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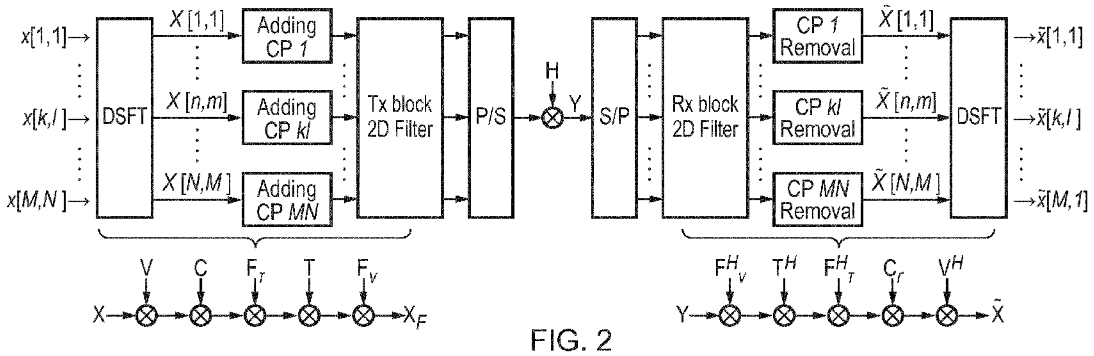

FIG. 2

(57) **Abstract:** A method of processing a modulated wireless communication signal, a network node, signal processing circuitry, computer program and receiver are disclosed. The method comprises: performing on the signal both an inverse Fourier transform operation to form a time domain representation of a signal and a Fourier transform operation to form a frequency domain representation of a signal, such that the signal is transformed to form a two dimensional multi carrier modulated signal; applying at least one of a frequency domain filter and a time domain window to the signal following at least one of the Fourier transform operations; and transmitting the filtered two dimensional multi carrier modulated signal via a wireless channel towards a receiver.

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PROCESSING WIRELESS COMMUNICATION SIGNALS

FIELD OF THE INVENTION

The invention relates to the field of processing modulated signals used in wireless communications.

BACKGROUND

A loss of signal quality due to channel fading is a crucial factor impacting wireless system performance. Channel fading occurs due to several factors, such as time selective fading which occurs with high speed nodes where Doppler effects on the signal cause issues, and frequency selective fading which is a multipath effect due to different signals reaching the destination with different delays. In order to address these issues signal equalisation is required to align the delays of Doppler shifts and multipath effects at the recipient.

Conventionally coded signals, coded using for example, OFDM orthogonal frequency division multiplexing can only address one of these fading factors. In order to be able to address multiple channel fading factors, it has been proposed to use a signal that uses multiple dimensional physical resources simultaneously such as time, frequency and space.

One such proposed technology is OTFS orthogonal time frequency and space. This technique extends the conventional OFDM from the frequency domain to the so-called delay domain (corresponding to the frequency selective fading) and Doppler domain (corresponding to the time selective fading). A 2-dimensional 2D multicarrier waveform is generated to improve performance degraded by both multipath and Doppler shift effects by equalising both of the frequency and time selective fading simultaneously.

However, in order to be able to address these issues well OTFS requires good synchronisation on both the delay and Doppler domains which results in heavy signalling due to the 2D modulation. Moreover OTFS requires guard-bands and guard time intervals which reduces the resources available for useful signalling.

It would be desirable to be able to generate a signal that could address channel ageing while limiting guard band requirements.

SUMMARY

A first aspect provides a method of processing a modulated wireless communication signal prior to transmitting said signal, said method comprising: performing on said signal both an inverse Fourier transform operation to form a time domain representation of a signal and a Fourier transform operation to form a frequency domain representation of a signal, such that said signal is transformed to form a two dimensional multi carrier modulated signal; applying at least one of a frequency domain filter and a time domain window to said signal following at least one of said Fourier transform operations; and transmitting said filtered two dimensional multi carrier modulated signal via a wireless channel towards a receiver.

Applying a Fourier Transform operation such as a discrete Fourier transform provides a frequency domain representation of a signal by relating the frequency domain of the signal to a new domain termed the delay domain. While performing an inverse Fourier Transform such as an inverse discrete Fourier transform relates the time domain of a signal to a new domain termed the Doppler domain. These two transforms can be viewed as a 2D Fourier transform or Symplectic Fourier Transform. By applying these Fourier transforms, a waveform in two dimensions is generated which allow both time selective and frequency selective fading to be addressed. Frequency selective fading occurs due to multipath effects while time selective fading occurs due to Doppler effects with a fast moving transmitter and/or receiver. The Fourier transforms on the signal spread the signal across both the time and frequency domain resulting in spreading of the different effects and providing an almost constant fading and improved quality signal. This technique is termed OTFS (orthogonal time frequency space).

One of the issues that arises with OTFS is that it requires guard-band and guard time-intervals to maintain the out-of- band emissions (OOBE) below a certain satisfactory level. The in band portion of a signal is the portion that carries the information while the spread of the portion of the signal that spreads beyond this central band does not carry useful information, may cause interference and generally degrades the quality of the signals. In this regard as the OTFS technique adopts a Symplectic Fourier transform to implement the 2D multicarrier modulation, the guard bands are unavoidably extended to 2D as well and hence spectral efficiency will be degraded. The inventors of the present invention have therefore determined that it would be advantageous to apply a filter to the signal in at least one of the Doppler domain (a frequency domain filter) and the delay domain (a time window). This removes or at least reduces signals that are out of band and reduces the need for a guard band to protect from interference from other signals.

It should be noted that due to the properties of the Fourier Transform operations they can be performed in any order. There is a matrix permutation performed between the two steps.

In some embodiments, the method comprises applying both the frequency domain filter and a time domain window to said signal.

Where both a frequency domain filter and a time domain window are applied to the signal, then the need for both a guard band and guard time intervals are reduced and in some cases completely avoided.

In some embodiments, said two filtering processes are applied as a single combined filter process.

Although the filtering processes may be formed as individual processes, for some embodiments they are performed as a single combined filter process which may improve the efficiency of the process and decrease the amount of hardware required. In other embodiments, filters used for conventional signalling processing such as F-OFDM may be reused for this process and in such a case it may make sense to use individual filters in order to reuse existing hardware and route the signals via these filters as required.

In some embodiments, the method further comprises applying a cycle prefix to said signal prior to performing said time domain filtering step or in some embodiments before both said time and frequency domain filtering step.

Cyclic prefixes may be added to the signals before they are time domain filtered to ensure that the channel effect is a circular convolution which in turn may be transformed to the frequency domain using a discrete Fourier transform.

In some embodiments, the method further comprises an initial step of performing serial to parallel conversion of said modulated signal to form a plurality of parallel modulated signals; said subsequent steps, prior to said transmitting step being performed on said plurality of parallel signals; and prior to transmitting said two dimensional multi carrier modulated signal performing a parallel to serial conversion of said plurality of two dimensional multi carrier modulated signals to form said two dimensional multi carrier modulated signal.

The processing steps performed in this method may be performed on a plurality of the signals arranged in parallel. This increases the speed of the processing and also allows matrix operations to be performed in a straightforward hardware and time efficient manner.

In some embodiments, the method further comprises transmitting a control signal indicative of at least one of said frequency band and time window of said at least one filter and indicative of said Fourier transform and inverse Fourier Transform operations applied to said modulated signal.

In order to aid the receiver in its task of reconstituting the original signal from the two dimensional multi-carrier modulated signal, information regarding the filters and the Fourier transform operations performed may be transmitted to the receiver via a control signal.

