

Claims

[1] [Claim 1] A method for receiving a signal, comprising an estimation step for estimating a time shift and a frequency shift that are embedded in the signal, wherein the estimation step refers to a non-commutative shift parameter space of co-dimension 2, wherein in the estimation step, the time shift and the frequency shift that are embedded in the signal are estimated with an operator including a half shift that is a shift symmetrical in time and frequency,

wherein the estimation step estimates the time shift and the frequency shifts that are embedded in the signal, with use of a time-frequency shift operator(TFSO) of type 1 representing an estimated time shift, frequency shift, and a phase term due to a half shift of the estimated time shift

[MFC1]

$$\mathcal{T}_{\hat{k}_d, \ell_\mu}^d,$$

a TFSO of type 2 representing time shift, an estimated frequency shift, and a phase term due to a half shift of the estimated frequency shift

[MFC2]

$$\mathcal{T}_{\hat{\ell}_D, -\hat{k}_\sigma}^{f,d},$$

a TFSO of type 3 representing an observable time shift to be estimated, an observable frequency shift to be estimated, and a phase term due to a half shift of the time shift to be estimated

[MFC3]

$$\mathcal{T}_{\hat{k}_d, \ell_D}^d$$

or a frequency dual of the TFSO of type 3

[MFC4]

$$\mathcal{T}_{\ell_D, -\hat{k}_d}^{f,d},$$

and a TFSO of type 4 representing the estimated time shift, the estimated frequency shift, and the phase term due to the half shift of the estimated time shift

[MFC5]

$$\mathcal{T}_{\hat{k}_d, \hat{\ell}_D}^d$$

or a frequency dual of the TFSO of type 4

[MFC6]

$$\mathcal{T}_{\hat{\ell}_D, -\hat{k}_d}^{f,d},$$

wherein the estimation step estimates the time shift and the frequency shift that are embedded in the signal, with use of a time-domain-cross-correlation function(TD-CCF) of type 1, represented in terms of the TFSOs of

type 1, of type 3, and of type 4, and a frequency-domain-cross-correlation function(FD-CCF) of type 2, represented in terms of the TFSOs of type 2, of type 3, and of type 4,

wherein the TD-CCF of type 1 and the FD-CCF of type 2 contain a phase distortion(PD) due to a non-commutative shift operation between modulation and demodulation by a carrier f_c and a time shift t_d

[MFC7]

$$e^{i2\pi t_d f_c}$$

or a discretized version of the PD

[MFC8]

$$W^{k_d \ell_c},$$

and a PD due to the phase term e^{ik} of the attenuation factor Ae^{ik} ,

wherein the estimation step includes two alternative updating steps: (1) updating the estimated frequency shift with reference to the TD-CCF of type 1 and (2) updating the estimated time shift with reference to the FD-CCF of type 2.

[2] [Claim 2] The method recited in claim 1, wherein the non-commutative shift parameter space of co-dimension 2 is a space obtained by 3-dimensionalizing a plane, which is defined by a first axis indicative of time and a second axis indicative of frequency, by attaching, to the plane, a third axis indicative of time-frequency shifts.

[3] [Claim 3] The method recited in any one claim among claims 1 and 2, wherein the estimation step estimates the time shift and the frequency shift that are embedded in the signal, with use of maximum-likelihood estimate(MLE)s of frequency shift for detecting N' time-domain(TD)-templates and MLEs of time shift for detecting N frequency-domain(FD)-templates.

[4] [Claim 4] A receiving apparatus for receiving a signal, comprising an estimation part for estimating a time shift and a frequency shift that are embedded in the signal, with reference to a non-commutative shift parameter space of co-dimension 2, wherein the estimation part estimates the time shift and the frequency shift that are embedded in the signal with use of an operator including a half shift that is a shift symmetrical in time and frequency,

wherein the estimation part estimates the time shift and the frequency shifts that are embedded in the signal, with use of a time-frequency shift operator(TFSO) of type 1 representing an estimated time shift, frequency shift, and a phase term due to a half shift of the estimated time shift

[MFC9]

$$\mathcal{T}_{\hat{k}_d, \ell_\mu}^d,$$

a TFSO of type 2 representing time shift, an estimated frequency shift, and a phase term due to a half shift of the estimated frequency shift

[MFC10]

$$\mathcal{T}_{\hat{\ell}_D, -k_\sigma}^{f,d},$$

a TFSO of type 3 representing an observable time shift to be estimated, an observable frequency shift to be estimated, and a phase term due to a half shift of the time shift to be estimated

