

RADAR DEVICE AND METHOD FOR PERFORMING RADAR DETECTION**Technical Field**

[0001] The present disclosure relates to radar devices and methods for performing radar detection.

Background

[0002] To support driver assistance system and application, both automotive radar sensing technology and vehicle-to everything (V2X) communication technology including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) communication may be used. In such an application, an automotive radar system is responsible for the detection of objects and obstacles and the vehicle's position and its velocity relative to the other objects. Depending on the application scenarios for emerging self-driving, three types of automotive radar sensors that operate at the 77 GHz frequency band, namely, the long range radar (LRR), the medium range radar (MRR) and the short range radar (SRR), have been considered. Vehicular communications allows vehicles to exchange safety messages or sensor data for applications such as do-not-pass warning and cooperative adaptive cruise control. For this purpose, dedicated short range communication (DSRC) that is based on the wireless local area network (WLAN) standard known as the IEEE 802.11p has been deployed to enable collision prevention application. Specifically, each DSRC-equipped vehicle broadcasts its basic state information such as location, velocity and acceleration several times per second over a range of a few hundred meters. The receiving object will then use these messages to determine if there is a collision threat. Although the design and development of automotive radar and DSRC-based vehicular communication can address the demands of a driver assistance system, it is neither cost effective nor operational efficient to use different spectrums and different sets of products for radar function and V2X communication separately. Efficient approaches would be desirable which allow the dual use of a radio waveform and signal processing for both radar (e.g. vehicular radar sensing) and radio communication (e.g. V2X communication).

Summary

[0003] According to one embodiment, a radar device is provided comprising a transmitter configured to transmit a first transmit signal and, after the first transmit signal, a second transmit signal, wherein the first transmit signal comprises at least a part of a preamble of a communication packet, a receiver and a radar processor configured to convolve a first receive signal received by the receiver with the first transmit signal and to generate a first delay-Doppler map, comprising, for each delay-Doppler bin of a set of delay-Doppler bins, a radar response value, from the result of the convolution of the first receive signal with the first transmit signal, convolve a second receive signal received by the receiver with the second transmit signal and to generate a second delay-Doppler map, comprising, for each delay-Doppler bin of the set of delay-Doppler bins, a radar response value, from the result of the convolution of the second receive signal with the second transmit signal, combine the first delay-Doppler map with the second delay-Doppler map by taking, for each delay-Doppler map bin of the set of delay-Doppler bins, the minimum of the value of the first delay-Doppler map for the delay-Doppler map bin and the value of the second delay-Doppler map for the delay-Doppler map bin and determine the range and velocity of one or more objects from the result of the combination.

[0004] According to one embodiment, the communication packet is a physical layer radio transmission frame.

[0005] According to one embodiment, the at least a part of the preamble is a first part of the preamble and the second transmit signal comprises a second part of the preamble or the second transmit signal comprises at least a part of the payload data of the communication packet.

[0006] According to one embodiment, the first transmit signal and the second transmit signal comprise a complementary pair of a Golay complementary code.

[0007] According to one embodiment, the transmitter is configured to transmit the first transmit signal by single-carrier transmission and to transmit the second transmit signal by multi-carrier transmission, wherein the second transmit signal comprises another part of the preamble.

[0008] According to one embodiment, the transmitter is configured to transmit the first transmit signal by single-carrier transmission and to transmit the second transmit signal by single-carrier transmission, wherein the second transmit signal comprises at least a part of the payload data of the communication packet. According to one embodiment, the transmitter is configured to transmit a plurality of first transmit signals and the radar processor is configured to convolve, for each first transmit signal, a respective first receive signal of a plurality of first receive signals with the first transmit signal and to generate the first delay-Doppler map by combining, per delay-Doppler bin, the results of the convolutions of the first receive signals with the first transmit signals.

[0009] According to one embodiment, the transmitter is configured to transmit a plurality of second transmit signals and the radar processor is configured to convolve, for each second transmit signal, a respective second receive signal of a plurality of second receive signals with the second transmit signal and to generate the second delay-Doppler map by combining, per delay-Doppler bin, the results of the convolutions of the second receive signals with the second transmit signals.

[0010] According to one embodiment, the combination of the first delay-Doppler map with the second delay-Doppler map gives a combined delay-Doppler map, wherein the transmitter is configured to transmit, after the second transmit signal, a third transmit signal and wherein the radar processor is configured to convolve a third receive signal received by the receiver with the third transmit signal and to generate a third delay-Doppler map, comprising, for each delay-Doppler bin of the set of delay-Doppler bins, a radar response value, from the result of the convolution of the third receive signal with the third transmit signal, combine the combined delay-Doppler map with the third delay-Doppler map by taking, for each delay-Doppler map bin of the set of delay-Doppler bins, the minimum of the value of the combined delay-Doppler map for the delay-Doppler map bin and the minimum of the value of the third delay-Doppler map for the delay-Doppler map bin and determine the range and velocity of one or more objects from the result of the combination of the combined delay-Doppler map with the third delay-Doppler map.

[0011] According to one embodiment, the first transmit signal is at least a part of a preamble of a physical layer radio transmission frame, the second transmit signal is at least a part of the preamble of a physical layer radio transmission frame and the third

transmit signal is at least a part of the payload data of the physical layer radio transmission frame.