A second aspect of the present invention provides signal processing circuitry operable to process a modulated wireless communication signal prior to said signal being transmitted, said signal processing circuitry comprising: Fourier transform circuitry configured to perform an inverse Fourier transform operation to form a time domain representation of a signal and further Fourier transform circuitry operable to perform a Fourier transform operation to form a frequency domain representation of a signal, such that said signal is transformed by said circuitry to form a two dimensional multi carrier modulated signal; at least one of a frequency domain filter and a time domain filter for filtering said two dimensional multi carrier modulated signal.

In some embodiments, the signal processing circuitry further comprises a serial to parallel converter operable to form a plurality of parallel signals from said modulated signal; said Fourier transform circuitry and further Fourier transform circuitry being operable to receive and transform said plurality of parallel signals; and parallel to serial conversion circuitry for performing a parallel to serial conversion on said plurality of signals to form a 2D multi carrier modulated signal.

In some embodiments, said signal processing circuitry comprises both of a frequency domain filter and a time domain filter.

In some embodiments, said frequency domain and time domain filter comprise a single filter block.

In some embodiments said signal processing circuitry further comprises circuitry operable to apply a cycle prefix to said signals.

In some embodiments, said signal processing circuitry further comprises a control signal generator for generating a control signal indicative of at least one of said frequency band and time window of said at least one filter and indicative of said Fourier transform and inverse Fourier Transform operations applied to said modulated signal.

A third aspect of the present invention provides a network node comprising signal processing circuitry according to a second aspect of the present invention, and further comprising transmitting circuitry for transmitting said two dimensional multi carrier modulated signal via a wireless channel towards a receiver, wherein said network node is one of a base station, an access point and a user equipment.

In some embodiments, the network node is an access point or a base station and comprises a plurality of said signal processing circuitry arranged in parallel, a bandwidth or time window of said at least one filter in at least one of said signal processing circuitry being different to a bandwidth or time window of said at least one filter in another of said signal processing circuitry.

The bandwidth of the frequency domain filter or the width of the time window of the time domain filter depends on the resources allocated to the original modulated signal that is being processed. Embodiments of the invention allow different amounts of resource to be allocated to different signals depending on their requirements. In this regard, devices such as Internet of Things devices do not require much resource as their signals are limited in bandwidth while mobile phones for example require significantly more resource for their signals. Dividing the available resources into equal parts as has conventionally been done may not make optimal use of the available resource and thus, embodiments, seek to divide the resource according to requirements. The amount of frequency and time resource allocated to a particular signal will affect the properties of the filter required. Thus, having signal processing circuitry with different filters allows signal processing circuitry with an appropriately sized filter to be selected depending on the signal being processed.

A fourth aspect of the present invention provides a method of processing a received two dimensional filtered multi carrier modulated signal, said method comprising: receiving a control signal indicative of at least one of a bandwidth and time window of said two dimensional multicarrier modulated signal and a Fourier transform and inverse Fourier transform operation; filtering said received signal using at least one of a frequency domain filter with a bandwidth indicated by said control signal and a time domain window with a time window indicated by said control signal; performing an inverse Fourier transform operation and a Fourier transform operation indicated by said control signal on said two dimensional multicarrier modulated signal to convert said two dimensional multi carrier modulated signal to a modulated time frequency domain signal.

Where a two dimensional filtered multi carrier signal has been used for wireless transmissions in order to reduce channel fading, then such a signal can be reformed into the modulated signal from which it stemmed, where information regarding the filtering coefficients and the Fourier transform operations are provided. Furthermore, filtering the received signal using corresponding filtering techniques improves the quality of the signal and helps reduce interference from other user equipment. In particular, the use of the filter can reduce the need for exact synchronisation between user equipment when multiple signals are sent from different user equipment as it reduces the overlap of the signals and helps in their separation.

In some embodiments, said method further comprises removing a cyclic prefix from said filtered signal.

In some cases the signals may have had a cyclic prefix added to it to provide circular convolution and in such a case this will be removed.

In some embodiments said method comprises filtering said signal using both of a time domain and frequency domain filter.

In some embodiments, the method comprises an initial step of performing a serial to parallel conversion of said received signal to form a plurality of parallel signals, said subsequent steps being performed on said plurality of parallel signals, said method comprising a final parallel to serial conversion step to convert said plurality of parallel modulated time frequency domain signals to a single modulated time frequency domain signal.

In some cases, the received signal will be formed into a plurality of parallel signals which will be processed together. This reduces the time required to process the signals and can allow efficient hardware systems applying matrix operations on the parallel signals to be used.

A fifth aspect of the present invention provides a receiver for receiving and processing a two dimensional multi carrier modulated signal, said receiver comprising: receiving circuitry for said receiving two dimensional multi carrier modulated signal and a control signal indicative of at least one of a bandwidth and time window of said two dimensional multicarrier modulated signal and a Fourier transform and inverse Fourier transform operation; filtering circuitry for filtering said received signal using said at least one bandwidth and time window indicated by said control signal; Fourier transform circuitry for performing an inverse Fourier transform operation and further Fourier transform circuitry for performing a Fourier transform operation each indicated by said control signal to convert said two dimensional multi carrier modulated signal to a modulated time frequency domain signal.

In some embodiments, the receiver further comprises serial to parallel converter operable to form a plurality of parallel signals from said received two dimensional multi carrier modulated signal upstream of said filtering circuitry and said Fourier transform circuitry.

In some embodiments, said filtering circuitry comprises both of a domain filter and a time domain filter.

In some embodiments, said frequency domain and time domain filter comprise a single filter block.

In some embodiments said receiver further comprises circuitry operable to remove a cycle prefix from said signals.

A sixth aspect of the present invention provides a network node according to a third aspect of the present invention and further comprising a receiver according to a fifth aspect of the present invention.

A seventh aspect of the present invention provides a computer program which when executed by a computer is operable to control said computer to perform a method according to a first or a fourth aspect of the present invention.

Further particular and preferred aspects are set out in the accompanying independent and dependent claims. Features of the dependent claims may be combined with features of the independent claims as appropriate, and in combinations other than those explicitly set out in the claims.

Where an apparatus feature is described as being operable to provide a function, it will be appreciated that this includes an apparatus feature which provides that function or which is adapted or configured to provide that function.

BRIEF DESCRIPTION OF THE DRAWINGS

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

Figure 1 illustrates an orthogonal time frequency space OTFS system according to the prior art;

Figure 2 illustrates a corresponding two dimensional frequency multi-carrier signal processing system according to an embodiment;

Figure 3 schematically illustrates a base station according to an embodiment;

Figure 4 schematically shows a massive MIMO system and problems experienced due to a Doppler effect;

Figure 5 schematically shows a corresponding system according to an embodiment;

Figure 6 schematically illustrates how embodiments facilitate broadband vehicle to vehicle communication; and

Figure 7 shows a flow diagram illustrating steps in a method for processing signals prior to transmission according to an embodiment; and

Figure 8 shows a flow diagram illustrating steps in a method for processing signals on receipt of the signals according to an embodiment.

DESCRIPTION OF THE EMBODIMENTS

Before discussing the embodiments in any more detail, first an overview will be provided.

OTFS is a new promising waveform which can mitigate the effect of frequency-and-time selective fading by using discrete Symplectic Fourier transforms (DSFT), where multiple time-frequency sub-carriers are transmitted. The receiver collects sub-carriers from the buffer and implements DSFT to recover the original modulated signals. OTFS provides a robust solution to combat channel ageing and hence shows a significant superiority in large scale antenna systems such as massive MIMO, compared with the conventional OFDM system.

However, the drawbacks of OTFS include the following:

Because OTFS simply adopts a Symplectic Fourier transform to implement the 2D multicarrier modulation, the guard bands are unavoidably extended to 2D as well and hence spectral efficiency will be degraded. As a reference, in a conventional LTE system, 10% of the allocated bandwidth is reserved as guard band. And in OTFS system, a portion of both bandwidth and TTI will have to be reserved as guard band and guard time slot, respectively, to maintain a reasonable level of 2D out-of-band emission (OOBE).

