MULTI-TARGET RADAR SENSING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore Patent Application No. 10202400927U filed on 28 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 radar sensing for detecting multiple targets, and a system and a radar thereof.

BACKGROUND

[0003] There exist various technical problems or challenges in radar detection, particularly in scenarios where targets are in proximity, moving rapidly, and/or when multiple users share the spectrum with sparse subcarriers.

[0004] Regarding difficulty in detecting multiple targets in proximity and rapid motion, for example, when targets are close to each other and moving rapidly, it becomes challenging for existing radar systems to distinguish individual targets and accurately track their movements. This situation can lead to confusion in identifying and tracking specific targets amid the clutter of overlapping radar returns.

[0005] Regarding technical problems due to masking of weaker targets (i.e., weaker target signals) by stronger targets (stronger target signals), for example, in situations where there is a significant difference in target signal strengths, existing radar detection algorithms may prioritize the strongest target. As a result, signals of weaker targets may be overshadowed or masked by the dominant signals of stronger targets.

[0006] Regarding degradation of target detection performance in a shared spectrum with sparse subcarriers, for example, when multiple users share the same spectrum and each user is allocated sparse subcarriers for radar detection, there is an increased risk of multi-user interference and a reduction in target detection performance due to limited bandwidth.

[0007] Regarding technical problems with the conventional strongest target detection method based on range or speed, for example, the conventional strongest target detection method based on range assumes that different targets are within non-overlapping range areas and their range separations are known, so that the strongest target can be searched in each range

area. This assumption can be restrictive in scenarios where targets are closely spaced, or the range areas are not known beforehand. Since this method may only detect the strongest target within each range area, weaker targets may remain undetected if there are multiple targets in the same range area. There is also a self-interference cancellation scheme, which is only used for static target cancellation, while moving targets cannot be cancelled.

[0008] In multi-user joint radar and communication (JRC) scenarios, only a small number of data subcarriers are used for radar sensing, which can be a constraint for conventional search methods that rely on a great number of subcarriers for range or speed differentiation.

[0009] A need therefore exists to provide a method of radar sensing for detecting multiple targets, and as well as a system and a radar thereof, that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional radar sensing methods, and more particularly, with improved effectiveness in detecting multiple targets. It is against this background that the present invention has been developed.

SUMMARY

[0010] According to a first aspect of the present invention, there is provided a method of radar sensing for detecting multiple targets, the method comprising:

determining a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term;

determining a range-Doppler map based on the channel estimation or the cyclic correlation;

detecting a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation; and

for each iteration of a plurality of iterations:

determining a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target;

modifying the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term;

determining a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and

detecting a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0011] According to a second aspect of the present invention, there is provided a system for radar sensing for detecting multiple targets, the system comprising:

at least one memory; and

at least one processor communicatively coupled to the at least one memory and configured to:

determine a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term;

determine a range-Doppler map based on the channel estimation or the cyclic correlation;

detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation; and

for each iteration of a plurality of iterations:

determine a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target;

modify the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term;

determine a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and

detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0012] According to a third aspect of the present invention, there is provided a radar for detecting multiple targets, the radar comprising:

one or more antennas; and

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

[0013] 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 radar sensing for detecting multiple targets according to the above-mentioned first aspect of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] 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 flow diagram of a method of radar sensing for detecting multiple targets, according to various embodiments of the present invention;

FIG. 2 depicts a schematic block diagram of a system for radar sensing for detecting multiple targets, according to various embodiments of the present invention;

FIG. 3 depicts a schematic block diagram of a radar (or a radar system) for detecting multiple targets, according to various embodiments of the present invention;

FIG. 4 depicts a schematic drawing of a system model for a multi-target joint radar and communication (JRC) system;

FIG. 5 depicts a schematic flow diagram of a method of radar sensing for detecting multiple targets (which may also herein be referred to as an iterative strong target cancellation method), according to various example embodiments of the present invention;

FIGs. 6 and 7 show range and speed detection performances, respectively, in the same range area scenario of three different target detection method, namely, the iterative strong target cancellation method, a conventional range-based search method and a conventional CFAR (Constant False Alarm Rate) method;

FIGs. 8 and 9 illustrate the superiority of the iterative strong target cancellation method over the conventional range-based search method and the conventional CFAR method in terms of range and speed detection, respectively; and

FIGs. 10-15 show the range and speed detection performances of the three different target detection method under two users, four users and eight users sharing scenarios, respectively.

DETAILED DESCRIPTION

[0015] Various embodiments of the present invention relate to a method of radar sensing for detecting multiple targets, and a system and a radar thereof.

[0016] As discussed in the background, conventional radar sensing methods can be ineffective in detecting multiple targets, particularly in scenarios where targets are in proximity, moving rapidly, and/or when multiple users share the spectrum with sparse subcarriers. In particular, amongst multiple targets, signals of weaker targets (or weaker target signals) may be overshadowed or masked by signals of stronger targets (or stronger target signals). As a result, such conventional radar sensing methods are not able to effectively detect multiple targets (including weaker targets). In this regard, various embodiments of the present invention provide a method of radar sensing for detecting multiple targets, and as well as a system and a radar thereof, that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional radar sensing methods, and more particularly, with improved effectiveness in detecting multiple targets.

[0017] FIG. 1 depicts a schematic flow diagram of a method 100 of radar sensing for detecting multiple targets, according to various embodiments of the present invention. The method 100 comprises: determining (at 106) a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term; determining (at 108) a range-Doppler map based on the channel estimation or the cyclic correlation; and detecting (at 110) a dominant target (e.g., having the strongest target signal) amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation. In particular, the method 100 further comprises, for each iteration of a plurality of iterations (e.g., each iteration for detecting a respective dominant target (e.g., the strongest target at the iteration) of the multiple targets): determining (at 112) a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target; modifying (at 114) the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the

first dominant target attributed correlation intermediate term from the correlation intermediate term; determining (at 116) a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and detecting (at 118) a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0018] For example, in the case of orthogonal frequency-division multiplexing (OFDM)-based radar sensing, the method 100 of radar sensing comprises: determining (at 106) a channel estimation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal; determining (at 108) a range-Doppler map based on the channel estimation; and detecting (at 110) a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation. In particular, the method 100 further comprises, for each iteration of a plurality of iterations: determining (at 112) a first dominant target attributed channel estimation based on the detected dominant target; modifying (at 114) the channel estimation comprising offsetting the first dominant target attributed channel estimation from the channel estimation; determining (at 116) a range-Doppler map based on the modified channel estimation; and detecting (at 118) a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation.

[0019] For example, in the case of fast cyclic correlation radar (FCCR)-based radar sensing, the method 100 comprises: determining (at 106) a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term; determining (at 108) a range-Doppler map based on the cyclic correlation; and detecting (at 110) a dominant target amongst the multiple targets based on the range-Doppler map determined based on the cyclic correlation. In particular, the method 100 further comprises, for each iteration of a plurality of iterations: determining (at 112) a first dominant target attributed correlation intermediate term based on the detected dominant target; modifying (at 114) the cyclic correlation comprising offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term; determining (at 116) a range-Doppler map based on the modified cyclic correlation; and detecting (at 118) a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified cyclic correlation.

[0020] The method 100 of radar sensing is advantageously effective in detecting multiple targets. In particular, at each iteration of a plurality of iterations, by detecting a dominant target (e.g., strongest target having the strongest signal) at the iteration and modifying the channel estimation or the cyclic correlation based on the dominant target attributed channel estimation or the dominant target attributed correlation intermediate term determined, effects or contribution of the detected dominant target to the channel estimation or the correlation intermediate term (and thus the cyclic correlation) can be minimized or removed such that a range-Doppler map can be determined based on the modified channel estimation or the modified cyclic correlation for effectively detecting the next dominant target. In this manner, signals of weaker targets originally masked by signals of stronger targets can be uncovered or detected iteratively, thereby significantly improved effectiveness in detecting multiple targets. 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 100 of radar sensing, as well as the corresponding system for radar sensing, is described in more detail according to various embodiments and example embodiments of the present invention.

[0021] In various embodiments, the above-mentioned detecting (at 110) the dominant target comprises: locating a peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation as corresponding to the dominant target; and determining a range and a speed of the dominant target based on the located peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation. Similarly, the above-mentioned detecting (at 118) the next dominant target comprises: locating a peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation as corresponding to the next dominant target; and determining a range and a speed of the next dominant target based on the located peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0022] In various embodiments, in the case of the above-mentioned determining (at 112) the first dominant target attributed channel estimation based on the detected dominant target (e.g., if or based on the multiple targets having different ranges), the above-mentioned determining (at 112) the first dominant target attributed channel estimation comprises determining an average of the channel estimation over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation over the set of data subcarriers.

[0023] In various embodiments, in the case of the above-mentioned determining (at 112) the first dominant target attributed correlation intermediate term based on the detected dominant target (e.g., if or based on the multiple targets having different ranges), the above-mentioned determining (at 112) the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed correlation intermediate term for representing a contribution of the detected dominant target to the correlation intermediate term over the set of data subcarriers.

[0024] In various embodiments, in the case of the above-mentioned modifying (at 114) the channel estimation, the above-mentioned offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation.

[0025] In various embodiments, in the case of the above-mentioned modifying (at 114) the cyclic correlation, the above-mentioned offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

[0026] In various embodiments, in the case of the above-mentioned determining (at 112) the first dominant target attributed channel estimation based on the detected dominant target (e.g., if or based on the multiple targets having different speeds), the above-mentioned determining (at 112) the first dominant target attributed channel estimation comprises determining an average of the channel estimation across a set of orthogonal frequency-division multiplexing (OFDM) symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation across the set of OFDM symbols.