[MFC11]

$$\mathcal{T}_{k_d, \ell_D}^d$$

or a frequency dual of the TFSO of type 3

[MFC12]

$$\mathcal{T}_{\ell_D, -k_d}^{f,d},$$

and a TFSO of type 4 representing the estimated time shift, the estimated frequency shift, and the phase term due to the half shift of the estimated time shift

[MFC13]

$$\mathcal{T}_{\hat{k}_d, \hat{\ell}_D}^d$$

or a frequency dual of the TFSO of type 4

[MFC14]

$$\mathcal{T}_{\hat{\ell}_D, -\hat{k}_d}^{f,d},$$

wherein the estimation part estimates the time shift and the frequency shift that are embedded in the signal, with use of a time-domain-cross-correlation function(TD-CCF) of type 1, represented in terms of the TFSOs of type 1, of type 3, and of type 4, and a frequency-domain-cross-correlation function(FD-CCF) of type 2, represented in terms of the TFSOs of type 2, of type 3, and of type 4,

wherein the TD-CCF of type 1 and the FD-CCF of type 2 contain a phase distortion(PD) due to a non-commutative shift operation between modulation and demodulation by a carrier f_c and a time shift t_d

[MFC15]

$$e^{i2\pi t_d f_c}$$

or a discretized version of the PD

[MFC16]

$$W^{k_d \ell_c},$$

and a PD due to the phase term e^{ik} of the attenuation factor Ae^{ik} ,

wherein the estimation part includes two alternative updating parts: (1) updating the estimated frequency shift with reference to the TD-CCF of type 1 and (2) updating the estimated time shift with reference to the FD-CCF of type 2.

[5] [Claim 5] A method for transmitting a signal, comprising a shift step for time-frequency shifting the signal to be transmitted, with reference to a non-commutative shift parameter space of co-dimension 2, wherein in the shift step, a time and a frequency of the signal to be transmitted are shifted by a half shift that is a shift symmetrical in time and frequency, wherein a doubly dispersive channel with a time shift [MFC17]

$$k_d$$

and a frequency shift

[MFC18]

$$\ell_D$$

, each to be estimated, is governed by not two one-parameter shift operators

[MFC19]

$$\mathcal{T}_{k_d,0}^d, \mathcal{T}_{0,\ell_D}^d$$

but a two-parameter operator, discrete versions of the time-frequency shift operator(TFSO), i.e., discrete analogues of von Neumann's TFSOs in the time domain(TD) and frequency domain(FD), respectively, defined by [MFC20]

$$\left. \begin{aligned} \mathcal{T}_{a,b}^d z[k] &\stackrel{\text{def}}{=} z[k-a] W^{-b(k-\frac{a}{2})}, a, b, k \in \mathbb{Z}, \\ \mathcal{T}_{b,-a}^{f,d} Z[\ell] &\stackrel{\text{def}}{=} Z[\ell-b] W^{a(\ell-\frac{b}{2})}, a, b, \ell \in \mathbb{Z}, Z[\ell] = \mathcal{F}^d[z(k)]. \end{aligned} \right\}$$

[MFC21]

$$k = \lfloor \frac{t}{\Delta t} \rfloor, \ell = \lfloor \frac{f}{\Delta f} \rfloor$$

denote the discretized time and frequency by sampling TD- and FD-signals with support length L , in durations

[MFC22]

$$\Delta t, \Delta f = (L\Delta t)^{-1}$$

, respectively, wherein W is the twiddle factor, defined as

[MFC23]

$$W = e^{\frac{-j2\pi}{L}}$$

, namely, the TFSO is defined by equally dividing the phase distortion(PD) such that

[MFC24]

$$\mathcal{T}_{k_d,\ell_D}^d \stackrel{\text{def}}{=} W^{k_d\ell_D/2} \mathcal{T}_{k_d,0}^d \cdot \mathcal{T}_{0,\ell_D}^d = W^{-k_d\ell_D/2} \mathcal{T}_{0,\ell_D}^d \cdot \mathcal{T}_{k_d,0}^d$$

, where the PD

[MFC25]

$$W^{\pm k_d\ell_D/2}$$

plays a role in invalidating the order that is in principle physically indeterminate, within the PD

[MFC26]

$$W^{\pm k_d \ell_D / 2}$$

to preserve the non-commutative property (NCP), i.e., a TFSO of type 3 representing

[MFC27]

$$k_d, \ell_D,$$

both to be estimated, and phase term due to a half shift of

[MFC28]

$$k_d$$

[MFC29]

$$\mathcal{T}_{k_d, \ell_D}^d,$$

where the half shift

[MFC30]

$$\frac{k_d}{2}$$

plays a role in adding a phase function (or PD)

[MFC31]

$$W^{\ell_D k_d / 2}$$

to a zero-PD in a TD signal or a frequency dual of the TFSO of type 3

[MFC32]

$$\mathcal{T}_{\ell_D, -k_d}^{f,d},$$

where the half shift

[MFC33]

$$\frac{k_d}{2}$$

plays a role in subtracting

[MFC34]

$$W^{\ell_D k_d / 2}$$

from a PD

[MFC35]

$$W^{\ell_D k_d}$$

in an FD signal.