The performance of OTFS degrades where there is not alignment among 2D subcarriers across delay and Doppler domains. In other words, any OTFS system requires stringent time and frequency alignment which results in heavy signaling overhead for synchronization, especially for the uplink transmission. Non-perfect 2D time-frequency alignment will lead to significant performance degradation.

Embodiments provide a 2D filtered multicarrier waveform (2D-FMC), which waveform is based on the OTFS waveform but provides additional filtering and addresses the main issues of the OTFS system stated above, focusing on the following perspectives:

(1) Relax the synchronization constraint;
(2) Reduce the OOBE in two dimensions;
(3) Provide flexible assignment of sub-bands and symbol lengths;
(4) Offer compatibility with UFMC (universal filtered multicarrier) F-OFDM (filtered orthogonal division multiplexing).
(5) Facilitate Massive MIMO (multiple input multiple output) and V2V (vehicle to vehicle) broadband communications in high speed mobility scenarios.

A 2-dimentional filtered multicarrier (2D-FMC) waveform is provided where the 2D filter's function is to perform digital filtering at both delay and Doppler domains. In this way 2D-FMC relaxes the nearly-perfect synchronization constraint and reduces the OOBE. It provides the flexibility of assigning multicarrier symbol length and sub-bands according to the physical resource requirements. In this regard different devices require different amounts of resource such that with appropriate allocation of resource and the use of corresponding filters the resource may be divided in a non-uniform way that is more appropriate to requirements. Furthermore, the filters required may be the same or similar to those used in UFMC or F-OFDM allowing for re-use of hardware available in such a system. Additionally, as the 2D-FMC waveform is based on the OTFS waveform it also addresses the frequency-and-time selective fading or the channel ageing problem of Massive MIMO based wireless systems.

Fig. 1 schematically shows an OTFS system for processing a signal. A modulated signal such as a OFDM signal is received as multiple signals in parallel in the time frequency domain x (k,l), and these are converted using a discrete Symplectic Fourier transform into signals X (n,m) where n denotes the time index and m the frequency bins. The signals are then sent to a parallel to serial converter whereafter they are transmitted wirelessly to a receiver. At the receiver they are converted back to parallel signals and Symplectic Fourier operations are performed to regenerate the original modulated signals.

The principles behind such OTFS processing are set out below. A frequency-and-time selective fading channel can generally be characterized by the delay and Doppler response, denoted by $h(\tau,\nu)$, where τ describes the delay spread and ν describes the Doppler shift. As such, the received signal can be expressed as

$$r(t)=\iint h(\tau,\nu)e^{j2\pi\nu(t-\tau)}s(t-\tau)d\nu d\tau, \qquad (1)$$

Using the channel equation (1), we can derive a channel model in the time-frequency domain for the given bandwidth and TTI time duration (of an OFDM system), which explicitly models Doppler effects. A multiplicative channel model w.r.t frequency-and-time selective fading is obtained as

$$Y[n,m]=H[n,m]X[n,m]+V[n,m], \qquad (2)$$

where $m=-\frac{M}{2}+1,\ldots,\frac{M}{2}$ denotes the frequency bins and $n=0,\ldots,N-1$ (measured in OFDM symbols) denotes time index, where N is the total number of OFDM symbols in the TTI. The channel time-frequency response $H[n,m]$ is transformed from the delay Doppler impulse response $h(\tau,\nu)$, given by

$$H[n,m] = \iint h(\tau,\nu) e^{j2\pi\nu nT} e^{-j2\pi m\Delta f\tau} d\nu d\tau, \qquad (3)$$

where T is the length of the OFDM symbol (plus the CP extension).

Based on the channel equations (2) and (3), it has been proposed to map the information bearing QAM symbols $x[k,l]$ to the time-frequency symbols $X[n,m]$ via a set of 2D complex exponential basis functions

$$X[n,m] = \frac{1}{MN}\sum_{k=0}^{N-1}\sum_{l=0}^{M-1} x[k,l] b_{k,l}[n,m], \qquad (4)$$

$$b_{k,l}[n,m] = e^{-j2\pi(\frac{ml}{M}-\frac{nk}{N})},$$

where the basis functions denoted by $b_{k,l}[n,m]$ have the following characteristics: 1) along the frequency bin dimension m, the basis functions $e^{-j2\pi(\frac{ml}{M})}$ constitute a set of DFT basis functions and relate the frequency domain to a new domain, which we call the delay domain; 2) along the time dimension n, the basis functions $e^{j2\pi(\frac{nk}{N})}$ constitute a set of IDFT basis functions and relate the time domain to another new domain, which we call the Doppler domain; and 3) in conclusion, the OTFS scheme allocates the information QAM symbols $x[k,l]$ in the delay-Doppler domain; these symbols are subsequently transformed into the familiar time-frequency domain via Eq. (6) which is shown later.

Figure 2 provides a schematic illustration of signal processing to generate a 2D-FMC waveform according to an embodiment and to generate a modulated signal from a received 2D-FMC. This circuitry may be present within a network node such as a base station, access point or other communication device such as a user equipment. In some cases both the transmission and reception circuitry may be present in each node, while in others only the reception or the transmission circuitry may be present.

A modulated signal such as a OFDM signal is input as multiple signals in parallel in the time frequency domain x (k,l) into discrete Symplectic Fourier transform circuitry where the signals are transformed to signals X (n,m) where n denotes the time index and m the frequency bins. Cyclic prefixes are then added to the individual signals to provide circular convolution and the resulting signals are filtered. In this regard a single time window filter or a frequency domain filter may be used, but in preferred embodiments a 2D filter which provides both time domain and frequency domain filtering is used. This removes out of band signals OOB and reduces the need for guard bands or guard time intervals.

The signals are then sent to a parallel to serial converter and are transmitted wirelessly as a serial signal to a receiver present in a different node in the network. The receiver performs serial to parallel conversion on the received signal, filters it using a filter corresponding to the transmission filter, removes the cyclic prefixes and then performs the Symplectic Fourier transform operations to regenerate the original modulated signal which can then be decoded.

The matrix operations that are performed on the signals are schematically shown below the block diagram of the processing circuitry. These show a different order of execution of the processes to that shown in the block diagrams. Owing to the nature of many of the operations performed the order in which they are performed is not important.

The schematic flow diagram of matrix operations shows an input modulated signal X having an inverse discrete Fourier transform operation performed on it, denoted by matrix V. This operation relates the time domain to the so-called Doppler domain which addresses the time selective fading of a channel. Cyclic prefixes are then added to the signal by matrix C to provide circular convolution and the signal is in this embodiment then filtered in the time domain. Using matrix F_τ A discrete Fourier transform operation denoted by matrix T which relates the frequency domain to the so-called delay domain and which address the frequency selective fading of a channel due to multipath effects is then performed and the signal is then passed through a frequency filter $F\nu$ to generate the 2D FMC signal.

The reverse matrix operations performed at the receiver after the signal has been transmitted wirelessly via a channel with properties denoted as H to generate a signal Y are also shown schematically as a set of matrix operations. Thus, the wirelessly transmitted signal Y is received and filtered in the frequency domain. A discrete Fourier transform operation is then performed followed by a filter in the time domain, the removal of the cyclic prefixes followed by an inverse discrete Fourier transform operation.

More details on the matrix operations performed are given below in which we use matrix representation to illustrate the idea of developing the 2D-FMC.