[0027] In various embodiments, in the case of the above-mentioned determining (at 112) the first dominant target attributed correlation intermediate term based on the detected dominant target (e.g., if or based on the multiple targets having different speeds), the above-mentioned determining (at 112) the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected

dominant target to obtain the first dominant target attributed correlation intermediate term for representing for a contribution of the detected dominant target to the correlation intermediate term across the set of OFDM symbols.

[0028] In various embodiments, in the case of the above-mentioned modifying (at 114) the channel estimation, the above-mentioned offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation.

[0029] In various embodiments, in the case of the above-mentioned modifying (at 114) the cyclic correlation, the above-mentioned offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

[0030] In various embodiments (e.g., if or based on the multiple targets having different ranges and different speeds), the above-mentioned modifying (at 114) the channel estimation or the cyclic correlation further comprises: determining a second dominant target attributed channel estimation or a second dominant target attributed correlation intermediate term based on the detected dominant target.

[0031] In various embodiments, in the case of the above-mentioned modifying (at 114) the channel estimation comprising the above-mentioned determining the second dominant target attributed channel estimation (e.g., if or based on the multiple targets having different ranges and different speeds), the above-mentioned determining the second dominant target attributed channel estimation comprises determining an average of the residual channel estimation across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed channel estimation for representing a contribution of the detected dominant target to the residual channel estimation across the set of OFDM symbols.

[0032] In various embodiments, in the case of the above-mentioned modifying (at 114) the cyclic correlation comprising the above-mentioned determining the second dominant target attributed correlation intermediate term (e.g., if or based on the multiple targets having different ranges and different speeds), the above-mentioned determining the second dominant target attributed correlation intermediate term comprises determining an average of the residual correlation intermediate term across a set of OFDM symbols of the transmitted signal subject

to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed correlation intermediate term for representing for a contribution of the detected dominant target to the residual correlation intermediate term across the set of OFDM symbols.

[0033] In various embodiments, in the case of the above-mentioned modifying (at 114) the channel estimation, the above-mentioned modifying (at 114) the channel estimation further comprises offsetting the second dominant target attributed channel estimation from the residual channel estimation. In this regard, the above-mentioned offsetting the second dominant target attributed channel estimation from the residual channel estimation comprises performing a subtraction on the residual channel estimation based on the second dominant target attributed channel estimation to obtain the modified channel estimation.

[0034] In various embodiments, in the case of the above-mentioned modifying (at 114) the cyclic correlation, the above-mentioned modifying (at 114) the cyclic correlation further comprises offsetting the second dominant target attributed cyclic correlation from the residual cyclic correlation. In this regard, the above-mentioned offsetting the second dominant target attributed correlation intermediate term from the residual correlation intermediate term comprises performing a subtraction on the residual correlation intermediate term based on the second dominant target attributed correlation intermediate term to obtain a modified correlation intermediate term, wherein the modified cyclic correlation is determined based on the modified correlation intermediate term.

[0035] In various embodiments, the method 100 of radar sensing is OFDM-based radar sensing. In this regard, the above-mentioned determining (at 106) the channel estimation comprises determining the channel estimation in a frequency domain based on the received signal and the transmitted signal. Furthermore, the above-mentioned determining (at 108) the range-Doppler map based on the channel estimation comprises performing a two-dimensional (2D) fast Fourier transform (FFT) on the channel estimation to obtain the range-Doppler map.

[0036] In various embodiments, the method 100 of radar sensing is FCCR-based radar sensing. In this regard, the above-mentioned determining (at 106) the cyclic correlation comprises performing a multiplication of a discrete Fourier transform (DFT) of the received signal and a conjugate of the DFT of the transmitted signal. Furthermore, the above-mentioned determining (at 108) the range-Doppler map based on the cyclic correlation comprises performing a DFT based on the cyclic correlation to obtain the range-Doppler map.

[0037] FIG. 2 depicts a schematic block diagram of a system 200 for radar sensing for detecting multiple targets, according to various embodiments of the present invention, corresponding to the above-mentioned method 100 of radar sensing for detecting multiple targets as described hereinbefore with reference to FIG. 1 according to various embodiments of the present invention. The system 200 comprises: at least one memory 202; and at least one processor 204 communicatively coupled (e.g., connected) to the at least one memory 202 and configured to perform the method 100 of radar sensing for detecting multiple targets according to various embodiments of the present invention. Accordingly, the at least one processor 204 is configured to: determine a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term; determine a range-Doppler map based on the channel estimation or the cyclic correlation; and detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation. In particular, the at least one processor 204 is further configured to, for each iteration of a plurality of iterations: determine a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target; modify the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term; determine a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0038] It will be appreciated by a person skilled in the art that the at least one processor 204 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 204 to perform various functions or operations. Accordingly, as shown in FIG. 2, the system 200 may comprise: a channel estimation / cyclic correlation determining module (or a channel estimation / cyclic correlation determining circuit) 206 configured to determine a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term; a range-Doppler map determining module

(or a range-Doppler map determining circuit) 208 configured to determine a range-Doppler map based on the channel estimation or the cyclic correlation; and a dominant target detecting module (or a dominant target detecting circuit) 210 configured to detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation. The system 200 further comprises: a dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module (or a dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining circuit) 212 configured to, for each iteration of a plurality of iterations, determine a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target; and a channel estimation / cyclic correlation modifying module (or a channel estimation / cyclic correlation modifying circuit) 214 configured to, for each iteration of a plurality of iterations, modify the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term. In various embodiments, the range-Doppler map determining module 208 is further configured to, for each iteration of a plurality of iterations, determine a range-Doppler map based on the modified channel estimation or the modified cyclic correlation. In various embodiments, the dominant target detecting module 210 is further configured to, for each iteration of a plurality of iterations, detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

[0039] Accordingly, in various embodiments, in the case of OFDM-based radar sensing, the system 200 may comprise a channel estimation determining module 206 configured to determine a channel estimation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal; a range-Doppler map determining module 208 configured to determine a range-Doppler map based on the channel estimation; and a dominant target detecting module 210 configured to detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation. The system 200 may further comprise: a dominant target attributed channel estimation determining module 212 configured to, for each iteration of a plurality of iterations, determine a first dominant target attributed channel estimation based on the detected dominant target; and a channel estimation modifying module 214 configured to, for each

iteration of a plurality of iterations, modify the channel estimation comprising offsetting the first dominant target attributed channel estimation from the channel estimation. In various embodiments, the range-Doppler map determining module 208 is further configured to, for each iteration of a plurality of iterations, determine a range-Doppler map based on the modified channel estimation. In various embodiments, the dominant target detecting module 210 is further configured to, for each iteration of a plurality of iterations, detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation.

[0040] Accordingly, in various embodiments, in the case of FCCR-based radar sensing, the system 200 may comprise: a cyclic correlation determining module 206 configured to determine a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term; a range-Doppler map determining module 208 configured to determine a range-Doppler map based on the cyclic correlation; and a dominant target detecting module 210 configured to detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the cyclic correlation. The system 200 further comprises: a dominant target attributed correlation intermediate term determining module 212 configured to, for each iteration of a plurality of iterations, determine a first dominant target attributed correlation intermediate term based on the detected dominant target; and a cyclic correlation modifying module 214 configured to, for each iteration of a plurality of iterations, modify the cyclic correlation comprising offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term. In various embodiments, the range-Doppler map determining module 208 is further configured to, for each iteration of a plurality of iterations, determine a range-Doppler map based on the modified cyclic correlation. In various embodiments, the dominant target detecting module 210 is further configured to, for each iteration of a plurality of iterations, detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified cyclic correlation.

[0041] Accordingly, in various embodiments, the system 200 for radar sensing for detecting multiple targets may be configured to be capable of one of or both of OFDM-based radar sensing and FCCR-based radar sensing.

[0042] 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 channel estimation / cyclic correlation determining module 206, the range-Doppler map determining module 208; and the dominant target detecting module 210, the dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module 212, the channel estimation / cyclic correlation modifying module 214 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 202 and executable by the at least one processor 204 to perform the corresponding functions or operations as described herein according to various embodiments of the present invention.

[0043] In various embodiments, the system 200 for radar sensing for detecting multiple targets corresponds to the method 100 of radar sensing for detecting multiple targets as described hereinbefore with reference to FIG. 1, therefore, various operations, functions or steps configured to be performed by the least one processor 204 may correspond to various operations, functions or steps of the method 100 described hereinbefore according to various embodiments, and thus need not be repeated with respect to the system 200 for clarity and conciseness. In other words, various embodiments described herein in context of methods (e.g., the method 100 of radar sensing for detecting multiple targets) are analogously valid for the corresponding systems or devices (e.g., the system 200 for radar sensing for detecting multiple targets), and vice versa. For example, in various embodiments, the at least one memory 202 may have stored therein the channel estimation / cyclic correlation determining module 206, the range-Doppler map determining module 208, the dominant target detecting module 210, the dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module 212 and/or the channel estimation / cyclic correlation modifying module 214, which respectively correspond to various operations, functions or steps of the method 200 of radar sensing for detecting multiple targets as described hereinbefore according to various embodiments, which are executable by the at least one processor 204 to perform the corresponding operations, functions or steps as described herein.

[0044] 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 200 for radar sensing for detecting multiple targets described hereinbefore may include at least one processor 204 and at

least one computer-readable storage medium (or memory) 202 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).

[0045] 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.

[0046] 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.

[0047] 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 200, 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.

[0048] 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.

