ORTHOGONAL TIME FREQUENCY SPACE (OTFS)-BASED RADAR SENSING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore Patent Application No. 10202400845V filed on 22 March 2024, the content of which being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] The present invention generally relates to a method of orthogonal time frequency space (OTFS)-based radar sensing, and a system thereof.

BACKGROUND

[0003] Recent study shows that the OTFS waveform is a promising candidate for the future communication. For example, it has been shown that OTFS has a much better performance than the orthogonal frequency division multiplexing (OFDM) for high mobility channels. However, OTFS was originally designed for communication functions/purposes and using OTFS for radar sensing has not been well studied. In particular, existing methods for radar sensing with OTFS waveform have a high computational complexity.

[0004] For example, there exists a conventional method that applies OTFS to radar sensing using a matched filter algorithm for OTFS-based radar sensing, which can measure the range and speed of the sensing target (e.g., disclosed in Raviteja *et al.*, "Orthogonal Time Frequency Space (OTFS) Modulation Based Radar System", 2019 IEEE Radar Conference (RadarConf), pages 1-6, April 2019 (hereinafter referred to as the Raviteja reference)). FIG. 1 depicts a schematic block diagram illustrating a conventional OTFS-based radar system architecture. Simulation results show that this conventional OTFS-based radar sensing method (or system) retain the inherent advantages of the multicarrier modulation of OFDM. Furthermore, it has a longer radar sensing range and/or faster target tracking rate as OTFS requires less cyclic prefix during the transmission.

[0005] In another conventional OTFS-based radar sensing method (e.g., disclosed in Zhang *et al.*, "Radar sensing via OTFS signaling: A delay Doppler signal processing perspective", IEEE International Conference on Communications (ICC), May 2023 (hereinafter referred to as the Zhang reference)), the potential connections between the OTFS and DD domain radar signal processing were explored. It was found that the range-Doppler matrix computing process

in radar sensing is exactly the demodulation of OTFS with a rectangular pulse shaping filter. Furthermore, this conventional OTFS-based radar sensing method estimates the fractional delay and Doppler parameters for radar sensing. It computes the pulse compression as V, which can be represented as:

$$V[k,l] = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} Y^*[n,m]X[[n-k]_N,[M-L]_M] \times a[n-k,m-l]e^{j2\pi\frac{(m-l)k}{NM}}, \quad \text{(Equation 1)}$$

where $k \in [0, N-1]$ and $l \in [0, M-1]$, and $a[k,l]$ is a phase offset.

[0006] The above-mentioned two conventional OTFS-based radar sensing methods may achieve decent performances in estimating the range and Doppler information of the target. However, both conventional OTFS-based radar sensing methods have a large computational complexity of $O((MN)^2)$. For example, to realize more efficient OTFS radar sensing, such as to meet the demands of various Integrated Communications and Sensing (ICAS) applications, it is important that an OTFS-based radar sensing method be not only accurate but also computationally efficient.

[0007] A need therefore exists to provide a method of OTFS-based radar sensing, and as well as a system and a radar thereof, that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional OTFS-based radar sensing methods, and more particularly, with improved computational efficiency. It is against this background that the present invention has been developed

SUMMARY

[0008] According to a first aspect of the present invention, there is provided a method of OTFS-based radar sensing, comprising:

performing an OTFS demodulation based on a time domain signal or a Delayed-Time (DT) domain signal received and reflected from one or more objects from a time domain signal or a DT domain signal transmitted, the time domain signal or the DT domain signal transmitted being generated from an OTFS modulation based on a first Delay-Doppler (DD) domain signal;

determining a two-dimensional (2D) range-Doppler map based on a first Time-Frequency (TF) domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and

performing radar sensing based on the 2D range-Doppler map.

[0009] According to a second aspect of the present invention, there is provided a system for OTFS-based radar sensing, the system comprising:

at least one memory; and

at least one processor communicatively coupled to the at least one memory and configured to perform the method of OTFS-based radar sensing according to the above-mentioned first aspect of the present invention.

[0010] According to a third aspect of the present invention, there is provided a radar for OTFS-based radar sensing, the radar comprising:

one or more antennas; and

the system for OTFS-based radar sensing according to the above-mentioned second aspect of the present invention communicatively coupled to the one or more antennas for performing radar sensing.

[0011] According to a fourth aspect of the present invention, there is provided a computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to perform the method of OTFS-based radar sensing according to the above-mentioned first aspect of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 depicts a schematic block diagram illustrating a conventional OTFS-based radar system architecture;

FIG. 2 depicts a schematic flow diagram of a method of OTFS-based radar sensing, according to various embodiments of the present invention;

FIG. 3 depicts a schematic block diagram of a system for OTFS-based radar sensing, according to various embodiments of the present invention;

FIG. 4 depicts a schematic block diagram showing a traditional architecture of OTFS modulation and demodulation;

FIG. 5A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method of OTFS-based radar sensing in the case of the OTFS-based monostatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various first example embodiments of the present invention;

FIG. 5B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based monostatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various second example embodiments of the present invention;

FIG. 6A depicts a schematic block diagram illustrating an example architecture of a bistatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various third example embodiments of the present invention;

FIG. 6B depicts a schematic block diagram illustrating an example architecture of a bistatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various fourth example embodiments of the present invention;

FIG. 7A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based monostatic radar sensing and Zak-based OTFS modulation/demodulation, according to various fifth example embodiments of the present invention;

FIG. 7B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based monostatic radar sensing and Zak-based OTFS modulation/demodulation, according to various sixth example embodiments of the present invention;

FIG. 8A depicts a schematic block diagram illustrating an example architecture of a bistatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and Zak-based OTFS modulation/demodulation, according to various seventh example embodiments of the present invention;

FIG. 8B depicts a schematic block diagram illustrating an example architecture of a bistatic radar performing an example method of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and Zak-based OTFS modulation/demodulation, according to various eighth example embodiments of the present invention;

FIG. 9 depicts a plot of simulation results (being a range-Doppler map at -20dB) obtained in an experiment for a method of OTFS-based monostatic radar sensing according to various example embodiments of the present invention;

FIG. 10 depicts a plot of estimation errors of the method of OTFS-based monostatic radar sensing according to various example embodiments of the present invention for two targets;

FIG. 11 depicts a plot of simulation results (being a range-Doppler map at -20dB) obtained in an experiment for a method of OTFS-based bistatic radar sensing according to various example embodiments of the present invention;

FIG. 12 depicts a plot of estimation errors of the method of OTFS-based bistatic radar sensing according to various example embodiments of the present invention for two targets;

FIG. 13 depicts a plot of estimation errors of the method of OTFS-based bistatic radar sensing according to various example embodiments of the present invention with a different modulation technique (256-QAM constellation) for two targets;

FIG. 14 depicts a plot of the estimation errors of the difference of the two targets;

FIG. 15 depicts a plot of comparison on estimation errors of the method of OTFS-based bistatic radar sensing according to various example embodiments of the present invention and a conventional OTFS-based radar sensing method for two targets; and

FIG. 16 depicts a plot of the estimation errors of the difference of the two targets

DETAILED DESCRIPTION

[0013] Various embodiments of the present invention relate to a method of OTFS-based radar sensing, and a system and a radar thereof.

[0014] As described in the background, there exist conventional OTFS-based radar sensing methods which may achieve decent performances in estimating the range and Doppler information of a target. However, such conventional methods have a large computational complexity, e.g., $O((MN)^2)$. For example, to realize more efficient OTFS radar sensing, such as to meet the demands of various Integrated Communications and Sensing (ICAS) applications, it is important that an OTFS-based radar sensing method be not only accurate but also computationally efficient. In this regard, various embodiments of the present invention provide a method of OTFS-based radar sensing, and a system and a radar thereof, that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional OTFS-based radar sensing methods, and more particularly, with improved computational efficiency, so as to enable OTFS-based radar sensing that is accurate and computationally efficient.

[0015] FIG. 2 depicts a schematic flow diagram of a method 200 of OTFS-based radar sensing, according to various embodiments of the present invention. The method 200 comprises

performing (at 206) an OTFS demodulation based on a time domain signal or a Delayed-Time (DT) domain signal received and reflected from one or more objects (e.g., sensing target(s)) from a time domain signal or a DT domain signal transmitted. In this regard, the time domain signal or the DT domain signal transmitted is generated from an OTFS modulation based on a first Delay-Doppler (DD) domain signal (e.g., comprising information symbols). The method 200 further comprises: determining (at 208) a two-dimensional (2D) range-Doppler map (may also be referred to as range-Doppler matrix) based on a first Time-Frequency (TF) domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and performing (at 210) radar sensing (e.g., determining range (i.e., distance) and/or speed of the object(s)) based on the 2D range-Doppler map.

[0016] In various embodiments, in the case of the OTFS modulation being configured to generate the time domain signal for transmission based on the first DD domain signal (i.e., OFDM-based OTFS modulation), the OTFS demodulation is performed based on the time domain signal received and reflected from the one or more objects from the time domain signal transmitted (i.e., OFDM-based OTFS demodulation). Furthermore, the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the time domain signal received.

[0017] In various embodiments, in the case of the OTFS modulation being configured to generate the DT domain signal for transmission based on the first DD domain signal (i.e., Zak-based OTFS modulation (i.e., based on Zak Transform)), the OTFS demodulation is performed based on the DT domain signal received and reflected from the one or more objects from the DT domain signal transmitted (i.e., Zak-based OTFS demodulation). Furthermore, the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the DT domain signal received.

[0018] The method 200 of OTFS-based radar sensing has been found to have significantly improved computational efficiency compared to conventional OTFS-based radar sensing methods, such as the two conventional OTFS-based radar sensing methods discussed in the background. In particular, various embodiments of the present invention advantageously found that, for OTFS-based radar sensing, the 2D range-Doppler map utilized to perform radar sensing can be efficiently and effectively determined based on a TF domain signal associated with the first DD domain signal and a TF domain signal associated with the time domain signal or the

DT domain signal received. Therefore, the method 200 of OTFS-based radar sensing according to various embodiments of the present invention enables OTFS-based radar sensing that is not only accurate but also computationally efficient. Accordingly, for example and as will be described later below according to various example embodiments of the present invention, an algorithm configured based on the method 200 OTFS-based radar sensing may be referred to as fast algorithm and a radar configured based on the method 200 or the algorithm may be referred to as a fast algorithm OTFS radar (FAOR). These advantages or technical effects, and/or other advantages or technical effects, will become more apparent to a person skilled in the art as the method 200 of OTFS-based radar sensing, as well as the corresponding system and radar for OTFS-based radar sensing, is described in more detail according to various embodiments and example embodiments of the present invention.

[0019] In various embodiments in the case of the OTFS modulation being configured to generate the time domain signal for transmission based on the first DD domain signal (i.e., OFDM-based OTFS modulation), the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal.

[0020] In various first embodiments, in the case of the OTFS-based radar sensing being monostatic radar sensing and the OTFS modulation being configured to generate the time domain signal for transmission (i.e., OFDM-based OTFS modulation), the method 200 further comprises performing the OTFS modulation comprising converting the first DD domain signal to a third TF domain and converting the third TF domain signal to the time domain signal for transmission by a transmitter antenna. Furthermore, the OTFS demodulation comprises converting the time domain signal received to a fourth TF domain signal and converting the fourth TF domain signal to a second DD domain signal associated with the time domain signal received (i.e., OFDM-based OTFS demodulation). In this regard, the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals.

