurements.

More specifically, the computer 16 forms a received signal vector denoted $X(t)$ from each of the received signals on the receiving channels 14 which comprises three components, the component of the wanted signal $S(t)$, the component of the thermal noise $B(t)$ and the interference component $J(t)$.

Further, the computer 16 is able to implement a method for detecting the presence of an interference signal.

The computer 16 is an electronic computer able to manipulate and/or transform data represented as electronic or physical quantities in registers of the system and/or memories into other similar data corresponding to physical data in the memories, registers or other types of display, transmission or storage devices.

The computer 16 includes a processor comprising a data processing unit, memories and an information medium reader. The computer also comprises a keyboard and a display unit.

As specific examples, the computer 16 comprises a single-core or multicore processor (such as a central processing unit (CPU), a graphics processing unit (GPU), a microcontroller and a digital signal processor (DSP)), a programmable logic circuit (such as an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA), a programmable logic device (PLD) and programmable logic arrays (PLA)), a finite state machine, a logic gate and discrete hardware components.

The computer program product includes a readable information medium.

A readable information medium is a medium readable by the computer 16, usually by the reader. The readable information medium is a medium suitable for storing electronic instructions and able to be coupled with a bus of a computer system.

As an example, the readable information medium is a floppy disk, an optical disc, a CD-ROM, a magnetic-optical disc, a ROM memory, a RAM memory, an EPROM memory, an EEPROM memory, a magnetic card or an optical card.

A computer program comprising program instructions is stored on the readable information medium.

The computer program can be loaded on the data processing unit and is capable of driving the implementation of the detection method.

The processing chain 20 is able to implement one or several operations on the received signal.

5 In particular, the processing chain 20 is able to carry out a digital conversion of the received analog signal.

The operation of the receiving device 12 is now illustrated in reference to figure 2, which is an example embodiment of a method for detecting the presence of an interference signal.

10 The method for detecting the presence of an interference signal aims to detect the presence of an interference signal in a signal received by a receiving device 12.

In other words, the detection method aims to detect whether the interference signal $J(t)$ is present.

The detection method is carried out by the computer 16.

15 The detection method comprises an obtaining step E50, a computing step E52, an estimating step E54 and a detection step E56.

During the obtaining step E50, two matrices are obtained.

The first determined matrix is the autocorrelation matrix of the received signal, this matrix being denoted R_{xx} .

20 By definition, $R_{XX} = E(X(t).X(t)^H)$ where $E()$ is an average operation, “.” is a multiplication operation and “^H” is a Hermitian conjugation operation.

The second determined matrix is the autocorrelation matrix of the unwanted signal, this matrix being denoted R .

By definition, $R = E((B(t) + J(t)).(B(t) + J(t))^H)$

25 According to a first example, in the obtaining step E50, the two matrices are received by the computer 16.

According to a second example, the obtaining step E50 includes a sub-step for collecting the received signals, a forming sub-step and a calculating sub-step.

30 During the collection sub-step, all of the signals received by each receiving channel are collected.

During the forming sub-step, the vector of the total signal X is formed from the collected signals.

During the calculating sub-step, the first matrix R_{xx} is calculated by applying the preceding formula on the vector of the total signal X .

35 The second matrix R is obtained by applying the preceding formula on an estimate of the noise supplied to the computer 16.

The estimate of the noise is for example supplied through an estimate of the channel matrix H defined by the preceding formula.

Such a channel matrix H is for example estimated by using reference sequences, series of known symbols placed at known instants of the received signal.

5 The channel matrix H is next used to calculate an estimate of the matrix $R_{SS} = E(S(t) * S(t)^H)$.

An estimate of the matrix R is next obtained through the subtraction operation $R = R_{XX} - R_{SS}$.

Any other method making it possible to obtain estimates of the matrices R_{XX} , R and
10 R_{SS} can also be considered.

During the calculating step E52, the eigenvalues of each of the determined matrices are calculated.

Any technique for determining eigenvalues may be considered in the calculating step, for example a triangulation technique.