[0049] 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 channel estimation / cyclic correlation determining module 206, the range-Doppler map determining module 208, the dominant target detecting module 210, the dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module 212 and/or the channel estimation / cyclic correlation modifying module 214) executable by one or more computer processors to perform a method 100 of radar sensing for detecting multiple targets as described hereinbefore with reference to FIG. 1 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 200 as shown in FIG. 2, for execution by at least one processor 204 of the system 200 to perform various operations, functions or steps of various methods described herein according to various embodiments of the present invention.

[0050] It will be appreciated by a person skilled in the art that various modules described herein (e.g., the channel estimation / cyclic correlation determining module 206, the range-Doppler map determining module 208, the dominant target detecting module 210, the dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module 212 and/or the channel estimation / cyclic correlation modifying module 214) 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 channel estimation / cyclic correlation determining module 206, the range-Doppler map determining module 208, the dominant target detecting module 210, the dominant target attributed channel estimation / dominant target attributed correlation intermediate term determining module 212 and/or the channel estimation / cyclic correlation modifying module 214), together with the at least one processor 204 and the at least one memory 202, 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).

[0051] FIG. 3 depicts a schematic block diagram of a radar (or a radar system) 300 for detecting multiple targets, according to various embodiments of the present invention. The radar 300 comprises one or more antennas 312, 314; and the system 200 for radar sensing for detecting multiple targets as described herein according to various embodiments of the present invention communicatively coupled (e.g., connected) to the one or more antennas 312, 314 for performing radar sensing. In various embodiments, the radar 300 may further comprise a radar transmitter 302 comprising a transmitter antenna 312 and is configured to perform signal modulation on a signal for transmission via the transmitter antenna 312. The radar 300 may further comprise a radar receiver 304 comprising a receiver antenna 314 and is configured to perform signal demodulation on a received signal via the receiver antenna 314. As shown in

FIG. 3, the system 300 may be communicatively coupled (connected) to the radar transmitter 302 and the radar receiver 304, for example, for obtaining the transmitted signal and the received signal. In various embodiments, the radar 300 may be a monostatic radar. In the case of a 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. It will be appreciated by a person skilled in the art that the present invention is not limited to a monostatic radar. For example, the present invention may also be applied to a bistatic radar. In the case of a bistatic radar, the system 300 may be located at the radar receiver 304 side and may thus be communicatively coupled (connected) to the radar receiver 304, for example, for obtaining the received signal. In this regard, for example, the transmitted signal may be estimated at the receiver side. For example, the radar receiver 304 may perform demodulation or decoding to obtain the estimated transmitted signal. In various embodiments, the system 200 for radar sensing for detecting multiple targets may be comprised in (e.g., integrated in) the receiver 304.

[0052] 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.

[0053] 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.

[0054] 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.

[0055] As discussed in the background, conventional radar sensing methods can be ineffective in detecting multiple targets, particularly in scenarios where targets are in proximity, moving rapidly, and/or when multiple users share the spectrum with sparse subcarriers. In particular, amongst multiple targets, signals of weaker targets (or weaker target signals) may be overshadowed or masked by signals of stronger targets (or stronger target signals). As a result, such conventional radar sensing methods are not able to effectively detect multiple targets (including weaker targets). In this regard, various example embodiments of the present invention provide a method of radar sensing for detecting multiple targets, and as well as a system and a radar thereof, that seeks to overcome, or at least ameliorate, one or more deficiencies in conventional radar sensing methods, and more particularly, with improved effectiveness in detecting multiple targets.

[0056] In particular, various example embodiments provide a method of radar sensing for detecting multiple targets based on strong target cancellation for overcoming, or at least ameliorating, deficiencies in conventional radar sensing methods. For example, in contrast to conventional radar sensing methods discussed in the background, the method of radar sensing according to various example embodiments does not rely on predefined non-overlapping range areas or speed intervals. In contrast, the method of radar sensing according to various example embodiments is configured to iteratively cancel the effects or contribution of the strongest target (at each iteration) amongst multiple targets to detect a next target (e.g., next dominant or strongest target) such that weaker targets amongst the multiple targets can be uncovered iteratively. This approach enables the detection of targets even when they are closely spaced or have overlapping range areas or have high speeds. The capability of the method to operate with sparse data subcarriers is also an advantage. Accordingly, by mitigating the effects of dominant targets through cancellation iteratively, the method of radar sensing according to various

example embodiments advantageously enhances weak signal detection even with limited subcarrier usage.

[0057] CFAR methods (or algorithms) are commonly employed for multi-target detection in radar systems, which can be used for JRC systems as well. These CFAR algorithms rely on comparing the power of potential targets to an estimated noise level and surrounding power level to make detection decisions. However, these CFAR algorithms suffer from various limitations, such as:

- high complexity and slow computation: CFAR algorithms often involve a two-dimensional (2D) search over the range-Doppler map or matrix (RDM) to detect possible targets. This process can be computationally intensive and may result in slower processing time, which is a technical issue in real-time applications or systems with limited processing capabilities.
- threshold selection complexity: Selecting an appropriate threshold for CFAR detection is non-trivial. The threshold must balance the trade-off between detection performance and the probability of false alarm (Pfa). This selection process requires careful consideration and often involves theoretical analysis or Monte Carlo simulations to optimize the threshold for specific scenarios.
- limited detection of weak targets: for example, in situations where target signal strengths have large differences, CFAR algorithms may prioritize the strongest targets, making it challenging to detect weaker targets that are masked by the dominant signals of stronger targets.

[0058] To address limitations of conventional radar sensing methods, various example embodiments provide a method of radar sensing for detecting multiple targets that utilizes iterative strong target cancellation, which has a number of technical advantages, such as:

- reduced complexity (enhanced efficiency): by cancelling the effects of dominant targets, the method is able to significantly reduce the complexity of the target detection process, as it does not require an exhaustive 2D search over the range-Doppler map to detect possible targets; and
- iterative detection for weaker targets: the iterative nature of the method allows for progressive cancellation of strong/dominant targets, thereby enabling or improving the detection of weaker targets that were previously obscured by strong interference (e.g., when they are in the presence of strong/dominant targets).

[0059] For illustration purposes, FIG. 4 depicts a schematic drawing of a system model for a multi-target joint radar and communication (JRC) system. The system comprises a transmitter (TX) configured to generate a communication signal according to a modulation protocol or standard, which is then sent to multiple targets through a transmitter antenna. The system further comprises a receiver (RX) configured to serve two purposes (perform two functions), namely, radar detection and conventional communication. In this regard, various example embodiments are directed to the radar detection aspect. As illustrated in FIG. 4, radar detection involves the radio signal from the transmitter antenna reaching the multiple targets and then being reflected to the receiver antenna. By capturing the reflected signal, the receiver is configured to estimate both the range (distance) and speed of the targets. It will be appreciated by a person skilled in the art that in FIG. 4, only two targets are illustrated for simplicity, namely, one strong target and one weak target, and that the present invention is not limited to detecting only two targets. In other words, the method of radar sensing according to various example embodiments may be applied to detect any number of targets as desired or as appropriate. For example, it will be appreciated by a person skilled in the art that in real-world scenarios, there can be any number of multiple targets to be detected. In various example embodiments, the method of radar sensing according to various example embodiments may be applied to detect any number of multiple targets one by one iteratively.

[0060] The system model may be described as follows. Let $\boldsymbol{s(t)}$ be the transmitted baseband signal. The signal reflected from radar targets is received at the receiver. Assuming that there are $\boldsymbol{L}$ radar targets, the received baseband discrete signal may be expressed as:

$$\boldsymbol{y(nT_b) = \sum_{l=1}^{L} h_l s(nT_b - \tau_l)\, e^{j2\pi n \varphi_l T_b} + w(nT_b)}$$

(Equation 1)

where $\boldsymbol{h_l = \alpha_l e^{-j2\pi(f_c+\varphi_l)\tau_l + j\varpi + j\vartheta_l}}$ denotes the complex channel gain of radar target $\boldsymbol{l}$ (random phase error is absorbed into this term as well), $\boldsymbol{\alpha_l}$ denotes the attenuation coefficient of radar target $\boldsymbol{l}$, $\boldsymbol{f_c}$ denotes the carrier frequency, $\boldsymbol{\varphi_l = \frac{u_l}{c} f_c}$ denotes the Doppler frequency shift induced by the moving of radar target $\boldsymbol{l}$, $\boldsymbol{u_l}$ denotes the relative speed of the radar target $\boldsymbol{l}$, $\boldsymbol{c}$ denotes the speed of light, $\boldsymbol{\tau_l}$ denotes the trip delay of radar target $\boldsymbol{l}$, $\boldsymbol{\varpi}$ denotes the initial phase, $\boldsymbol{\vartheta_l}$ denotes a phase error, $\boldsymbol{T_b}$ denotes the sampling period and $\boldsymbol{w(nT_b)}$ denotes the noise term.