[0021] In various first embodiments, the above-mentioned determining the 2D cyclic correlation based on the first and second DD domain signals comprises: determining a 2D fast Fourier transform (FFT) of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering) of the first DD domain signal or determining a conjugate of a 2D FFT of the first DD domain signal to obtain the first TF domain signal associated with the first DD domain

signal; determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the time domain signal received; and performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a fourth TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the fourth TF domain signal.

[0022] In various second embodiments, in the case of the OTFS-based radar sensing being monostatic radar sensing and the OTFS modulation being configured to generate the time domain signal for transmission (i.e., OFDM-based OTFS modulation), the method 200 further comprises performing the OTFS modulation comprising converting the first DD domain signal to the first TF domain signal and converting the first TF domain signal to the time domain signal for transmission by a transmitter antenna. Furthermore, the OTFS demodulation comprises converting the time domain signal received to the second TF domain signal (i.e., OFDM-based OTFS demodulation). Accordingly, the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the third TF domain signal.

[0023] In various third embodiments, in the case of the OTFS-based radar sensing being bistatic radar sensing and the OTFS modulation being configured to generate the time domain signal for transmission (i.e., OFDM-based OTFS modulation), the first DD domain signal comprises pilot data. In this regard, the OTFS demodulation (for the receiver side or chain) comprises converting the time domain signal received to a third TF domain signal and converting the third TF domain signal to a second DD domain signal associated with the time domain signal received (i.e., OFDM-based OTFS demodulation). Furthermore, the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the second DD domain signal and a third DD domain signal. In this regard, the third DD domain signal comprises the pilot data of the first DD domain signal. In this regard, the pilot data comprised in the third DD domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (pilot symbols)). Therefore, the pilot data is available to (e.g., stored at) the receiver side or chain.

[0024] In various third embodiments, the above-mentioned determining 2D cyclic correlation based on the second and third DD domain signals comprises: determining a 2D FFT

of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering) of the third DD domain signal or determining a conjugate of a 2D FFT of the third DD domain signal to obtain the first TF domain signal associated with the first DD domain signal; determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the time domain signal received; and performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a fourth TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the fourth TF domain signal. The OTFS modulation (for the transmitter side or chain) comprises converting the first DD domain signal (comprising the pilot data) to a fifth TF domain and converting the fifth TF domain signal to the time domain signal for transmission by a transmitter antenna.

[0025] In various fourth embodiments, in the case of the OTFS-based radar sensing being bistatic radar sensing and the OTFS modulation being configured to generate the time domain signal for transmission (i.e., OFDM-based OTFS modulation), the first DD domain signal comprises pilot data. The first TF domain signal associated with the first DD domain signal comprises pilot data (in the TF domain) corresponding to the pilot data of the first DD domain signal (the pilot data being available to (e.g., stored at) the receiver side). In this regard, the pilot data comprised in the first TF domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (or pilot symbols)). Furthermore, the OTFS demodulation (for the receiver side or chain) comprises converting the time domain signal received to the second TF domain signal. Accordingly, the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the third TF domain signal. The OTFS modulation (for the transmitter side or chain) comprises converting the first DD domain signal (comprising the pilot data) to a fourth TF domain and converting the fourth TF domain signal to the time domain signal for transmission by a transmitter antenna.

[0026] In various embodiments, in the case of the OTFS modulation being configured to generate the DT domain signal for transmission based on the first DD domain signal (i.e., Zak-based OTFS modulation), the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the

DT domain signal received and the first TF domain signal associated with the first DD domain signal.

[0027] In various fifth embodiments, in the case of the OTFS-based radar sensing being monostatic radar sensing and the OTFS modulation being configured to generate the DT domain signal for transmission (i.e., Zak-based OTFS modulation), the method 200 further comprises performing the OTFS modulation comprising converting the first DD domain signal to the DT domain signal for transmission. Furthermore, the OTFS demodulation comprises converting the DT domain signal received to a second DD domain signal associated with the DT domain signal received (i.e., Zak-based OTFS demodulation). In this regard, the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals.

[0028] In various fifth embodiments, the above-mentioned determining the 2D cyclic correlation based on the first and second DD domain signals comprises: determining a 2D fast Fourier transform (FFT) of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering) of the first DD domain signal or determining a conjugate of a 2D FFT of the first DD domain signal to obtain the first TF domain signal associated with the first DD domain signal; determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the DT domain signal received; and performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the third TF domain signal.

[0029] In various six embodiments, in the case of the OTFS-based radar sensing being monostatic radar sensing and the OTFS modulation being configured to generate the DT domain signal for transmission (i.e., Zak-based OTFS modulation), the method 200 further comprises performing the OTFS modulation comprising converting the first DD domain signal to the DT domain signal for transmission by a transmitter antenna. Furthermore, the OTFS demodulation comprises converting the DT domain signal received to the second TF domain signal (i.e., Zak-based OTFS demodulation). Accordingly, the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the third TF domain signal.

[0030] In various seventh embodiments, in the case of the OTFS-based radar sensing being bistatic radar sensing and the OTFS modulation being configured to generate the DT domain signal for transmission (i.e., Zak-based OTFS modulation), the first DD domain signal comprises pilot data. In this regard, the OTFS demodulation (for the receiver side or chain) comprises converting the DT domain signal received to a second DD domain signal associated with the DT domain signal received. Furthermore, the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the second DD domain signal and a third DD domain signal (for the receiver side or chain). In this regard, the third DD domain signal comprising the pilot data of the first DD domain signal. In this regard, the pilot data comprised in the third DD domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (pilot symbols)). Therefore, the pilot data is available to (e.g., stored at) the receiver side or chain.

[0031] In various seventh embodiments, the above-mentioned determining the 2D cyclic correlation based on the second and third DD domain signals comprises: determining a 2D FFT of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering) of the third DD domain signal or determining a conjugate of a 2D FFT of the third DD domain signal to obtain the first TF domain signal associated with the first DD domain signal; determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the DT domain signal received; and performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. The 2D range-Doppler map may then be obtained or determined based on the third TF domain signal. The OTFS modulation (for the transmitter side or chain) comprises converting the first DD domain signal (comprising the pilot data) to the DT domain signal for transmission by a transmitter antenna.

[0032] In various eighth embodiments, in the case of the OTFS-based radar sensing being bistatic radar sensing and the OTFS modulation being configured to generate the DT domain signal for transmission (i.e., Zak-based OTFS modulation), the first DD domain signal comprises pilot data. The OTFS demodulation (for the receiver side or chain) comprises converting the DT domain signal received to the second TF domain signal (i.e., Zak-based OTFS demodulation). Furthermore, the above-mentioned determining (at 208) the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal. In this regard, the first TF domain

signal is determined by converting a second DT domain signal to the first TF domain signal. In this regard, the second DT domain signal comprising pilot data (in the DT domain) corresponding to the pilot data of the first DD domain signal (the pilot data in the DT domain being available to (e.g., stored at) the receiver side or chain). In this regard, the pilot data comprised in the second DT domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (or pilot symbols)). The 2D range-Doppler map may then be obtained based on the third TF domain signal. The OTFS modulation (for the transmitter side or chain) comprises converting the first DD domain signal (comprising the pilot data) to the DT domain signal for transmission by a transmitter antenna.

[0033] FIG. 3 depicts a schematic block diagram of a system 300 for OTFS-based radar sensing, according to various embodiments of the present invention, corresponding to the above-mentioned method 200 of OTFS-based radar sensing as described hereinbefore with reference to FIG. 2 according to various embodiments of the present invention. The system 300 comprises: at least one memory 302; and at least one processor 304 communicatively coupled (e.g., connected) to the at least one memory 302 and configured to perform the method 200 of OTFS-based radar sensing according to various embodiments of the present invention. Accordingly, the at least one processor 304 is configured to: perform OTFS demodulation based on a time domain signal or a DT domain signal received and reflected from one or more objects from a time domain signal or a DT domain signal transmitted, the time domain signal or the DT domain signal transmitted being generated from an OTFS modulation based on a first DD domain signal; determine a 2D range-Doppler map based on a first TF domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and perform radar sensing based on the 2D range-Doppler map.

[0034] It will be appreciated by a person skilled in the art that the at least one processor 304 may be configured to perform various functions or operations through set(s) of instructions (e.g., software modules) executable by the at least one processor 304 to perform various functions or operations. Accordingly, as shown in FIG. 3, the system 300 may comprise: a OTFS demodulation module (or a OTFS demodulation circuit) 306 configured to perform OTFS demodulation based on a time domain signal or a DT domain signal received and reflected from one or more objects from a time domain signal or a DT domain signal transmitted, the time domain signal or the DT domain signal transmitted being generated from an OTFS modulation based on a first DD domain signal; a 2D range-Doppler map module (or

a 2D range-Doppler map circuit) 308 configured to determine a 2D range-Doppler map based on a first TF domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and a radar sensing module (or a radar sensing circuit) 310 configured to perform radar sensing based on the 2D range-Doppler map.

[0035] It will be appreciated by a person skilled in the art that the above-mentioned modules are not necessarily separate modules, and two or more modules may be realized by or implemented as one functional module (e.g., a circuit or a software program) as desired or as appropriate without deviating from the scope of the present invention. For example, two or more of the OTFS demodulation module 306, the 2D range-Doppler map module 308 and the radar sensing module 310 may be realized (e.g., compiled together) as one executable software program (e.g., embedded control firmware), which for example may be stored in the at least one memory 302 and executable by the at least one processor 304 to perform the corresponding functions or operations as described herein according to various embodiments of the present invention.

[0036] In various embodiments, the system 300 for OTFS-based radar sensing corresponds to the method 200 of OTFS-based radar sensing as described hereinbefore with reference to FIG. 2, therefore, various operations, functions or steps configured to be performed by the least one processor 304 may correspond to various operations, functions or steps of the method 200 described hereinbefore according to various embodiments, and thus need not be repeated with respect to the system 300 for clarity and conciseness. In other words, various embodiments described herein in context of methods (e.g., the method 200 of OTFS-based radar sensing) are analogously valid for the corresponding systems or devices (e.g., the system 300 for OTFS-based radar sensing), and vice versa. For example, in various embodiments, the at least one memory 302 may have stored therein the OTFS demodulation module 306, the 2D range-Doppler map module 308 and the radar sensing module 310, which respectively correspond to various operations, functions or steps of the method 200 of OTFS-based radar sensing as described hereinbefore according to various embodiments, which are executable by the at least one processor 304 to perform the corresponding operations, functions or steps as described herein.

[0037] A computing system, a controller, a microcontroller or any other system providing a processing capability may be provided according to various embodiments in the present invention. Such a system may be taken to include one or more processors and one or more

computer-readable storage mediums. For example, the system 300 for OTFS-based radar sensing described hereinbefore may include at least one processor 304 and at least one computer-readable storage medium (or memory) 302 which are for example used in various processing carried out therein as described herein. A memory or computer-readable storage medium used in various embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[0038] In various embodiments, a "circuit" may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a "circuit" may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A "circuit" may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code, e.g., Java. Any other kind of implementation of various functions or operations may also be understood as a "circuit" in accordance with various other embodiments. Similarly, a "module" may be a portion of a system according to various embodiments in the present invention and may encompass a "circuit" as above, or may be understood to be any kind of a logic-implementing entity therefrom.