[0012] According to one embodiment, the combination of the first delay-Doppler map with the second delay-Doppler map gives a combined delay-Doppler map, wherein the transmitter is configured to transmit, after the second transmit signal, a sequence of third transmit signals and wherein the radar processor is configured to generate, starting from the combined delay-Doppler map and until a final delay Doppler map, a sequence of delay-Doppler maps by, for each third transmit signal, convolving the third receive signal received by the receiver with the third transmit signal and generating a respective third delay-Doppler map, comprising, for each delay-Doppler bin of the set of delay-Doppler bins, a radar response value, from the result of the convolution of the third receive signal with the third transmit signal and generating a respective delay-Doppler map for the sequence by combining the delay-Doppler map which is currently the last delay-Doppler map of the sequence with the third delay-Doppler map by taking, for each delay-Doppler map bin of the set of delay-Doppler bins, the minimum of the value of the combined delay-Doppler map for the delay-Doppler map bin and the minimum of the value of the third delay-Doppler map for the delay-Doppler map bin and to determine the range and velocity of one or more objects from the final delay-Doppler map of the sequence.

[0013] According to one embodiment, the first transmit signal is at least a part of a preamble of a physical layer radio transmission frame, the second transmit signal is at least a part of the preamble of a physical layer radio transmission frame and the third transmit signals are consecutive segments of the payload data of the physical layer radio transmission frame.

[0014] According to one embodiment, a computer program element is provided including program instructions, which, when executed by one or more processors, cause the one or more processors to perform one of the methods described above.

[0015] According to one embodiment, a computer-readable medium is provided including program instructions, which, when executed by one or more processors, cause the one or more processors to perform one of the methods described above.

[0016] It should be noted that embodiments described in context of one or the radar device are analogously valid for the method for performing radar detection and vice versa.

Brief Description of the Drawings

[0017] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various aspects are described with reference to the following drawings, in which:

Figure 1 shows a vehicle equipped with a radar system.

Figure 2 illustrates a first signalling scheme for vehicular communication and automotive radar sensing.

Figure 3 illustrates a second signalling scheme for vehicular communication and automotive radar sensing.

Figure 4 shows the structure and modulation scheme of a PHY (physical layer) frame.

Figure 5 shows a CEF (channel estimation field) packet according to an embodiment.

Figure 6 illustrates radar signal processing according to an embodiment.

Figures 7A, 7B and 7C show an AF (ambiguity function) comparison of an LFM (linear frequency modulated) chirp used in automotive radar, an IEEE 802.11ad design and the approach of figure 6, respectively.

Figure 8 illustrates radar processing using delay-Doppler map fusion between a delay-Doppler map generated by the approach of figure 6 and delay-Doppler maps generated from communication single-carrier data.

Figure 9 shows the results of three iterations of delay-Doppler fusion.

Figure 10 illustrates the fusion of the delay-Doppler map generated from a single-carrier data segment with more than 256 bit with a delay-Doppler map

generated from a CEF as illustrated in figure 5 in the manner of figure 6.

Figure 11 shows in a first diagram a plot of the AF for a length-256 min-point GCC (Golay complementary code) approach and in a second diagram the fused AF with length-8192 single-carrier data.

Figure 12 shows a graph indicating the zero-delay cut of the plot of the diagrams.

Figure 13 illustrates the overlapping of received echoes of a transmitted CEF packet for a three-target case.

Figure 14 shows the delay-Doppler map generated for this three target case using a min-point GCC approach with length 256 bit.

Figure 15 shows a performance comparison between IEEE 802.11ad and an embodiment.

Figure 16 illustrates another three-target scenario.

Figure 17 shows the corresponding delay-Doppler response in the presence of three targets for IEEE 802.11ad and for the min-point GCC approach according to an embodiment.

Figure 18 shows a radar device according to an embodiment.

Figure 19 shows a flow diagram illustrating a method for radar detection.

Description

[0018] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and aspects of this disclosure in which the invention may be practiced. Other aspects may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various aspects of this disclosure are not necessarily mutually exclusive, as some aspects of this disclosure can be combined with one or more other aspects of this disclosure to form new aspects.

[0019] The embodiments described herein may for example be applied for radar sensing in a vehicle for autonomous driving or assisting the driver.

[0020] Figure 1 shows a vehicle 100.

[0021] The vehicle 100 includes a radar device (or radar system) 101 that includes an antenna arrangement 102, a frontend 103 and a radar processor 104.

[0022] The antenna arrangement 102, the frontend 103 (and optionally components (e.g. circuitry) which are part of the radar processor 104) form a radar sensor.

[0023] The frontend 103 for example includes one or more (radar) transmit circuits and one or more (radar) receiver circuits. The antenna arrangement 102 may include multiple transmit antennas in the form of a transmit antenna array and multiple receive antennas in the form of a receive antenna array or one or more antennas used both as transmit and receive antennas. In the latter case, the frontend 103 for example includes a duplexer (i.e. a circuit to separate transmitted signals from received signals).

[0024] For the detection of an object 106, e.g. another vehicle, the radar processor 104 transmits, using the frontend 103 and the antenna arrangement 102, a radio transmit signal 105.

[0025] The radio transmit signal 105 is reflected by the object 106 resulting in an echo 107.

[0026] The radar device 101 receives the echo 107 and the radar processor 104 calculates information about position, speed and direction of the object 106 with respect to the vehicle 100. The radar processor 104 may then for example supply this calculated information to a vehicle controller 108 of the vehicle 100, e.g. for autonomous driving of the vehicle 100, to facilitate operation of the vehicle 100.

[0027] The vehicle 100 may further comprise a radio communication device 109 for radio communication of useful data, e.g. including a communication baseband processor. The communication module 109 may have its own frontend and antenna arrangement but uses, according to various embodiments, the frontend 103 and the antenna arrangement 102 for communication.

[0028] The object 106 may also be capable of radio communication such that the vehicle 100, using its communication module 109, may exchange data with the object 106, e.g. using vehicle-to-vehicle (V2V) communication in case that the object is another vehicle. It should be noted that the object 106 may also be another device supporting radio communication and the vehicle 100 may then for example use vehicle-to-everything (V2X) communication for communicating data with the object.