[0061] The radar receiver may be configured to determine the delay τ_l (corresponding to range) and Doppler shift φ_l (corresponding to the relative speed). Let $\varepsilon_l = \tau_l/T_b$, $v_l = \varphi_l T_b$. Note that $\varepsilon_l = \tau_l/T_b$ may not be an integer. If so, ε_l may be chosen as the nearest integer to τ_l/T_b. To simplify notations, denote $y(nT_b)$ by $y(n)$, $s(nT_b)$ by $s(n)$, and $w(nT_b)$ by $w(n)$, and the received baseband discrete signal may be expressed as:

$$y(n) = \sum_{l=1}^{L} h_l s(n - \varepsilon_l)\, e^{j2\pi n v_l} + w(n), n = 0, 1, \ldots.$$

(Equation 2)

[0062] The above system model is applicable to any waveform. For example, the transmitted time domain signal is assumed to have a block structure and each block has a cyclic prefix (CP). The signal $s(n)$ is composed of M blocks with each block having a length of $N_a = N + N_p$, where N is the length of data block and N_p is the length of CP. In each block, the first N_p symbols (the CP) are the repetition of the last N_p symbols. OFDM and CP-SC are the two most popular waveforms with this structure. To cater for this structure, the received discrete signal $y(n)$ may be divided into blocks of length N_a. In each block, the first N_p elements (corresponding to the CP of that block) are discarded. The block m (after discarding the CP) is denoted as $y_m(n)$, $n = 0, 1, \ldots, N-1$, $m = 0, 1, \ldots, M-1$. Assuming that the normalized delay is always smaller than the CP length $\varepsilon_l \leq N_p$, the received discrete signal may be expressed as:

$$y_m(n) = \sum_{l=1}^{L} \hat{h}_l s_m(\langle n - \varepsilon_l \rangle_N) e^{j2\pi n v_l} e^{j2\pi m N_a v_l} + w_m(n)$$

(Equation 3)

where $\hat{h}_l = h_l e^{j2\pi N_p v_l}$ and $\langle n \rangle_K$ denotes the remainder of n modulo K: $\langle n \rangle_K = n \bmod K$.

[0063] OFDM radar makes use of the channel estimation of the reflected signal to determine the range and speed of radar targets, which may be summarized by the following steps.

[0064] 1. Calculate the discrete Fourier transform (DFT) of signal: denoting $Y_m(k)$ as the DFT of the received signal $y_m(n)$, $S_m(k)$ as the DFT of the transmit signal $s_m(n)$, $W_m(k)$ as the DFT of the noise term $w_m(n)$, respectively, the following approximation may be obtained for small Doppler shift case:

$$Y_m(k) = NS_m(k)\sum_{l=1}^{L}\hat{h}_l e^{-j\frac{-2\pi k\varepsilon_l}{N}} e^{j2\pi mN_a v_l} + W_m(k)$$

(Equation 4)

[0065] 2. Obtain frequency domain channel estimation with zero-forcing: dividing $Y_m(k)$ by $NS_m(k)$, the frequency domain channel estimation may be obtained as:

$$H(k,m) = \frac{Y_m(k)}{NS_m(k)} = \sum_{l=1}^{L}\hat{h}_l e^{-j\frac{2\pi k\varepsilon_l}{N}} e^{j2\pi mN_a v_l} + W_m(k)$$

(Equation 5)

[0066] Accordingly, $Y_m(k)$ represents the frequency-domain representation of the received OFDM signal after applying DFT to the time-domain received signal $y_m(n)$. Since the DFT transforms a discrete-time signal into its frequency components, $Y_m(k)$ exists in the frequency domain, while $y_m(n)$ exists in the time domain. It will be understood by a person skilled in the art that m (OFDM symbol index) refers to the index of the OFDM symbol in a transmission frame. In an OFDM system, data is transmitted in multiple OFDM symbols, each containing information across different subcarriers. In addition, k (subcarrier index) represents the index of a specific subcarrier in the OFDM system. Each subcarrier corresponds to a frequency component, and k ranges from 0 to $N-1$, where N is the total number of subcarriers in the system. Thus, $Y_m(k)$ represents the received signal in the frequency domain at the k-th subcarrier of the m-th OFDM symbol.

[0067] 3. Obtain RDM matrix with 2D FFT: performing 2D fast Fourier transform (FFT) on the estimated channel obtained in Equation (5), the RDM matrix may be obtained as:

$$\hat{H}(k,m) = \frac{1}{\sqrt{MN}}\sum_{b=0}^{M-1}\sum_{a=0}^{N-1} H(a,b)e^{j\frac{2\pi ak}{N}} e^{j\frac{-2\pi bm}{M}},$$

(Equation 6)

Accordingly, $\hat{H}(k,m)$ represents the range-Doppler map obtained by applying a 2D-FFT to the frequency-domain channel $H(a,b)$. $\hat{H}(k,m)$ exists in the range-Doppler domain, whereby one dimension corresponds to range (distance) and the other dimension corresponds to Doppler shift (velocity). It will be understood by a person skilled in the art that k (range index) represents the range or distance of a target. It is obtained from the FFT along the fast-time domain (typically corresponding to time delays due to signal propagation). In addition, m (Doppler index) represents the Doppler frequency shift, which is related to the relative velocity of the target. It is obtained from the FFT along the slow-time domain (typically corresponding to multiple

OFDM symbols). Thus, $\widehat{\boldsymbol{H}}(\boldsymbol{k},\boldsymbol{m})$ represents the response of the system in the range-Doppler domain, where each element indicates the strength of the received signal for a specific range $\boldsymbol{k}$ and velocity $\boldsymbol{m}$.

[0068] 4. Detect strongest target: the range $\boldsymbol{\varepsilon_1}$ and speed $\boldsymbol{v_1}$ of the strongest target are obtained by finding the peak in the RDM matrix, namely, $\left|\widehat{\boldsymbol{H}}(\boldsymbol{k},\boldsymbol{m})\right|$, such as according to Equation (7) below. Accordingly, this step allows the identification of the dominant target's position and motion characteristics.

$$(\boldsymbol{k_1},\boldsymbol{m_1}) = \boldsymbol{arg}\ \underset{(\boldsymbol{k},\boldsymbol{m})}{\boldsymbol{max}}\left|\widehat{\boldsymbol{H}}(\boldsymbol{k},\boldsymbol{m})\right|$$

(Equation 7)

The normalized range and speed may then be obtained as: $\boldsymbol{\varepsilon_1} = \boldsymbol{k_1}, \boldsymbol{v_1} = \boldsymbol{m_1}/(\boldsymbol{MN_a})$.

[0069] The fast cyclic correlation radar (FCCR) was derived from maximum likelihood (ML) principle and may be used for any waveform with the CP structure. Theoretically, it is nearly optimal given that the delay is within the CP range. FCCR makes use of the cyclic correlation between the transmitted signal and the received signal to determine the range and speed of radar targets, which may be summarized by the following steps.

[0070] 1. Calculate cyclic correlation: The received signal is correlated with the transmitted signal to obtain the cyclic correlation. The cyclic correlation of the received signal and transmitted signal may be calculated as follows:

$$\boldsymbol{r}(\boldsymbol{n},\boldsymbol{m}) = \sum_{\boldsymbol{p}=\boldsymbol{0}}^{\boldsymbol{N}-\boldsymbol{1}} \boldsymbol{y_m}(\boldsymbol{p})\boldsymbol{s_m^*}(\langle \boldsymbol{p}-\boldsymbol{n}\rangle_{\boldsymbol{N}}), \boldsymbol{n} = \boldsymbol{0},\boldsymbol{1},\ldots,\boldsymbol{N}-\boldsymbol{1}$$

(Equation 8)

Accordingly, $\boldsymbol{r}(\boldsymbol{n},\boldsymbol{m})$ represents the cyclic correlation (or cyclic correlation function), which is obtained by correlating the time-domain received signal with the transmitted signal. Since correlation is performed in the time domain, $\boldsymbol{r}(\boldsymbol{n},\boldsymbol{m})$ exists in the time-delay domain. It will be understood by a person skilled in the art that $\boldsymbol{n}$ (index within an OFDM symbol) represents the time index within a single OFDM symbol. It ranges from 0 to $\boldsymbol{N}-1$, where $\boldsymbol{N}$ is the length of each OFDM symbol. In addition, $\boldsymbol{m}$ (OFDM symbol index) represents the index of the OFDM symbol in the block structure. It ranges from 0 to $\boldsymbol{M}-1$, where $\boldsymbol{M}$ is the total number of OFDM symbols. Thus, $\boldsymbol{r}(\boldsymbol{n},\boldsymbol{m})$ represents the cyclic correlation of the received signal at a specific time index $\boldsymbol{n}$ within an OFDM symbol and for the $\boldsymbol{m}$-th OFDM symbol.

[0071] 2. Obtain the RDM: The RDM, denoted as $\mathbf{R(n,k)}$, may be obtained by determining the discrete Fourier transform (DFT) of the cyclic correlation data $\boldsymbol{r(n,m)}$ on the second dimension, which provides information about the targets' range and speed distribution.

$$\boldsymbol{R(n,k)} = \sum_{\boldsymbol{m=0}}^{\boldsymbol{M-1}} \boldsymbol{r(n,m)} e^{j\frac{-2\pi mk}{M}}.$$

(Equation 9)

Accordingly, when performing the DFT of the cyclic correlation data $\boldsymbol{r(n,m)}$ on the second dimension, the second dimension refers to the OFDM symbol index $\boldsymbol{m}$. In other words, the DFT is applied across the OFDM symbols (indexed by $\boldsymbol{m}$) to transform the data from the time domain to the frequency domain. Therefore, the second dimension is the $\boldsymbol{m}$-axis, and the DFT transforms $\boldsymbol{r(n,m)}$ in terms of how it varies across different OFDM symbols.

[0072] 3. Detect Strongest Target: The range $\boldsymbol{\varepsilon_1}$, speed $\boldsymbol{v_1}$ of the strongest target are obtained by finding the peak in the RDM matrix, namely, $|\mathbf{R(n,k)}|$, such as according to Equation (10) below. Accordingly, this step allows the identification of the dominant target's position and motion characteristics.

$$(\boldsymbol{n_1}, \boldsymbol{k_1}) = \boldsymbol{arg\ \underset{(n,k)}{max}|R(n,k)|}$$

(Equation 10)

The normalized range and speed may then be obtained as: $\boldsymbol{\varepsilon_1 = n_1}$, $\boldsymbol{v_1 = k_1/(MN_a)}$.