The matrix interpretation of generating the filtered 2D waveform signals can be represented as

$$\mathbf{X}_F = \left[\mathbf{F}_\upsilon \mathbf{T}\left(\mathbf{F}_\tau \mathbf{C}\mathbf{V}\mathbf{X}\right)^T\right]^T, \qquad (5)$$

where $\mathbf{X}$ represents the modulated complex symbols, whose dimension is $N \times M$; $\mathbf{V}$ is IFFT (inverse finite Fourier transform) matrix whose dimension is $N \times N$; $\mathbf{C}$ is the CP (cyclic prefix) matrix with a dimension of $(N+\mu)\times N$ and μ is the length of CP; $\mathbf{F}_\tau$ is the matrix of TX band pass filter whose dimension is $(N+\mu)\times(N+\mu)$; $\mathbf{T}$ is FFT matrix whose dimension is $M \times M$; and $\mathbf{F}_\upsilon$ is the matrix of TX time-domain windowing with a dimension of $M \times M$; $\mathbf{X}_F$ represents the resulted 2D signals whose dimension is $M \times (N+\mu)$.

DSFT (discrete Symplectic Fourier transform) can be decomposed into a product of IFFT and FFT operations, given by

Define DSFT as TV^T' (6)

As a metaplectic operator, DSFT has a special characteristic, i.e., the inverse operation of DSFT is itself:

$$(\mathrm{DSFT})^{-1} = \mathrm{DSFT}. \qquad (7)$$

The above properties of DSFT allow us to reuse the FFT and IFFT components in current LTE (similar to SC-FDMA) without introducing too much additional complexity.

The received signal can be expressed as:

$$\mathbf{Y} = \left[\mathbf{H}_\upsilon \left(\mathbf{H}_\tau \mathbf{X}_F\right)^T\right]^T + \mathbf{N}. \qquad (8)$$

where $\mathbf{Y}$'s dimension is $M \times (N+\mu)$; $\mathbf{H}_\upsilon$ represents the time-selective fading channel whose dimension is $M \times M$; $\mathbf{H}_\tau$ represents the frequency-selective fading channel whose dimension is $(N+\mu)\times(N+\mu)$; $\mathbf{N}$ is the frequency-time domain noise.

The recovery procedure can be summarized as:

$$\tilde{\mathbf{X}} = \mathbf{V}^H \mathbf{C}_r \mathbf{F}_\tau^H \left(\mathbf{T}^H \mathbf{F}_\upsilon^H \mathbf{Y}^T\right)^T, \qquad (9)$$

where $\mathbf{F}_\upsilon^H$ is the matrix of RX time-domain windowing whose dimension is $M \times M$; $\mathbf{T}^H$ is the IFFT matrix whose dimension is $M \times M$; $\mathbf{F}_\tau^H$ is the RX band pass filter whose dimension is $(N+\mu)\times(N+\mu)$; $\mathbf{C}_r$ is the CP removal matrix whose dimension is $N\times(N+\mu)$; and $\mathbf{V}^H$ is the FFT matrix whose dimension is $N \times N$.

Figure 3 shows a base station 10 processing signals destined for different devices. A modulator 20 is shown receiving the signals UE1 and UE2 destined for mobile phones and IT1 destined for an Internet of Things device. The modulator 20 generates modulated signals using modulating circuitry, which may be OFDM circuitry. These signals are then sent through serial to parallel converters 22 to a plurality of signal processing circuitry 30 according to an embodiment. This circuitry is similar to that shown as blocks “DSFT”, “adding CP” and “Tx block 2D filter” in Figure 2. This plurality of signal processing circuitry 30 is arranged as parallel circuitry 30a, 30b, 30c and each generates 2D-FMC signals from the original modulated signals. The multiple signal processing circuitry 30a, 30b, 30c arranged in parallel and which process the different signals from the different devices, may have different properties and in particular signal processing circuitry 30a to which the Internet of things signal is sent has a narrowband filter block compared to the filter block of circuitry 30b and 30c. This is due to the resources allocated to the Internet of Things signal being less than those allocated to the user equipment signals. The processed parallel signals from each device are then sent to a parallel to serial convertor 32 whereafter they are output via a transmitter to be transmitted wirelessly to the different devices.

It should be noted that the 2D filter shown as a single block in Figure 2 can be decomposed as two 1D filters and this allows the re-use of filters present in the hardware for modulation techniques such as UFMC and F-OFDM. The DSFT operation which is shown as a single block in Figure 2 can be decomposed as a product of IFFT and FFT, again allowing some of the hardware components of current F-OFDM or UFMC to be re-used.

In summary, at the Transmitter (TX), after generating the DFTS symbols and appending the cyclic prefix (CP) in the Doppler domain, a digital frequency-domain band pass filter covering the allocated bandwidth is applied in the Doppler domain and a time-domain windowing covering the whole TTI is applied in the delay domain. The frequency-domain band pass filters and time-domain windows jointly serve as a TX block 2D filter.

At the Receiver (RX), similarly, the block 2D filter will be jointly formed by the corresponding band pass filter applied in the Doppler domain and the time-domain window in the delay domain. Then, by passing the filtered signals to CP removal procedure and DSFT, the original modulated signal can be recovered.

The benefits of 2D-FMC w.r.t. the above technique features can be summarized as follows:

- Reducing the frequency-and-time OOBE in two dimensions;
- Relaxing the global synchronization across Doppler and delay domains.
- Providing flexible assignment of symbol lengths and sub-bands according to the physical resource requirements.
- Offering compatibility with unified filtered multicarrier (UFMC) and filtered OFDM by re-using their existing hardware components for overcoming the frequency-and-time selective fading or the channel aging problem of Massive MIMO.
- Facilitating Massive MIMO for broadband communications in frequency-and-time selective fading scenario. The conventional Massive MIMO with OFDM (as seen in Fig. 4) cannot provide the broadband service as the Doppler effect due to the high velocity breaks the subcarriers' orthogonality. In contrast, the proposed 2D-FMC allows Massive MIMO systems (as seen in Fig. 5) to serve the broadband communications with acquiring the rough beam angle only by tracking.
- Facilitating the broadband V2V communications with high speed mobility. As seen in Fig. 6, high rate communications between two vehicles with high speeds are available by using 2D-FMC as 2D-FMC overcomes the frequency-and-time selective fading.

Figure 7 schematically shows steps performed in a method at a transmitter within a network node such as a base station. Signals destined for a plurality of devices are generated and modulated using for example OFDM prior to being output to a plurality of serial to parallel converters. Each of the set of parallel signals are then transformed using Symplectic Fourier transform operations to generate a 2D multicarrier signal and cyclic prefixes are added. The signals are then filtered in both the time and frequency domain to generate the 2D-FMC signals. Parallel to serial conversion is then performed on each set of signals which are then output to a wireless transmitter. It should be noted that the order shown of the Fourier transform operations, cyclic prefix additions and filtering is merely an example and these steps could be performed in a different order with the following constraints. The cyclic prefix operation should be performed after the inverse fast Fourier Transform and the filtering in the time domain should be after the cyclic prefix operation. There should be a matrix permutation of the results matrix between the IDFT and the DFT. The below gives examples of permitted orders of execution:

IDFT (inverse discrete Fourier transform, operated in a column manner)-DFT(discrete Fourier transform operated in a row manner)-matrix transpose-CP-Filter1-Filter2
or
IDFT-CP-DFT-Filter1-Filter2
or
DFT-IDFT-CP-Filter2-Filter1
or
DFT-IDFT-CP-Fiter2-Filter1

In general the following constraints in order apply: CP should be after IDFT and the filter in the time domain should be after CP, there should be a permutation between IDFT and DFT.