[0029] Figure 2 illustrates a first signalling scheme for vehicular communication and automotive radar sensing.

[0030] In figure 2, a vehicle 201 (e.g. corresponding to vehicle 100) transmits two separate signals 202, 203 to an object 204 (e.g. corresponding to object 106) for data communication (first signal 202) and radar (second signal 203, whose reflection is received for radar detection by the vehicle 201).

[0031] Figure 3 illustrates a second signalling scheme for vehicular communication and automotive radar sensing.

[0032] In figure 3, a vehicle 301 (e.g. corresponding to vehicle 100) transmits a single signal 302 to an object 303 (e.g. corresponding to object 106) for both data communication and radar.

[0033] This means that the object 303 receives the signal (having a suitable waveform as described below) for communication and its reflected echo 304 can be used by the vehicle 301 for radar processing (detection of the object 303, determining its range, velocity and/or direction from the vehicle 301).

[0034] In the following, approaches are described to achieve a combined usage of a signal for communication and radar, e.g. to achieve a joint, simultaneous V2X communication and automotive radar sensing by making use of one single signalling waveform.

[0035] It should be noted that schemes for such joint radar-communication can typically generally be categorized into two approaches: accomplishing the additional radar function by leveraging on the communication waveforms, or achieving the additional communication function by exploiting the radar waveforms. For example, a linear frequency modulated (LFM) signal (also called chirped signal) which is a radar waveform may be used for communication co-design. However, although the LFM chirp signal may be considered for wireless spread-spectrum communications, it has not been widely adopted in V2X communication standards, either in the WLAN-based Wi-Fi system or in the cellular-based 3GPP LTE system. Therefore, the more promising method may be seen in that to make use of the communication specification to further develop the radar function. Orthogonal frequency-division multiplexing (OFDM) signalling may be used to estimate the radar parameters and there is IEEE 802.11p-based OFDM radar

processing. However, despite that OFDM is a suitable waveform for both communication and radar, the side lobe levels are not ideal for radar ranging. Moreover, due to the insufficient bandwidth, the IEEE 802.11p-based radar waveforms cannot meet the range and speed resolution requirement of automotive sensing. Another approach is a joint vehicular communication and radar system that operate at a millimetre wave (mmWave) 60 GHz band based on the IEEE 802.11ad WLAN standard specification. The high frequency in the IEEE 802.11ad allows it to use more bandwidth which enables the transmission of data at high data rates up to multiple gigabits per second. It should be noted that since cellular V2X (C-V2X) that is based on the 3GPP LTE technology could in future be upgraded to 5G which is also adopting mmWave signals as its transmission medium, it is of great interest and opportunity to develop a new multi-function system using mmWave for radar sensing and V2X communication.

[0036] Another approach is to make use of the single-carrier (SC) physical layer (PHY) frame structure of IEEE 802.11ad. Specifically, the preamble packet of the SC PHY frame that is used in data communication for frame synchronization and channel state information (CSI) estimation may be exploited in the design for simultaneous radar parameter estimation. A reason for selecting the preamble of the SC PHY frame may lie in that it has similar structure to that in other PHY frames, and furthermore, the implementation of the SC PHY frame is often mandatory (depending on the application). Since the SC PHY frame is configured according to a communication specification, its suitability of its preamble for automotive sensing should typically be examined by a radar performance metric. The ambiguity function (AF) is a measure for determining the goodness of a given radar signal waveform, where this goodness is measured by its range and Doppler resolution. Denoting the complex baseband radar signal as $s(t)$, the narrowband AF is defined as:

$$|\chi(\tau, \nu)| = \left| \int_{-\infty}^{\infty} s(t) s^*(t - \tau) \exp(j2\pi\nu t) dt \right| \quad (1)$$

[0037] (It should be noted that there are several versions for the AF definition, e.g., sometimes, the squared magnitude and the logarithmic scale are adopted, the definition here uses the magnitude).

[0038] The usage of narrowband AF definition is due to the fact that the recommended channelization in the IEEE 802.11ad comprises four channels, each 2.16 GHz wide, centred on 58.32 GHz, 60.48 GHz and 64.80 GHz, respectively. Hence, in comparison to the centred frequency, the channel width is much smaller. The AF in (1) is a two-dimensional function $|\chi(\tau, \nu)|$ of time delay τ and Doppler frequency ν that characterizes the response of a matched filter (e.g. in frontend 103) in the presence of uncompensated Doppler. The evaluation of the AF for various radar waveforms may be done via a graphic plot of $|\chi(\tau, \nu)|$ rather than an analytical expression. In the plot, the emphasis is on the side lobe relative to the main lobe.

[0039] Using AF plots, it can be seen the SC PHY preamble is feasible for radar sensing. According to various embodiments, its signal waveform design is adapted to achieve a better AF performance, such as that a lower side lobe for non-zero Doppler can be obtained to facilitate radar function. This means that according to various embodiments, a waveform design and signal processing for the dual radar-communication function (i.e. dual use of a radio waveform and signal processing for both radar, e.g. vehicular radar sensing, and radio communication, e.g. V2X communication) are provided with, according to various embodiments, minimum modification to the SC PHY frame structure and with essentially no performance degradation on the communication and improved radar sensing capability (e.g. as measured by AF plotting).

[0040] Specifically, according to various embodiments, the following are provided:

- A time-frequency signal processing and waveform design via point-wise minimum operation. The design is built upon the two pairs of Golay complementary code (GCC) whose structure conforms to the SC PHY preamble. One GCC pair (first part of preamble) remains unchanged, and hence, the CSI estimation in communication function is intact, and the other GCC pair (second part of preamble) is adapted for multi-carrier transmission. The obtained AF plot exhibits a “thumbtack” diagram with the desirable feature of side lobe-free zone inside a delay-Doppler region of interest.
- An AF fusion scheme to incorporate the communication single-carrier data sequence to further enhance AF performance, in particular, side lobe lowering

and Doppler resolution improvement. Thus, a communication single-carrier data packet can also be utilized for radar.