15 At the end of the calculating step E52, a set of eigenvalues is thus obtained for each of the matrices.

In particular, thus known are the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$, the smallest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_N(R)$, the largest eigenvalue of the autocorrelation matrix of the received
20 total signal $\lambda_1(R_{xx})$ and the smallest eigenvalue of the autocorrelation matrix of the total signal $\lambda_N(R_{xx})$.

The relationship in terms of order (smaller or larger) is to be understood in absolute value. The largest eigenvalue is thus, for example, the largest value in absolute value.

The signal of each of the receiving channels 14 is next recombined to obtain a
25 recombined signal.

To this end, the principle of spatial adaptive processing is used.

The principle of spatial adaptive processing is to determine the weight vector $\mathbf{w}$ with which the signal the signal [sic] $\mathbf{X}(t)$ is recombined into a signal y so as to obtain a single-channel signal according to the formula:

$$30 \quad y(t) = \mathbf{w}^H * \mathbf{X}(t)$$

Where H is the Hermitian transpose and $*$ is the conjugate operation.

The quantity $y(t)$ here is a scalar.

The preceding formula is an application to spatial filtering only, resulting from the recombination of the antennas.

35 In a variant, spatial-temporal structures are used which involve symbols from earlier instants in the recombination.

According to another variant or in addition, the antenna processing is done in the frequency domain.

The calculation of the vector $\mathbf{w}$ is done with the aim of optimizing the signal to interference plus noise ratio estimated in the step which follows.

During the estimating step E54, the signal to interference plus noise ratio is estimated.

Such a signal to interference plus noise ratio is often designated using the acronym SINR. Hereinafter, the term “SINR ratio” is used to refer to the signal to interference plus noise ratio.

The SINR ratio corresponds to the power ratio between the wanted signal $S(t)$ on the one hand and the sum of the thermal noise $B(t)$ and the interference component $J(t)$ on the other hand. The SINR ratio is thus defined by the relationship:

$$SINR = \frac{P_S}{P_J + P_B}$$

Where P_S is the power of the wanted signal $S(t)$, P_B is the power of the thermal noise $B(t)$ and P_J is the power of the interference component $J(t)$.

The instantaneous power of the received total signal is written according to the following formula:

$$P_X = X(t)^H * X(t)$$

A similar operation can be defined to obtain the values of P_S , P_J and P_B .

In the case where the thermal noise is modeled by a Gaussian white noise, it is common practice to liken the power of the thermal noise P_B to the variance of the random variable denoted σ^2 .

According to one particular example, the estimate of the SINR ratio comprises an estimate of the power of the wanted signal done from calculations on the reference sequences of the received signal. This estimate constitutes the numerator of the preceding formula.

The theoretical estimate of the noise power output from spatial processing by recombination according to the vector $\mathbf{w}$ is $P_J + P_B = \mathbf{w}^H R \mathbf{w}$. It is specified that this estimating step can be calculated directly from processing on the recombined signal y . The latter being a single-channel signal, conventional techniques for estimating the Signal-to-Noise Ratio (SNR) can be applied and will yield values similar to the SINR ratio.

At the end of the estimating step E54, the SINR ratio is thus known.

During the detection step E56, the presence or absence of interference is detected as a function of at least one calculated eigenvalue and the estimated SINR ratio.

In order to carry out such a detection step E56, several techniques will be described, knowing that these techniques can be combined with one another.

For example, the presence of interference is detected only when both techniques indicate the presence of the interference. If one technique indicates the presence of interference and the other does not, an absence of interference is detected.

According to a first technique, the largest eigenvalue of the autocorrelation matrix is compared to the unwanted signal $\lambda_1(R)$ with a threshold S .

The threshold S depends on the SINR ratio.

Simulations of the evolution of the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ with the value of the estimated SINR ratio in the presence of interference and without interference make it possible to determine this threshold.

The threshold then corresponds to the minimum difference making it possible to discriminate between the two situations.