In summary, the matrix interpretation of generating the filtered 2D waveform signals can be represented as

$$\mathbf{X}_F = \left[\mathbf{F}_\upsilon \mathbf{T}\left(\mathbf{F}_\tau \mathbf{CVX}\right)^T\right]^T,$$

where $\mathbf{X}$ represents the modulated complex symbols, whose dimension is $N \times M$; $\mathbf{V}$ is IFFT matrix whose dimension is $N \times N$; $\mathbf{C}$ is the CP matrix with a dimension of $(N+\mu)\times N$ and μ is the length of CP; $\mathbf{F}_\tau$ is the matrix of TX band pass filter whose dimension is $(N+\mu)\times(N+\mu)$; $\mathbf{T}$ is FFT matrix whose dimension is $M \times M$; and $\mathbf{F}_\upsilon$ is the matrix of TX time-domain windowing with a dimension of $M \times M$; $\mathbf{X}_F$ represents the resulted 2D signals whose dimension is $M \times (N+\mu)$.

The transpose in $\left(\mathbf{F}_\tau \mathbf{CVX}\right)^T$ means the permutation over the resultant signal matrix. The above equation follows the order of 1. IDFT; 2. Adding the CP; 3. Filtering in time domain; 4. permutation on the resulted signal matrix; 5. DFT; 6. Filtering in frequency domain.

But we can do the other way around:

$$\mathbf{X}_F = \mathbf{F}_\tau \mathbf{C} \mathbf{V} \left(\mathbf{F}_\upsilon \mathbf{T} \mathbf{X} \right)^T ,$$

which follows the order of DFT-Filter on time-Permutation-IDFT-CP-Filter on frequency.

In the embodiments, you can take the order of

1. IDFT;
2. Adding the CP;
3. Filtering in time domain;
4. Permutation on the resulted signal matrix;
5. DFT;
6. Filtering in frequency domain

as an example, and we can say there are many order of above operations which can generate 2D-FMC signals, such as 123456 or 564123. The only principles we need to follow is:

1. CP should be always after IDFT;
2. Filtering on time domain should be after CP.
3. The permutation must be between IDFT and DFT.

Figure 8 schematically shows steps performed in a method at a receiver within a node such as a user equipment or base station. A 2D FMC signal is received as is an indication of the filter characteristics, cyclic prefixes and Fourier transform operations used to generate the signal. These latter indications are received in a control signal. Parallel to serial conversion of the signal is then performed and the parallel signals are filtered with a filter having the indicated characteristics. The Fourier transform operations are then performed and the cyclic prefixes removed. The modulated signal can then be decoded using a conventional decoder such as an OFDM decoder if that was the form of the original modulation. It should be noted that the order shown of the Fourier transform operations cyclic prefix removal and filtering is merely an example and these steps could be performed in a different order with the following constraints. The cyclic prefix removal should be before the IDFT and the filtering in the time domain should be before the cyclic prefix removal. There should be a permutation between IDFT and DFT.

A person of skill in the art would readily recognize that steps of various above-described methods can be performed by programmed computers. Herein, some embodiments are also intended to cover program storage devices, e.g., digital data storage media, which are machine or computer readable and encode machineexecutable or computer-executable programs of instructions, wherein said instructions perform some or all of the steps of said above-described methods. The program storage devices may be, e.g., digital memories, magnetic storage media such as a magnetic disks and magnetic tapes, hard drives, or optically readable digital data storage media. The embodiments are also intended to cover computers programmed to perform said steps of the above-described methods.

The functions of the various elements shown in the Figures, including any functional blocks labelled as "processors" or "logic", may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" or "logic" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, network processor, application specific integrated circuit (ASIC), field programmable gate array (FPGA), read only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, any switches shown in the Figures are conceptual only. Their function may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

It should be appreciated by those skilled in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

CLAIMS

1. A method of processing a modulated wireless communication signal prior to transmitting said signal, said method comprising:

performing on said signal both an inverse Fourier transform operation to form a time domain representation of a signal and a Fourier transform operation to form a frequency domain representation of a signal, such that said signal is transformed to form a two dimensional multi carrier modulated signal;

applying at least one of a frequency domain filter and a time domain window to said signal following at least one of said Fourier transform operations; and

transmitting said filtered two dimensional multi carrier modulated signal via a wireless channel towards a receiver.

2. A method according to claim 1, comprising applying both of a frequency domain filter and a time domain window to said signal.

3. A method according claim 2, wherein said two filtering processes are applied as a single combined filter process.

4. A method according to any preceding claim, comprising applying a cycle prefix to said signal prior to performing said filtering step.

5. A method according to any preceding claim, further comprising:

an initial step of performing serial to parallel conversion of said modulated signal to form a plurality of parallel modulated signals;

said subsequent steps, prior to said transmitting step being performed on said plurality of parallel signals; and

prior to transmitting said two dimensional multi carrier modulated signal performing a parallel to serial conversion of said plurality of two dimensional multi carrier modulated signals to form said two dimensional multi carrier modulated signal.

6. A method according to any preceding claim, said method further comprising transmitting a control signal indicative of at least one of said frequency band and time window of said at least one filter and indicative of said Fourier transform and inverse Fourier Transform operations applied to said modulated signal.

7. Signal processing circuitry operable to process a modulated wireless communication signal prior to said signal being transmitted, said signal processing circuitry comprising:

Fourier transform circuitry configured to perform an inverse Fourier transform operation to form a time domain representation of a signal and further Fourier transform circuitry operable to perform a Fourier transform operation to form a frequency domain representation of a signal, such that said signal is transformed by said circuitry to form a two dimensional multi carrier modulated signal;

at least one of a frequency domain filter and a time domain filter for filtering said two dimensional multi carrier modulated signal.

8. Signal processing circuitry according to claim 7, further comprising:

a serial to parallel converter operable to form a plurality of parallel signals from said modulated signal;

said Fourier transform circuitry and further Fourier transform circuitry being operable to receive and transform said plurality of parallel signals; and

parallel to serial conversion circuitry for performing a parallel to serial conversion on said plurality of signals to form a 2D multi carrier modulated signal.

9. A network node comprising signal processing circuitry according to claim 7 or 8, and further comprising transmitting circuitry for transmitting said two dimensional multi carrier modulated signal via a wireless channel towards a receiver, wherein said network node is one of a base station, an access point and a user equipment.

10. A method of processing a received two dimensional filtered multi carrier modulated signal, said method comprising:

receiving a control signal indicative of at least one of a bandwidth and time window of said two dimensional multicarrier modulated signal and a Fourier transform and inverse Fourier transform operation;

filtering said received signal using at least one of a frequency domain filter with a bandwidth indicated by said control signal and a time domain window with a time window indicated by said control signal;

performing an inverse Fourier transform operation and a Fourier transform operation indicated by said control signal on said two dimensional multicarrier modulated signal to convert said two dimensional multi carrier modulated signal to a modulated time frequency domain signal.

11. A method according to claim 10, further comprising removing a cyclic prefix from said filtered signal.

12. A method according to claim 10 or 11, comprising an initial step of performing a serial to parallel conversion of said received signal to form a plurality of parallel signals, said subsequent steps being performed on said plurality of parallel signals, said method comprising a final parallel to serial conversion step to convert said plurality of parallel modulated time frequency domain signals to a single modulated time frequency domain signal.