[0073] FIG. 5 depicts a schematic flow diagram of a method of radar sensing for detecting multiple targets (which may also herein be referred to as an iterative strong target cancellation method) according to various example embodiments of the present invention. The method may include:

- Initial detection: the method may begin by using an existing FCCR technique or an existing OFDM technique to detect the range and speed of the dominant (e.g., strongest target with the strongest target signal) in an environment with multiple targets. This initial detection provides information about the dominant target's position and motion characteristics.
- Cancellation of strong targets: After the strongest or dominant target is identified, the method may proceed to cancel the determined effects of the strongest target in the correlation intermediate term (for FCCR-based radar sensing) or the channel estimation (for OFDM-based radar sensing). This is achieved by averaging the correlation intermediate term (for FCCR-based radar sensing) or the channel estimation (for OFDM-based radar sensing), compensated or adjusted by the detected range and/or

speed of the dominant target. By doing so, the signal contribution from the dominant target is suppressed, allowing weaker targets to become more discernible.

- Iterative detection: The cancellation step can be performed iteratively to sequentially cancel the strongest targets one by one (a respective one at each iteration). Each iteration aims to uncover a next target (e.g., next dominant or strongest target). Therefore, signals of weaker targets that were previously masked by the stronger target signals can be uncovered iteratively.
- Range and speed detection: With the interference from the dominant target reduced or removed, the method performs range and speed detection again at each iteration. At each iteration, it utilizes the RDM calculated based on the new or modified cyclic correlation (for FCCR-based radar sensing) or the new or modified channel estimation (for OFDM-based radar sensing) obtained after strong target cancellation. This process is repeated at each iteration until all targets, including weak targets, are detected.

[0074] Accordingly, with reference to FIG. 5 according to various example embodiments of the present invention, steps 2-5 define the cancellation of strong targets. After the strongest target is identified, the method proceeds to cancel its determined effects in the channel estimation (for OFDM-based radar sensing) or correlation intermediate term (for FCCR-based radar sensing) over subcarriers and/or across OFDM symbols. This is achieved by averaging the channel estimation or correlation intermediate term, compensated or adjusted by the detected range and/or speed of the dominant target. By doing so, at each iteration, the signal contribution from the dominant target detected at the iteration is suppressed, allowing weaker targets to become more discernible. Iterative detection is then performed in steps 6-8 where the cancellation steps can be performed iteratively to sequentially cancel the strongest targets one by one (a respective one at each iteration). Each iteration aims to uncover a next target (e.g., next dominant or strongest target). Therefore, signals of weaker targets that were previously masked by the stronger target signals can be uncovered iteratively.

[0075] By way of illustrative examples for better understanding, the iterative strong target cancellation method according to various example embodiments of the present invention will be described below in further detail with respect to two example cases, namely, OFDM radar and FCCR.

Iterative Strong Target Cancellation with OFDM Radar

[0076] In various example embodiments, the iterative strong target cancellation method with OFDM radar includes the following steps.

[0077] 1. Initial strong target detection with OFDM radar: Calculate frequency domain channel estimation $\boldsymbol{H(k,m)}$ based on transmit and receive signals and perform 2D FFT on $\boldsymbol{H(k,m)}$ to obtain the corresponding RDM matrix $\left|\widehat{\boldsymbol{H}}\boldsymbol{(k,m)}\right|$. The range $\boldsymbol{\varepsilon_1}$ and speed $\boldsymbol{v_1}$ of the dominant target (e.g., strongest target with the strongest target signal amongst multiple targets) may then be obtained by finding the peak of RDM matrix $\left|\widehat{\boldsymbol{H}}\boldsymbol{(k,m)}\right|$ as described hereinbefore.

[0078] 2. Average channel estimation over subcarriers with range compensation (e.g., if or based on multiple targets having different ranges) (e.g., corresponding to determining the first dominant target attributed channel estimation described hereinbefore according to various embodiments of the present invention): The obtained frequency domain channel estimation $\boldsymbol{H(k,m)}$ in step 1 may be averaged over subcarriers with compensation or adjustment based on the detected range of the strongest target, so as to obtain the influence or contribution of the strongest target to the channel estimation. For example, the average of channel estimation over subcarriers subjected to compensation or adjustment based on the detected range of the strongest target may be expressed as:

$$\bar{\boldsymbol{H}}(\boldsymbol{m}) = \frac{\boldsymbol{1}}{\boldsymbol{N}}\sum_{\boldsymbol{k=0}}^{\boldsymbol{N-1}} \boldsymbol{H(k,m)}\ \boldsymbol{e}^{\boldsymbol{j\frac{2\pi k\varepsilon_1}{N}}}.$$

(Equation 11)

[0079] Without wishing to be bound by theory but for better understanding, the following theoretical proof is provided.

$$\bar{\boldsymbol{H}}(\boldsymbol{m}) = \tfrac{\boldsymbol{1}}{\boldsymbol{N}}\textstyle\sum_{\boldsymbol{k=0}}^{\boldsymbol{N-1}} \boldsymbol{H(k,m)}\ \boldsymbol{e}^{\boldsymbol{j\frac{2\pi k\varepsilon_1}{N}}} = \widehat{\boldsymbol{h}}_{\boldsymbol{1}}\boldsymbol{e}^{\boldsymbol{j2\pi mN_a v_1}} + \textstyle\sum_{\boldsymbol{l=2}}^{\boldsymbol{L}} \widehat{\boldsymbol{h}}_{\boldsymbol{l}}\,\boldsymbol{e}^{\boldsymbol{j2\pi mN_a v_l}} \left(\tfrac{\boldsymbol{1}}{\boldsymbol{N}}\textstyle\sum_{\boldsymbol{k=0}}^{\boldsymbol{N-1}} \boldsymbol{e}^{\boldsymbol{-j\frac{2\pi k(\varepsilon_l-\varepsilon_1)}{N}}}\right).$$

(Equation 12)

[0080] For $\varepsilon_l \neq \varepsilon_1$, the following may be obtained:

$$\frac{\boldsymbol{1}}{\boldsymbol{N}}\sum_{\boldsymbol{k=0}}^{\boldsymbol{N-1}} \boldsymbol{e}^{\boldsymbol{-j\frac{2\pi k(\varepsilon_l-\varepsilon_1)}{N}}} = \frac{\boldsymbol{1}}{\boldsymbol{N}}\frac{\boldsymbol{1-e^{-j2\pi k(\varepsilon_l-\varepsilon_1)}}}{\boldsymbol{1-e^{-j\frac{2\pi k(\varepsilon_l-\varepsilon_1)}{N}}}} = 0.$$

(Equation 13)

[0081] Thus, $\bar{\boldsymbol{H}}(\boldsymbol{m}) \approx \widehat{\boldsymbol{h}}_{\boldsymbol{1}}\boldsymbol{e}^{\boldsymbol{j2\pi mN_a v_1}}$.

(Equation 14)

[0082] Hence, the residual term in the channel estimation after strong target cancellation is:

$$\boldsymbol{H(k,m) = H(k,m) - \bar{H}(m)\, e^{j\frac{-2\pi k\varepsilon_1}{N}} = \sum_{l=2}^{L} \hat{h}_l e^{-j\frac{2\pi k\varepsilon_l}{N}} e^{j2\pi m N_a v_l}}\ .$$

(Equation 15)

[0083] When multiple targets have different speed, the following may be obtained:

$$\breve{H}(k) = \frac{1}{M}\sum_{m=1}^{M} H(k,m)\, e^{-j2\pi m N_a v_1}$$

$$= \hat{h}_1 e^{-j\frac{2\pi k\varepsilon_1}{N}} + \sum_{l=2}^{L} \hat{h}_l e^{-j\frac{2\pi k\varepsilon_l}{N}} \left(\frac{1}{M}\sum_{m=1}^{M} e^{-j2\pi m N_a (v_l - v_1)} \right).$$

(Equation 16)

[0084] For $(v_l - v_1) \approx 0$, it can be seen that:

$$\frac{1}{M}\sum_{m=1}^{M} e^{-j2\pi m N_a (v_l - v_1)} = \frac{1}{M}\frac{1 - e^{-j2\pi M N_a (v_l - v_1)}}{1 - e^{-j2\pi N_a (v_l - v_1)}}$$

(Equation 17)

approaches zero as M approaches to infinite. Thus, for large M, the following may be obtained:

$$\breve{H}(k) \approx \hat{h}_1 e^{-j\frac{2\pi k\varepsilon_1}{N}}.$$

(Equation 18)

[0085] Hence, the residual term in the channel estimation (residual channel estimation) after strong target cancellation is:

$$\tilde{H}(n,m) = H(k,m) - \breve{H}(k)\ e^{j2\pi m N_a v_1} = \sum_{l=2}^{L} \hat{h}_l e^{-j\frac{2\pi k\varepsilon_l}{N}} e^{j2\pi m N_a v_l}\ .$$

(Equation 19)

[0086] From the analysis above, it can be seen $\tilde{H}(n,m)$ contains information solely from the remaining targets and is independent of the strongest target. $\bar{H}(m)$ is obtained by averaging $H(k,m)$ over the data subcarriers, meaning it represents a smoothed or aggregated version of the channel response in the frequency domain but without subcarrier resolution. Thus, $\bar{H}(m)$ exists in the time-frequency domain, where the subcarrier dimension has been averaged out, leaving a single value per OFDM symbol. It will be understood by a person skilled in the art that m (OFDM symbol index) represents the index of the OFDM symbol in time. Since the subcarrier information has been averaged, $\bar{H}(m)$ now provides a global channel estimate for

the entire symbol rather than per-subcarrier details. Thus, $\bar{H}(m)$ represents the averaged channel response for the m-th OFDM symbol, capturing the overall frequency-domain channel conditions at that specific symbol time.