[0039] Some portions of the present disclosure may be explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm may be, and generally, conceived to be a self-consistent sequence of steps leading to a desired result.

[0040] The present specification also discloses a system (e.g., which may also be embodied as one or more devices or apparatuses), such as the system 300, for performing various operations, functions or steps of various methods described herein. Such a system may be specially constructed for the required purposes or may comprise a general purpose computer system selectively activated or reconfigured by a computer program stored in the computer

system. In general, various algorithms that may be presented herein are not limited to being implemented or executed by any particular computer system. Alternatively, the construction of more specialized computer system to perform various operations, functions or steps of various methods described herein may be provided as desired or as appropriate without going beyond the scope of the present invention.

[0041] In addition, the present specification also at least implicitly discloses computer program(s) or software/functional module(s), in that it would be apparent to a person skilled in the art that various operations, functions or steps of various methods described herein may be put into effect by computer code. The computer program(s) is not intended to be limited to any particular programming language and implementation thereof, and it will be appreciated by a person skilled in the art that a variety of programming languages and coding thereof may be used to implement the computer program(s). Moreover, the computer program(s) is not intended to be limited to any particular control flow as there are a variety of programming languages which can use different control flows. It will be appreciated by a person skilled in the art that a computer program may be stored on any computer-readable storage medium (non-transitory computer-readable storage medium), such as but not limited to, a magnetic disk, an optical disk or a memory chip. For example, a computer program stored on a computer-readable storage medium may be loaded and executed on a computer system to implement various operations, functions or steps of various methods described herein according to various embodiments of the present invention.

[0042] Accordingly, in various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium), comprising instructions (e.g., the OTFS demodulation module 306, the 2D range-Doppler map module 308 and/or the radar sensing module 310) executable by one or more computer processors to perform a method 200 of OTFS-based radar sensing as described hereinbefore with reference to FIG. 2 according to various embodiments of the present invention. Accordingly, various computer programs or software modules described herein may be stored in a computer program product receivable by a system therein, such as the system 300 as shown in FIG. 3, for execution by at least one processor 304 of the system 300 to perform various operations, functions or steps of various methods described herein according to various embodiments of the present invention.

[0043] It will be appreciated by a person skilled in the art that various modules described herein (e.g., the OTFS demodulation module 306, the 2D range-Doppler map

module 308 and/or the radar sensing module 310) may be software module(s) realized by computer program(s) or set(s) of instructions executable by a computer processor to perform various functions or operations. Various modules described herein (e.g., the OTFS demodulation module 306, the 2D range-Doppler map module 308 and/or the radar sensing module 310), together with the at least one processor 304 and the at least one memory 302, may also be implemented as hardware module(s) being functional hardware unit(s) designed to perform various functions or operations. More particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC) or a Field Programmable Gate Array (FPGA). Numerous other possibilities exist. It will also be appreciated by a person skilled in the art that a combination of hardware and software modules may be implemented. Furthermore, various operations, functions or steps of various methods described herein may be performed in parallel rather than sequentially as desired or as appropriate (e.g., as long as it does not render the method(s) inoperable or unsatisfactory for its intended purpose).

[0044] In various embodiments, there is provided a radar (or a radar system) for OTFS-based radar sensing. The radar comprises one or more antennas; and the system 300 for OTFS-based radar sensing as described herein according to various embodiments of the present invention (e.g., according to various first embodiments, various second embodiments, various third embodiments, various fourth embodiments, various fifth embodiments, various sixth embodiments, various seventh embodiments or various eighth embodiments) communicatively coupled (e.g., connected) to the one or more antennas for performing radar sensing. For example, a radar transmitter may comprise a transmitter antenna and is configured to perform OTFS modulation as described herein according to various embodiments of the present invention. Similarly, a radar receiver may comprise a receiver antenna and is configured to perform OTFS demodulation as described herein according to various embodiments of the present invention. For example, in the case of monostatic radar, it will be appreciated by a person skilled in the art that one antenna may be provided or configured to function or serve to transmit and receive radio signals (i.e., function as transmitter and receiver (transceiver) antenna), although separate antennas for transmitting and receiving radio signals may be preferred for various technical purposes. For example, in the case of monostatic radar, the 2D range-Doppler map module 308 and the radar sensing module 310 may be communicatively

coupled (e.g., connected) to both the radar transmitter (comprising the transmitter antenna and the OTFS modulation module as described herein according to various embodiments of the present invention) and the radar receiver (comprising the receiver antenna and the OTFS demodulation module 306 as described herein according to various embodiments of the present invention). For example, in the case of bistatic radar, the 2D range-Doppler map module 308 and the radar sensing module 310 may be communicatively coupled (e.g., connected) to the radar receiver (comprising the receiver antenna and the OTFS demodulation module 306 as described herein according to various embodiments of the present invention). In this regard, in the case of bistatic radar, the radar transmitter and the radar receiver are located at different locations, and thus, the system 300 may be located at the receiver side and communicatively coupled (e.g., connected) to the radar receiver. Accordingly, there may be provided a system comprising the 2D range-Doppler map module 308 and the radar sensing module 310 communicatively coupled (e.g., connected) to the radar receiver (for bistatic radar) or to the radar transmitter and receiver (for monostatic radar) as described herein according to various embodiments of the present invention. For better understanding and illustration purpose, example architectures of various radars (e.g., monostatic radar and bistatic radar) configured to perform OTFS-based radar sensing will be described later below with reference to FIGs. 5A, 5B, 6A, 6B, 7A, 7B, 8A and 8B according to various example embodiments of the present invention.

[0045] It will be appreciated by a person skilled in the art that the terminology used herein is for the purpose of describing various embodiments only and is not intended to be limiting of the present invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0046] Any reference to an element or a feature herein using a designation such as "first", "second" and so forth does not limit the quantity or order of such elements or features, unless stated or the context requires otherwise. For example, such designations may be used herein as a convenient way of distinguishing between two or more elements or instances of an element. Thus, a reference to first and second elements does not necessarily mean that only two elements can be employed, or that the first element must precede the second element, unless stated or the

context requires otherwise. In addition, a phrase referring to "at least one of" a list of items refers to any single item therein or any combination of two or more items therein.

[0047] In order that the present invention may be readily understood and put into practical effect, various example embodiments of the present invention will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present invention may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art.

[0048] According to various example embodiments of the present invention, there is provided a method of OTFS-based radar sensing with improved computational efficiency, and an algorithm configured based on the method of OTFS-based radar sensing may herein be referred to as a fast algorithm and a radar configured based on the method or the algorithm may be referred to as a fast algorithm OTFS radar (FAOR). Accordingly, fast radar sensing with OTFS waveform is provided. In this regard, OTFS modulation technique has been shown to provide significant error performance advantages over orthogonal frequency division multiplexing (OFDM) over delay-Doppler channels.

[0049] FIG. 4 depicts a schematic block diagram showing a traditional architecture of OTFS modulation and demodulation, and more specifically, OFDM-based OTFS modulation and demodulation. At the transmitter side (OTFS modulation), the Delay-Doppler (DD) domain signal (DD domain data) $X[m,n]$ is converted to a Time-Frequency (TF) domain signal (TF domain data) $\tilde{X}[k,l]$ through the inverse symplectic fast Fourier transform (ISFFT). The TF domain signal $\tilde{X}[k,l]$ is then converted to a time domain signal $s(t)$ using the Heisenberg Transform. The time domain signal $s(t)$ is then transmitted from the transmitter antenna. At the receiver side (OTFS demodulation), the received time domain signal $s(t)$ by a receiver antenna is converted to a TF domain signal (TF domain data) $\tilde{Y}[k,l]$ using the Wigner transform. The TF domain signal $\tilde{Y}[k,l]$ is then converted to a DD domain signal (DD domain data) $Y[m,n]$ using the symplectic fast Fourier transform (SFFT).

[0050] The OTFS architecture shown in FIG. 4 may be simplified by combining the column FFT (fast Fourier transform) in the ISFFT and the IFFT (inverse fast Fourier transform) in the Heisenberg Transform. The simplified OTFS architecture involves the Zak Transform and thus may herein be referred to as Zak-based OTFS. In the simplified OTFS architecture, at the

transmitter side (OTFS modulation), the DD domain signal (DD domain data) $X(m,n)$ is converted to a DT domain signal (DT domain data) X_{zak} through the row IFFT operation. The DT domain signal X_{zak} is then transmitted from the transmitter antenna. At the receiver side (OTFS demodulation), the received DT domain signal (DT domain data) Y_{zak} is converted to a DD domain signal (DD domain data) $Y(m,n)$ through the row FFT operation.

[0051] In OTFS signal model, data (information symbols) is placed in DD domain (N sub-blocks of length M). For the T-length rectangular pulses (T is the length of a sub-block), the received DD domain signal that passed through the channel can be approximated as:

$$Y(m,n) \approx \sum_{p=1}^{P} h_p e^{j2\pi\left(\frac{m-l_p}{M}\right)\frac{k_p}{N}} a_p(m,n) X\left(< m-l_p >_M, < n-k_p >_N\right) + \eta(m,n)$$

(Equation 2)

where $X(m,n)$ denotes the DD domain transmitted signal samples, l_p denotes the normalized range, $l_p = \tau_p/T_s$, $T_s = 1/(M\Delta f)$, and k_p denotes the normalized Doppler frequency $k_p = Nf_pT = Nf_p/\Delta f$; $0 \le l_p \le M-1, 0 \le k_p \le N-1$, and

$$a_p(m,n) = \begin{cases} 1, l_p \le m \le M-1 \\ \frac{N-1}{N} e^{-j2\pi\left(\frac{n-k_p}{N}\right)}, 0 \le m \le l_p - 1 \end{cases}$$

(Equation 3)

[0052] OTFS radar sensing may determine the number of reflectors P, range l_p, and/or speed k_p, for given DD domain signals $Y(m,n)$ and $X(m,n)$. Based on the received signal expression (according to Equation 2), the maximum allowed round trip delay τ_p is M sample period, and the maximum allowed Doppler frequency v_p is $\Delta f = \frac{1}{T}$, where Δf is the subcarrier spacing and T_s is the sample period, T is the duration of one sub-block. The M_{cp} is the length of the cyclic prefix in OFDM and B is the bandwidth.

[0053] A motivation of using OTFS radar instead of OFDM radar is to meet the demands of various Integrated Communications and Sensing (ICAS) scenarios and applications, such as autonomous vehicles/vessels, robot and smart drones, remote control and teleoperation, XR (extended reality) and immersive media, health care and home security, disaster relief, digital twin and so on. Although OFDM may be able to perform robust radar detection with low complexity, it has several drawbacks that limits its application in practice. The high peak-average power ratio problem leads to low power efficiency. In high mobility environments, the Doppler effects affect the orthogonality between subcarriers. Moreover, the high mobility

communication also causes unexpected variations of channel response, which increase the burden of OFDM channel estimation.

[0054] In recent study, OTFS radar is considered as a promising alternative to OFDM radar. It is more reliable in high mobility multipath environments. From radar sensing perspective, it shares the inherent advantages of the multicarrier modulation of OFDM. Table 1 below shows that a longer radar sensing range and/or faster target tracking rate can be achieved by OTFS radar as OTFS radar requires less cyclic prefix during the transmission. Furthermore, OTFS radar can be used for larger Doppler frequency estimation in high mobility environments.