13. A receiver for receiving and processing a two dimensional multi carrier modulated signal, said receiver comprising:

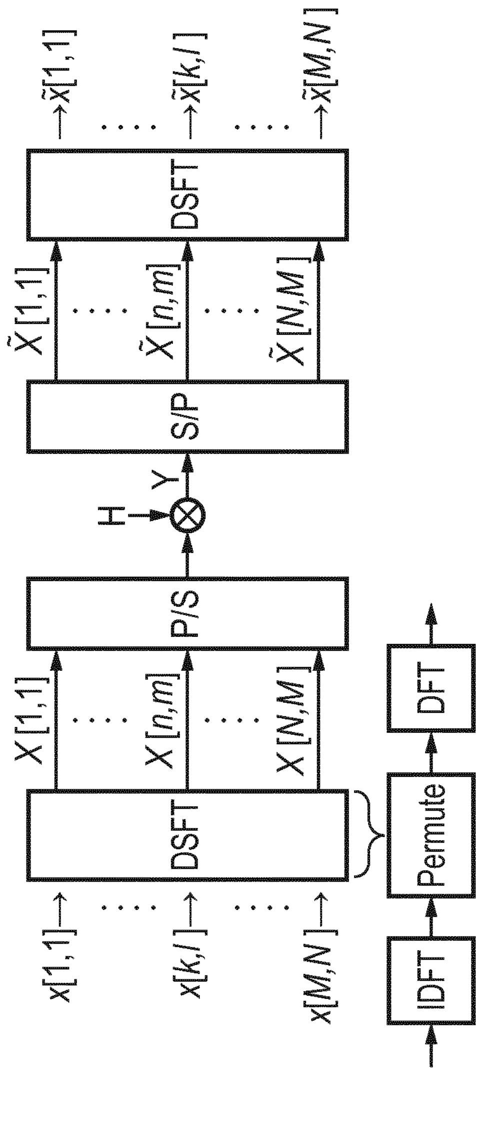
receiving circuitry for said receiving two dimensional multi carrier modulated signal and a control signal indicative of at least one of a bandwidth and time window of said two dimensional multicarrier modulated signal and a Fourier transform and inverse Fourier transform operation;

filtering circuitry for filtering said received signal using said at least one bandwidth and time window indicated by said control signal;

Fourier transform circuitry for performing an inverse Fourier transform operation and further Fourier transform circuitry for performing a Fourier transform operation each indicated by said control signal to convert said two dimensional multi carrier modulated signal to a modulated time frequency domain signal.

14. A network node according to claim 9 and further comprising a receiver according to claim 13.

15. A computer program which when executed by a computer is operable to control said computer to perform a method according to any one of claims 1 to 6 and 10 to 12.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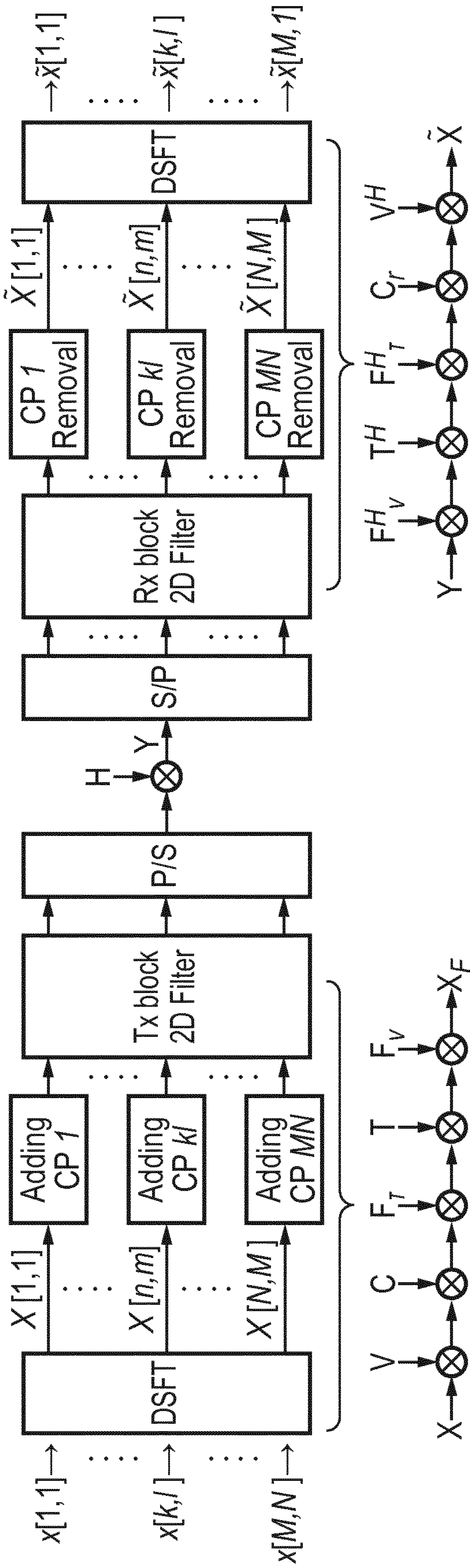
x̃[M,N]
IDFT
Permute
DFT

FIG. 1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Adding CP kl
Adding CP MN
Tx block 2D Filter
P/S
H
Y
S/P
Rx block 2D Filter
CP 1 Removal
CP kl Removal
CP MN Removal
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X̃[n,m]
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C
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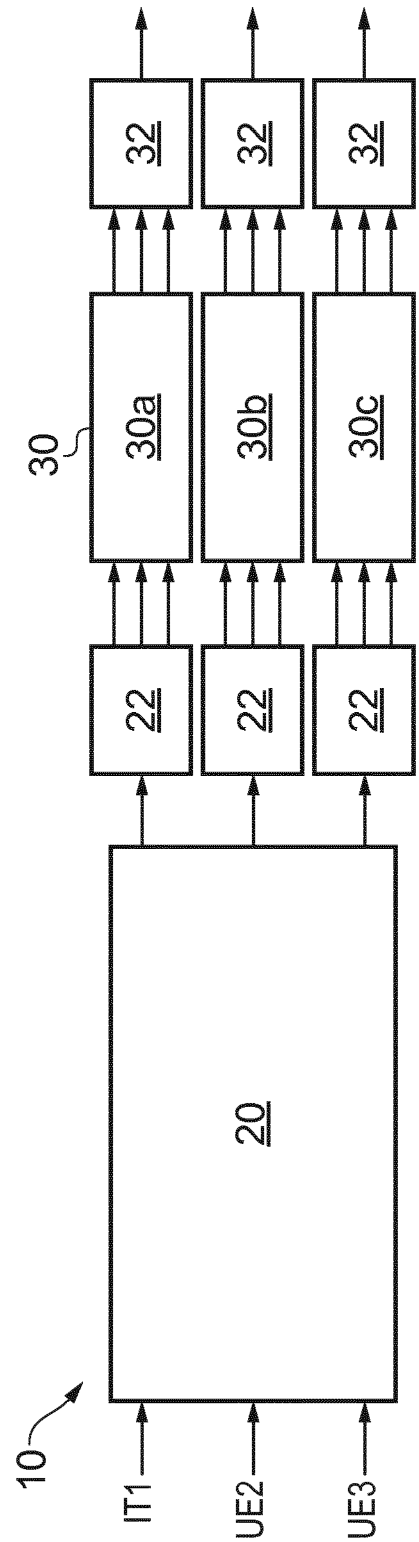
V^H
X̃

FIG. 2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IT1
UE2
UE3
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22
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30b
30c
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32
32