[0041] In the following, a GCC-based signal processing procedure and the resulting AF, an AF fusion algorithm are described.

[0042] First, the time-frequency GCC radar signal and a point-wise minimization radar processing procedure are described.

[0043] As mentioned above, the AF is a major tool for studying and analyzing radar waveforms. An ideal AF is represented by a spike of infinitesimal width that peaks at the original, namely, $(\tau, \nu) = (0, 0)$, and is zero everywhere else. This is an impulse function and has no ambiguities in the delay or Doppler shift. The feature of infinitesimal width at the original allows the delay and Doppler parameters to be estimated at the same time and with an arbitrarily high degree of accuracy. Unfortunately, due to maximum value and volume invariance properties of AF it can be been mathematically shown that a waveform with such an ideal AF does not exist. A waveform which gives an approximation to the ideal AF that satisfies various AF properties is therefore desirable. It should be noted that no analytic method exists for deriving the corresponding signal by first defining its desired AF. Therefore, the design of a radar signal and corresponding radar processing algorithm with desirable characteristics of the AF is typically based on a “trial and error” approach, through which the AF diagrams of different signals are evaluated to determine which of them is suitable for the specific application.

[0044] In the following, a scheme for joint V2X communication and automotive sensing is described that optimizes the trade-off between communication, radar sensing and conformity with SC PHY frame structure.

[0045] Figure 4 shows the structure and modulation scheme of a PHY frame 400.

[0046] The SC PHY frame 400 consists of a preamble packet that is composed of a short training field (STF) 401 and a channel estimation field (CEF), 402, a header packet 403 that contains important information such as the modulation and coding scheme (MCS) and the length of PHY frame, a communication single-carrier data packet 404 whose length varies in terms of number of bytes/octets, and an optional AGC (Automatic Gain Control) and training (TRN) packet 405 which can be used to optimize a beam forming setting.

[0047] According to an embodiment, the STF 401 and the CEF 402 in the preamble are generated from GCC with the two 128-bit building blocks Ga128 and Gb128 as specified in table 1 and table 2.

The Sequence $Ga_{128}(n)$, to be transmitted from left to right, up to down																																
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
-1	-1	+1	+1	+1	+1	+1	+1	-1	+1	-1	-1	+1	+1	-1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1																														

Table 1: Ga128

The Sequence $Gb_{128}(n)$, to be transmitted from left to right, up to down																															
-1	-1	+1	+1	+1	+1	+1	+1	-1	+1	-1	-1	+1	+1	-1	-1	-1	+1	+1	-1	-1	-1	+1	+1	-1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	-1	-1	+1	+1	-1	-1	-1	+1	+1	-1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	-1	-1	+1	+1	-1	-1	+1	-1	+1	+1	-1	-1
+1	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	+1	-1	-1	+1	+1	-1	-1	+1	+1	-1	-1	+1	-1	+1	+1	-1	-1

Table 2: Gb128

[0048] The ‘a’ and ‘b’ indicate that Ga128 and Gb128 form a complementary pair.

[0049] According to various embodiments, two pairs of GCC are used in the CEF packet 402.

[0050] Figure 5 shows a CEF packet 500 according to an embodiment.

The CEF packet 500 comprises Ga128 and Gb128 complementary sequences which are grouped into 512-bit groups labelled Gu512 and Gv512. Thus, the CEF 500 consists of two 512-bit sequences followed by $-Gb_{128}$. The Gu512 sequence and Gv512 sequence consist of a 256-bit complementary pair, denoted, respectively, as $[Ga_{256,u} \ Gb_{256,u}]$ and $[Ga_{256,v} \ Gb_{256,v}]$. For communication function, the receiver (i.e. a receiver of object 303 in the example of figure 3) uses the Gu512 and Gv512 blocks to perform two independent CSI estimations and sums the results to produce a composite CSI estimate.

[0051] With a bandwidth of 1760 MHz, the bit duration of the CEF packet 500 is

$$T_s = 1 / (1760 \times 10^6) = 5.68 \times 10^{-4} \mu s.$$

[0052] Thus, the length of the interval of each of Ga256,u, Gb256,u, Ga256,v and Gb256,v is

$$256T_s = 0.1454 \mu s$$

and the total length of the CEF packet 500 is

$$1152T_s = 0.6544 \mu s.$$

[0053] The radar signal processing (e.g. performed by radar processor 104) for radar using the CEF packet 500 is based on the dual time-frequency signal processing.

[0054] Figure 6 illustrates radar signal processing according to an embodiment.

[0055] Upon reception of the CEF packet 500, the radar processor processes the sequences Ga256,u and Gb256,u and, in parallel to this process, processes the sequences Ga256,v and Gb256,v.

[0056] Specifically, each of the received Ga256,u and Gb256,u sequences (which are delayed and have a Doppler shift with respect to the respective transmitted Ga256,u and Gb256,u sequences) are each convolved with the transmitted Ga256,u sequence and Gb256,u sequence, respectively, (in accordance with equation (1)) to determine a respective delay-Doppler map in 601 and 602. These delay-Doppler maps are summed and normalized 607 to generate a delay-Doppler map 615 (abbreviated as d-D map in figure 6) for the first preamble part (Gu512).

[0057] The sequences Ga256,v and Gb256,v sequences are transmitted using OFDM (by processing them by an inverse fast Fourier transform (IFFT) in 603 and 604 on the transmitter side). The radar processor convolves the received „OFDM Ga256,v“ and „OFDM Gb256,v“ sequences with the transmitted Ga256,v and Gb256,v sequences to determine a respective delay-Doppler map in 605 and 606. These delay-Doppler maps are summed and normalized in 608 to generate a delay-Doppler map 609 for the second preamble part (Gv512).