Table 1 - Comparison between OTFS radar and OFDM radar

	Maximum range	**Range resolution**	**Maximum speed**	**Speed resolution**
OTFS radar	MT_s	$\frac{c}{2B}$	$\frac{c\Delta f}{4f_c}$	$\frac{c\Delta f}{4Nf_c}$
OFDM radar	$M_{cp}T_s$	$\frac{c}{2B}$	$\frac{c\Delta f}{4f_c}$	$\frac{c\Delta f}{4Nf_c}$

[0055] According to various example embodiments, after careful study of the input-output relationship of the OTFS system based on delay-Doppler channel model, an OTFS-based radar sensing method (or a FAOR for sensing with OTFS signal) is developed. In this regard, the OTFS-based radar sensing method is not only accurate but also computationally efficient (significantly enhanced computational efficiency).

[0056] In various example embodiments, the OTFS-based radar sensing method may determine a 2D cyclic correlation based on the transmitted signal and the received signal. For example, the OTFS-based radar sensing method may determine a 2D cyclic correlation of the DD domain received signal (i.e., the DD domain signal derived from a received signal after being reflected from object(s)/target(s)) and a conjugate of the reordered DD domain transmitted signal (i.e., the DD domain signal from which a signal for transmission is derived). In particular, various example embodiments provide a fast method (computationally efficient manner) of determining the 2D cyclic correlation, including determining the 2D range-Doppler map based on a TF domain signal associated with the DD domain transmitted signal and a TF domain signal associated with the time domain signal or the DT domain signal received, thus resulting in a fast implementation or algorithm (computationally efficient implementation or

algorithm) for OTFS-based radar sensing, which may be referred to as fast algorithm OTFS radar (FAOR) sensing. Advantageously, the OTFS-based radar sensing method may be applied to both monostatic radar sensing and bistatic radar sensing. For monostatic radar sensing, the entire DD domain transmitted signal may be used for determining the 2D cyclic correlation. For bistatic radar sensing, the pilot data (or pilot symbols) embedded in the DD domain transmitted signal may be utilized (i.e., the pilot data being prior knowledge at the receiver side) for determining the 2D cyclic correlation (e.g., pilot-based FAOR sensing whereby only a part of the DD domain transmitted signal (in particular, predefined pilot symbols) is known at the receiver). A 2D range-Doppler map may then be determined or formed from the 2D cyclic correlation, and radar sensing may then be performed based on the 2D range-Doppler map determined. Various methods or algorithms known in the art may be applied to perform radar sensing based on a 2D range-Doppler map, and thus, it is not necessary to describe them herein for clarity and conciseness. By way of an example and without limitation, constant false alarm (CFAR) algorithms may be directly applied for radar sensing using a 2D range-Doppler map. Compared to conventional OTFS-based radar sensing methods, the OTFS-based radar sensing method (e.g., the FAOR sensing) according to various example embodiments has significantly higher computational efficiency. For example, the computational complexity of the FAOR sensing according to various example embodiments of the present invention is $O(NM \log_2(MN))$, while the computational complexity of the conventional OTFS-based radar sensing methods (disclosed in the Raviteja and Zhang references) described in the background is $O((MN)^2)$. Accordingly, the FAOR sensing according to various example embodiments of the present invention may have the same order of computational complexity as OFDM radar sensing, while having a larger allowable/possible sensing range.

[0057] In various example embodiments, to further reduce the computational complexity of the OTFS-based radar sensing method (or the FAOR sensing), the intermediate signal information (e.g., in the TF domain or the DT domain) in the transmitter and receiver chains may be directly utilized to determine the 2D range-Doppler map for radar sensing.

[0058] Accordingly, the OTFS-based radar sensing method (or the FAOR sensing) according to various example embodiments of the present invention has a number of technical advantages. For example, the OTFS-based radar sensing method can be applied to not only monostatic radar sensing but also to bistatic radar sensing by utilizing pilot data (pilot symbols). The OTFS-based radar sensing method has a much lower computational complexity compared to state-of-the-art OTFS radar sensing technology. The OTFS-based radar sensing method is

robust to different modulation types. In various example embodiments, the OTFS-based radar sensing method is configured to leverage intermediate signal information in the transmitter and receiver chains directly for radar sensing for further computational complexity reduction under different OTFS schemes. Accordingly, the OTFS-based radar sensing method according to various example embodiments enables low complexity and reliable radar sensing with OTFS signal for both monostatic radar and bistatic radar, which for example is a promising technology for ICAS in 6G wireless communication technology. For example, to meet the increasing demand for various ICAS applications, it is advantageous to realize high performance and low complexity radar sensing with the OTFS waveform for both monostatic radar and bistatic radar.

[0059] Example methods of OTFS-based radar sensing will now be described according to various example embodiments of the present invention. Each example method comprises: performing an OTFS demodulation based on a time domain signal or a Delayed-Time (DT) domain signal received and reflected from one or more objects (e.g., sensing target(s)) from a time domain signal or a DT domain signal transmitted. In this regard, the time domain signal or the DT domain signal transmitted is generated from an OTFS modulation based on a first Delay-Doppler (DD) domain signal. Each example method further comprises: determining a 2D range-Doppler map based on a first Time-Frequency (TF) domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and performing radar sensing (e.g., determining distance/range and/or speed of the object(s)) based on the 2D range-Doppler map.

[0060] As described hereinbefore, OTFS modulation/demodulation may be OFDM-based OTFS modulation/demodulation or Zak-based OTFS modulation/demodulation.

[0061] Accordingly, in various example embodiments, in the case of the OTFS modulation being configured to generate the time domain signal for transmission based on the first DD domain signal (i.e., OFDM-based OTFS modulation), the OTFS demodulation is performed based on the time domain signal received and reflected from the one or more objects from the time domain signal transmitted (i.e., OFDM-based OTFS demodulation). In this regard, the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the time domain signal received. In various example embodiments, in the case of the OTFS modulation being configured to generate the DT domain signal for transmission based on the first DD domain signal (i.e., Zak-based OTFS modulation), the OTFS demodulation is performed based on the DT domain signal received and reflected from the one or more objects from the DT domain

signal transmitted (i.e., Zak-based OTFS demodulation). In this regard, the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the DT domain signal received.

[0062] Example methods of OTFS-based radar sensing in the case of OFDM-based OTFS modulation/demodulation will now be described according to various example embodiments of the present invention. In various example embodiments, in the case of OFDM-based OTFS modulation/demodulation, the above-mentioned determining the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal.

[0063] FIG. 5A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 500 of OTFS-based radar sensing in the case of the OTFS-based monostatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various first example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various first embodiments of the present invention). A monostatic radar comprises a single set of transmitter, receiver and antennas, whereby the transmitter and receiver are co-located. Accordingly, FIG. 5A illustrates FAOR sensing of a monostatic radar with OFDM-based OTFS.

[0064] The method 500 comprises: performing (for the receiver side or chain) an OFDM-based OTFS demodulation based on a time domain signal received at a receiver antenna and reflected from one or more objects from a time domain signal transmitted by a transmitter antenna. In this regard, the time domain signal is generated from an OFDM-based OTFS modulation (for the transmitter side or chain) based on a first DD domain signal $X(m,n)$. The method 500 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The method 500 further comprises performing (for the transmitter side or chain) the OFDM-based OTFS modulation comprising converting (e.g., based on ISFFT) the first DD domain signal $X(m,n)$ to a third TF domain signal $\tilde{X}(k,l)$ and converting (e.g., based on IFFT) the third TF domain signal $\tilde{X}(k,l)$ to the time domain signal for transmission (by the transmitter antenna). Furthermore, the OFDM-based OTFS demodulation comprises converting (e.g., based on FFT)

the time domain signal received (by a receiver antenna) to a fourth TF domain signal $\tilde{Y}(k,l)$ and converting (e.g., based on SFFT) the fourth TF domain signal $\tilde{Y}(k,l)$ to a second DD domain signal $Y(m,n)$ associated with the time domain signal received. In this regard, the 2D range-Doppler map $Z_{RDM}(k,l)$ is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals $X(m,n)$, $Y(m,n)$.

[0065] In various first example embodiments, the above-mentioned determining the 2D cyclic correlation based on the first and second DD domain signals $X(m,n)$, $Y(m,n)$ comprises: determining a 2D FFT of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering $X(<-m>_M, <-n>_N)$, which may be denoted as $X(-m,-n)$ for simplicity) of the first DD domain signal $X(m,n)$ or determining a conjugate of a 2D FFT of the first DD domain signal $X(m,n)$ to obtain the first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$; determining a 2D FFT of the second DD domain signal $Y(m,n)$ to obtain the second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received; and performing the multiplication of the second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received and the first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a fourth TF domain signal $\hat{Z}(k,l)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the fourth TF domain signal $\hat{Z}(k,l)$, for example, by determining the 2D IFFT of the fourth TF domain signal $\hat{Z}(k,l)$.

[0066] Accordingly, in the case of monostatic radar according to various example embodiments of the present invention, the entire DD domain transmitted signal $X(m,n)$ (i.e., the first DD domain signal $X(m,n)$ from which the time domain signal for transmission is derived under the OTFS modulation) may be used for radar sensing purpose. In various first example embodiments, as described above, radar sensing may be performed by determining the 2D cyclic correlation of the DD domain received signal $Y(m,n)$ and the conjugate of the reordered DD domain transmitted signal $X^*(<-m>_M, <-n>_N)$. In this regard, $X^*(<-m>_M, <-n>_N)$ denotes the cyclic reverse reordering of $X^*(m,n)$, which may also herein be denoted by $X^*(-m,-n)$ for simplicity, where $<p>_Q$ means the remainder of p modulo Q for any integer numbers p and Q. The 2D range-Doppler map $Z_{RDM}(k,l)$ may be determined based on the computation of the 2D cyclic correlation, which may be expressed as:

$$Z_{RDM}(k,l) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} Y(m,n)X^*(<m-k>_M, <n-l>_N)$$
$$k = 0,1,\ldots,M-1; l = 0,1,\ldots,N-1.$$

(Equation 4)

[0067] Radar sensing (e.g., range (i.e., distance) and speed detection of targets) may then be performed based on the 2D range-Doppler map $Z_{RDM}(k,l)$ determined.

[0068] As mentioned above, various example embodiments provide a fast method (computationally efficient manner) of determining the 2D cyclic correlation, thus resulting in a fast implementation or algorithm (computationally efficient implementation or algorithm (reduced complexity)) which may be implemented with 2D FFT. According to various first example embodiments, a fast implementation for FAOR in monostatic radar sensing may include:

- compute the 2D FFT of the conjugate of $X(-m,-n)$ (cyclic reverse reordering of $X(m,n)$) or compute the conjugate of the 2D FFT of $X(m,n)$ (the first DD domain signal) to obtain $\hat{X}^*(k,l)$ (the first TF domain signal);
- compute the 2D FFT of $Y(m,n)$ (the second DD domain signal) to obtain $\hat{Y}(k,l)$ (the second TF domain signal);
- compute $\hat{Z}(k,l) = \hat{Y}(k,l)\hat{X}^*(k,l)$, ($\hat{Z}(k,l)$ corresponds to the fourth TF domain signal); and
- compute the 2D IFFT of the $\hat{Z}(k,l)$ to obtain the 2D range-Doppler map $Z_{RDM}(k,l)$.