By way of specific example, if the evolution in greatest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ as a function of the SINR ratio is, in the absence of interference, greater than a positive constant a , such that $\lambda_1(R) > a$ over the entire considered range of SINR while the evolution in the presence of interference is a decreasing linear function $\lambda_1(R) = a - b \cdot \text{SINR}$ with b a negative constant, the threshold S can be chosen as equal to 99% of a .

Another way of understanding this mechanism is to consider the variation of the threshold as a function of the SINR ratio.

This threshold S is, for example, constant as a function of the SINR ratio.

According to another example, the threshold S is an affine function of the SINR ratio.

According to the described example, when the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ is strictly below the threshold S , the presence of an interference signal is detected.

On the contrary, when the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ is strictly above the threshold S , the absence of an interference signal is detected.

According to a more elaborate variant, a non-determination interval (doubt zone) is provided taking account of a safety margin.

Thus, when the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ is strictly below 110% of the threshold S , the presence of an interference signal is detected.

On the contrary, when the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ is strictly above 90% of the threshold S , the absence of an interference signal is detected.

For the cases where the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ is between 90% of the threshold S and 110% of the threshold S , it is not possible to discriminate between the presence and the absence of an interference signal.

The safety margin of 10% proposed as an example can be reduced or increased depending on the detection sensitivity.

According to a second technique, instead of comparing the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ with a threshold, it is the ratio between the largest eigenvalue of the autocorrelation of the received signal $\lambda_1(R_{xx})$ and the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ which is compared.

According to a third technique, instead of comparing the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ with a threshold, it is the ratio between the largest eigenvalue of the autocorrelation of the received signal $\lambda_1(R_{xx})$ and the smallest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_N(R)$ which is compared.

Each technique thus corresponds to a series of following operations: applying a function to at least one eigenvalue, comparing to a threshold depending on the estimated SINR ratio, and detecting the presence of interference as a function of the result of the comparison.

Examples have been shown for a function equal to an identity function or a division function.

However, other functions can be considered, such as a multiplication function.

Furthermore, the eigenvalues used in the examples are the extreme values.

Nevertheless, the use of non-extreme eigenvalues can also be considered, in particular a linear combination of these values.

Thus, in a variant or in addition, the trace of the matrices (sum of the diagonal elements) is also used.

In each of the aforementioned cases, it is determined whether interference is absent or present (to within a margin of doubt for some embodiments).

The detection method therefore provides information on any presence of interference.

The method is based on digital processing of signals coming from several receiving channels. The implementation of the method only involves a modification of the operation of the computer and no addition of extra hardware into the platform 10. The method in fact

uses a set of techniques conventionally implemented in a system of the SIMO (single input multiple output) type.

The method is therefore easy to implement.

Further, the method does not assume obtaining *a priori* knowledge of the antennas, and in particular of their position. In this sense, the method operates independently of the antennas.

The method is applicable to any receiving device comprising several receiving channels, even only two. In particular, the method is usable for systems other than satellite navigation systems.

Furthermore, the method is robust in that the method does not depend on the waveform of the interfering transmitter. The method is capable of detecting any interfering waveform, such as a narrowband interfering transmitter, a broadband interfering transmitter or an additive white Gaussian noise (more often designated using the abbreviation AWGN) channel.

The robustness also comes from the fact that the method also works for low signal-to-noise ratios, even when these signal-to-noise ratios are lower than the nominal operating points of the receiving devices.

The present method further applies without usage limitations regarding the frequency band, and in particular in the HF (High Frequency) band, UHF (Ultra High Frequency) band or C band (from 4 GHz to 8 GHz).

Further, the method has been described in the context of SIMO processing, but applies identically to MIMO (multiple input multiple output) processing.

The method even makes it possible to analyze characteristics of the interfering transmitter by providing information on the power. In this sense, the detection method can be interpreted as a characterization method or an analysis method.

To this end, for example, the method comprises a step for calculating an estimator of the power ratio PR between the power of the interference signal $J(t)$ and the power of the thermal noise $B(t)$.

The estimator depends on at least one previously calculated eigenvalue.