[0058] The delay-Doppler map 615 for the first preamble part and the delay-Doppler map 609 for the second preamble part are then combined by a point-wise minimum operation 611 to generate a final delay-Doppler map 612 wherein the delay-Doppler map 609 for the second preamble part may first be aligned in 610 if necessary.

[0059] For data communication, the receiver (e.g. of object 303) uses Gu512 and Gv512 to perform two independent channel estimations. Thus, the approach makes use of the

redundancy of the GCC sequences in the CEF packet 500 to achieve the additional radar function.

[0060] For the radar function, as described the sequences Ga256,u, Gb256,u, OFDM Ga256,v and OFDM Gb256,v are used as radar waveforms to generate the delay-Doppler map 612 delay-Doppler map, from which the radar processor estimates the parameters of the delay (and thus range) and Doppler (and thus velocity) of the targets (i.e. one or more objects).

[0061] Mathematically, denote Ga256,v and Gb256,v as $X[0], X[1], \dots, X[255]$, and the corresponding „OFDM Ga256,v“ and „OFDM Gb256,v“ as $x[0], x[1], \dots, x[255]$. Then

$$x[n] = 1/\sqrt{N} \sum_{m=0}^{N-1} X[m] \exp\left(j2\pi mn/N\right) \quad (2)$$

where $N=256$, and $n=0, 1, \dots, 255$.

[0062] The motivation behind this approach may be two-fold. First, if instead of assigning the ‘a/b’ sequence along time axis with index $T, 2T, \dots, (N-1)T$, the sequence is assigned along frequency axis with index $f, 2f, \dots, (N-1)f$, then, due to the complementary property, the first GCC pair Ga256,u and Gb256,u can be expected to clear out delay side lobes in time domain, while the second GCC pair OFDM Ga256,v and OFDM Gb256,v can be expected to clear out the Doppler side lobes in frequency domain. The summing and normalizing in 607 for example denotes the following operations:

$$AF_{\text{sum}}(k, \omega) = |AF_{\text{Ga256,u}}(k, \omega) + \omega^N AF_{\text{Gb256,u}}(k, \omega)| \quad (3a)$$

$$AF_{\text{sum,norm}}(k, \omega) = AF_{\text{sum}}(k, \omega) / \text{Max}(AF_{\text{sum}}(k, \omega)) \quad (3b)$$

where $AF_{\text{Ga256,u}}(k, \omega)$ and $AF_{\text{Gb256,u}}(k, \omega)$ are the AFs of the sequences of Ga256,u and Gb256,u, respectively, $\omega = e^{-j2\pi k/N_s}$, and N_s is the length of the oversampled sequence of Ga256,u or Gb256,u.

[0063] In other words, the summation of the two delay-Doppler maps may be a “composite sum” as shown by Equation (3a), instead of “normal” summation. By using composite sum, the main lobe width on the 0 delay cut of the AF can be reduced to half of it (see Figures 7B and 7C described below).

[0064] For the OFDM GCC part in Fig 5, the $AF_{Ga256,u}(k, \omega)$ and $AF_{Gb256,u}(k, \omega)$ in equation (3a) are replaced by $AF_{OFDM,Ga256,v}(k, \omega)$ and $AF_{OFDM,Gb256,v}(k, \omega)$ respectively.

[0065] Second, if the delay-Doppler maps for the two preamble parts are further combined via an appropriate operation, it can be expected that the resulting final delay-Doppler map will have better performance. The combining operation is in this embodiment the point-wise minimum selection operation in 611. This means that after a possible alignment in 610 of the delay-Doppler map for the second preamble part 609 the final delay-Doppler map 612 is created by performing point-wise minimum processing on the delay-Doppler map for the first preamble part 615 and the delay-Doppler map for the second preamble part 609, i.e., for a delay-Doppler bin, if the magnitude of the value of the delay-Doppler map for the first preamble part 615 (shown as first square 613) is smaller than that of the delay-Doppler map for the first preamble part 609 (shown as second square 614), the corresponding delay-Doppler bin in the final delay-Doppler map 612 will have the value of the delay-Doppler map for the first preamble part 615 and vice versa. A rationale behind this operation may be as follows: if a target is truly present, it will be present in both delay-Doppler map for the first preamble part 615 and delay-Doppler map for the second preamble part 609. Therefore, by selecting the point-wise minimum between the two delay-Doppler maps, one will get a significant response only if there is a response in both delay-Doppler maps. The side lobe response will be attenuated if the side lobe structure of radar waveforms used to generate the two delay-Doppler maps are disunited.

[0066] As discussed before, in radar waveform design, the ideal impulse AF that is completely free of side lobe over the entire delay and Doppler domain is impossible. Typically the design of an approach that can generate a “thumbtack-like” AF is the main focus. This is because in practical application, it is usually sufficient to have an ambiguity response that is “thumbtack-like” inside the delay-Doppler region that is of interest for radar illumination and imaging. The min-point GCC AF as achieved by the approach of figure 6 not only exhibits a “thumbtack-like” shape, but also generates zero-side lobe zones. In particular, a side lobe-free zone inside a delay-Doppler region around the origin can be achieved. Therefore, the approach of figure 6 with the resulting min-point GCC

delay-Doppler map 612 leads to improved radar sensing which makes only use of two pairs of GCC in preamble CEF with minimum frame structure modification, while allowing the same GCC pairs to be used for CSI estimation of communication function. In this sense, this “radar-communication” co-design may provide a unified platform for future joint V2X communication and automotive radar sensing.