FIG. 3

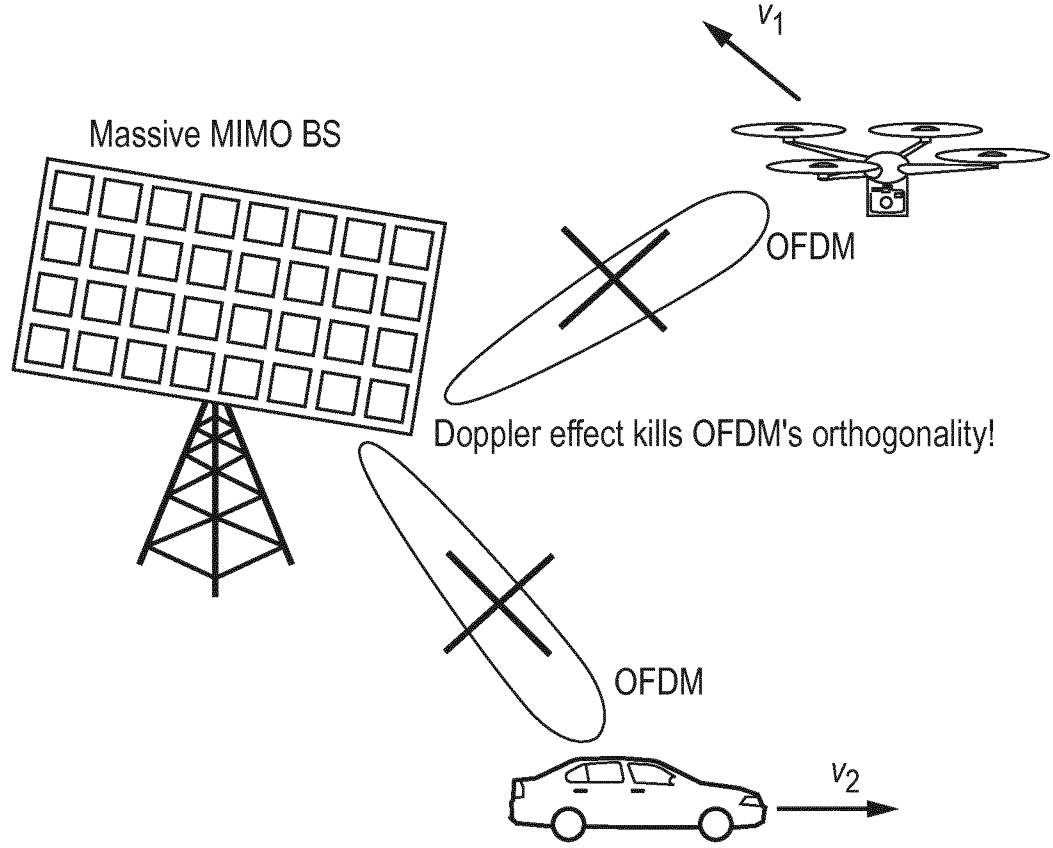
v_1
Massive MIMO BS
OFDM
Doppler effect kills OFDM's orthogonality!
OFDM
v_2

FIG. 4

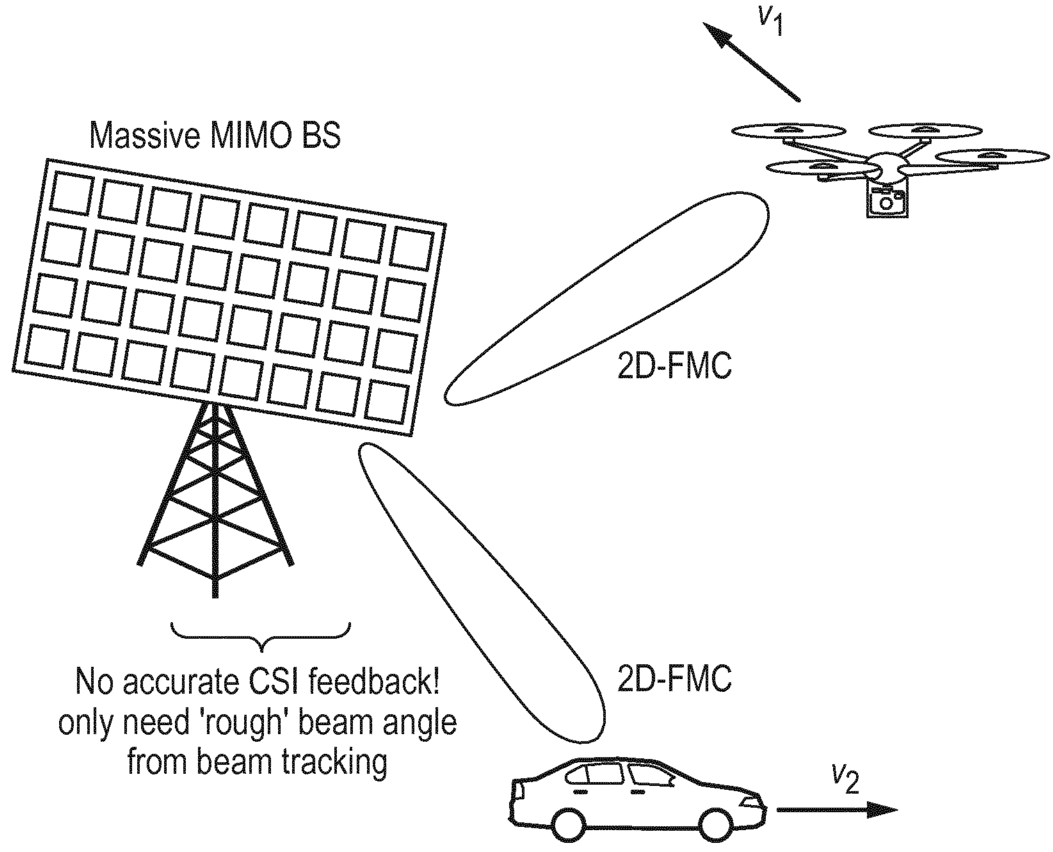
v_1
Massive MIMO BS
2D-FMC
2D-FMC
No accurate CSI feedback!
only need 'rough' beam angle
from beam tracking
v_2