[0087] 3. Cancel strongest target in frequency domain channel (e.g., corresponding to offsetting the first dominant target attributed channel estimation from the channel estimation as described hereinbefore according to various embodiments of the present invention): To mitigate the interference from the detected strongest target and facilitate the detection of weaker targets, the determined effects or contribution caused by the strongest target in the channel estimation term in frequency domain is cancelled or removed. The residual channel estimation term after strong/dominant signal cancellation in frequency domain may be given by:

$$\tilde{H}(k,m) = H(k,m) - \bar{H}(m)\, e^{j\frac{-2\pi k\varepsilon_1}{N}}$$

(Equation 20)

[0088] 4. Average channel estimation across OFDM Symbols with speed compensation (e.g., if or based on multiple targets having different speeds or if or based on multiple targets having different ranges and speeds) (e.g., corresponding to determining the first dominant target attributed channel estimation if or based on multiple targets having different speeds (without different ranges) or corresponding to the second dominant target attributed channel estimation if or based on multiple targets having different ranges and speeds as described hereinbefore according to various embodiments of the present invention): The obtained $H(k,m)$ is averaged across OFDM symbols with compensation or adjustment based on the detected speed of the strongest target, which may be given by:

$$\breve{H}(k) = \frac{1}{M}\sum_{m=1}^{M} H(k,m)\, e^{-j2\pi m N_a v_1}$$

(Equation 21)

[0089] 5. Cancel strongest target across OFDM symbols (e.g., corresponding to offsetting the first dominant target attributed channel estimation from the channel estimation (from step 1 above) if or based on multiple targets having different speeds (without different ranges) or corresponding to the offsetting the second dominant target attributed channel estimation from the residual channel estimation (from step 3 above) if or based on multiple targets having different ranges and speeds as described hereinbefore according to various embodiments of the present invention): The effects or contribution caused by the strongest target in channel estimation term are cancelled across OFDM symbols. The residual channel estimation term (or

modified or updated channel estimation) after strong signal cancellation across OFDM symbols may be given by:

$$\tilde{H}(k,m) = H(k,m) - \check{H}(k)\ e^{j2\pi m N_a v_1}$$

(Equation 22)

where $H(k,m)$ may be the channel estimate from step 1 above (if or based on multiple targets having different speeds (without different ranges)) or the residual channel estimate from step 3 above (if or based on multiple targets having different ranges and speeds).

[0090] 6. Recompute RDM based on modified or updated channel estimation: Recomputing RDM matrix by performing 2D FFT on updated channel estimation term as:

$$\check{H}(k,m) = \frac{1}{\sqrt{MN}} \sum_{b=0}^{M-1} \sum_{a=0}^{N-1} \tilde{H}(a,b) e^{j\frac{2\pi ak}{N}} e^{j\frac{-2\pi bm}{M}}$$

(Equation 23)

[0091] 7. Re-detection range and speed: Re-detection of the range and speed of the remaining strongest target after strongest target cancellation by finding the peak in the updated RDM matrix $\check{H}(k,m)$ according to Equation (24) below. This step helps to ensure the correct estimation of the remaining strongest target's range and speed after cancellation.

$$(k_2, m_2) = \arg\max_{(k,m)} \left|\check{H}(k,m)\right|$$

(Equation 24)

The normalized range and speed may then be obtained as: $\epsilon_2 = k_2$, $v_2 = m_2/(MN_a)$.

[0092] 8. Iterative cancellation and detection: The method then returns to step 2, where the strong target cancellation is performed iteratively. This allows for the progressive detection of weaker targets by cancelling one strong target at a time, until all expected targets are detected.

Iterative Strong Targets Cancelation with FCCR Radar

[0093] In various example embodiments, the iterative strong targets cancellation method with FCCR radar includes the following steps:

[0094] 1. Initial strong target detection with FCCR Radar: Denoting $Y_m(k)$ as the DFT of the received signal $y_m(n)$, $S_m(k)$ as the DFT of the transmit signal $s_m(n)$, the cyclic correlation $r(n,m)$ may be determined based on the cyclic convolution theorem as:

$$r(n,m) = \frac{1}{N} \sum_{k=0}^{N-1} Q(k,m) e^{j\frac{2\pi nk}{N}}$$

(Equation 25)

where

$$Q(k,m) = Y_m(k)\, S_m^*(k)$$

(Equation 26)

Accordingly, $r(n,m)$ represents the cyclic correlation between the received signal and the transmitted signal, computed using the cyclic convolution theorem. $Q(k,m)$ (which may herein be referred to as correlation intermediate term) represents the product of the DFT of the received signal ($y_m(n)$) (denoted by $Y_m(k)$) and the conjugate of the DFT of the transmitted signal ($s_m(n)$) (denoted by $S_m(k)$). It will be understood by a person skilled in the art that n (index within each OFDM symbol) corresponds to the time domain and represents the index within each OFDM symbol. It indicates time shifts or delays within a given symbol, and typically ranges from 0 to $N-1$, where N is the length of each OFDM symbol. m (OFDM symbol index) corresponds to the index of the OFDM symbol in the sequence of transmitted symbols. It indicates the position of the m-th OFDM symbol in the overall transmission frame. The range of m is from 0 to $M-1$, where M is the total number of OFDM symbols. k (subcarrier index) corresponds to the subcarrier index in the frequency domain, with values from 0 to $N-1$, where N is the number of subcarriers in the OFDM system. $r(n,m)$ is in the time domain since it represents the cyclic correlation between the received signal and the transmitted signal. The index n is a time index, and the correlation is calculated within the time domain for each OFDM symbol m. $Q(k,m)$ is in the frequency domain, as it represents the product of the DFT of the received signal $Y_m(k)$ and the conjugate of the DFT of the transmitted signal $S_m(k)$. The index k corresponds to the subcarrier index, and the DFTs $Y_m(k)$ and $S_m(k)$ represent the signals in the frequency domain.

[0095] The RDM, denoted as $\mathbf{R(n,k)}$, may then be determined by performing the DFT of the cyclic correlation data $r(n,m)$ on the second dimension. The peak of the RDM matrix $|\mathbf{R(n,k)}|$ may then be determined to obtain the range ε_1 and speed v_1 of the dominant target (e.g., strongest target with the strongest target signal amongst multiple targets) as described hereinbefore. When performing the DFT of the cyclic correlation data $r(n,m)$ on the second dimension, the second dimension refers to the OFDM symbol index m. In other words, the DFT is applied across the OFDM symbols (indexed by m) to transform the data from the time domain to the frequency domain. Therefore, the second dimension is the m-axis, and the DFT transforms $r(n,m)$ in terms of how it varies across different OFDM symbols.

[0096] 2. Average correlation intermediate term over subcarriers with range compensation (e.g., if or based on multiple targets having different ranges) (e.g., corresponding to determining

the first dominant target attributed correlation intermediate term described hereinbefore according to various embodiments of the present invention): The obtained correlation intermediate term $\boldsymbol{Q(k,m)}$ in step 1 is averaged over subcarriers with compensation or adjustment based on the detected range of the strongest target, so as to obtain the influence or contribution of the strongest target. For example, the average of correlation over data subcarriers subjected to compensation or adjustment based on the detected range of the strongest target may be expressed as:

$$\bar{\boldsymbol{Q}}(\boldsymbol{m}) = \frac{\mathbf{1}}{\boldsymbol{N}} \sum_{\boldsymbol{k=0}}^{\boldsymbol{N-1}} \boldsymbol{Q(k,m)} e^{j\frac{2\pi k\varepsilon_1}{N}}$$

(Equation 27)

[0097] 3. Cancel strongest target over subcarriers (e.g., corresponding to offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term as described hereinbefore according to various embodiments of the present invention): To mitigate the interference from the detected dominant target, the effects or contribution caused by the strongest target in the correlation intermediate term over subcarriers is cancelled or removed. The residual correlation intermediate term after strong/dominant signal cancellation in frequency domain may be given by:

$$\tilde{\boldsymbol{Q}}(\boldsymbol{k,m}) = \boldsymbol{Q(k,m)} - \bar{\boldsymbol{Q}}(\boldsymbol{m}) e^{j\frac{-2\pi k\varepsilon_1}{N}}$$

(Equation 28)

[0098] 4. Average correlation intermediate term across OFDM symbols with speed compensation (e.g., if or based on multiple targets having different speeds or if or based on multiple targets having different ranges and speeds) (e.g., corresponding to determining the first dominant target attributed correlation intermediate term if or based on multiple targets having different speeds (without different ranges) or corresponding to the second dominant target attributed correlation intermediate term if or based on multiple targets having different ranges and speeds as described hereinbefore according to various embodiments of the present invention): The average of correlation intermediate term subjected to compensation or adjustment based on the speed of the strongest target may be given by:

$$\breve{\boldsymbol{Q}}(\boldsymbol{k}) = \frac{\mathbf{1}}{\boldsymbol{M}} \sum_{\boldsymbol{m=1}}^{\boldsymbol{M}} \boldsymbol{Q(k,m)} e^{-j2\pi m N_a v_1}$$

(Equation 29)

[0099] 5. Cancel strongest target across OFDM symbols (e.g., corresponding to offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term (from step 1 above) if or based on multiple targets having different speeds (without different ranges) or corresponding to the offsetting the second dominant target attributed correlation intermediate term from the residual correlation intermediate term (from step 3 above) if or based on multiple targets having different ranges and speeds as described hereinbefore according to various embodiments of the present invention): The effects or contribution caused by the strongest target in the correlation intermediate term are cancelled across OFDM symbols. The residual correlation intermediate term (or modified correlation intermediate term) after strong signal cancellation across OFDM symbols may be given by:

$$\tilde{\boldsymbol{Q}}(\boldsymbol{k},\boldsymbol{m}) = \boldsymbol{Q}(\boldsymbol{k},\boldsymbol{m}) - \check{\boldsymbol{Q}}(\boldsymbol{k})\boldsymbol{e}^{j2\pi m N_a v_1}$$

(Equation 30)

where $\boldsymbol{Q}(\boldsymbol{k},\boldsymbol{m})$ may be the correlation intermediate term from step 1 above (if or based on multiple targets having different speeds (without different ranges)) or the residual correlation intermediate term from step 3 above (if or based on multiple targets having different ranges and speeds).