[0067] Figures 7A, 7B and 7C show an AF comparison of an LFM chirp used in automotive radar, an IEEE 802.11ad design and the min-point GCC approach of figure 6, respectively. Unlike the AFs 702, 703 with a “thumbtack-like” shape shown in figure 7B (peak-to-max-side lobe ratio=2.2867, $N = 256, N_s = 512$) and 7C (peak-to-max-side lobe ratio=6.9832, $N = 256, N_s = 512$), respectively, the AF 701 for the LFM chirp shown in figure 7A exhibits a slowly decay diagonal ridge. The AF volume is essentially concentrated at the area of this ridge region, leading to very lower side lobes outside the ridge region. However, one drawback of the LFM chirp is that relatively strong side lobes remain in the autocorrelation function along the zero-Doppler cut of AF. This reveals that LFM chirp cannot serve well as the preamble for channel impulse response extraction for communication functions. As pointed out before, one emphasis of radar waveform design is on the side lobe relative to the main lobe in AF plotting. Comparing figure 7C with figure 7B, it can be seen that the min-point GCC AF has a significant performance improvement over the AF of IEEE 802.11ad. Further, it can be shown that both zero Doppler cut and zero delay cut of the min-point GCC AF are impulse function with no side lobe, i.e., the side lobe has been completely annihilated. It is worthwhile to stress that although Ga256,u and Gb256,u in Gu512 and Ga256,v and Gb256,v in Gv512 are complementary pairs, the sequences Gu512 and Gv512 are not complementary to each other.

[0068] According to various embodiments, the performance of the min-point GCC approach can be further improved by exploiting delay-Doppler fusion with communication single-carrier data. The resulting improvement is two-fold. First, it can further suppress the side lobe; second, it helps improving Doppler resolution.

[0069] Figure 8 illustrates radar processing using delay-Doppler map fusion between a delay-Doppler map 801 generated by min-point GCC (as described with reference to figure 6) and delay-Doppler maps 802, 803, 804 generated from communication single-

carrier data. The fusion (combination) of the delay-Doppler map 801 generated by min-point GCC with the delay-Doppler maps 802, 803, 804 generated from communication single-carrier data happens sequentially according to a sequence of point-wise minimum selection operations 805, 806, 807.

[0070] Each point-wise minimum selection operation 805, 806, 807 combines the delay-Doppler map generated by min-point GCC or resulting from a previous one of the point-wise minimum selection operations, with a respective delay-Doppler map 802, 803, 804 generated from a communication single-carrier data (i.e. by radar processing of the echo of a communication single-carrier data segment of the data 404 in the frame 400).

[0071] Typically, the single-carrier data packet 404 is much longer than the CEF preamble 402. Therefore, the single-carrier data packet 404 is divided into the multiple segments and the delay-Doppler map fusion is implemented in this successive manner.

[0072] Specifically, the delay-Doppler map from min-point GCC is first generated. The entire single-carrier data packet 404 is then divided into single-carrier data segments, and the delay-Doppler map 805, 806, 807 for each single-carrier data segment is generated (e.g. similarly as generating a delay-Doppler map from a GCC sequence). The delay-Doppler map fusion is performed successively as described above until all single-carrier data segments (i.e. all delay-Doppler maps 805, 806, 807 generated from single-carrier data segments) have been utilized.

[0073] As indicated in figure 4, there are four types of data constellations that can be utilized, namely, BPSK, QPSK, 16QAM and 64QAM for the frame 400. Simulations show that the four modulation schemes have the same ensemble AF performance measured by various metrics such as peak side lobe, average side lobe, peak-to-peak-side lobe ratio and so on. Thus, without loss of generality, 16QAM is chosen in the following examples as the data modulation.

[0074] Figure 9 shows the results of three iterations of delay-Doppler fusion starting from the AF for min-point GCC (shown in a first diagram 901). The GCC bit interval and data symbol duration are set to the inverse bandwidth. The sequence length of GCC and each 16QAM is 256. This implies that three separate segments of 256-length data sequences are used in the delay-Doppler map fusion. The diagrams 902, 903, 904 show

the resulting AFs after fusion with one, two and three single-carrier data segment(s), respectively.

[0075] It can be seen that as the fusion iteration increases, the performance of the fused AF improves. This can be quantified by the measurement of the peak-to-max-side lobe ratio, which increases from 6.9832 in initial min-point GCC AF to 11.3251 after delay-Doppler map fusion with three data segments. It should be noted that although 16QAM is adopted here for delay-Doppler map fusion, the simulation results show that other signal constellations such as BPSK, QPSK and 64QAM can also be used, and the same conclusion can be drawn. This is important as it states that the AF fusion process does not impose a restriction on the data modulation schemes adopted in communication.

[0076] The Doppler resolution can also be further improved by fusing the (oversampled) delay-Doppler map of the 256-length min-point GCC approach with the delay-Doppler map of a longer data sequence (e.g., length of $n \times 256$ where n is the oversampling rate).

[0077] Figure 10 illustrates the fusion of the delay-Doppler map generated from a single-carrier data segment with more than 256 bit with a delay-Doppler map generated from a CEF as illustrated in figure 5 in the manner of figure 6.

[0078] In figure 10, the solid square markers represent the sampling point along the delay axis 1001 for generating a delay-Doppler map using min-point GCC whereas the solid circle marker represent the sampling points for generating a delay-Doppler map from a single-carrier data segment along the delay axis 1001. It should be noted that along the delay axis 1001, the sampled interval for the GCC sequence (i.e., the interval between two solid squares) is the same as the sampled interval for the data sequence (i.e., the interval between two solid circles) because both are equal to the inverse bandwidth. (Since the GCC packet 500 is shorter than the single-carrier data segment in this example, the total interval of GCC is shorter than that of the single-carrier data segment).