For example, an estimator is the ratio between the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ and the smallest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_N(R)$.

Such an estimator can be improved in the case where the noise level is known because it has been provided to the computer 16. The noise level is denoted σ^2 and is connected to the noise factor of the receiving chain.

In such a case, the method comprises an additional step for calculating an estimator of the power ratio RP as a function of the eigenvalues and the provided noise level.

According to the described example, it is considered that the estimator is equal to the ratio between the largest eigenvalue of the autocorrelation matrix of the unwanted signal $\lambda_1(R)$ and the noise level.

The detection method is thus also a method for characterizing an interference signal when such a signal is present.

In some cases, the method is also able to provide an indication of the number of interfering transmitters (in the case where the number of antennas is aligned with the number of interfering transmitters).

CLAIMS

1. A method for detecting any presence of an interference signal in a signal received by a receiving device (12), the received signal comprising a wanted component and an unwanted component, the receiving device (12) comprising N receiving channels (14) and a computer (16), N being an integer greater than or equal to 2, the method being implemented by the computer (16), the method comprising a step for:

- obtaining at least one matrix among an autocorrelation matrix of the signal received by each receiving channel (14), and an autocorrelation matrix of the unwanted component so as to obtain at least one determined matrix,
- calculating the eigenvalues of the at least one determined matrix,
- estimating the signal to interference plus noise ratio of the recombined signal, the recombined signal being obtained by recombination of the signals of each of the N receiving channels (14), and
- detecting any presence of an interference signal as a function of at least one of the calculated eigenvalues and of the estimated signal to interference plus noise ratio.

2. The method according to claim 1, wherein the detection step comprises the following operation:

- applying a function to at least one eigenvalue,
- comparison of the result of the function obtained after carrying out the applying operation to a threshold depending on the estimated signal to interference plus noise ratio, and
- detecting any presence of interference as a function of the result of the comparison.

3. The method according to claim 2, wherein the function is an identity function, a linear function, a trace function, a division function or a multiplication function.

4. The method according to any one of claims 1 to 3, wherein, during the detection step, each eigenvalue is chosen from the list made up of the largest eigenvalue of the autocorrelation matrix of the received signal, the largest eigenvalue of the autocorrelation matrix of the unwanted component, the smallest eigenvalue of the autocorrelation matrix of the received signal, the smallest eigenvalue of the autocorrelation matrix of the unwanted component.

5. The method according to any one of claims 1 to 4, wherein the method further includes a step for obtaining an estimator of the power ratio between the power of the interference signal and the power of the thermal noise of the receiving device (12), the estimator depending on the calculated eigenvalues.

6. A computer (16) suitable for detecting any presence of an interference signal in a signal received by a receiving device (12), the received signal comprising a wanted component and an unwanted component, the receiving component (12) comprising N receiving channels (14), N being an integer greater than or equal to 2, the computer (16) being able to:

- obtain at least one matrix among an autocorrelation matrix of the signal received by each receiving channel (14), and an autocorrelation matrix of the unwanted component so as to obtain at least one determined matrix,
- calculate eigenvalues of the at least one determined matrix,
- estimate the signal to interference plus noise ratio of the recombined signal, the recombined signal being obtained by recombination of the signals of each of the N receiving channels (14), and
- detect any presence of an interference signal as a function of at least one of the calculated eigenvalues and of the estimated signal to interference plus noise ratio.

7. A receiving device (12) comprising a computer (16) according to claim 6.

8. A platform (10) comprising a computer (16) according to claim 6 and a receiving device (12) according to claim 7.

9. A computer program product including a readable information medium, on which a computer program is stored comprising program instructions, the computer program being able to be loaded on a data processing unit and suitable for driving the implementation of at least one step of a method according to any one of claims 1 to 5 when the computer program is implemented on the data processing unit.

10. A readable information medium including program instructions forming a computer program, the computer program being able to be loaded on a data processing unit and suitable for driving the implementation of at least one step of a method according to any one of claims 1 to 5 when the computer program is implemented on the data processing unit.