[00100] 6. Calculate updated cyclic correlation: IFFT is performed on $\tilde{\boldsymbol{Q}}(\boldsymbol{k},\boldsymbol{m})$ to obtain the modified or updated cyclic correlation given by for each OFDM symbol to obtain:

$$\tilde{\boldsymbol{r}}(\boldsymbol{n},\boldsymbol{m}) = \frac{\boldsymbol{1}}{\boldsymbol{N}}\sum_{\boldsymbol{k}=\boldsymbol{0}}^{\boldsymbol{N-1}} \tilde{\boldsymbol{Q}}(\boldsymbol{k},\boldsymbol{m})\boldsymbol{e}^{\boldsymbol{j}\frac{\boldsymbol{2\pi nk}}{\boldsymbol{N}}}$$

(Equation 31)

[00101] 7. Recompute RDM based on updated correlation: Recomputing RDM matrix $\tilde{\boldsymbol{R}}(\boldsymbol{n},\boldsymbol{k})$ by calculating the DFT of the updated correlation term (or updated cyclic correlation) $\tilde{\boldsymbol{r}}(\boldsymbol{n},\boldsymbol{m})$ on the second dimension (i.e., the OFDM symbol index $\boldsymbol{m}$):

$$\tilde{\boldsymbol{R}}(\boldsymbol{n},\boldsymbol{k}) = \sum_{\boldsymbol{m}=\boldsymbol{0}}^{\boldsymbol{M-1}} \tilde{\boldsymbol{r}}(\boldsymbol{n},\boldsymbol{m})\boldsymbol{e}^{\boldsymbol{j}\frac{\boldsymbol{-2\pi mk}}{\boldsymbol{M}}}$$

(Equation 32)

[00102] 8. Re-detection range and speed: Re-detection of the range and speed of the strongest target after strongest target cancellation by finding the peak in the updated RDM matrix $\tilde{\boldsymbol{R}}(\boldsymbol{n},\boldsymbol{k})$ according to Equation (33) below. This step helps to ensure the correct estimation of the remaining strongest target's range and speed after cancellation.

$$(\boldsymbol{n_2},\boldsymbol{k_2}) = \arg\max_{(n,k)} \left|\tilde{\boldsymbol{R}}(\boldsymbol{n},\boldsymbol{k})\right|$$

(Equation 33)

The normalized range and speed may then be obtained as: $\boldsymbol{\varepsilon_2 = n_2}$, $\boldsymbol{v_2 = k_2/(MN_a)}$.

[00103] 9. Iterative Cancellation and Detection: The method then returns to step 2, where the strong target cancellation is performed iteratively. This allows for the progressive detection of weaker targets by cancelling one strong target at a time, until all expected targets are detected.

[00104] Simulation results of the iterative strong targets cancellation multi-target detection method or algorithm according to various example embodiments of the present invention (hereinafter referred to as the present method or algorithm) using the 5G NR signal generated by the MATLAB 5G toolbox will now be discussed. The simulation settings/parameters are shown in Table 1 below.

Table 1: Simulation Parameters

Channel bandwidth	50 MHz
Carrier frequency	5.9 GHz
Subcarrier spacing	15 KHz
Modulation scheme	QPSK
FFT size	4096
Symbols per slot	14
Slots per subframe	1
Slots per frame	10
Range of radar objects	[90 240] m
Speed of radar objects	[0 100] km/h

[00105] In the simulation, the focus is on comparing the performance of three different algorithms in detecting the weak target, given that the strong target is detectable by all algorithms. The three different algorithms are a conventional strongest target detection method based on range (or range-based search method), a conventional CFAR (Constant False Alarm Rate) method and the iterative strong targets cancellation method according to various example embodiments of the present invention (which may herein be referred to as the present method). The conventional range-based search method identifies targets based on their predetermined range, searching within specific range bins to detect the strongest target. The CRAR method compares the power of potential targets to an estimated noise level and the surrounding power level for detection. The iterative strong targets cancellation method iteratively cancels out the interference from strong targets, improving detection accuracy and enhancing the signal-to-

noise ratio for weaker targets. The power of the weak target is assumed to be 10 dB weaker than the strong target, and three specific scenarios are considered in the simulation, including same range area, same range, and multiple users sharing the spectrum.

[00106] In the same range area scenario, both the strong and weak targets are in the same range area, i.e., between 90 and 240 meters. It means that they are at different distances from the radar, but their range values fall within a specific region. This scenario tests the algorithms' ability to distinguish and detect targets that are closely spaced in range. FIGs. 6 and 7 show the range and speed detection performance in the same range area scenario, respectively. It can be observed that the conventional range-based search method struggles to differentiate between the targets, leading to poor performance in detecting the weaker target. Similarly, the conventional CFAR method, which relies on thresholding based on noise estimate and surrounding signal strengths, may prioritize the stronger target, and fail to detect the weaker one effectively. In contrast, the present method provides accurate range and speed detection for the weak target when the signal-to-noise ratio (SNR) is greater than -25 dB. This result demonstrates the effectiveness of the present method in enhancing weak signal detection under challenging conditions with strong interference.

[00107] In the same range scenario, both the strong and weak targets have exactly the same range value. It means that they are located at the same distance from the radar. This scenario challenges the algorithms to differentiate between targets with identical range values and detect the weaker one. FIGs. 8 and 9 illustrate the superiority of the present method over conventional range-based search and CFAR methods in terms of range and speed detection, respectively. In this case, the traditional range-based search method may incorrectly identify the strong target as the weak target since both targets have the same range value. As a result, the conventional range detection appears to give good performance but leads to inaccurate speed detection, as the method detects the speed of the strong target instead of the weak target. Similarly, the conventional CFAR method also struggles in this scenario, as it may prioritize the stronger target and fail to detect the weaker target accurately. In contrast, the present method with strong target cancellation exhibits remarkable performance even in this extreme case. By cancelling the effects of the strong target, the present method is still able to accurately detect the range and speed of the weaker target. This ability to correctly identify the weaker target despite having the same range value as the strong target showcases the robustness and effectiveness of the present method.

[00108] The scenario involving multiple users sharing the spectrum, which can introduce interference and make target detection more challenging. FIGs. 10-15 show the range and speed detection performance of the three different algorithms under two users, four users and eight users sharing scenarios, respectively. In this complex scenario, each user only has access to a limited number of subcarriers for radar detection and the presence of other users might also affect the detection of the weak target. From FIGs. 10-15, it can be seen that the present method (iterative strong target cancellation approach) demonstrates excellent performance in range and speed detection even in scenarios with multiple users sharing the spectrum. When two users share the spectrum as shown in FIGs. 10 and 11, accurate range and speed detection can be achieved when SNR is slightly greater than -20 dB. In the worst-case scenario, where eight users share the spectrum and only 1/8 subcarriers are used for radar detection for each user as shown in FIGs. 14-15, the present method still achieves good range and speed detection accuracy when the SNR is greater than -10 dB. In comparison, traditional methods such as the range-based search and CFAR methods are not able to detect weak targets effectively in this scenario, as they use only a small number of subcarriers for radar detection and there are a lot of interference from other users. Accordingly, as demonstrated, the present method is highly effective in enabling accurate range and speed detection in situations where multiple users share the spectrum, even when resources are constrained. The present method outperforms traditional methods, which struggle to detect weak targets under similar conditions.

[00109] Accordingly, a method for iterative strong targets cancellation for multi-targets detection in JRC systems is provided according to various example embodiments of the present invention. The method employs strong signal cancellation to mitigate the effects of dominant targets, enabling the detection of weaker signals even in the presence of strong interference. This method can be done iteratively to cancel strong targets one by one, until all desired weak targets are detected. In addition, this method has low complexity and addresses various challenges associated with JRC systems. Its ability to detect weak signals in the presence of strong interference, superior performance compared to conventional methods, adaptability to different JRC systems, effectiveness in close-distance and high-speed scenarios, and compatibility with spectrum sharing make it a promising and valuable solution for integrated radar and communication applications.

[00110] Accordingly, the iterative strong targets cancellation method according to various example embodiments provides a number of technical advantages for JRC systems, such as but not limited to the following.

[00111] Improved weak target detection: By employing strong target cancellation, the method enhances the system's ability to detect weaker targets even in the presence of strong interference. This is particularly beneficial in crowded or challenging environments where strong targets from nearby sources could obscure the detection of weaker targets.

[00112] Addressing close-distance and high-speed scenarios: The method is effective in scenarios where multiple targets are closely spaced, potentially even at the same location, and have high relative velocities. This makes it well-suited for dynamic environments where targets may be in proximity to each other and rapidly moving.