[0079] On the other hand, in the Doppler domain, oversampling is used for generating the delay-Doppler map using min-point GCC for the following reason: suppose that the GCC length is T and the data length is $4T$ as shown in figure 10 (i.e., single-carrier data segment length is assumed to be four times of the length of the GCC packet 500). Then, the GCC Doppler resolution is equal to $1/T$ (the duration indicated by the distance between two solid upward-oriented triangles along the Doppler axis 1002 in figure 10),

whereas the data Doppler resolution is equal to $1/4T$ (the duration indicated by the distance between two solid downward-oriented triangles along the Doppler axis 1002 in figure 10). Therefore, in order to align the two AF diagram grids so that the point wise minimum operation can be used for delay-Doppler map fusion, oversampling four times in the Doppler domain for the delay-Doppler map generated using min-point GCC is performed. In figure 10, these oversampling points are denoted by the empty upward-oriented triangles along the Doppler axis 1002.

[0080] Figure 11 shows in a first diagram 1101 a plot of the AF for length-256 min-point GCC and in a second diagram 1102 the fused AF with length-8192 data (i.e., $8192=256 \times 32$ with oversampling rate 32). Without loss of generality, 16QAM is assumed for data modulation.

[0081] Figure 12 shows a graph 1200 indicating the zero-delay cut of the plot of the diagrams 1101, 1102.

[0082] It can be seen that with delay-Doppler map fusion the Doppler main lobe of min-point GCC is much narrowed, which shows that the Doppler resolution performance is improved. Although an alternative way to improve the Doppler resolution is to construct longer GCC pairs, there is a clear disadvantage in using longer GCC pairs. It is seen from figure 4 that longer GCC will lead to more CEF overhead and result in poor throughput and energy efficiency. This overhead can be avoided by using delay-Doppler map fusion with delay-Doppler maps generated from data of the single-carrier data packet 404. Although the Doppler side lobe of 16QAM sequence is not exactly zero because the communication data is random and changes from frame to frame, numerical simulation shows that the first side lobe magnitude is at about -23 dB, which is very low. Thus, the Doppler resolution is 32 times narrower and the first side lobe is -23 dB below the main lobe.

[0083] In the above examples, AF performance and Doppler resolution have been described for the single-target case. In the following, the corresponding performance for a multi-target scenario is described. It may be studied using the delay-Doppler response of the radar sensor. Unlike the single-target case, the radar echo for the sensing signals Ga256u, Gb256u, OFDM Ga256v and OFDM Gb256v case is a summed as well as overlapped waveform in the multi-target.

[0084] Figure 13 illustrates the overlapping of received echoes 1301, 1302, 1303 of a transmitted CEF packet 402 for a three-target case. The radar processor convolves the resulting received overlapped waveform with each of Ga256u, Gb256u, OFDM Ga256v and OFDM Gb256v, correspondingly, to generate four respective 2D delay-Doppler maps. The radar processor creates a delay-Doppler map for the first preamble part by processing (Equation (3a) and (3b)) of the first delay-Doppler map (for Ga256u) and the second delay-Doppler map (for Gb256u) and a delay-Doppler map for the second preamble part by processing (Equation (3a) and (3b)) of the third delay-Doppler map (for OFDM Ga256v) and the fourth delay-Doppler map (for OFDM Gb256v).

[0085] The radar processor generates the final delay-Doppler response (i.e. the final delay-Doppler map) by the point-wise minimum process described above, i.e., the final delay-Doppler response bin value for a delay-Doppler bin is the minimum between the values of the delay-Doppler map for the first preamble part and the delay-Doppler map for the second preamble part of that delay-Doppler bin (as described above in context of figure 6). The delay-Doppler map allows seeing how far the targets (reflectors) are and how quickly they are approaching or receding with respect to the radar-transmitting vehicle.

[0086] In Figure 13 it is illustrated that the echoes 1301, 1302, 1303 arrive at the radar sensor with different delays, each with different line types representing different Doppler frequency (reflector velocity).

[0087] Figure 14 shows the delay-Doppler map (delay-Doppler response) 1400 generated for this three target case using min-point GCC with length 256 bit.

[0088] The result shows that the min-point GCC algorithm works well in such a scenario: the radar processor can successfully distinguish the three targets although their radar signal echoes are interfering with each other severely.

[0089] Figure 15 shows a performance comparison between IEEE 802.11ad and an embodiment (consisting of time-frequency GCC radar signals, point-wise minimization radar processing, and delay-Doppler map AF fusion). A first diagram 1501 shows the AF plot of IEEE 802.11ad and a second diagram 1502 shows a zoom-in view of the second diagram of 1501. For the purpose of comparison, the coordinate scale and denotations are similar. Specifically, t denotes delay, T_s is the bit duration, n denotes Doppler shift, and

$T_p = 512T_s$. The second diagram 1502 demonstrates a large improvement in Doppler resolution. Moreover, comparing with the first diagram 1501 Fig.14, the AF side lobes in Fig.15 are extremely low.

[0090] Figure 16 illustrates another three-target scenario. A stationary vehicle 1601 (e.g. corresponding to vehicle 100) a radar signal R and the vehicles 1602, 1615 and 1604 (assumed to have the same range R , but moving differently with respect to the stationary vehicle 1601) reflect the radar signal and return radar echoes 1605, 1606, 1607, respectively, with zero, positive and negative Doppler shifts.

[0091] Figure 17 shows the corresponding delay-Doppler response in the presence of three targets for IEEE 802.11ad (first diagram 1701) and for the min-point GCC approach according to an embodiment (second diagram 1702). It can be seen from the first 1701 diagram that the radar device is not able to resolve the multiple targets in that case. This means that the stationary vehicle 1601 cannot sense the three vehicles 1602, 1603, 1604, in that case while the using the min-point GCC approach the stationary vehicle 1601 can sense the three vehicles 1602, 1615, 1604 as can be seen from the second diagram 1702.