[0069] FIG. 5B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 550 of OTFS-based radar sensing in the case of OTFS-based monostatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various second example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various second embodiments of the present invention). For example, in ICAS, the communication function and radar sensing function are integrated in the same device. Therefore, the same device can be used for communication and sensing at the same time. In this regard, signal information in the communication chain can be used for sensing and the sensing information can help the channel estimation and resource optimization for communication. For OTFS system, various example embodiments found that intermediate signal information in the OTFS transmitter and receiver chains can be directly used in the method 550 of OTFS-based radar sensing to further reduce computational complexity. Accordingly, the method 550 of OTFS-based radar sensing may be referred to as a simplified OTFS-based radar sensing for monostatic radar sensing and for OFDM-based OTFS, and thus may be referred to as a simplified FAOR sensing for monostatic radar sensing and for OFDM-based OTFS.

[0070] The method 550 comprises: performing (for the receiver side or chain) an OTFS demodulation based on a time domain signal received and reflected from one or more objects from a time domain signal transmitted by a transmitter antenna. In this regard, the time domain signal is generated from an OFDM-based OTFS modulation (for the transmitter side or chain) based on a first DD domain signal $X(m,n)$. The method 500 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\tilde{X}(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\tilde{Y}(k,l)$ associated with the time domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The method 550 further comprises performing (for the transmitter side or chain) the OFDM-based OTFS modulation comprising converting (e.g., based on ISFFT) the first DD domain signal $X(m,n)$ to the first TF domain signal $\tilde{X}(k,l)$ and converting (e.g., based on IFFT) the first TF domain signal $\tilde{X}(k,l)$ to the time domain signal for transmission by the transmitter antenna. Furthermore, the OFDM-based OTFS demodulation comprises converting (e.g., based on FFT) the time domain signal received to the second TF domain signal $\tilde{Y}(k,l)$. Accordingly, the above-mentioned determining the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal $\tilde{Y}(k,l)$ associated with the time domain signal received and the first TF domain signal $\tilde{X}(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a third TF domain signal $\tilde{Z}(k,l)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the third TF domain signal $\tilde{Z}(k,l)$, for example, by determining the 2D IFFT of the third TF domain signal $\tilde{Z}(k,l)$.

[0071] Accordingly, in the case of the OTFS-based monostatic radar sensing and OFDM-based OTFS modulation according to various second example embodiments, the example method 550 of OTFS-based radar sensing may be simplified to further reduce computational complexity. In particular, various second example embodiments found that intermediate signal information (the first and second TF domain signals $\tilde{X}(k,l)$, $\tilde{Y}(k,l)$ in various second example embodiments) in the transmitter and receiver chains are directly used to perform radar sensing. In this regard, instead of performing 2D FFT of the DD domain transmitted signal $X(m,n)$ and the DD domain received signal $Y(m,n)$ as described according to various first example embodiments, the TF domain transmitted signal (the first TF domain signal) $\tilde{X}(k,l)$ and the TF domain received signal (the second TF domain signal) $\tilde{Y}(k,l)$ are directly used for performing radar sensing, whereby the first and second TF domain signals $\tilde{X}(k,l)$, $\tilde{Y}(k,l)$ can be directly obtained from the transmitter and receiver chains, respectively. Therefore, the method 550 of OTFS-based radar sensing advantageously further reduces computational complexity.

Accordingly, to obtain the 2D range-Doppler map $Z_{RDM}(k,l)$ according to various second example embodiments of the present invention, the method 550 may include:

- compute the multiplication of the TF domain transmitted signal (the first TF domain signal) $\tilde{X}(k,l)$ and the TF domain received signal (the second TF domain signal) $\tilde{Y}(k,l)$ to obtain TF domain signal $\tilde{Z}(k,l)$ (the third TF domain signal), i.e., $\tilde{Z}(k,l) = \tilde{Y}(k,l)\tilde{X}(k,l)$; and
- compute the 2D IFFT of the TF domain signal $\tilde{Z}(k,l)$ to obtain the 2D Range-Doppler map $Z_{RDM}(k,l)$.

[0072] FIG. 6A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 600 of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various third example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various third embodiments of the present invention). For a bistatic radar, the transmitter and the receiver are at different locations. Therefore, information symbols of the DD domain transmitted signal is not available/accessible at the receiver side. Accordingly, FIG. 6A illustrates FAOR sensing of a bistatic radar with OFDM-based OTFS. To realize the dual functionalities of ICAS (i.e., communication and sensing functions), the information symbols of the DD domain transmitted signal cannot be predefined for radar sensing since the DD domain transmitted signal must be capable of carrying information symbols that are not predefined to enable the communication function. To address this issue and enable the method of OTFS-based radar sensing for bistatic radar sensing, various example embodiments apply pilot symbols (pilot data). In particular, in the DD domain transmitted signal, pilot symbols are added which is known as prior knowledge at the receiver side (i.e., predefined pilot symbols). In this regard, various example embodiments found that the method 600 of OTFS-based radar sensing is able to use pilot symbols for radar sensing without causing much interference to the communication function.

[0073] In the same manner as the method 500 of OTFS-based radar sensing described above according to various first example embodiments for the case of monostatic radar sensing, the method 600 of OTFS-based radar sensing according to various third example embodiments of the present invention for the case of bistatic radar sensing also determines the 2D cyclic correlation of the DD domain received signal (the second DD domain signal) $Y(m,n)$ with the conjugate of the reordered DD domain transmitted signal $X^*(-m,-n)$ of the DD domain transmitted signal (the first DD domain signal) $X(m,n)$. The 2D range-Doppler map

$Z_{RDM}(k,l)$ may be determined or generated based on the computation of the 2D cyclic correlation. However, instead of using the entire DD domain transmitted signal $X(m,n)$, only part of the transmitted signal is utilized, namely, the pilot data (pilot symbols) $X_1(m,n)$ added to the DD domain transmitted signal $X(m,n)$.

[0074] Accordingly, in various third example embodiments, the method 600 comprises: performing (for the receiver side or chain) an OFDM-based OTFS demodulation based on a time domain signal received and reflected from one or more objects from a time domain signal transmitted. In this regard, the time domain signal is generated from an OFDM-based OTFS modulation (for the transmitter side or chain) based on a first DD domain signal $X(m,n)$ comprising pilot data (pilot symbols) $X_1(m,n)$ added thereto. The method 600 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The OTFS demodulation comprises converting (e.g., based on IFFT) the time domain signal received to a third TF domain signal $\tilde{Y}(k,l)$ and converting (e.g., based on SFFT) the third TF domain signal $\tilde{Y}(k,l)$ to a second DD domain signal $Y(m,n)$ associated with the time domain signal received. In this regard, the 2D range-Doppler map $Z_{RDM}(k,l)$ is determined based on determining a 2D cyclic correlation based on the second DD domain signals $Y(m,n)$ and a third DD domain signal $X_1(m,n)$. In this regard, the third DD domain signal $X_1(m,n)$ comprises the pilot data $X_1(m,n)$ of the first DD domain signal $X(m,n)$. In this regard, the pilot data comprised in the third DD domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (pilot symbols)). Therefore, the pilot data is available to (e.g., stored at) the receiver side or chain.

[0075] In various third example embodiments, the above-mentioned determining 2D cyclic correlation based on the second and third DD domain signals $Y(m,n)$, $X_1(m,n)$ comprises: determining a 2D FFT of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering $X_1(-m,-n)$) of the third DD domain signal $X_1(m,n)$ or determining a conjugate of a 2D FFT of the third DD domain signal $X_1(m,n)$ to obtain the first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$; determining a 2D FFT of the second DD domain signal $Y(m,n)$ to obtain the second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received; and performing the multiplication of the second TF domain signal $\hat{Y}(k,l)$ associated with the time domain signal received and the first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a fourth TF

domain signal $\hat{Z}(k,l)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be determined based on the fourth TF domain signal $\hat{Z}(k,l)$, for example, by determining the 2D IFFT of the fourth TF domain signal $\hat{Z}(k,l)$. The OTFS modulation (for the transmitter side or chain) comprises converting (e.g., based on ISFFT) the first DD domain signal $X(m,n)$ (comprising the pilot data $X_1(m,n)$) to a fifth TF domain $\tilde{X}(k,l)$ (comprising the pilot data $\tilde{X}_1(k,l)$) and converting (e.g., based on IFFT) the fifth TF domain signal $\tilde{X}(k,l)$ to the time domain signal for transmission by the transmitter antenna.

[0076] In various third example embodiments, the DD domain signal (the third DD domain signal) $X_1(m,n)$ may define as $X_1(m,n) = s_p(m,n)$, if (m,n) is the pilot grid and $s_p(m,n)$ is the pilot symbols, otherwise, $X_1(m,n) = 0$. In this regard, the 2D range-Doppler map $Z_{RDM}(k,l)$ may be determined based on the computation of the 2D cyclic correlation, which may be expressed as:

$$Z_{RDM}(k,l) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} Y(m,n)\hat{X}_1^*(< m-k >_M, < n-l >_N)$$
$$k = 0,1,\dots,M-1; l = 0,1,\dots,N-1.$$

(Equation 5)

[0077] Radar sensing (e.g., range and speed detection of targets) may then be performed based on the 2D range-Doppler map $Z_{RDM}(k,l)$ determined.

[0078] In the same or similar manner as described above according to various first example embodiments, various third example embodiments provide a fast method (computationally efficient manner) of determining the 2D cyclic correlation, thus resulting in a fast implementation or algorithm (computationally efficient implementation or algorithm (reduced complexity)) which may be implemented with 2D FFT. According to various third example embodiments, a fast implementation for FAOR in bistatic radar sensing may include:

- compute the 2D FFT of the conjugate of $X_1(-m,-n)$ or compute the conjugate of the 2D FFT of $X_1(m,n)$ (the third DD domain signal) to obtain $\hat{X}_1^*(k,l)$ (the first TF domain signal);
- compute the 2D FFT of $Y(m,n)$ (the second DD domain signal) to obtain $\hat{Y}(k,l)$ (the second TF domain signal);
- compute $\hat{Z}(k,l) = \hat{Y}(k,l)\hat{X}_1^*(k,l)$, ($\hat{Z}(k,l)$ corresponds to the fourth TF domain signal); and
- compute the 2D IFFT of the $\hat{Z}(k,l)$ to obtain the 2D range-Doppler map $Z_{RDM}(k,l)$.

[0079] FIG. 6B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 650 of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and OFDM-based OTFS modulation/demodulation, according to various fourth example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various fourth embodiments of the present invention). In particular, similar to the method 550 of OTFS-based radar sensing being a simplification of the method 500 of OTFS-based radar sensing for further reducing computational complexity, the method 650 of OTFS-based radar sensing is a simplification of the method 600 of OTFS-based radar sensing in the same or similar manner also for further reducing computational complexity. Accordingly, the method 650 of OTFS-based radar sensing may be referred to as a simplified OTFS-based radar sensing for bistatic radar sensing and for OFDM-based OTFS, and thus may be referred to as a simplified FAOR sensing for bistatic radar sensing and for OFDM-based OTFS.