[00113] Adaptability to spectrum Sharing: The method's ability to work with sparse data subcarriers further enhances its practicality and resource efficiency in JRC scenarios. Spectrum sharing is a critical aspect of JRC systems, and the method's ability to handle sparse data subcarriers ensures efficient utilization of the shared spectrum.

[00114] Adaptability to JRC systems: The method's versatility allows it to be applied to various types of JRC systems, including OFDM, SC-CP, 5G, 5G side link, and 6G OTFS systems. This adaptability makes it suitable for different integrated systems, enabling its use across a wide range of applications.

[00115] Performance comparison: The method outperforms conventional range or speed-based methods and CFAR algorithms in terms of target detection accuracy and robustness. This superiority indicates that the method is more effective in detecting targets accurately and reliably, even under challenging conditions.

[00116] 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 radar sensing for detecting multiple targets, the method comprising:

determining a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term;

determining a range-Doppler map based on the channel estimation or the cyclic correlation;

detecting a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation; and

for each iteration of a plurality of iterations:

determining a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target;

modifying the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term;

determining a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and

detecting a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

2. The method according to claim 1, wherein

said detecting the dominant target comprises:

locating a peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation as corresponding to the dominant target; and

determining a range and a speed of the dominant target based on the located peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation, and

said detecting the next dominant target comprises:

locating a peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation as corresponding to the next dominant target; and

determining a range and a speed of the next dominant target based on the located peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

3. The method according to claim 2, wherein

said determining the first dominant target attributed channel estimation comprises determining an average of the channel estimation over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation over the set of data subcarriers, or

said determining the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed correlation intermediate term for representing a contribution of the detected dominant target to the correlation intermediate term over the set of data subcarriers.

4. The method according to claim 3, wherein

said offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation, or

said offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

5. The method according to claim 2, wherein

said determining the first dominant target attributed channel estimation comprises determining an average of the channel estimation across a set of orthogonal frequency-division multiplexing (OFDM) symbols of the transmitted signal subject to an adjustment based on the

determined speed of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation across the set of OFDM symbols, or

said determining the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the first dominant target attributed correlation intermediate term for representing for a contribution of the detected dominant target to the correlation intermediate term across the set of OFDM symbols.

6. The method according to claim 5, wherein

said offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation, or

said offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

7. The method according to claim 4, wherein said modifying the channel estimation or the cyclic correlation further comprises:

determining a second dominant target attributed channel estimation or a second dominant target attributed correlation intermediate term based on the detected dominant target,

said determining the second dominant target attributed channel estimation comprises determining an average of the residual channel estimation across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed channel estimation for representing a contribution of the detected dominant target to the residual channel estimation across the set of OFDM symbols, or

said determining the second dominant target attributed correlation intermediate term comprises determining an average of the residual correlation intermediate term across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed correlation

intermediate term for representing for a contribution of the detected dominant target to the residual correlation intermediate term across the set of OFDM symbols.

8. The method according to claim 7, wherein said modifying the channel estimation or the cyclic correlation further comprises:

offsetting the second dominant target attributed channel estimation from the residual channel estimation, comprises performing a subtraction on the residual channel estimation based on the second dominant target attributed channel estimation to obtain the modified channel estimation, or

offsetting the second dominant target attributed correlation intermediate term from the residual correlation intermediate term, comprises performing a subtraction on the residual correlation intermediate term based on the second dominant target attributed correlation intermediate term to obtain a modified correlation intermediate term, wherein the modified cyclic correlation is determined based on the modified correlation intermediate term.

9. The method according to claim 1, wherein

the radar sensing is OFDM-based radar sensing,

said determining the channel estimation comprises determining the channel estimation in a frequency domain based on the received signal and the transmitted signal, and

said determining the range-Doppler map based on the channel estimation comprises performing a two-dimensional (2D) fast Fourier transform (FFT) on the channel estimation to obtain the range-Doppler map.

10. The method according to claim 1, wherein

the radar sensing is fast cyclic correlation radar (FCCR)-based radar sensing,

said determining the cyclic correlation comprises performing a multiplication of a discrete Fourier transform (DFT) of the received signal and a conjugate of the DFT of the transmitted signal, and

said determining the range-Doppler map based on the cyclic correlation comprises performing a DFT based on the cyclic correlation to obtain the range-Doppler map.

11. A system for radar sensing for detecting multiple targets, the system comprising:

at least one memory; and

at least one processor communicatively coupled to the at least one memory and configured to:

determine a channel estimation or a cyclic correlation based on a received signal and a transmitted signal, wherein the received signal is reflected from multiple targets from the transmitted signal and the cyclic correlation is determined based on a correlation intermediate term;

determine a range-Doppler map based on the channel estimation or the cyclic correlation;

detect a dominant target amongst the multiple targets based on the range-Doppler map determined based on the channel estimation or the cyclic correlation; and

for each iteration of a plurality of iterations:

determine a first dominant target attributed channel estimation or a first dominant target attributed correlation intermediate term based on the detected dominant target;

modify the channel estimation or the cyclic correlation comprising offsetting the first dominant target attributed channel estimation from the channel estimation or offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term;

determine a range-Doppler map based on the modified channel estimation or the modified cyclic correlation; and

detect a next dominant target amongst the multiple targets based on the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

12. The system according to claim 11, wherein

said detect the dominant target comprises:

locating a peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation as corresponding to the dominant target; and

determining a range and a speed of the dominant target based on the located peak in the range-Doppler map determined based on the channel estimation or the cyclic correlation, and

said detect the next dominant target comprises:

locating a peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation as corresponding to the next dominant target; and

determining a range and a speed of the next dominant target based on the located peak in the range-Doppler map determined based on the modified channel estimation or the modified cyclic correlation.

13. The system according to claim 12, wherein

said determine the first dominant target attributed channel estimation comprises determining an average of the channel estimation over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation over the set of data subcarriers, or

said determine the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term over a set of data subcarriers subject to an adjustment based on the determined range of the detected dominant target to obtain the first dominant target attributed correlation intermediate term for representing a contribution of the detected dominant target to the correlation intermediate term over the set of data subcarriers.

14. The system according to claim 13, wherein

said offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation, or

said offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

15. The system according to claim 12, wherein

said determine the first dominant target attributed channel estimation comprises determining an average of the channel estimation across a set of orthogonal frequency-division multiplexing (OFDM) symbols of the transmitted signal subject to an adjustment based on the

determined speed of the detected dominant target to obtain the first dominant target attributed channel estimation for representing a contribution of the detected dominant target to the channel estimation across the set of OFDM symbols, or

said determine the first dominant target attributed correlation intermediate term comprises determining an average of the correlation intermediate term across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the first dominant target attributed correlation intermediate term for representing for a contribution of the detected dominant target to the correlation intermediate term across the set of OFDM symbols.

16. The system according to claim 15, wherein

said offsetting the first dominant target attributed channel estimation from the channel estimation comprises performing a subtraction on the channel estimation based on the first dominant target attributed channel estimation to obtain a residual channel estimation, or

said offsetting the first dominant target attributed correlation intermediate term from the correlation intermediate term comprises performing a subtraction on the correlation intermediate term based on the first dominant target attributed correlation intermediate term to obtain a residual correlation intermediate term.

17. The system according to claim 14, wherein said modify the channel estimation or the cyclic correlation further comprises:

determining a second dominant target attributed channel estimation or a second dominant target attributed correlation intermediate term based on the detected dominant target,

said determining the second dominant target attributed channel estimation comprises determining an average of the residual channel estimation across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed channel estimation for representing a contribution of the detected dominant target to the residual channel estimation across the set of OFDM symbols, or

said determining the second dominant target attributed correlation intermediate term comprises determining an average of the residual correlation intermediate term across a set of OFDM symbols of the transmitted signal subject to an adjustment based on the determined speed of the detected dominant target to obtain the second dominant target attributed correlation

intermediate term for representing for a contribution of the detected dominant target to the residual correlation intermediate term across the set of OFDM symbols.

18. The system according to claim 17, wherein said modify the channel estimation or the cyclic correlation further comprises:

offsetting the second dominant target attributed channel estimation from the residual channel estimation, comprises performing a subtraction on the residual channel estimation based on the second dominant target attributed channel estimation to obtain the modified channel estimation, or

offsetting the second dominant target attributed correlation intermediate term from the residual correlation intermediate term, comprises performing a subtraction on the residual correlation intermediate term based on the second dominant target attributed correlation intermediate term to obtain a modified correlation intermediate term, wherein the modified cyclic correlation is determined based on the modified correlation intermediate term.

19. The system according to claim 11, wherein

the radar sensing is OFDM-based radar sensing,

said determine the channel estimation comprises determining the channel estimation in a frequency domain based on the received signal and the transmitted signal, and

said determine the range-Doppler map based on the channel estimation comprises performing a 2D fast Fourier transform (FFT) on the channel estimation to obtain the range-Doppler map.

20. The system according to claim 11, wherein

the radar sensing is fast cyclic correlation radar (FCCR)-based radar sensing,

said determine the cyclic correlation comprises performing a multiplication of a discrete Fourier transform (DFT) of the received signal and a conjugate of the DFT of the transmitted signal, and

said determine the range-Doppler map based on the cyclic correlation comprises performing a DFT based on the cyclic correlation to obtain the range-Doppler map.

21. A radar for detecting multiple targets, the radar comprising:

one or more antennas; and

the system for radar sensing for detecting multiple targets according to claim 11 communicatively coupled to the one or more antennas for performing radar sensing.