[0092] In summary, according to various embodiments, a radar device is provided as illustrated in figure 18.

[0093] Figure 18 shows a radar device 1800 according to an embodiment.

[0094] The radar device 1800 comprises a transmitter 1801 configured to transmit a first transmit signal and, after the first transmit signal, a second transmit signal, wherein the first transmit signal comprises at least a part of a preamble of a communication packet, and a receiver 1802.

[0095] The radar device further comprises a radar processor 1803 configured to

- convolve a first receive signal received by the receiver with the first transmit signal and to generate a first delay-Doppler map, comprising, for each delay-Doppler bin of a set of delay-Doppler bins, a radar response value, from the result of the convolution of the first receive signal with the first transmit signal;
- convolve a second receive signal received by the receiver with the second transmit signal and to generate a second delay-Doppler map, comprising, for each delay-Doppler bin of the set of delay-Doppler bins, a radar

response value, from the result of the convolution of the second receive signal with the second transmit signal;

- combine the first delay-Doppler map with the second delay-Doppler map by taking, for each delay-Doppler map bin of the set of delay-Doppler bins, the minimum of the value of the first delay-Doppler map for the delay-Doppler map bin and the value of the second delay-Doppler map for the delay-Doppler map bin; and
- determine the range and velocity of objects from the result of the combination.

[0096] According to various embodiments, in other words, delay-Doppler maps are generated from different signals (e.g. a time-domain signal and a frequency-domain signal or a channel estimation packet and one or more single-carrier data packets) and the delay-Doppler maps are combined using a min-point approach, i.e. by taking the point-wise (i.e. bin-wise) minimum of the two delay-Doppler maps.

[0097] For each delay-Doppler map bin, the value of the first delay-Doppler map for the delay-Doppler map bin and the value of the second delay-Doppler map are normalized and/or absolute values.

[0098] According to various embodiments, a method is provided as illustrated in figure 19.

[0099] Figure 19 shows a flow diagram 1900 illustrating a method for radar detection.

[00100] In 1901, a first transmit signal is transmitted, wherein the first transmit signal comprises at least a part of a preamble of a communication packet.

[00101] In 1902, a second transmit signal is transmitted after the first transmit signal.

[00102] In 1903, a first receive signal is received (with a timing such that it can be expected to receive echoes of the first transmit signal reflected by objects to be detected).

[00103] In 1904, a second receive signal is received (with a timing such that it can be expected to receive echoes of the second transmit signal reflected by objects to be detected).

[00104] In 1905, the first receive signal is convolved with the first transmit signal and a first delay-Doppler map is generated, comprising, for each delay-Doppler bin of a set of

delay-Doppler bins, a radar response value, from the result of the convolution of the first receive signal with the first transmit signal.

[00105] In 1906, the second receive signal is convolved with the second transmit signal and a second delay-Doppler map is generated, comprising, for each delay-Doppler bin of the set of delay-Doppler bins, a radar response value, from the result of the convolution of the second receive signal with the second transmit signal.

[00106] In 1907, the first delay-Doppler map is combined with the second delay-Doppler map by taking, for each delay-Doppler map bin of the set of delay-Doppler bins, the minimum of the value of the first delay-Doppler map for the delay-Doppler map bin and the value of the second delay-Doppler map for the delay-Doppler map bin.

[00107] In 1908, the range and velocity of one or more objects are determined from the result of the combination.

[00108] It should be noted that the order of the processing does not necessarily need to follow the order shown in figure 19. For example, the first delay-Doppler map may be generated before or while receiving the second receive signal.

[00109] The components of the radar device 1800 and the method of figure 19 may be implemented by one or more circuits. In an embodiment, 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. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a "circuit" in accordance with an alternative embodiment.

[00110] According to a first embodiment, a method for transmitting and receiving data using dual time-frequency Golay complementary code (GCC) for both time and frequency is provided comprising:

- i) a first GCC pair of Ga sequence and Gb sequence is transmitted in time domain using single-carrier (SC) modulation;
- ii) a second GCC pair of Ga sequence and Gb sequence is transmitted in frequency domain using Orthogonal frequency-division multiplexing (OFDM) modulation; and
- iii) SC GCC (step i) and OFDM GCC (step ii) are transmitted sequentially.

[00111] According to a second embodiment, a method for reception using radar sensing based on minimum-point GCC selection according to the first embodiment is provided, comprising

- i) computing a first ambiguity function (AF) based on the SC GCC pair;
- ii) computing a second AF based on the OFDM GCC pair;
- iii) aligning the second AF in the delay-Doppler domain;
- iv) obtaining a final AF (minimum-point GCC AF) using a point-wise minimum selection between the first AF (step i) and the second AF (step iii).

[00112] The radar scheme described requires a minimum modification to the communication frame structure. The combination of SC GCC, OFDM GCC, and point-wise minimum processing provide a significant and unique performance improvement for automotive radar sensing.

[00113] According to a third embodiment, a method of using ambiguity function (AF) fusion to suppress side lobes and increasing Doppler resolution in data communication is provided comprising

- i) treating a communication single-carrier data packet as additional radar waveform segment wherein the single-carrier data packet is random but known to a transmitting vehicle;
- ii) computing a communication single-carrier data AF;
- iii) implementing AF fusion between the minimum-point GCC AF and the communication single-carrier data AF by the point-wise minimum selection process according to the method of the second embodiment;
- iv) dividing the single-carrier data packet into a plurality of single-carrier data segments, and repeating the operation (in step iii) for every single-carrier data segment in single-carrier data packet.

[00114] While specific aspects have been described, 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 spirit and scope of the aspects of this disclosure as defined by the appended claims. The scope 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.