[0080] According, in various fourth example embodiments, the method 650 comprises: performing (for the receiver side or chain) an OFDM-based OTFS demodulation based on a time domain signal received and reflected from one or more objects from a time domain signal transmitted. In this regard, the time domain signal is generated from an OFDM-based OTFS modulation (for the transmitter side or chain) based on a first DD domain signal $X(m,n)$ comprising pilot data (pilot symbols) $X_1(m,n)$ added thereto. In this regard, the first TF domain signal $\tilde{X}_1(k,l)$ associated with the first DD domain signal $X(m,n)$ comprises pilot data (in the TF domain) corresponding to the pilot data $\tilde{X}_1(k,l)$ of the first DD domain signal $X(m,n)$ (the pilot data $\tilde{X}_1(k,l)$ being available to (e.g., stored at) the receiver side or chain). In this regard, the pilot data comprised in the first TF domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (or pilot symbols)). The method 650 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\tilde{X}_1(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\tilde{Y}(k,l)$ associated with the time domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The OTFS demodulation comprises converting (e.g., based on IFFT) the time domain signal received to the second TF domain signal $\tilde{Y}(k,l)$. Accordingly, the above-mentioned determining the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal $\tilde{Y}(k,l)$ associated with the time domain signal received and the first TF domain signal $\tilde{X}_1(k,l)$ (comprising the pilot data $\tilde{X}_1(k,l)$ in the TF domain) associated with the first DD domain signal to obtain a third TF domain signal $\tilde{Z}(k,l)$. The 2D range-

Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the third TF domain signal $\tilde{Z}(k,l)$, for example, by determining the 2D IFFT of the third TF domain signal $\tilde{Z}(k,l)$. The OFDM-based OTFS modulation comprises converting (e.g., based on ISFFT) the first DD domain signal $X(m,n)$, comprising the pilot data $X_1(m,n)$, to a fourth TF domain $\tilde{X}(k,l)$ and converting (e.g., based on IFFT) the fourth TF domain signal $\tilde{X}$ to the time domain signal for transmission by a transmitter antenna.

[0081] As described hereinbefore, the OFDM-based OTFS architecture may be simplified by combining the column FFT (fast Fourier transform) in the ISFFT and the IFFT (inverse fast Fourier transform) in the Heisenberg Transform. The simplified OTFS architecture involves the Zak Transform and thus is also known as Zak-based OTFS. In the simplified OTFS architecture, at the transmitter side (Zak-based OTFS modulation), the DD domain signal (DD domain data) $X(m,n)$ is converted to a DT domain signal (DT domain data) X_{zak} through the row IFFT operation. The DT domain signal X_{zak} is then transmitted from the transmitter antenna. At the receiver side (OTFS demodulation), the received DT domain signal (DT domain data) Y_{zak} is converted to a DD domain signal (DD domain data) $Y(m,n)$ through the row FFT operation.

[0082] Example methods of OTFS-based radar sensing in the case of Zak-based OTFS modulation/demodulation will now be described according to various example embodiments of the present invention. In various example embodiments, in the case of the Zak-based OTFS modulation/demodulation, the above-mentioned determining the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal.

[0083] FIG. 7A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 700 of OTFS-based radar sensing in the case of OTFS-based monostatic radar sensing and Zak-based OTFS modulation/demodulation, according to various fifth example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various fifth embodiments of the present invention). Accordingly, FIG. 7A illustrates FAOR sensing of a monostatic radar with Zak-based OTFS. The method 700 of OTFS-based radar sensing is the same as or similar to the method 500 of OTFS-based radar sensing described hereinbefore according to various first example embodiments except that the method 700 applies Zak-based OTFS instead of OFDM-based OTFS.

[0084] The method 700 comprises: performing (for the receiver side or chain) an OTFS demodulation (Zak-based OTFS demodulation) based on a DT domain signal Y_{Zak} received by a receiver and reflected from one or more objects from a DT domain signal X_{Zak} transmitted by a transmitter antenna. In this regard, the DT domain signal X_{Zak} is generated (for the transmitter side or chain) from a Zak-based OTFS modulation based on a first DD domain signal $X(m,n)$. The method 700 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The method 700 further comprises performing (for the transmitter side or chain) the Zak-based OTFS modulation comprising converting (e.g., based on row IFFT) the first DD domain signal $X(m,n)$ to the DT domain signal X_{Zak} for transmission by the transmitter antenna. Furthermore, the Zak-based OTFS demodulation comprises converting (based on row FFT) the DT domain signal Y_{Zak} received to a second DD domain signal $Y(m,n)$ associated with the DT domain signal received. In this regard, the 2D range-Doppler map $Z_{RDM}(k,l)$ is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals $X(m,n)$, $Y(m,n)$.

[0085] In various fifth example embodiments, the above-mentioned determining the 2D cyclic correlation based on the first and second DD domain signals $X(m,n)$, $Y(m,n)$ comprises: determining a 2D FFT of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering $X(-m,-n)$) of the first DD domain signal $X(m,n)$ or determining a conjugate of a 2D FFT of the first DD domain signal to obtain the first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$; determining a 2D FFT of the second DD domain signal $Y(m,n)$ to obtain the second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal received; and performing the multiplication of the second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal Y_{Zak} received and the first TF domain signal $\hat{X}^*(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a third TF domain signal $\hat{Z}(k,l)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the third TF domain signal $\hat{Z}(k,l)$, for example, by determining the 2D IFFT of the third TF domain signal $\hat{Z}(k,l)$. Accordingly, the method 700 of OTFS-based radar sensing is simplified using Zak-based OTFS to further reduce computational complexity.

[0086] FIG. 7B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 750 of OTFS-based radar sensing in the case

of OTFS-based monostatic radar sensing and Zak-based OTFS modulation/demodulation, according to various sixth example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various sixth embodiments of the present invention). The method 750 of OTFS-based radar sensing is the same as or similar to the method 550 of OTFS-based radar sensing described hereinbefore according to various second example embodiments except that the method 750 applies Zak-based OTFS instead of OFDM-based OTFS. Accordingly, the method 750 of OTFS-based radar sensing may be referred to as a simplified OTFS-based radar sensing for monostatic radar sensing and for Zak-based OTFS, and thus may be referred to as a simplified FAOR sensing for monostatic radar sensing and for Zak-based OTFS.

[0087] The method 750 comprises: performing (for the receiver side or chain) a Zak-based OTFS demodulation based on a DT domain signal received Y_{Zak} and reflected from one or more objects from a DT domain signal X_{Zak} transmitted. In this regard, the DT domain signal X_{Zak} is generated (for the transmitter side or chain) from a Zak-based OTFS modulation based on a first DD domain signal $X(m,n)$. The method 500 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\tilde{X}_{Zak}(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\tilde{Y}_{Zak}(k,l)$ associated with the DT domain signal received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The method 750 further comprises performing (for the transmitter side or chain) the Zak-based OTFS modulation comprising converting (based on row IFFT) the first DD domain signal $X(m,n)$ to the DT domain signal X_{Zak} for transmission by the transmitter antenna. Furthermore, the Zak-based OTFS demodulation comprises converting (based on column FFT) the DT domain signal Y_{Zak} received to the second TF domain signal $\tilde{Y}_{Zak}(k,l)$. Accordingly, the above-mentioned determining the 2D range-Doppler map $Z_{RDM}(k,l)$ comprises performing the multiplication of the second TF domain signal $\tilde{Y}_{Zak}(k,l)$ associated with the DT domain signal received and the first TF domain signal $\tilde{X}_{Zak}(k,l)$ associated with the first DD domain signal to obtain a third TF domain signal. The first TF domain signal $\tilde{X}_{Zak}(k,l)$ is determined based the DT domain signal X_{Zak}, for example, by converting the DT domain signal X_{Zak} to the first TF domain signal $\tilde{X}_{Zak}(k,l)$ based on column FFT. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the third TF domain signal $\tilde{Z}_{Zak}(k,l)$, for example, by determining the 2D IFFT of the third TF domain signal $\tilde{Z}_{Zak}(k,l)$.

[0088] Accordingly, in the case of OTFS-based monostatic radar sensing and Zak-based OTFS modulation/demodulation according to various sixth example embodiments, the method

750 of OTFS-based radar sensing is simplified to further reduce computational complexity. In particular, the DT domain transmitted and received signals from the transmitter and receiver chains, respectively, in Zak-based OTFS are directly used in the method 750 to perform radar sensing. Instead of performing 2D FFT of the DD domain transmitted signal $X(m,n)$ and the DD domain received signal $Y(m,n)$ as described hereinbefore according to various fifth example embodiments, the TF domain transmitted signal (the first TF domain signal) $\tilde{X}_{Zak}(k,l)$ and the TF domain received signal (the second TF domain signal) $\tilde{Y}_{Zak}(k,l)$ derived from the DT domain signal X_{Zak} transmitted and the DT domain signal Y_{Zak} received, respectively, are used directly for performing radar sensing. Therefore, the method 750 of OTFS-based radar sensing advantageously further reduces computational complexity. Accordingly, to obtain the 2D range-Doppler map $Z_{RDM}(k,l)$ according to various sixth example embodiments of the present invention, the method 750 may include:

- Compute the FFT on the columns of both DT domain signals X_{zak} and Y_{zak} to transfer/convert them into the TF domain signals (the first and second TF domain signals), respectively, which may be expressed as $\tilde{Y}_{zak} = FFT_{\downarrow}[Y_{zak}]$ and $\tilde{X}_{zak} = FFT_{\downarrow}[X_{zak}]$;
- Compute the multiplication of the first and second TF domain signals $\tilde{Y}_{zak}$ and $\tilde{X}_{zak}$ to obtain the third domain signal, i.e., $\tilde{Z}_{zak}(k,l) = \tilde{Y}_{zak}(k,l)\tilde{X}_{zak}(k,l)$; and
- Compute the 2D IFFT of the $\tilde{Z}_{zak}(k,l)$ to obtain the 2D Range-Doppler map $Z_{RDM}(k,l)$.

[0089] FIG. 8A depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 800 of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and Zak-based OTFS modulation/demodulation, according to various seventh example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various seventh embodiments of the present invention). The method 800 of OTFS-based radar sensing is the same as or similar to the method 600 of OTFS-based radar sensing described hereinbefore according to various third example embodiments except that the method 800 is based on Zak-based OTFS instead of OFDM-based OTFS. Accordingly, FIG. 8A illustrates FAOR sensing of a bistatic radar in Zak-based OTFS. In the same or similar manner as the method 600 of OTFS-based radar sensing, the method 800 of OTFS-based radar sensing according to various example embodiments apply pilot symbols for bistatic radar sensing. In particular, in the DD domain transmitted signal, pilot symbols (or pilot data) are added which is known as prior knowledge at the receiver side (i.e., predefined pilot symbols).

[0090] In the same or similar manner as the method 600 of OTFS-based radar sensing described above according to various third example embodiments for the case of monostatic radar sensing, the method 800 of OTFS-based radar sensing according to various seventh example embodiments of the present invention for the case of bistatic radar sensing also determines the 2D cyclic correlation of the DD domain received signal (the second DD domain signal) $Y(m,n)$ with the conjugate of the reordered DD domain transmitted signal $X_1^*(-m,-n)$ of the DD domain transmitted signal (the first DD domain signal) $X(m,n)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may be determined or generated based on the computation of the 2D cyclic correlation. However, instead of using the entire DD domain transmitted signal $X(m,n)$, only part of the transmitted signal is utilized, namely, the pilot data (pilot symbols) $X_1(m,n)$ added to the DD domain transmitted signal $X(m,n)$.