[6] [Claim 6] The method recited in claim 5, wherein the shift step generates the signal to be transmitted by phase-shift-keying(PSK)-modulating a chip pulse wave in the time domain(TD) by the TD-phase code(PC) of

period N and PSK-modulating the TD-PSK modulated TD-pulse wave by the FD-PC of period N' to generate a multicarrier version of the TD-PSK modulated TD-pulse wave_z

wherein the shift part shifts the time shift and the frequency shifts that are embedded in a signal, by data duration and carrier spacing

[MFC36]

$$(T_s, F_s)$$

to design non-overlapped superposition of signals in the time frequency plane(TFP) for data communication, and by chip duration and sub-carrier spacing

[MFC37]

$$(T_c, F_c)$$

to design

[MFC38]

$$N', N$$

TD- and FD- templates, embedded into the signal for M-ary detection based on the maximum-likelihood functionals having several associated consequential PDs, with use of a TFSO of type 4 representing the data duration and carrier spacing with data address

[MFC39]

$$\vec{p} = (p, p')$$

and the phase term due to the half shift of the data duration

[MFC40]

$$\mathcal{T}_{pNM.p'N'M'}^d$$

or a frequency dual of the TFSO of type 4

[MFC41]

$$\mathcal{T}_{p'N'M',-pNM}^{f,d}$$

and with use of a TFSO of type 4 representing the chip duration and sub-carrier spacing with chip address

[MFC42]

$$(m, m')$$

, and the phase term due to the half shift of the chip duration

[MFC43]

$$\mathcal{T}_{mM.m'M'}^d$$

or a frequency dual of the TFSO of type 4

[MFC44]

$$\mathcal{T}_{m'M',-mM}^{f,d}$$

wherein, these time-frequency shiftings are typical examples of exploiting inevitable PDs caused by the NCP that is characterized the canonical commutation relation (CCR) of time-frequency shifts

[MFC45]

$$[\mathcal{T}_{\tau,0}, \mathcal{T}_{0,\nu}] = -2i \sin(\pi\tau\nu) \mathcal{T}_{\tau,\nu}$$

that corresponds to the Heisenberg's uncertainty principle in quantum mechanics (QM), mathematically supported by the uniqueness of the CCRs, the Stone-von Neumann Theorem (SvNT) [MFC46]

$$[Q, P] = QP - PQ = i\hbar,$$

where Q, P denote the position and momentum operators,

[MFC47]

$$\hbar = h/(2\pi)$$

the reduced Plank's constant, and implies that

[MFC48]

$$[\mathcal{T}_{\tau,0}, \mathcal{T}_{0,\nu}] = 0, \text{ PD-free, i.e., } \tau\nu \in \mathbb{N}$$

, namely, the symmetrical TFSO

[MFC49]

$$\mathcal{T}_{\tau,\nu}$$

Is formally identical to von Neumann's two-parameter family of unitary operators,

[MFC50]

$$U(a) = e^{iaQ}, V(b) = e^{ibP}, a, b \in \mathbb{R},$$

referred to as SvNT

[MFC51]

$$S(a, b) = e^{-\frac{1}{2}iab} U(a) V(b)$$

[7] [Claim 7] A transmitter apparatus for transmitting a signal, comprising a time-frequency shift part for time-frequency shifting the signal to be transmitted, with reference to a non-commutative shift parameter space of co-dimension 2, wherein the time-frequency shift part time-frequency shifts the signal to be transmitted by a half shift that is a shift symmetrical in time and frequency, wherein the half shifts in the TD and FD play an important role in (i) adding and subtracting the PDs to equal a PD in the TD and FD; (ii) at the same time invalidating the order of non-commutative time and frequency shifts; (iii) attempting a reconciliation between exactly

evaluating several kinds of PDs caused by time-frequency shifts and completely cancelling-out those PDs,

and the shift part shifts a frequency shift

[MFC52]

$$\ell_c$$

to modulate a baseband signal to its passband one, with use of a TFSO of type 4 representing