FIG. 5

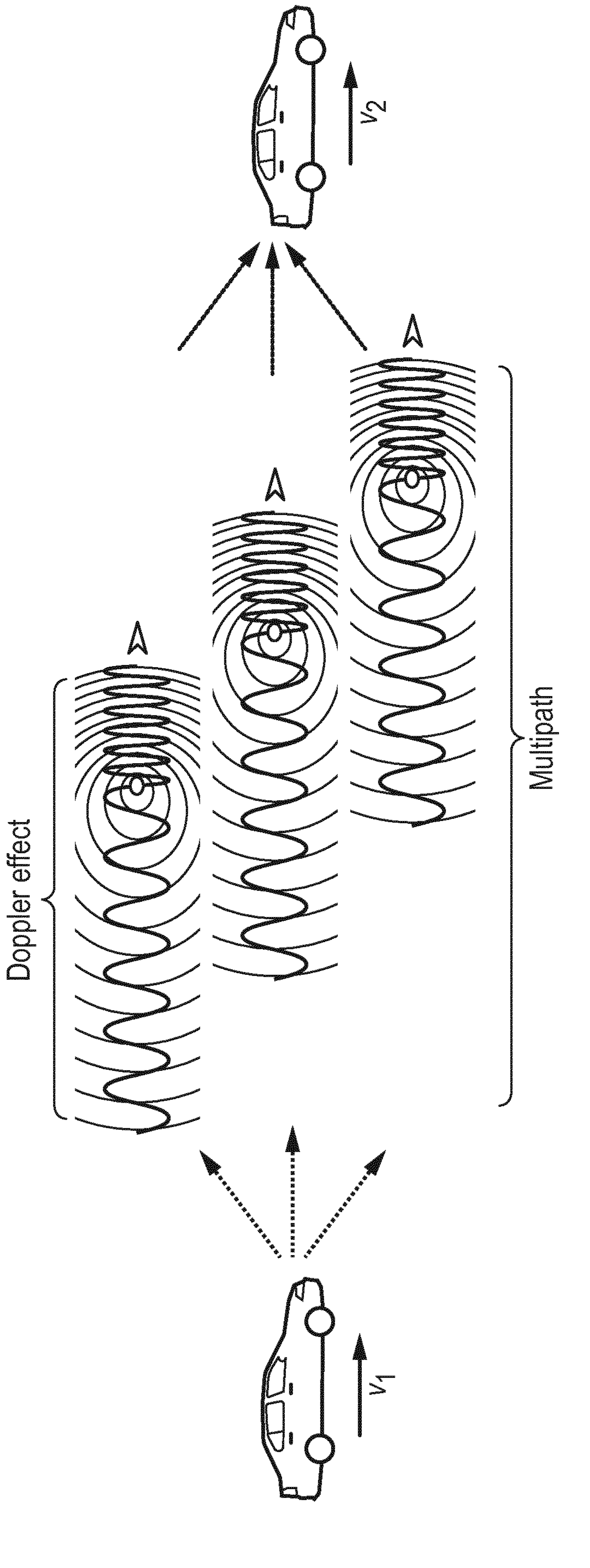

FIG. 6

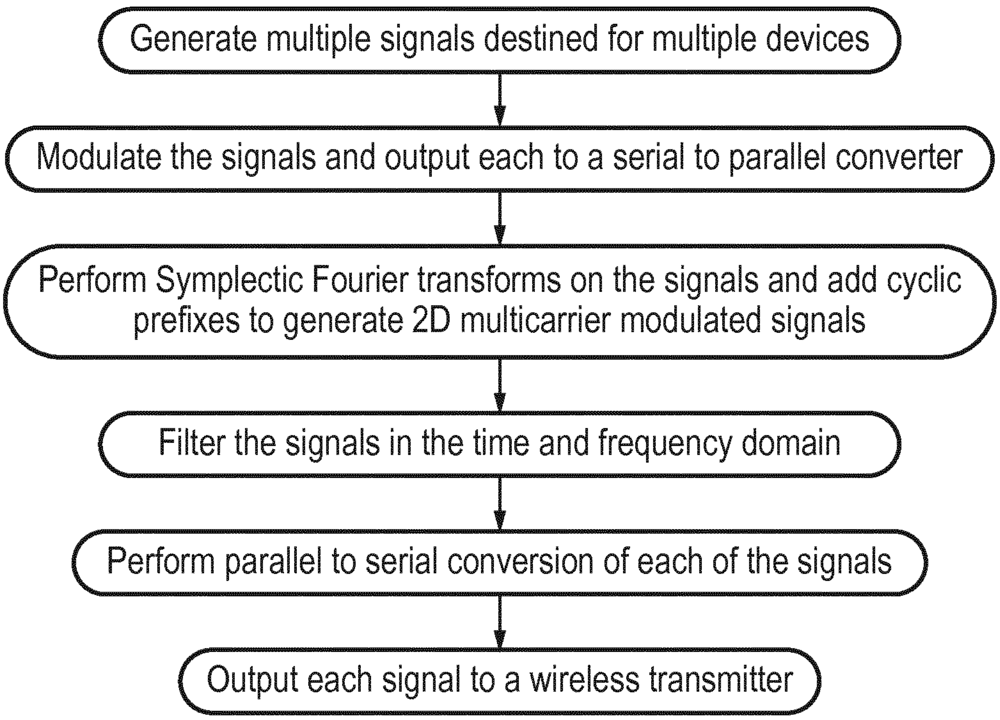
Generate multiple signals destined for multiple devices
Modulate the signals and output each to a serial to parallel converter
Perform Symplectic Fourier transforms on the signals and add cyclic prefixes to generate 2D multicarrier modulated signals
Filter the signals in the time and frequency domain
Perform parallel to serial conversion of each of the signals
Output each signal to a wireless transmitter

FIG. 7

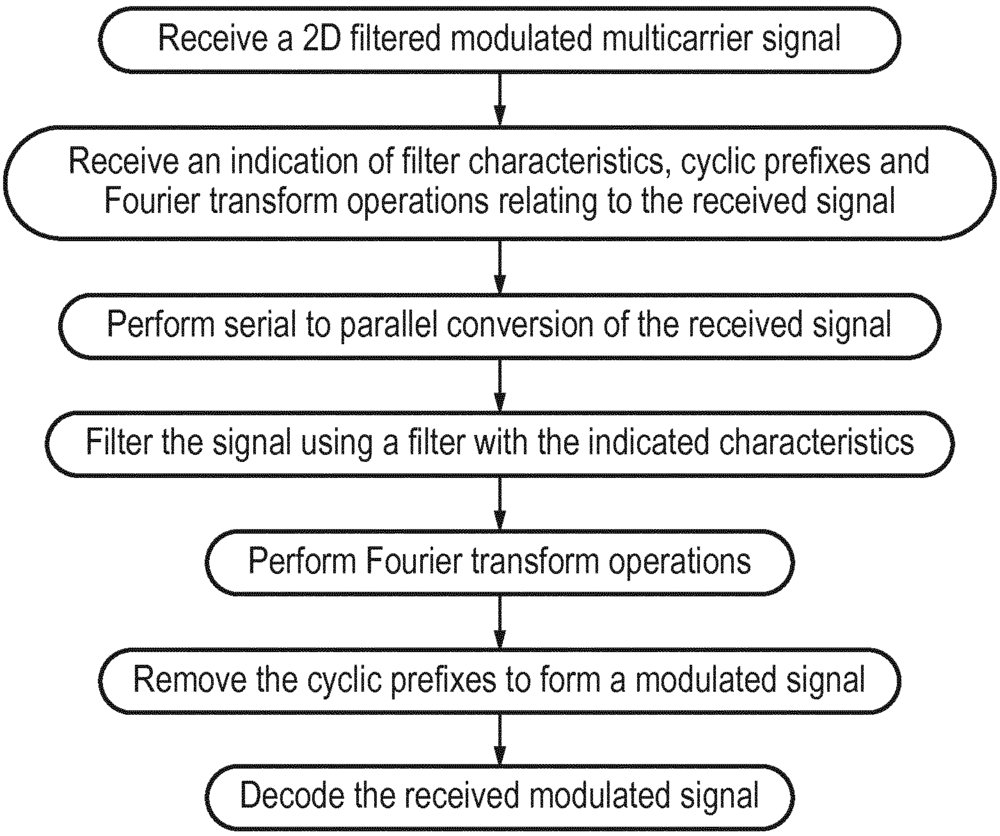
Receive a 2D filtered modulated multicarrier signal
Receive an indication of filter characteristics, cyclic prefixes and Fourier transform operations relating to the received signal
Perform serial to parallel conversion of the received signal
Filter the signal using a filter with the indicated characteristics
Perform Fourier transform operations
Remove the cyclic prefixes to form a modulated signal
Decode the received modulated signal

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/079316

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L27/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	COHERE TECHNOLOGIES: "Performance evaluation of OTFS waveform in single user scenarios", 3GPP DRAFT; R1-167593 PERFORMANCE EVALUATION OF OTFS IN SINGLE USER SCENARIOS-AM, 3RD GENERATION PARTNERSHIP PROJECT (3GPP), MOBILE COMPETENCE CENTRE ; 650, ROUTE DES LUCIOLES ; F-06921 SOPHIA-ANTIPOL , no. Gothenburg, Sweden; 20160822 - 20160826 13 August 2016 (2016-08-13), XP051142585, Retrieved from the Internet: URL:http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_86/Docs/ [retrieved on 2016-08-13] page 1 - page 5 -----	1-15

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 January 2018	22/01/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	González Gutiérrez

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/079316

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	COHERE TECHNOLOGIES ET AL: "OTFS Modulation Waveform and Reference Signals for New RAT", 3GPP DRAFT; R1-163619 OTFS WAVEFORM FOR NEW RAT, 3RD GENERATION PARTNERSHIP PROJECT (3GPP), MOBILE COMPETENCE CENTRE ; 650, ROUTE DES LUCIOLES ; F-06921 SOPHIA-ANTIPOLIS CEDEX ; FRANCE , vol. RAN WG1, no. Busan, South Korea; 20160411 - 20160415 18 April 2016 (2016-04-18), XP051090363, Retrieved from the Internet: URL:http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_84b/Docs/ [retrieved on 2016-04-18] the whole document -----	1-15
A	US 2014/169433 A1 (HADANI RONNY [US] ET AL) 19 June 2014 (2014-06-19) the whole document -----	1-15

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/079316

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014169433 A1	19-06-2014	US 2014169433 A1	19-06-2014
		US 2017207817 A1	20-07-2017