[0091] According, in various seventh example embodiments, the method 800 comprises: performing (for the receiver side or chain) a Zak-based OTFS demodulation based on a DT domain signal Y_{Zak} received and reflected from one or more objects from a DT domain signal X_{Zak} transmitted. In this regard, the DT domain signal X_{Zak} transmitted is generated (for the transmitter side or chain) from a Zak-based OTFS modulation based on a first DD domain signal $X(m,n)$ comprising pilot data (pilot symbols) $X_1(m,n)$ added thereto. The method 800 further comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on a first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal Y_{Zak} received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The OTFS demodulation comprises converting (e.g., based on row FFT) the DT domain signal Y_{Zak} received to a second DD domain signal $Y(m,n)$ associated with the DT domain signal Y_{Zak} received. In this regard, the 2D range-Doppler map $Z_{RDM}(k,l)$ is determined based on determining a 2D cyclic correlation based on the second DD domain signals $Y(m,n)$ and a third DD domain signal $X_1(m,n)$. In this regard, the third DD domain signal $X_1(m,n)$ comprises the pilot data $X_1(m,n)$ of the first DD domain signal $X(m,n)$. In this regard, the pilot data $X_1(m,n)$ comprised in the third DD domain signal is prior knowledge at the receiver side (i.e., predefined pilot data (pilot symbols)). The OTFS modulation (for the transmitter side or chain) comprises converting (e.g., based on row IFFT) the first DD domain signal $X(m,n)$ (comprising the pilot data $X_1(m,n)$) to the DT domain signal X_{Zak} for transmission by the transmitter antenna.

[0092] In various seventh example embodiments, the above-mentioned determining 2D cyclic correlation based on the second and third DD domain signals $Y(m,n)$, $X_1(m,n)$

comprises: determining a 2D FFT of a conjugate of a reordered DD domain signal (e.g., cyclic reverse reordering $X_1(-m,-n)$) of the third DD domain signal $X_1(m,n)$ or determining a conjugate of a 2D FFT of the third DD domain signal to obtain the first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$; determining a 2D FFT of the second DD domain signal $Y(m,n)$ to obtain the second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal received; and performing the multiplication of the second TF domain signal $\hat{Y}(k,l)$ associated with the DT domain signal received and the first TF domain signal $\hat{X}_1^*(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a third TF domain signal $\hat{Z}(k,l)$. The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be determined based on the third TF domain signal $\hat{Z}(k,l)$, for example, by determining the 2D IFFT of the third TF domain signal $\hat{Z}(k,l)$.

[0093] FIG. 8B depicts a schematic block diagram illustrating an example architecture of a monostatic radar performing an example method 850 of OTFS-based radar sensing in the case of OTFS-based bistatic radar sensing and Zak-based OTFS modulation/demodulation, according to various eighth example embodiments of the present invention (e.g., corresponding to the method 200 of OTFS-based radar sensing as described hereinbefore according to various eighth embodiments of the present invention). The method 850 of OTFS-based radar sensing is the same as or similar to the method 650 of OTFS-based radar sensing described hereinbefore according to various fourth example embodiments except that the method 850 is based on Zak-based OTFS instead of OFDM-based OTFS. In particular, similar to the method 800 of OTFS-based radar sensing being a simplification of the method 600 of OTFS-based radar sensing for further reducing computational complexity, the method 850 of OTFS-based radar sensing is a simplification of the method 650 of OTFS-based radar sensing in the same or similar manner also for further reducing computational complexity. Accordingly, the method 850 of OTFS-based radar sensing may be referred to as a simplified OTFS-based radar sensing for bistatic radar sensing and for Zak-based OTFS, and thus may be referred to as a simplified FAOR sensing for bistatic radar sensing and for Zak-based OTFS.

[0094] According, in various eighth example embodiments, the method 850 comprises: performing (for the receiver side or chain) an OTFS demodulation based on a DT domain signal Y_{Zak} received and reflected from one or more objects from a DT domain signal X_{Zak} transmitted. In this regard, the DT domain signal X_{Zak} is generated (for the transmitter side or chain) from a Zak-based OTFS modulation based on a first DD domain signal $X(m,n)$ comprising pilot data (pilot symbols) $X_1(m,n)$ added thereto. The method 850 further

comprises: determining a 2D range-Doppler map $Z_{RDM}(k,l)$ based on the first TF domain signal $\tilde{X}_{1,zak}(k,l)$ associated with the first DD domain signal $X(m,n)$ and a second TF domain signal $\tilde{Y}(k,l)$ associated with the DT domain signal Y_{Zak} received; and performing radar sensing based on the 2D range-Doppler map $Z_{RDM}(k,l)$. The Zak-based OTFS demodulation comprises converting (e.g., based on column FFT) the DT domain signal Y_{Zak} received to the second TF domain signal $\tilde{Y}(k,l)$. The above-mentioned determining the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal $\tilde{Y}(k,l)$ associated with the DT domain signal received and the first TF domain signal $\tilde{X}_{1,zak}(k,l)$ associated with the first DD domain signal $X(m,n)$ to obtain a third TF domain signal $\tilde{Z}_{Zak}(k,l)$. In this regard, the first TF domain signal $\tilde{X}_{1,zak}(k,l)$ is determined by converting (e.g., based on column FFT) a second DT domain signal $X_{1,zak}$ to the first TF domain signal $\tilde{X}_{1,zak}(k,l)$ In this regard, the second DT domain signal $X_{1,zak}$ comprising pilot data (in the DT domain) corresponding to the pilot data of the first DD domain signal $X(m,n)$ (the pilot data being available to (e.g., stored at) the receiver side or chain). In this regard, the pilot data (in the DT domain) comprised in the second DT domain signal $X_{1,zak}$ is prior knowledge at the receiver side (i.e., predefined pilot data (or pilot symbols)). The 2D range-Doppler map $Z_{RDM}(k,l)$ may then be obtained based on the third TF domain signal $\tilde{Z}_{Zak}(k,l)$), for example, by determining the 2D IFFT of the third TF domain signal $\tilde{Z}_{Zak}(k,l)$. The OTFS modulation (for the transmitter side or chain) comprises converting the first DD domain signal $X(m,n)$ (comprising the pilot data $X_1(m,n)$) to the DT domain signal X_{Zak} for transmission by a transmitter antenna.

[0095] To demonstrate the computational efficiency of methods of OTFS-based radar sensing according to various example embodiments of the present invention, FAOR sensing with different modulation techniques, as well as different use cases (monostatic radar sensing and bistatic radar sensing) were tested in experiments conducted according to various example embodiments of the present invention. Various parameters associated with the experiments conducted are provided below:

- for the OTFS settings, the central frequency is set to 60 GHz;
- the number of subcarriers in frequency is 4096 (M) and the number of symbols in time is 100 (N);
- the frame size is 3.33 ms;
- the modulation technique used is 4-QAM constellation; and
- subcarrier spacing is 30 KHz and the bandwidth is 122.88 MHz.

[0096] In the experiments, three objects/targets were set with the following specification: Power [0, -10, -40] dB, Speed [0, 122] km/h, Range [0, 300] m.

[0097] First, the example method 700 of OTFS-based radar sensing (FOAR sensing) for monostatic radar sensing according to various fifth example embodiments was tested in a monostatic sensing scene. For monostatic radar, the transmitter and receiver are co-located. Accordingly, full knowledge of transmitted signal is available at the receiver, thus all information symbols can be utilized for radar sensing purpose. The FAOR sensing for monostatic radar sensing was tested in the monostatic radar scenario with 1,000 frames. The simulation results are plotted in FIG. 9, which is the range-Doppler map (RDM) at SNR -20dB. The plot shown in FIG. 10 is the estimation errors (average absolute error) of the FAOR sensing of the two strongest targets. 1000 tests were executed. Accordingly, the simulation results verify the effectiveness of the FAOR sensing method according to various example embodiments for accurate range and speed detection in low SNR.

[0098] In addition, the example method 600 of OTFS-based radar sensing (FOAR sensing) for bistatic radar sensing according to various third example embodiments was tested in bistatic sensing scene. A bistatic radar is constructed in the manner such that the transmitter and the receiver are at different locations. Therefore, the receiver cannot have full information/knowledge of the transmitted signal. To address this issue, the FAOR takes the advantages of the pilot symbols in the transmitted signal. Based on the prior knowledge of pilot symbols within the transmitted signal, the FAOR performs the radar sensing. The experiment setup for the bistatic radar scene is the same as the monostatic radar scene, including the three targets in the sensing task. Only 1/8 of the transmitted signals are used as pilot signals. The FAOR sensing for bistatic radar sensing was tested in bistatic radar condition with 1000 frames. The simulation results are plotted in FIG. 11, which is the range-Doppler map (RDM) at SNR -20dB. The plot shown in FIG. 12 is the estimation errors (average absolute error) of the FAOR sensing of the two strongest targets. 1000 tests were executed. Accordingly, the simulation results verify that FAOR sensing method according to various example embodiments works well with limited pilot signal for bistatic sensing.

[0099] In addition, the FAOR sensing according to various example embodiments was tested in experiments with different modulation techniques. In the experiments described above, 4-QAM constellation was applied. In the experiments with different modulation techniques, 256-QAM constellation was applied and the results are shown in FIGs. 13 and 14. In particular, FIG. 13 shows the estimation errors (average absolute error) of the FAOR sensing of targets

under bistatic radar condition, while FIG. 14 shows the error of the difference of the two targets. The performances are similar to that at 4-QAM constellation, which verifies that the FAOR method according to various example embodiments is robust to signal modulation schemes.

[00100] The FOAR sensing according to various example embodiments is compared with conventional methods, namely, (1) the matched filtering method for radar sensing with OTFS signal disclosed in the Raviteja reference, and (2) the method for radar sensing with OTFS signal disclosed in the Zhang reference.

[00101] The FAOR sensing according to various example embodiments was compared with the conventional method in Zhang reference. Their estimation errors, error of the difference of targets and their computational complexities were evaluated. FIG. 15 shows a plot of comparison on estimation errors of the two targets and FIG. 16 shows a plot of comparison on error of the difference of the two targets for two targets. The simulation results verify that the FAOR sensing according to various example embodiments achieves similar or better sensing performances compared to the radar sensing method disclosed in the Zhang reference (labeled as Zhang). Table 2 below shows a comparison on computational complexity. As can be seen, the FAOR gives a decent performance with a lower SNR. Besides, the FAOR has a much lower complexity compared to conventional methods in the Raviteja and Zhang references.

Table 2 - Comparison on Computational Complexity

Method	Complexity
FAOR	$O(NM\log_2(MN))$
the Raviteja reference (Matched Filter)	$O((MN)^2)$
the Zhang reference	$O((MN)^2)$

[00102] Accordingly, example methods of OTFS-based radar sensing have been described according to various example embodiments of the present invention, which may also be referred to as FAOR sensing.