[MFC53]

$$\ell_c$$

and a phase term due to a half shift of

[MFC54]

$$\ell_c,$$

[MFC55]

$$\mathcal{T}_{\ell_c,0}^{f,d}$$

, on the other hand, the shift part at the receiver shifts the frequency shift

[MFC56]

$$-\ell_c$$

to demodulate the passband signal to its baseband one, with use of a TFSO of type 4 representing

[MFC57]

$$\ell_c$$

and a phase term due to a half shift of

[MFC58]

$$-\ell_c,$$

[MFC59]

$$\mathcal{T}_{-\ell_c,0}^{f,d}$$

, such modulation/demodulation under the dispersive channel with

[MFC60]

$$(k_d \cdot \ell_D)$$

gives the TFSO of type 3 representing

[MFC61]

$$k_d, \ell_D$$

, a phase term due to a half shift of

[MFC62]

$$k_d$$

with an additional PD

[MFC63]

$$\mathcal{T}_{0,-\ell_c}^d \mathcal{T}_{k_d,\ell_D}^d \mathcal{T}_{0,\ell_c}^d = W^{k_d \ell_c} \mathcal{T}_{k_d,\ell_D}^d$$

which operates on a TD-signal, together with attenuation factor

[MFC64]

$$Ae^{i\kappa}$$

in a received signal.

[8] [Claim 8] A transmitter-receiver system, comprising:

a transmitter apparatus; and

a receiver apparatus,

the transmitter apparatus including a time-frequency shift part for time-frequency shifting a signal to be transmitted, with reference to a non-commutative shift parameter space of co-dimension 2, wherein the time-frequency shift part time-frequency shifts the signal to be transmitted by a half shift that is a shift symmetrical in time and frequency,

the receiver apparatus including an estimation part for estimating a time shift and a frequency shift that are embedded in the signal to be transmitted, with reference to the non-commutative shift parameter space of co-dimension 2, wherein the estimation part estimates the time shift and the frequency shift that are embedded in the signal with use of an operator including a half shift that is a shift symmetrical in time and frequency,

wherein the estimation part estimates the time shift and the frequency shifts that are embedded in the signal, with use of a time-frequency shift operator(TFSO) of type 1 representing an estimated time shift, frequency shift, and a phase term due to a half shift of the estimated time shift

[MFC65]

$$\mathcal{T}_{\hat{k}_d,\ell_\mu}^d,$$

a TFSO of type 2 representing time shift, an estimated frequency shift, and a phase term due to a half shift of the estimated frequency shift

[MFC66]

$$\mathcal{T}_{\ell_D,-k_\sigma}^{f,d},$$

a TFSO of type 3 representing an observable time shift to be estimated, an observable frequency shift to be estimated, and a phase term due to a half shift of the time shift to be estimated

[MFC67]

$$\mathcal{T}_{k_d, \ell_D}^d$$

or a frequency dual of the TFSO of type 3

[MFC68]

$$\mathcal{T}_{\ell_D, -k_d}^{f,d},$$

and a TFSO of type 4 representing the estimated time shift, the estimated frequency shift, and the phase term due to the half shift of the estimated time shift

[MFC69]

$$\mathcal{T}_{\hat{k}_d, \hat{\ell}_D}^d$$

or a frequency dual of the TFSO of type 4

[MFC70]

$$\mathcal{T}_{\hat{\ell}_D, -\hat{k}_d}^{f,d},$$

wherein the estimation part estimates the time shift and the frequency shift that are embedded in the signal, with use of a time-domain-cross-correlation function(TD-CCF) of type 1, represented in terms of the TFSOs of type 1, of type 3, and of type 4, and a frequency-domain-cross-correlation function(FD-CCF) of type 2, represented in terms of the TFSOs of type 2, of type 3, and of type 4,

wherein the TD-CCF of type 1 and the FD-CCF of type 2 contain a phase distortion(PD) due to a non-commutative shift operation between modulation and demodulation by a carrier f_c and a time shift t_d

[MFC71]

$$e^{i2\pi t_d f_c}$$

or a discretized version of the PD

[MFC72]

$$W^{k_d \ell_c},$$

and a PD due to the phase term e^{ik} of the attenuation factor Ae^{ik} ,

wherein the estimation part includes two alternative updating parts: (1) updating the estimated frequency shift with reference to the TD-CCF of type 1 and (2) updating the estimated time shift with reference to the FD-CCF of type 2.