[00103] In various example embodiments, the FAOR computes the 2D cyclic correlation of the received delay Doppler (DD) domain signal $Y(m,n)$ with the conjugate of the DD domain transmitted signal $X^*(-m,-n)$. The 2D range-Doppler map may then be formed after this 2D

cyclic correlation. In particular, in various example embodiments, the 2D cyclic correlation may be computed by a fast algorithm as follows:

i. For mono-static radar, the FAOR may compute the 2D FFT of transmitted signal $X(m,n)$, which is denoted as $\hat{X}(k,l)$. While for bi-static radar, define $X_1(m,n) = s_p(m,n)$, if (m,n) is the pilot grid and $s_p(m,n)$ is the pilot symbol, otherwise, $X_1(m,n) = 0$. Then, the FAOR may compute the 2D FFT of $X_1(m,n)$, which is denoted as $\hat{X}_1(k,l)$.

ii. Compute the 2D FFT of $Y(m,n)$, which is denoted as $\hat{Y}(k,l)$.

iii. For mono-static radar, the FAOR computes $\hat{Z}(k,l) = \hat{Y}(k,l)\hat{X}^*(k,l)$. For bi-static radar $\hat{Z}(k,l) = \hat{Y}(k,l)\,\hat{X}_1^*(k,l)$.

iv. Compute the 2D IFFT of the $\hat{Z}(k,l)$, which results in the 2D range-Doppler map.

[00104] For OFDM-based OTFS, the FAOR can be further simplified to reduce complexity as follows:

i. the FAOR utilizes intermediate OTFS communication information in the transmitter and receiver chains directly instead of performing 2D FFT of the DD domain transmitted signal $X(m,n)$ and the DD domain received signal $Y(m,n)$.For example, the TF domain transmitted signal $\tilde{X}(k,l)$ and the TF domain received signal $\tilde{Y}(k,l)$ are used directly for FAOR. In this regard, $\tilde{X}(k,l)$ and $\tilde{Y}(k,l)$ can be directly obtained from the transmitter and receiver chains, respectively. Thus, this approach further reduces complexity.

ii. Compute the multiplication of the TF domain transmitted signal and TF domain received signal: $\tilde{Z}(k,l) = \tilde{Y}(k,l)\tilde{X}(k,l)$. The same approach described above for handling with bistatic radar may be used by considering the pilot symbols.

iii. Compute the 2D FFT of the $\tilde{Z}(k,l)$ and generate the 2D range-Doppler map.

[00105] For Zak-based OTFS, the FAOR can be further simplified to reduce complexity as follows.

i. the FAOR utilizes the transmitted and received signals from the transmitter and receiver chains, respectively, for Zak-based OTFS. In Zak-based OTFS, the transmitted signal X_{zak} and Y_{zak} are in Delay-Time (DT) domain. The FAOR performs FFT on the columns of both X_{zak} and Y_{zak} to transfer them into the Time-Frequency (TF) domain, which can be represented as $\tilde{Y}_{zak} = FFT_{\downarrow}[Y_{zak}]$ and $\tilde{X}_{zal} = FFT_{\downarrow}[X_{zak}]$.

ii. Compute the multiplication $\tilde{Z}_{zak}(k,l) = \tilde{Y}_{zak}(k,l)\tilde{X}_{zak}(k,l)$. The same approach described above for handling with bistatic radar may be used by considering the pilot

symbols.

iii. Compute the 2D FFT of the $\tilde{Z}_{zak}(k,l)$, which is the 2D range-Doppler map.

[00106] Accordingly, the method of OTFS-based radar sensing according to various example embodiments of the present invention has a number of technical advantages, such as but not limited to:

- enables a low complexity radar sensing algorithm with the OTFS signal, for example, having a much lower complexity than conventional methods whereby the computational complexity is reduced to $O(NM\log_2(MN))$ from $O((MN)^2)$, while the sensing performance is not worse;
- can be used for both monostatic radar and bistatic radar. For bistatic radar, the FAOR uses the known pilot data at the receiver for radar sensing;
- robust to different modulation types; and
- has the same order of complexity with OFDM radar, while having larger allowable sensing range. For example, the max sensing range of FAOR is increased to MT_s from $M_{cp}T_s$, where M is the total block length and M_{cp} is the CP length, $M_{cp} \ll M$.

[00107] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method of orthogonal time frequency space (OTFS)-based radar sensing, comprising:

performing an OTFS demodulation based on a time domain signal or a Delayed-Time (DT) domain signal received and reflected from one or more objects from a time domain signal or a DT domain signal transmitted, the time domain signal or the DT domain signal transmitted being generated from an OTFS modulation based on a first Delay-Doppler (DD) domain signal;

determining a two-dimensional (2D) range-Doppler map based on a first Time-Frequency (TF) domain signal associated with the first DD domain signal and a second TF domain signal associated with the time domain signal or the DT domain signal received; and

performing radar sensing based on the 2D range-Doppler map.

2. The method according to claim 1, wherein

the OTFS demodulation is performed based on the time domain signal received and reflected from the one or more objects from the time domain signal transmitted, the time domain signal transmitted being generated from the OTFS modulation based on the first DD domain signal, and

the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the time domain signal received.

3. The method according to claim 2, wherein

said determining the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal.

4. The method according to claim 3, wherein

the OTFS-based radar sensing is monostatic radar sensing,

the method further comprises performing the OTFS modulation comprising converting the first DD domain signal to a third TF domain and converting the third TF domain signal to the time domain signal for transmission,

the OTFS demodulation comprises converting the time domain signal received to a fourth TF domain signal and converting the fourth TF domain signal to a second DD domain signal associated with the time domain signal received, and

the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals.

5. The method according to claim 4, wherein said determining the 2D cyclic correlation based on the first and second DD domain signals comprises:

determining a 2D fast Fourier transform (FFT) of a conjugate of a reordered DD domain signal of the first DD domain signal or determining a conjugate of a 2D FFT of the first DD domain signal to obtain the first TF domain signal associated with the first DD domain signal;

determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the time domain signal received; and

performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a fourth TF domain signal.

6. The method according to claim 3, wherein

the OTFS-based radar sensing is monostatic radar sensing,

the method further comprises performing the OTFS modulation comprising converting the first DD domain signal to the first TF domain signal and converting the first TF domain signal to the time domain signal for transmission,

the OTFS demodulation comprises converting the time domain signal received to the second TF domain signal, and

said determining the 2D range-Doppler map comprises:

performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal; and

determining the 2D range-Doppler map based on the third TF domain signal.

7. The method according to claim 3, wherein

the OTFS-based radar sensing is bistatic radar sensing,

the first DD domain signal comprises pilot data,

the OTFS demodulation comprises converting the time domain signal received to a third TF domain signal and converting the third TF domain signal to a second DD domain signal associated with the time domain signal received, and

the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the second DD domain signal and a third DD domain signal, the third DD domain signal comprising the pilot data of the first DD domain signal.

8. The method according to claim 7, wherein said determining the 2D cyclic correlation based on the second and third DD domain signals comprises:

determining a 2D FFT of a conjugate of a reordered DD domain signal of the third DD domain signal or determining a conjugate of a 2D FFT of the third DD domain signal to obtain the first TF domain signal associated with the first DD domain signal;

determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the time domain signal received; and

performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a fourth TF domain signal.

9. The method according to claim 3, wherein

the OTFS-based radar sensing is bistatic radar sensing,

the first DD domain signal comprises pilot data,

the first TF domain signal associated with the first DD domain signal comprises pilot data corresponding to the pilot data of the first DD domain signal,

the OTFS demodulation comprises converting the time domain signal received to the second TF domain signal, and

said determining the 2D range-Doppler map comprises:

performing the multiplication of the second TF domain signal associated with the time domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal; and

determining the 2D range-Doppler map based on the third TF domain signal.

10. The method according to claim 1, wherein

the OTFS demodulation is performed based on the DT domain signal received and reflected from the one or more objects from the DT domain signal transmitted, the DT domain signal transmitted being generated from the OTFS modulation based on the first DD domain signal, and

the 2D range-Doppler map is determined based on the first TF domain signal associated with the first DD domain signal and the second TF domain signal associated with the DT domain signal received.

11. The method according to claim 10, wherein

said determining the 2D range-Doppler map comprises performing a multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal.

12. The method according to claim 11, wherein

the OTFS-based radar sensing is monostatic radar sensing,

the method further comprises performing the OTFS modulation comprising converting the first DD domain signal to the DT domain signal for transmission,

the OTFS demodulation comprises converting the DT domain signal received to a second DD domain signal associated with the DT domain signal received, and

the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the first and second DD domain signals.

13. The method according to claim 12, wherein said determining the 2D cyclic correlation based on the first and second DD domain signals comprises:

determining a 2D fast Fourier transform (FFT) of a conjugate of a reordered DD domain signal of the first DD domain signal or determining a conjugate of a 2D FFT of the first DD domain signal to obtain the first TF domain signal associated with the first DD domain signal;

determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the DT domain signal received; and

performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal.

14. The method according to claim 11, wherein

the OTFS-based radar sensing is monostatic radar sensing,

the method further comprises performing the OTFS modulation comprising converting the first DD domain signal to the DT domain signal for transmission, and

the OTFS demodulation comprises converting the DT domain signal received to the second TF domain signal, and

said determining the 2D range-Doppler map comprises:

performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal; and

determining the 2D range-Doppler map based on the third TF domain signal.

15. The method according to claim 11, wherein

the OTFS-based radar sensing is bistatic radar sensing,

the first DD domain signal comprises pilot data,

the OTFS demodulation comprises converting the DT domain signal received to a second DD domain signal associated with the DT domain signal received, and

the 2D range-Doppler map is determined based on determining a 2D cyclic correlation based on the second DD domain signal and a third DD domain signal, the third DD domain signal comprising the pilot data of the first DD domain signal.

16. The method according to claim 15, wherein said determining the 2D cyclic correlation based on the second and third DD domain signals comprises:

determining a 2D FFT of a conjugate of a reordered DD domain signal of the third DD domain signal or determining a conjugate of a 2D FFT of the third DD domain signal to obtain the first TF domain signal associated with the first DD domain signal;

determining a 2D FFT of the second DD domain signal to obtain the second TF domain signal associated with the DT domain signal received; and

performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal.

17. The method according to claim 11, wherein

the OTFS-based radar sensing is bistatic radar sensing,

the first DD domain signal comprises pilot data,

the OTFS demodulation comprises converting the DT domain signal received to the second TF domain signal,

said determining the 2D range-Doppler map comprises performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal, wherein the first TF domain signal is determined by converting a second DT domain signal to the first TF domain signal, the second DT domain signal comprising pilot data corresponding to the pilot data of the first DD domain signal, and

said determining the 2D range-Doppler map comprises:

performing the multiplication of the second TF domain signal associated with the DT domain signal received and the first TF domain signal associated with the first DD domain signal to obtain a third TF domain signal; and

determining the 2D range-Doppler map based on the third TF domain signal.

18. A system for orthogonal time frequency space (OTFS)-based radar sensing, the system comprising:

at least one memory; and

at least one processor communicatively coupled to the at least one memory and configured to perform the method of OTFS-based radar sensing according to any one of claims 1 to 17.

19. A radar for OTFS-based radar sensing, the radar comprising:

one or more antennas; and

the system for OTFS-based radar sensing according to claim 18 communicatively coupled to the one or more antennas for performing radar sensing.

20. A computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to perform the method of OTFS-based radar sensing according to any one of claims 1 to 17.